RESIDUAL EFFECTS OF FERTILIZER PHOSPHORUS
AS MEASURED BY
CROP YIELDS, PHOSPHORUS UPTAKE, AND SOIL ANALYSIS

A Thesis

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MASTER OF SCIENCE

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ABSTRACT

Field and greenhouse experiments were conducted on a calcareous soil to investigate the long-term effects of large amounts of applied phosphorus on crop yields, phosphorus uptake, and water and $NaHCO_3$ extractable soil phosphorus. The effects of broadcast and seed drilled phosphorus on crop yields and phosphorus uptake were also determined.

It was found that wheat responded well to applied phosphorus; seed drilled phosphorus was more effective in increasing the yields of wheat than was broadcast phosphorus. Small amounts of phosphorus had to be added with the seed even on the plots receiving large amounts of broadcast phosphorus in order to obtain maximum yields of wheat. Phosphorus uptake by wheat increased with increased rates of either broadcast or seed drilled phosphorus. In contrast, flax was not responsive to applied phosphorus. Seed drilled phosphorus in combination with large amounts of broadcast phosphorus decreased the yields of flax. Phosphorus uptake by flax, however, was increased by applied phosphorus.

The studies also indicated that phosphorus added in large amounts not only benefited the crop fertilized but remained available for succeeding crops as well. Barley grown in 1968 responded to broadcast applications of phosphorus made in 1966. However, small amounts of seed drilled phosphorus were needed even on the plots previously broadcast with large amounts of fertilizer phosphorus in order to obtain maximum yields of barley. Phosphorus uptake by barley was also increased by either previously broadcast or seed drilled phosphorus.

Greenhouse studies showed that the degree of yield responses to previously and newly applied phosphorus varied with plant species; and was found to increase in the order of flax, barley, rape. Barley and rape

showed a better response to newly applied phosphorus than to the previously added phosphorus. Flax, however, showed a better response to previously applied phosphorus than to the newly added phosphorus.

It was found that the $NaHCO_3$-extractable phosphorus content of the soil was increased by broadcast phosphorus applications for a number of years.

Solubility studies indicated that the prominent reaction product of monocalcium phosphate applied broadcast was probably octacalcium phosphate. This reaction product was found to exist in soils for a period of at least three years, and was available to plants.

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I. INTRODUCTION

The need for adding fertilizer phosphorus to Western Canadian soils in order to achieve high yields has been widely recognized and problems connected with its efficient use have prompted scores of investigations. In spite of this interest a thorough understanding of the factors affecting soil and fertilizer phosphorus availability has not been attained. In fact, the multitude of different reaction products that phosphorus enters into with soils has made it difficult to characterize in the soil and to assess its availability to plants. A more complicated task in evaluating the availability of applied phosphorus appears from the fact that its availability is determined by many soil, fertilizer and plant factors.

Since Manitoba contains large acreages of calcareous soils, a large number of experiments with phosphorus fertilizers have been conducted on soils containing carbonates. Undoubtedly the ultimate value of these investigations is their use in making recommendations to farmers concerning phosphorus fertilizer use.

Fertilizer phosphorus applied to calcareous soils has been found to be available to plants for a long period of time (13, 15). Solubility studies applied to soil phosphate systems have also supported this conclusion (8, 70). Soil fertility investigations have indicated that fertilization with phosphorus not only increases the yield of the crop fertilized, but also has a great influence on the yields of succeeding crops (22, 36). The findings that the recovery of fertilizer phosphorus by the first crop grown is far from complete, that most phosphorus not found in the harvested crops remains in the plow layer, and that the applied phosphorus remains available for a long time essentially account for the residual behavior of applied phosphorus.

In so far as fertilizer recommendations are concerned, rates and methods of application are of particular importance. In general, drilling fertilizer phosphorus with the seed has been found to be superior to a broadcast application (19, 40, 43, 74). Based on this evidence, farmers in Manitoba have been recommended to apply fertilizer phosphorus with the seed, at rates up to 40 lb. P_2O_5 per acre. However, broadcasting large amounts of fertilizer phosphorus in order to bring soils rapidly to an acceptable level of available phosphorus may be a desirable practice if maximum yields on extremely phosphate deficient soils are to be attained.

Since experimental data on the efficiency of broadcast and seed drilled applications of phosphorus fertilizers for crops grown in Manitoba are rather limited, and there is considerable agronomic evidence that rather large applications of phosphorus are needed on calcareous soils with low native phosphorus content, field and greenhouse experiments were designed to determine:

1. The effects of broadcast and seed drilled phosphorus on crop yields and phosphorus uptake.
2. The long-term effects of large amounts of applied phosphorus on crop yields, phosphorus uptake, and water and $NaHCO_3$ extractable phosphorus.

II. REVIEW OF LITERATURE

An extensive review of the literature by Olsen (51) indicates that various forms of calcium phosphate predominate in calcareous soils. Hydroxyapatite was the most stable form found. Recently, Weir and Soper (79) applied the concept of chemical potentials in studying the form of soil phosphate present in some calcareous Manitoba soils and found the solubility of soil phosphate to approximate that of octacalcium phosphate ($Ca_4H(PO_4)_3 \cdot 3\ H_2O$), which is more soluble than hydroxyapatite but less soluble than dicalcium phosphate dihydrate. These workers believed that either octacalcium phosphate or dicalcium phosphate dihydrate govern the phosphate solution concentration in calcareous soils.

Solubility product principles applied to soil phosphate systems as a means of characterization of the reaction products have in general supported the conclusion that some crystalline phosphate compounds of calcium and magnesium are the reaction products of phosphate applied to calcareous soil systems. It has been shown that when monocalcium phosphate is added to soils, dicalcium phosphate dihydrate is the initial reaction product (34, 37, 38, 39). Lehr and Brown (34) also showed that dicalcium phosphate dihydrate was slowly transformed, through hydrolysis, to octacalcium phosphate and finally to hydroxyapatite. An investigation conducted on a calcareous Saskatchewan soil by Beaton _et al_. (3) using infra-red absorption analysis showed that dicalcium phosphate dihydrate forms when a soluble phosphate, acid in reaction, is added to a calcareous soil. Other workers (8, 35) found the same phosphate reaction product when phosphate fertilizers of high water solubility, such as concentrated superphosphate and monocalcium phosphate, were applied to soils.

Brown and Lehr (8) showed that dicalcium phosphate dihydrate formed both at the site of application due to hydrolysis, and in the soil immediately surrounding it, and that this phosphate persisted in soils for a long period of time. Racz and Soper (60) showed that soils having a water soluble calcium to magnesium ratio of approximately 1.5 or less precipitated added phosphate as dimagnesium phosphate trihydrate and trimagnesium phosphates in addition to the calcium phosphates usually found. Investigations on the solubility of H_3PO_4, KH_2PO_4, and K_2HPO_4 added to four Manitoba soils also showed that the added phosphorus was probably precipitated as dicalcium phosphate dihydrate and dimagnesium phosphate trihydrate (61). These authors suggested that phosphorus added to these soils would be readily available to plants, since both reaction products, dicalcium phosphate dihydrate and dimagnesium phosphate trihydrate, were relatively soluble.

The initial phosphate reaction products such as dicalcium phosphate dihydrate are metastable. With time, the phosphate compounds initially formed react with the soil solution to form less soluble phosphates. However, the conversion of the relatively soluble phosphates to less soluble forms is very slow. It has been reported that two or three years may be required in soils before the initial reaction product is fully converted to less soluble forms (51). Since the initial reaction products which are relatively soluble are converted to less soluble forms, the rate at which phosphorus reacts with calcium and magnesium in the soil and subsequent changes in the forms of phosphorus would affect not only the availability of recently added phosphorus, but also its residual value in soils.

Adsorbed and other forms of phosphorus in soils are also increased by phosphorus fertilization (51, 66) and they are found to be available to plants (31, 36).

Lewis et al. (36) reported that phosphate fixation in calcareous soils was not as significant a factor of time and placement of fertilizer phosphorus as in acid soils. In studying the content of available phosphorus in calcareous soils of Central Asia, Chumachenko (13) indicated that phosphorus added to these soils remained in a form available to plants for a long period of time.

Elbagouri (15) investigated the effect of soil carbonate on the availability of added and native phosphorus in some calcareous Manitoba soils and concluded that soil carbonate content was not a criterion of their phosphorus supplying power, and phosphorus added to these soils was readily available to plants regardless of the $CaCO_3$ content of the soils. Added phosphorus remained available for a considerable period of time despite the gradual reduction in its availability.

The amounts of phosphorus extracted from soils by chemical extractants have been widely used in assessing the availability to plants of phosphorus in soils. Many chemical extractants have proven to be very useful in assessing fertilizer phosphorus requirements for various crops. Among the various procedures, a method employing 0.5 M $NaHCO_3$ as an extracting solution (52) has been found to aid in predicting the phosphorus requirements as determined by crop responses to applications of fertilizer phosphorus (15, 20, 23, 25, 41, 52, 53, 72, 80, 81). Bingham (4) reported that the $NaHCO_3$ method was applicable, especially for neutral and alkaline soils. Martin and Mikkelsen (42) found H_2O and $NaHCO_3$ extractants to be reliable for measuring phosphorus available to grain crops planted on a wide variety of acid-to-alkaline soils in California. Robertson (64) compared an acid and an alkaline extracting solution for measuring available phosphorus in 79 Alberta soils. Of these soils, 23 had pHs above 7.0 and 18 contained free $CaCO_3$. He found that both acid (0.03 N NH_4F + 0.03 N H_2SO_4) and alkaline (0.5 M $NaHCO_3$) extractable phosphorus were highly correlated with barley growth in the greenhouse; the correlation coefficient for percent yield and available phosphorus by the $NaHCO_3$ method was slightly higher than that for percent yield and available phosphorus by the NH_4F + H_2SO_4 method. Seatz and Stanberry (67) made a comprehensive review of literature on the reliability of chemical methods in assessing phosphorus availability and reported better results with extractants other than $NaHCO_3$.

Field and greenhouse studies were conducted by Olson et al. (54) during a 5-year period comparing phosphate fertilizer carriers for small grains over a wide range of Nebraska soil conditions. Comparative effectiveness of phosphate carriers was found to be: ammonium phosphate $\geq$ concentrated superphosphate $\geq$ ordinary and ammoniated superphosphate, metaphosphate and high solubility nitric phosphate $>$ low solubility nitric and fused tricalcium phosphates $>$ rock phosphate. They also stated that effective placement and fertilizer nitrogen were prime factors in promoting efficient utilization of phosphate carriers. In general, phosphate fertilizers with high water solubility proved superior in calcareous soils to those with low water solubility (1, 76). Rogers et al.(65) reported that mono-, di-, and tricalcium phosphates ranked in the order named in effectiveness on alkaline and calcareous soils. They also indicated that the ammonium phosphates appeared unusually well adapted for use on alkaline or calcareous soils because of their high solubility, combination of nitrogen and phosphorus of which both are freqhently needed, and residual acidity. An investigation by Rennie and Soper (62) showed that a marked increase in phosphorus utilization occurred only when the nitrogen added was in the ammonium form. They explained that the ammonium ion indirectly influenced the plant's ability to take up phosphorus rather than altering in any way the availability of the applied phosphorus.

The effect of physical forms of fertilizer material on the availability of phosphorus was also investigated (25). Superphosphate in granular and powder forms were compared in four typical Israeli agricultural soils, three of which were alkaline and calcareous. The results showed that under greenhouse conditions no difference in efficiency was found between these two forms.

Broadcasting phosphorus fertilizers on the soil surface followed by adequate incorporation during seedbed preparation is one of the cheapest and most effective methods of phosphorus application in alkaline soils (67, 69). Webb _et al_. (76) found that on calcareous soils a highly water soluble source of phosphorus, such as concentrated superphosphate, was likely to be more effective as a broadcast application for corn than were most slightly soluble sources. Fine and Carson (19), however, showed that phosphate application with the seed was approximately twice as effective as a broadcast application. Lutz _et al_. (40) concluded from their study of rate and placement of phosphorus for small grains in eleven experiments in Georgia, Mississippi, and Virginia that broadcasting 40 lb. P_2O_5 per acre was 42% as effective as application with the seed. Rates higher than 40 lb. with the seed caused yield reduction in some experiments, presumably because of seedling injury. Mattingly and Widdowson (43) reported that the percentage recovery of phosphorus from superphosphate drilled in with the seed was greater at all stages of growth of barley than from superphosphate broadcast on the seedbed. Both drilled and broadcast superphosphate increased the uptake of soil phosphorus by barley during the early stages of growth. At harvest, however, there was less soil phosphate in crops receiving superphosphate than in the unfertilized crops. The superiority of seed drilled to broadcast applications of phosphorus fertilizers has also been reported by Vavra and Bray (74). Generally, the method of placement is not as critical in determining the efficiency of the fertilizer on calcareous soils as on acid soils (67).

Plant species and even varieties differ greatly in their ability to obtain sufficient phosphorus from soils testing low in extractable phosphorus (21, 50, 66, 67). Racz et al. (59) reported from a comparison of a variety of field crops in Manitoba that plant species also varied in their response to more soluble phosphates. Only rape responded to applications of phosphate fertilizer applied alone and in combination with nitrogen when flax, rape, and a cereal crop were grown within one experimental plot. Further investigations conducted on the phosphorus and nitrogen utilization by rape, flax, and wheat also gave similar results, i.e. fertilizers containing nitrogen and/or phosphorus produced greater yield increases of rape than of wheat or flax. They explained that it was probably due to the more rapid uptake and the greater requirement of rape for these elements. Investigations by Webber (77) on the phosphorus feeding habits of flax, cereals, and rape showed that for plants grown in the greenhouse in phosphorus deficient soils, the ratio of soil phosphorus to fertilizer phosphorus contained in the plant tissue was in the order: flax > wheat > rape. Mitchell et al. (47) obtained varietal differences in response to phosphate fertilizer by barleys. These differences were not accompanied by a significant difference in uptake of soil or fertilizer phosphorus. Barley showed a significantly greater ability to utilize the applied phosphorus than wheat, but there was no significant difference between wheat and oats, or barley and oats. A greenhouse experiment was conducted by Kalra and Soper (30) to determine the phosphorus requirements of rape, oats, soybeans, and flax at various stages of growth. Radioactive phosphorus was used in order to differentiate between the amount of phosphorus derived from the fertilizer and from the calcareous soil. The results showed that "A" values differed amongst these crops and at different stages of growth for the same crop. The "A" values decreased in the order soybeans, flax, oats, and rape. They indicated that soybeans were much more efficient than rape, oats, and flax in extracting soil phosphorus. For most of the growth cycle rape and flax were similar in absorbing phosphorus from the soil and in this respect oats were less efficient, except for the last two stages of growth. It appeared that the differences amongst the "A" values of rape, oats, and flax were largely due to differences in their abilities to extract fertilizer phosphorus.

Results from 433 experiments in the United States, summarized by Terman (71) indicated that crop responses to phosphate fertilizers were obtained in 71% of the tests, and legume-grass hay and small grains showed greater response than cotton and corn. In general, phosphorus uptake by responsive crops increased with increasing rates of fertilizer. Mitchell et al. (46) reported that the phosphorus uptake by wheat was increased by the applied phosphorus. Boatwright and Haas (6) showed that fertilization increased phosphorus uptake by the whole wheat plant from emergence until maturity. Maximum phosphorus uptake on all fertilizer treatments and differences in total phosphorus absorption attributable to fertilizers occurred at heading. As plants matured, phosphorus uptake was reduced. Apparently wheat plants absorbed all of their phosphorus prior to heading. In a review of work done in Saskatchewan, Dion et al. (14) reported that although the wheat plant took up phosphorus from soil and fertilizer until maturity, the main absorption of fertilizer phosphorus took place well before the plant matured. The average recovery from small applications of phosphorus fertilizer (11-48-0) by wheat was about 22%. The percentage recovery tended to decrease as the rate of application increased, although the actual amount of phosphorus taken up from the fertilizer may increase. In early stages of growth, the larger amount of phosphorus taken up by the plant was obtained from the fertilizer; thereafter the soil supplied the greater portion. In some cases, the fertilized wheat may use greater amounts of soil phosphorus than the unfertilized crop where light applications were the practice. However, for heavier applications the reverse appeared to hold true. Halstead et al. (26) found from greenhouse experiments that the uptake of phosphorus by alfalfa increased with increasing rates to 2000 lb. P_2O_5 per acre. The average phosphorus content of the first crop increased from 0.18% without superphosphate to 0.54% with 2000 lb. P_2O_5 per acre.

In general, less than one-fourth of the fertilizer phosphorus applied to soils is absorbed by the first crop grown (48,66). The residual portion is not subject to any appreciable leaching, and thus accumulates in the plow layer. Both total inorganic and extractable phosphorus contents of soil are increased by phosphorus fertilization (18, 56, 63, 66, 68, 72, 78).

Not only does phosphorus fertilization increase the yield of the crop fertilized, but the yields of succeeding crops are influenced as well (22, 36). As a result of a large number of investigations conducted on the nature of soil phosphorus and phosphorus fertilizer use, the residual behavior of applied phosphorus has been recognized. Olsen (51) states that the residual value of applied phosphate is greatest in neutral soils, somewhat less in alkaline and calcareous soils, and least in acid soils.

In studying nitrogen and phosphorus fertilization for production of crested wheatgrass and native grass in alkaline and calcareous soils in Northeastern Montana, Black (5) reported that nitrogen and nitrogen-phosphorus fertilization, with rates varying from 0 to 45 kg. N/ha. and 0 to 43 kg. P/ha., consistently increased forage yields of both grasses. Plant responses were greatest the year of fertilization, but residual effects were significant one to two years later. Plant phosphorus content was increased substantially by applied phosphorus the year of application and three years later, regardless of nitrogen treatment.

Campbell (11) measured residual effects for eight years of 0, 26, 52, 105, and 210 lb. P per acre applied for barley in a six-year rotation of barley, three years alfalfa, corn, and sugar beets grown on calcareous Thurlow clay loam at Huntley, Montana. Amounts of P removed by crops in 9 years totaled 96, 109, 124, 136, and 179 pounds, respectively. Corresponding recoveries of applied P were 49, 54, 38, and 40%. Most of the phosphorus from the 26 lb. P per acre application was used in four years. Residual response, over the entire period, increased with higher rates. It was also shown that residual phosphorus soluble in $NaHCO_3$ decreased with continued crop removal of applied phosphorus. Carlson _et al_. (12) evaluated the effect of nitrogen and phosphorus fertilization on crop yield under irrigation in both a non-legume rotation (barley, corn, potatoes) and a legume rotation (barley, three years alfalfa, corn, potatoes) on Gardena loam at Upham, North Dakota. They reported that phosphorus was available to potatoes five years after it was added to barley. Ensminger and Pearson (18) found a considerable effect from phosphate fertilizers, and reported that accumulation of total acid soluble and absorbed phosphorus was proportional to the rate of phosphorus applied. Fuller and McGeorge (22) showed that the phosphorus added to calcareous Arizona soils was not all fixed in a wholly insoluble form. The field observations made by them indicated that phosphate fertilizers added to irrigated Arizona soils may influence crop production for many years.

Haddock and Linton (24) conducted a five-year crop rotation experiment, potatoes - sugar beets - peas - two years alfalfa, on a highly calcareous Millville loam (pH 8.0) at Logan, Utah, in order to study the response of peas to superphosphate (44 lb. P per acre). They found that yields of both pea vines and canning peas were increased significantly by added phosphate. Yield response was in the order: current season application > one year residual (phosphorus applied to sugar beets) > two year residual (phosphorus applied to potatoes). In all three cases the yields were significantly higher than the checks. They concluded that the crop utilization of available P could only partly explain the decreased responses from residual phosphorus. They believed that phosphate fixation into unavailable form must have taken place. They also found that all phosphorus applied in the current season could be extracted by the sodium bicarbonate method.

Hunter and his co-workers (28) investigated the residual effects of phosphorus fertilizer on an Eastern Oregon soil treated with 0, 26, 53, 105, and 210 lb. P per acre. Measurements of soluble phosphorus in soil, soil phosphorus content in plant, A-values, and yield and compositional responses to added phosphorus fertilizer were employed to evaluate levels of available residual phosphorus in soil. All methods of evaluation indicated that 210 lb. P per acre were adequate for all crops in the six-year rotation (barley, three years alfalfa, corn, sugar beets). Residual phosphorus from the 105-pound rate was inadequate for maximum yield of beets. Essentially no residual phosphorus remained in the sixth year from the 26- and 53-pound applications.

Residual effects of phosphorus fertilizer in an irrigated rotation in the Southwest were studied by Leamer (33) through two cycles of alfalfa and two intervening crops of sorghum. He concluded that increased yields were obtained until phosphorus equal to the amount applied was removed in harvested crops. Olsen et al. (53) used "A" values and four chemical extraction methods to evaluate the availability of residual phosphorus in three calcareous soils from experimental plots which had received phosphate treatments under long-term crop rotations. The calculated "A" values indicated that the relative efficiency of the phosphate residues compared to a freshly added resin phosphate (equal in availability to superphosphate) varied from 26% to 56%. They stated that the variations could be affected by many factors, including $CaCO_3$ content, soil type, texture, and form of phosphate added. It was also evident that the initial level of available P was an important factor positively affecting the relative efficiency of the residual phosphorus. Peck et al. (56) studied the accumulation and decline of available phosphorus and potassium in a heavily fertilized Honeoye silt loam soil, and found that during years of application of fertilizer phosphorus and potassium, residual soil phosphorus and potassium accumulated in available forms as measured by soil test. The higher the rate of application of fertilizer phosphorus and potassium the higher was the accumulation of available soil phosphorus and potassium. When application was discontinued, a rapid decline in residual available soil phosphorus and potassium occurred. However, after eight years without application, a highly significant residual soil phosphorus effect remained.

Investigations conducted by Ridley and Hedlin (63) on the effect of mineral fertilizers and manures on the phosphorus content of a clay soil in a long-term crop rotation in Manitoba showed that additions of phosphate fertilizers increased both the total inorganic and the extractable phosphorus content of the soil. Moving 12-year average yields of wheat first crop, and barley third crop in the rotation indicated that the response to phosphorus was apparent only in the first year, with no residual effect on crops, due to relatively low rates of application. Another long-term soil fertility experiment was conducted by Spratt and McCurdy (68) on an Indian Head clay soil in Saskatchewan. Several rates of monoammonium phosphate (11-48-0) were added over a period of 20 years. A rotation of wheat, wheat, fallow was employed. The results indicated that total phosphorus and available phosphorus were increased by the additions of phosphorus over a period of twenty years. The yield potential of the soil studied was also changed, due to the residual behavior of previously applied phosphorus.

Thomas (72) studied the availability of residual phosphorus in a calcareous soil in South Dakota, and found that recovery of fertilizer phosphorus during a five-year period was very low. Maximum recovery was 27.7% of the 26.2-pound P addition. Uptake of phosphorus by alfalfa was significantly related to phosphorus extractable in $NaHCO_3$ and in dilute acid + NH_4F. Amounts of extractable and total phosphorus in the soil after five years of cropping were significantly correlated to prior fertilizer additions. Weeks and Miller (78) summarized the results obtained from their study on the residual effects of phosphates used on long-term field experiments. Phosphorus reserves were built up where use of phosphates was continued and depleted where their use was discontinued. They emphasized that when a reserve was built up in the soil it could be used for many years though its effectiveness during that time was largely dependent on the amount of P applied and to a lesser extent on the form in which it was applied.

McAuliffe _et al_. (44) demonstrated that added phosphorus remained effective after eight to thirteen years. The residual effects of fertilizer phosphorus previously applied to soils were also reported by Herron and Erhart (27), McLean and Hoelscher (45), Prince (58), and Stanberry _et al_. (69).

The general understanding of the conditions under which phosphate fertilizers are likely to have a well-marked residual effect has been helped by the concept of a pool of labile phosphate at a definite thermodynamic potential (66). If enough phosphate is incorporated into the soil to appreciably lower the phosphate potential, the fertilizer will have a long continued residual effect. The phosphate potential remains at a reasonably constant value, except when phosphate is removed from the pool by cropping. A heavy dressing of phosphate fertilizer will usually have a more marked residual effect than a light, as it will reduce the phosphate potential more.

III. MATERIALS AND METHODS

A. FIELD EXPERIMENTS

Field studies were initiated on farm land at Winkler in 1966 to determine the effects of broadcast phosphorus and phosphorus drilled with the seed on yields and phosphorus uptake by wheat and flax, and to evaluate the residual availability of the broadcast phosphorus on subsequent crops. Soils on this field are calcareous, very fine sandy loam, and are members of Altona association as described by Ellis and Shafer (16). The experimental plots were designed as split plot randomized block, with four replicates. The plan of the experimental plots is illustrated in Figure I. It consisted of sixteen blocks (45 feet by 96 1/3 feet each) which were separated from each other by paths of 8 feet and 10 feet as shown. The blocks received broadcast applications of monocalcium phosphate (0-45-0) at rates of 0, 100, 200, and 400 lb. P_2O_5 per acre in May 1966. Each block was divided into two main plots, A and B, and each of these in turn was divided into four subplots of equal size, numbered 1, 2, 3 and 4 (Figure I).

Drilled phosphorus applications were applied as follows: in the first year of the experiment all number 1 subplots were subdivided and received five levels of drilled monoammonium phosphate (11-48-0), namely, 0, 10, 20, 40, and 80 lb. P_2O_5 per acre. The relatively large subplots facilitated the use of an eight-run seed drill for seeding and drilling the fertilizer with the seed. Thus, each seed drilled phosphorus treated plot contained eight rows of crop. Since the potassium content of the soil was found to be sufficient for plant growth, only nitrogen in the form of ammonium nitrate ($33\frac{1}{2}$-0-0) at the rate of 90 lb. N per acre was applied broadcast on the experimental plots at seeding time in each year to supply adequate nitrogen.

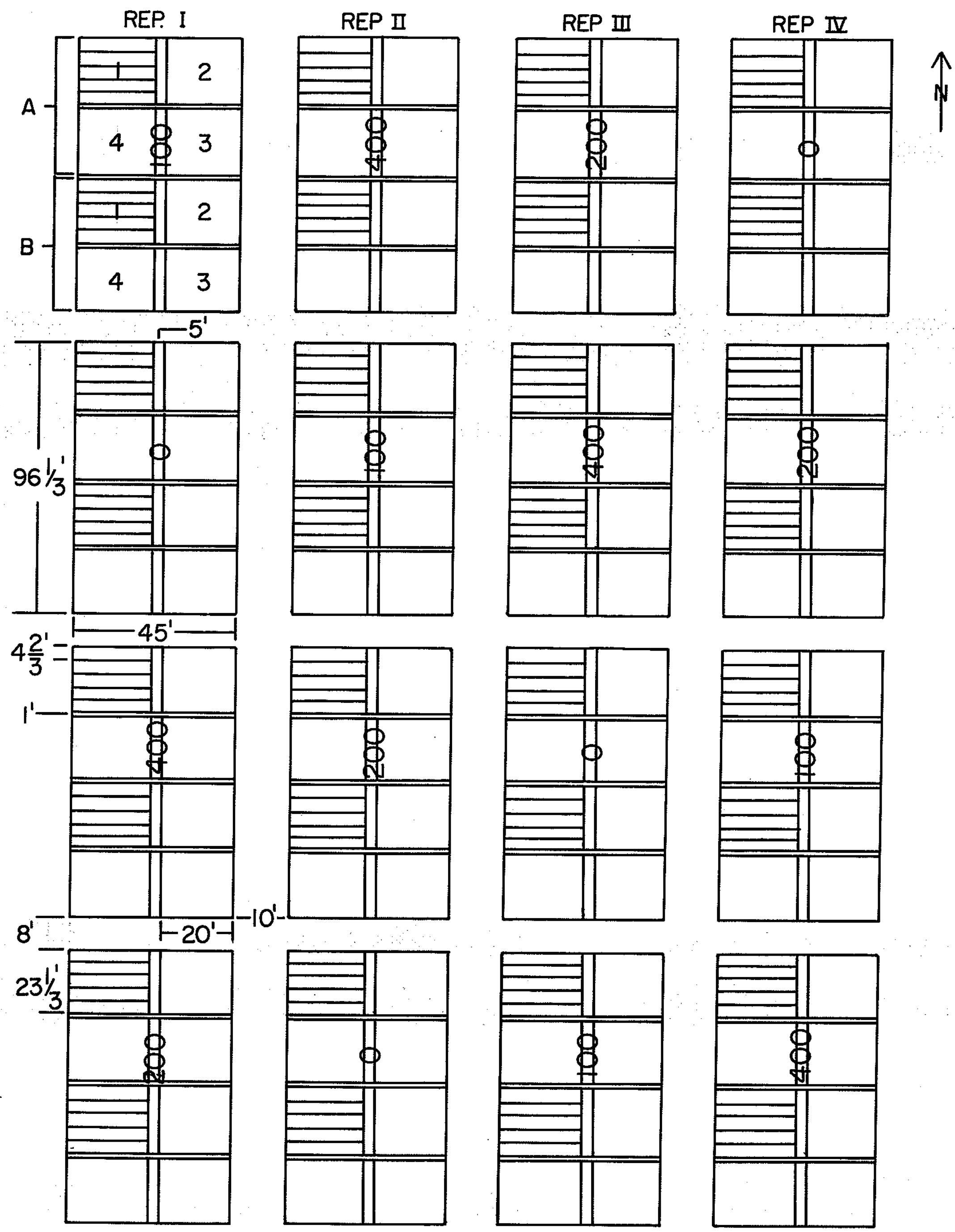

Figure I. Plan of The Experimental Plots at Winkler.

In 1966 wheat (Triticum aestivum, L.) and flax (Linum usitatissimum, L. 'Redwood') were grown on the main plot A's and the main plot B's, respectively. Only the first subplots (No. 1) were treated with seed drilled applications while the other three were normally cropped under the appropriate broadcast applications. Figure I shows how the first subplots were split for seed drilled treatments in 1966. The plots were fallowed in 1967 due to poor germination of the crops. In 1968 barley (Hordeum vulgare, L. 'Conquest') and flax were grown on the third subplots (No. 3) of the main plot A's and the main plot B's, respectively, but only barley was harvested since flax plots were plowed down because of poor germination and weeds.

Two sets of composite soil samples were taken from the 0- to 6-inch depth from uncropped areas, one on the eastern side and one on the western side of the experimental plot in the fall of 1966. The samples were air-dried, well mixed and ground to pass through a 2-mm. sieve for laboratory analysis. A representative sample of the soil was taken and the following properties were determined: texture, pH, the soluble salt content (conductivity), the organic matter content, inorganic carbon content, cation exchange capacity (C.E.C.), and $NaHCO_3$-extractable phosphorus. The methods used for these determinations are described in the section of analytical procedures. The data are summarized in Table 1.

In order to study the effect of broadcast phosphorus on the extractable phosphorus content of the soils, plots were sampled in the fall of 1966, and in both spring and fall of 1967 and 1968. In 1966 four composite samples were taken representing the 0, 100, 200, and 400 lb. P_2O_5 per acre broadcast phosphorus applications. All other samplings involved four composite samples for each rate, i.e. one from each replicate. All soil samples were air-dried

TABLE 1

SOIL CHARACTERISTICS

Location	Soil Association	Texture	pH	Conductivity (mmhos/cm.)	% $CaCO_3$	Organic Matter (%)	C.E.C. (meq./100g.)	$NaHCO_3$-ext. P (ppm.)
Winkler	Altona	V.F.S.L.	7.6	0.40	6.6	3.6	15.2	6.5

and ground to pass through 2-mm. sieve for laboratory analysis of $NaHCO_3$-extractable phosphorus and solubility studies.

In 1966 the effect of fertilizer phosphorus on germination of wheat and flax was determined after the crops had grown for 3 weeks. The germination counts were determined from the number of plants in a 10-foot length of the two centre rows in each seed drilled phosphorus treated plot. The check plot was assigned the value of 100% germination and the other treatments were compared to the check. In 1968 the germination counts were also determined for barley. In order to determine the phosphorus uptake of barley at an early stage of growth (six weeks after seeding), plant samples were clipped from a 2-foot section of one of the second guard rows. The plant samples were oven-dried at 70°C. for 24 hours, weighed, and then finely ground for total phosphorus analysis.

At maturity, wheat, flax, and barley were harvested from a 10-foot section of the two centre rows in each seed drilled phosphorus treated plot. The harvested samples were air-dried and threshed. The grain and straw were weighed separately, and the yields were calculated in hundredweight per acre. The representative samples were then finely ground for total phosphorus determinations.

B. GREENHOUSE EXPERIMENTS

The soils used for two greenhouse studies were collected prior to seeding in the spring of 1968. Four composite samples were taken at a depth of 0 to 6 inches from the 0, 100, 200, and 400 lb. P_2O_5 per acre 1966 - broadcast plots designed for the 1968 study, i.e. from the third subplots (No. 3).

1. First Greenhouse Experiment

This experiment was designed to compare the availability to barley, rape, and flax of previously and newly applied phosphorus. The previously applied phosphorus treatments were represented by the soils collected from the 1966-broadcast plots, while the newly applied phosphorus treatments were obtained by mixing the pelleted phosphorus fertilizer (11-48-0) with the soil taken from the check plot at the rates of 100, 200, and 400 lb. P_2O_5 per acre. As a result, this experiment consisted of seven fertilizer treatments including a treatment without added phosphate. The experiment was replicated four times. Half-gallon porcelain glazed pots were used. Two kilograms of soil were placed in each of 84 pots. A representative sample of soil from each treatment was passed through a 2-mm. sieve and retained for $NaHCO_3$-extractable phosphorus determinations.

The seeds of barley (*Hordeum vulgare*, L. 'Conquest'), rape (*Brassica napus*, L. 'Tanka'), and flax (*Linum usitatissimum*, L. 'Redwood') were planted at a depth of 1.5 cm below the soil surface on June 15, 1968. The 84 pots were arranged in a completely randomized block design. A few days after emergence, the plants were thinned so that four healthy and well-spaced plants were allowed to grow in each pot. Since the potassium level was found to be sufficient for plant growth, only NH_4NO_3 solution was applied, equivalent to 200 lb. N per acre, in three equal increments 12, 25, and 35 days after seeding. Water was added periodically to bring the moisture level in the soil to approximately field capacity. The pots were rotated on the bench twice a week. A day-length of 16 hours was provided. The supplementary light was obtained from "Sylvania" fluorescent tubes which supplied an intensity of about 1000 ft.-c. The temperature in the greenhouse ranged from 80° to 90° F during the day and 70° to 75°F at night.

Forty-five days after seeding, the aboveground portions of all crops were harvested. The harvested plant materials were air-dried and then oven-dried at 70°C for 24 hours. The dry weights were recorded and the samples were finely ground for total phosphorus determinations.

2. Second Greenhouse Experiment

Since flax was not responsive to the newly applied phosphorus when added in pelleted form as indicated by the results of the first greenhouse experiment, the second greenhouse experiment was conducted with flax using fertilizer phosphorus in powdered form. This experiment was similar to the first one except that the fertilizer (11-48-0) used for the newly applied phosphorus treatments was ground before being mixed with the check soil, and only flax was used as a test crop. It was planted on November 1, 1968. This time twelve plants were allowed to grow in each of twenty-eight pots. The harvesting procedures used were as outlined previously.

C. ANALYTICAL PROCEDURES

1. Soil texture. Soil texture was determined by the pipette method.

2. pH. Soil pH was determined on a soil-water saturated paste using a glass electrode.

3. Conductivity. The electrical resistance of an extract from a saturated paste of the soil-water was measured using a conductivity bridge.

4. Organic matter content. The organic matter content of the soil was estimated by the dichromate method described by Peech *et al.* (57).

5. Inorganic carbon content. Inorganic carbon content was determined by digesting the sample with 1.2 N HCl and collecting the CO_2 evolved in a

Nesbitt tube containing Ascarite (63). The result was expressed as per cent $CaCO_3$.

6. Cation exchange capacity. The method outlined by Peech *et al.* (57) was used for the determination of the cation exchange capacity of the soil.

7. Sodium bicarbonate extractable phosphorus. The soil samples were analyzed for extractable phosphorus using 0.5 M $NaHCO_3$ at pH 8.5 according to the procedure described by Olsen *et al.* (52).

8. Total phosphorus content in plant material. A representative sample of the plant material was digested with HNO_3-H_2SO_4-$HClO_4$ ternary acid mixture according to the procedure outlined by Jackson (29). The suggested predigestion with nitric acid was omitted. The total phosphorus content was determined colorimetrically by the vanadomolybdate method (2).

9. Determination of the solubility of phosphorus in soils.

In order to obtain information on the availability of fertilizer phosphorus added to the soils under which this investigation was conducted, solubility product principles were applied to the soil-phosphate system. The solubility of phosphorus in the soil samples taken from the 0, 100, 200, and 400 lb. P_2O_5 per acre broadcast phosphorus treated plots in the fall of 1966, and in both spring and fall of 1967 and 1968 were determined. 100 ml. distilled water was added to 10 g. soil and the system equilibrated by shaking for 24 hours at $25 \pm 1^\circ C$. The pH of the suspension was measured after the shaking period and the suspension filtered. The calcium and magnesium concentrations of the filtrate were then determined using EDTA (73) and the phosphorus concentration was analyzed colorimetrically using the molybdophosphoric blue color method (29). The solubility of phosphorus in the soils was calculated as outlined by Racz and Soper (61).

IV. RESULTS AND DISCUSSION

A. FIELD EXPERIMENTS

1. 1966 Field Experiment

Wheat

The yields of wheat grown in 1966 as affected by broadcast and seed drilled phosphorus are given in Table 2 and Figure II. Both grain and straw yields are means of four replicates. Despite the relatively low yields due to a period of excess rainfall in June,1966, yield data still show good response to added phosphorus.

The grain yields of wheat were significantly increased by the broadcast phosphorus applications (Figure II). These consistent increases, statistically highly significant, indicate that the soil phosphorus supply which was originally low in the soil (Table 1) was an important factor in limiting plant growth. Phosphorus drilled with the seed also increased the grain yields on all broadcast phosphorus treated plots except on the 400 lb. P_2O_5 per acre treatment in which a decrease in yield with increased seed drilled phosphorus resulted. Since there was no detrimental effect of seed drilled phosphorus on seed germination, this reduction in yield was probably due to a decrease in availability of other nutrient elements, caused by high levels of soluble phosphorus. In fact, the deficiencies of nutrient elements, such as iron and zinc, induced by heavy applications of fertilizer phosphorus have been reported by many investigators (7, 9, 10, 17, 32, 55, 75). This problem has been found to be greatest on soils that are calcareous.

The magnitude of yield increases with respect to seed drilled applications of fertilizer phosphorus was obviously greatest on the 0 lb. P_2O_5 per acre broadcast plots where an average increase of approximately 8 cwt. per acre

TABLE 2
WHEAT YIELD AND PHOSPHORUS UPTAKE AS AFFECTED BY
BROADCAST AND SEED DRILLED PHOSPHORUS (1966 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast–Drilled	Emergence (%)	Yield (cwt./acre)		P content (%)		P uptake (lb.P/acre)		
		Grain	Straw	Grain	Straw	Grain	Straw	Total
0– 0	100	10.45	27.91	0.30	0.06	3.14	1.67	4.81
0–10	109	14.71	33.35	0.33	0.05	4.85	1.67	6.52
0–20	106	15.20	29.80	0.34	0.04	5.17	1.19	6.36
0–40	110	16.99	35.45	0.33	0.06	5.61	2.13	7.74
0–80	101	18.38	42.16	0.39	0.06	7.17	2.53	9.70
100– 0	104	16.49	37.50	0.37	0.07	6.10	2.63	8.73
100–10	104	16.40	35.65	0.40	0.07	6.56	2.50	9.06
100–20	115	17.83	35.55	0.40	0.07	7.13	2.49	9.62
100–40	107	19.16	36.40	0.40	0.07	7.66	2.55	10.21
100–80	99	18.71	42.83	0.40	0.09	7.48	3.85	11.33
200– 0	105	15.69	38.11	0.40	0.08	6.28	3.05	9.33
200–10	115	20.11	38.92	0.40	0.10	8.04	3.89	11.93
200–20	114	19.65	44.53	0.42	0.10	8.25	4.45	12.70
200–40	106	19.97	41.55	0.42	0.10	8.39	4.16	12.55
200–80	105	19.59	44.17	0.40	0.10	7.84	4.42	12.26
400– 0	111	19.59	39.01	0.40	0.10	7.84	3.90	11.74
400–10	115	20.73	41.67	0.40	0.12	8.29	5.00	13.29
400–20	111	17.55	34.78	0.43	0.12	7.55	4.17	11.72
400–40	115	18.44	38.21	0.42	0.10	7.74	3.82	11.56
400–80	106	18.08	43.29	0.41	0.11	7.41	4.76	12.17
L.S.D. Broadcast	NS	2.82 4.05	NS	–	–	–	–	–
5% 1% Drilled	4.9 7.9	1.33 1.77	2.76 3.69	–	–	–	–	–
Broadcast x Drilled	NS	2.66 3.55	5.53 7.38	–	–	–	–	–

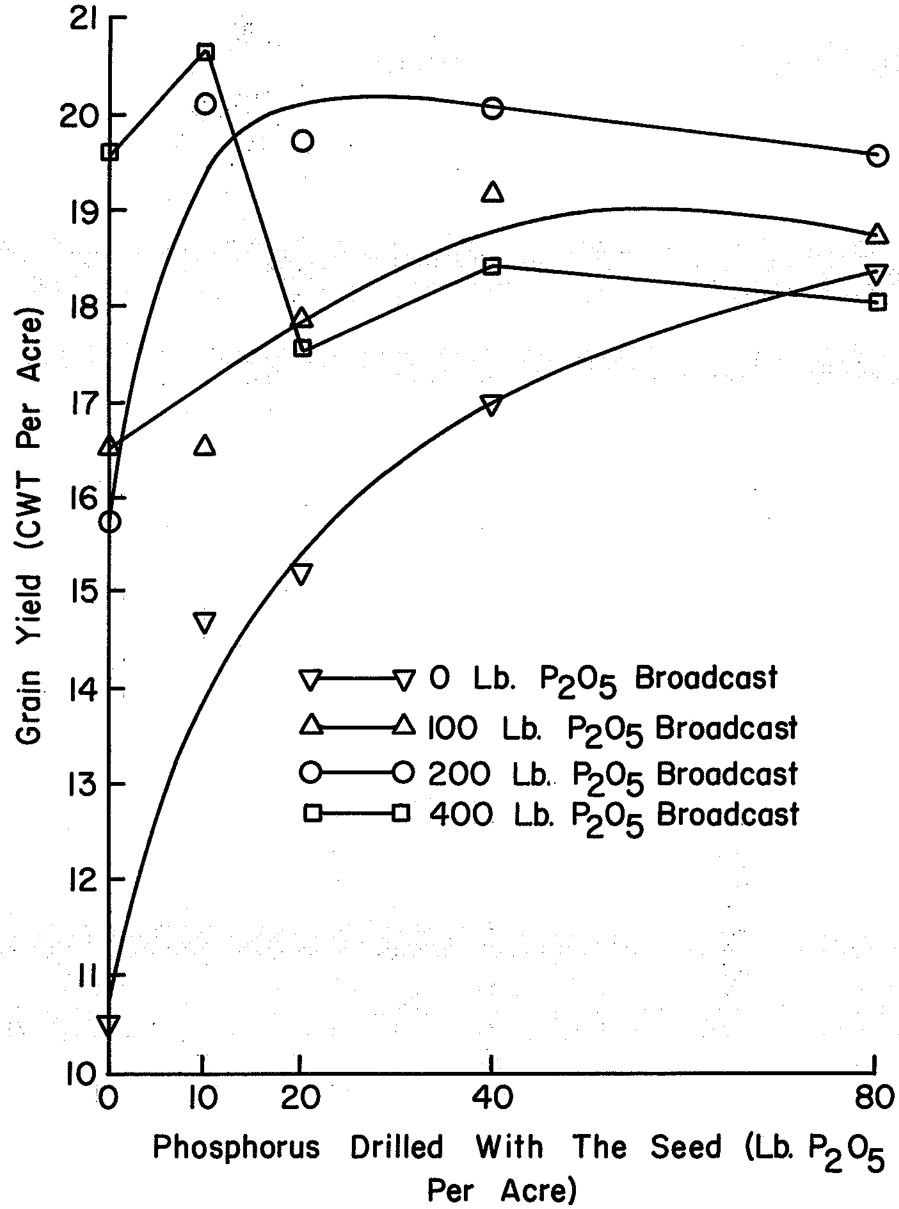

Figure II. Effect of Broadcast and Seed Drilled Phosphorus on Yield of Wheat (1966 Field Experiment) was obtained when the rate was increased from 0 to 80 lb. P_2O_5 per acre. Addition of 80 lb. P_2O_5 with the seed on these plots yielded only 1.21 cwt. less than the maximum yield obtained on the broadcast phosphorus treated plots without any drilled phosphorus. This indicates not only the effectiveness of seed drilled phosphorus but also the need of adding fertilizer phosphorus to these soils in order to obtain high yields. The greater positional availability and the early growth stimulation as influenced by seed drilled phosphorus undoubtedly account for its effectiveness in increasing yields. In spite of its effectiveness, however, the maximum yield of wheat in this experiment could not be achieved by seed drilled phosphorus even with the rate of 80 lb. P_2O_5 per acre, the maximum rate employed. This indicates the need of adding more phosphorus to these soils. Yield responses were obtained with heavy broadcast applications of fertilizer phosphorus up to the rate of 400 lb. P_2O_5 per acre. The maximum rate of broadcast phosphorus with high rates of drilled phosphorus failed to produce the maximum yield. The fact that the yields of wheat obtained on the plots treated with 100 and 200 lb. P_2O_5/acre broadcast were increased by seed drilled phosphorus, reveals the significance of the combined effect or the interaction of broadcast and seed drilled phosphorus on wheat yield production. Subsequent increases in phosphorus absorption, as a result of the early growth effect accompanied by increasing root growth, as affected by seed drilled phosphorus may account for the existence of such an interaction. According to statistical analyses, significant interactions existed between broadcast and seed drilled phosphorus on both grain and straw yields of wheat.

Whereas grain yield responses were consistently obtained, the yields of wheat straw were not increased significantly by broadcast phosphorus. Rates lower than 80 lb. P_2O_5 per acre with the seed also failed to produce significant increases in straw yields. It was therefore obvious that broadcast and seed drilled phosphorus had little effect on straw yields of wheat.

Table 2 also shows the effect of broadcast and seed drilled phosphorus on phosphorus uptake by wheat. The phosphorus content of both grain and straw was increased by broadcast phosphorus. However, little effect was obtained from phosphorus drilled with the seed.

Phosphorus uptake by wheat consistently increased with increasing rates of broadcast phosphorus. Applications of phosphorus with the seed also increased the phosphorus uptake by wheat on all broadcast phosphorus treated plots except on the 400 lb. P_2O_5 per acre treatment where the uptake of phosphorus was lower for the 20, 40 and 80 lb. P_2O_5 per acre treated plots than for the 10 lb. P_2O_5 per acre treated plot. The decreases in yields with increased seed drilled phosphorus on this treatment as previously discussed might well account for the reduction in phosphorus uptake.

The efficiency of phosphorus fertilizer use in terms of the amounts of phosphorus recovered from the fertilized crops was calculated using the equation:

$$\text{Efficiency or \% recovery} = \frac{\text{P uptake from the treatment} - \text{P uptake from the check}}{\text{P applied}} \times 100$$

The calculated data of the recovery of broadcast and seed drilled phosphorus as indicated by wheat are shown in Table 3. The validity of these computations depends on the assumption that phosphorus fertilization did not alter the phosphorus supplying capacity of the soil, i.e. the fertilizer phosphorus did not affect the uptake of soil phosphorus by the wheat crop. The investigation by Campbell (11) indicated that added phosphorus did not appreciably affect the removal of indigenous soil phosphorus. Thus, although a tracer was not used the calculated values can be used to estimate the efficiency of

TABLE 3

EFFICIENCY OF BROADCAST AND SEED DRILLED PHOSPHORUS AS INDICATED BY THE PHOSPHORUS UPTAKE BY WHEAT

(1966 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast(1)-Drilled(2)	Efficiency or % recovery (average of 4 replicates)	
0- 0		-
0-10		39.18
0-20		17.76
0-40		16.78
0-80		14.01
100- 0	8.98(3)	
100-10		7.56
100-20		10.20
100-40		8.48
100-80		7.45
200- 0	5.18(3)	
200-10		59.58
200-20		38.61
200-40		18.45
200-80		8.39
400- 0	3.97(3)	
400-10		35.52
400-20		- 0.23
400-40		- 1.03
400-80		1.23

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

(2) Monoammonium phosphate (11-48-0) drilled with the seed.

(3) Efficiency of broadcast phosphorus.

fertilizer phosphorus utilization.

The efficiency or percent recovery of broadcast phosphorus as determined by the wheat crop was very low, decreasing from 8.98% to 3.97% with increasing rates of broadcast phosphorus. The results are in agreement with those reported by Campbell (11) involving the applications of concentrated superphosphate to a calcareous Montana soil cropped to barley in the first year of a six-year rotation experiment designed to evaluate the residual effects of fertilizer phosphorus.

Despite their great variability, the data calculated for the efficiency of seed drilled phosphorus are comparatively high, also decreasing with increasing rates of phosphorus applied. The mean efficiencies obtained from the applications of 10, 20, 40, and 80 lb. P_2O_5 per acre with the seed on all plots were 35.46, 16.59, 10.67, and 7.77, respectively.

<u>Flax</u>

The yields of flax grown in 1966 as affected by broadcast and seed drilled phosphorus are shown in Table 4. The flax yields which are averages of four replicates are extremely low, presumably due primarily to a period of excess rainfall occurring during the growing period in June, 1966. Statistical analyses of the grain and straw yield data showed no yield responses of flax to either broadcast or seed drilled phosphorus. That flax is not responsive to additions of fertilizer phosphorus regardless of soil phosphate levels is commonly found from the studies conducted on Manitoba soils.

The grain yields of flax were decreased when 200 and 400 lb. P_2O_5 per acre were broadcast (Figure III). The decreases in availability of other nutrient elements as affected by high levels of applied phosphorus, as

TABLE 4
FLAX YIELD AND PHOSPHORUS UPTAKE AS AFFECTED BY
BROADCAST AND SEED DRILLED PHOSPHORUS (1966 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast-Drilled	Emergence (%)	Yield (cwt./acre)		P content (%)		P uptake (lb.P/acre)		
		Grain	Straw	Grain	Straw	Grain	Straw	Total
0- 0	100	4.25	21.04	0.44	0.10	1.87	2.10	3.97
0-10	99	4.88	22.60	0.45	0.10	2.20	2.26	4.46
0-20	83	4.41	23.47	0.46	0.12	2.03	2.82	4.85
0-40	76	5.06	26.57	0.51	0.12	2.58	3.19	5.77
0-80	62	4.96	30.20	0.53	0.10	2.63	3.02	5.65
100- 0	111	5.53	26.79	0.48	0.12	2.65	3.21	5.86
100-10	93	5.02	28.41	0.54	0.12	2.71	3.41	6.12
100-20	96	6.30	29.73	0.51	0.11	3.21	3.27	6.48
100-40	80	4.67	37.71	0.54	0.12	2.52	4.53	7.05
100-80	59	4.41	30.65	0.57	0.14	2.51	4.29	6.80
200- 0	100	3.74	30.39	0.57	0.14	2.13	4.25	6.38
200-10	101	4.47	37.93	0.59	0.14	2.64	5.31	7.95
200-20	86	4.25	30.23	0.57	0.14	2.42	4.23	6.65
200-40	67	4.17	38.54	0.59	0.11	2.46	4.24	6.70
200-80	54	3.03	36.87	0.59	0.11	1.79	4.06	5.85
400- 0	91	3.96	31.55	0.58	0.13	2.30	4.10	6.40
400-10	85	5.00	32.26	0.56	0.15	2.80	4.84	7.64
400-20	79	4.02	33.68	0.59	0.13	2.37	4.38	6.75
400-40	56	4.07	34.78	0.60	0.15	2.44	5.22	7.66
400-80	54	2.93	39.86	0.60	0.13	1.76	5.18	6.94
L.S.D. Broadcast	NS	NS	NS	-	-	-	-	-
5% Drilled	7.7							
1% Drilled	10.3	NS	NS	-	-	-	-	-
Broadcast x Drilled	NS	NS	NS	-	-	-	-	-

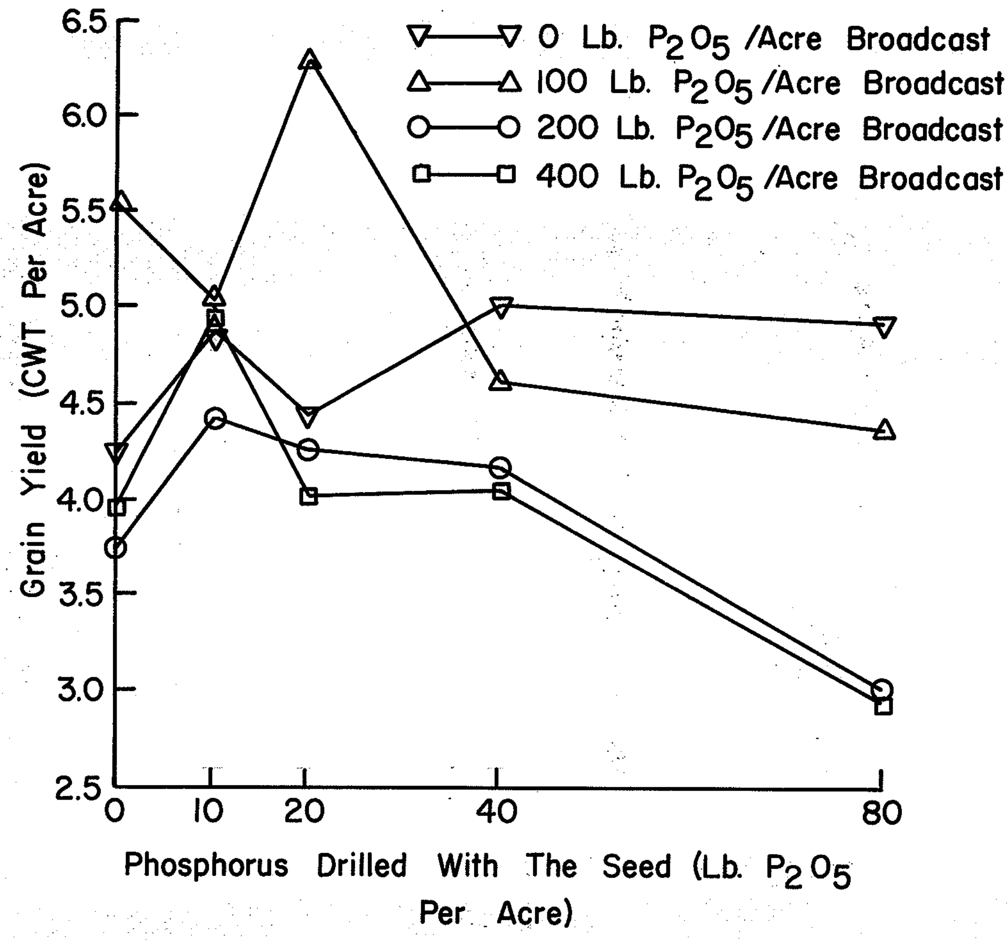

Figure III. Effect of Broadcast and Seed Drilled Phosphorus on Yield of Flax (1966 Field Experiment) previously discussed in the case of wheat, probably account for these yield reductions as well. While the grain yields of flax were not affected to any great degree by seed drilled phosphorus on the 0 and 100 lb. P_2O_5 per acre broadcast phosphorus treated plots, the yields on the 200 and 400 lb. P_2O_5 per acre treatments consistently decreased with increasing rates of seed drilled phosphorus. Part of this yield reduction may have been due to poor germination as affected by seed drilled phosphorus. Since the yields of flax with increasing rates of seed drilled phosphorus on the 0 and 100 lb. P_2O_5 per acre treatments were not decreased due to poor germination, it is also possible that with the extremely high levels of broadcast phosphorus adding phosphorus with the seed only increased the problems created by adding high levels of phosphorus.

The emergence of flax greatly decreased with increasing rates of seed drilled phosphorus (Table 4), suggesting that drilling fertilizer phosphorus (monoammonium phosphate) with the seed is not suitable as a method of adding phosphorus to soils sown to flax. The detrimental effect of fertilizer phosphorus placed in a band with the seed on emergence of flax was also reported by Nyborg (49).

The straw yields of flax were increased by the broadcast phosphorus. Applications of phosphorus with the seed also increased the straw yields on all broadcast phosphorus treated plots. Increases in yields of flax straw, however, were not statistically significant.

Table 4 shows the effect of broadcast and seed drilled phosphorus on phosphorus uptake by flax. The phosphorus content of both grain and straw was increased by broadcast phosphorus. The seed drilled phosphorus increased the phosphorus content of flax grain, but it had little effect on phosphorus content of the straw.

Phosphorus uptake by flax grain as affected by broadcast and seed drilled phosphorus followed trends similar to those of the grain yields. This was also true for the phosphorus uptake by flax straw. The total phosphorus uptake by flax, however, increased with increasing rates of broadcast phosphorus. Applications of fertilizer phosphorus with the seed also increased the total phosphorus uptake by flax except for the 200-80 treatment where the uptake of phosphorus by flax was less than for the flax grown on the 200-0 plot.

Flax was found to accumulate more phosphorus in the straw than in the grain while in the case of wheat, the greater portion of the phosphorus taken up was found in the grain. A comparison of the total phosphorus uptake indicated that flax utilized substantially less phosphorus than did wheat. This is not in agreement with the results reported by Racz et al. (59) from which they concluded that the total amount of phosphorus utilized by flax to complete its growth equalled that of wheat. The extremely low yields of flax in this experiment as affected by a period of excess rainfall and/or the possibility of an element other than phosphorus limiting growth might well explain the disagreement of the results.

Table 5 shows the calculated % recovery of broadcast and seed drilled phosphorus by flax. The efficiency or % recovery of broadcast monocalcium phosphate was extremely low, decreasing from 4.33% to 1.39% with rates of broadcast phosphorus increasing from 100 to 400 lb. P_2O_5 per acre. The efficiency of seed drilled monoammonium phosphate varied considerably, but generally decreased with increasing rates of seed drilled phosphorus. The % recovery of drilled phosphorus on all plots averaged 10.39, 6.07, 6.55, and 1.88% when 10, 20, 40, and 80 lb. P_2O_5 per acre were added, respectively. The extremely low utilization of broadcast phosphorus and phosphorus drilled

TABLE 5

EFFICIENCY OF BROADCAST AND SEED DRILLED PHOSPHORUS AS INDICATED BY THE PHOSPHORUS UPTAKE BY FLAX

(1966 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast(1)-Drilled(2)	Efficiency or % recovery (average of 4 replicates)
0- 0	-
0-10	11.23
0-20	10.08
0-40	10.31
0-80	4.81
100- 0	4.33(3)
100-10	5.96
100-20	7.10
100-40	6.82
100-80	2.69
200- 0	2.76(3)
200-10	35.97
200-20	3.09
200-40	1.83
200-80	- 1.52
400- 0	1.39(3)
400-10	28.41
400-20	4.01
400-40	7.22
400-80	1.55

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

(2) Monoammonium phosphate (11-48-0) drilled with the seed.

(3) Efficiency of broadcast phosphorus.

with the seed does in part explain why flax does not usually respond to the additions of phosphorus fertilizers. Although flax did not utilize the added phosphorus efficiently, the uptake of phosphorus by flax was increased by the additions of phosphorus fertilizers. This increase, however, was not accompanied by a yield increase, again indicating that an element other than phosphorus probably limited the growth of flax.

2. <u>1968 Field Experiment</u>

After having been fallowed in 1967, the experimental plots were cropped to barley and flax in 1968 in an attempt to evaluate the residual effects of fertilizer phosphorus broadcast in 1966. The flax plots were plowed down because of weed growth, data using barley as the test crop were obtained.

The yield of plant material of barley, clipped six weeks after seeding, as affected by previously broadcast and seed drilled phosphorus is shown in Table 6. The yield of barley at six weeks after seeding was increased significantly by the 200 and 400 lb. P_2O_5 per acre rates of phosphorus broadcast in 1966. The significant responses of barley at its early stage of growth to the previously broadcast phosphorus at rates of 200 and 400 lb. P_2O_5 per acre indicate the importance of the residual effects of fertilizer phosphorus.

Application of 10 lb. P_2O_5 per acre with the seed significantly increased the yields of plant material on all plots except on the plots treated with 400 lb. P_2O_5 per acre broadcast. Higher rates of seed drilled phosphorus produced additional yield increases in all instances. In this experiment there was no adverse effect of seed drilled phosphorus on the emergence of barley. Statistical analyses showed that there was no interaction between broadcast and seed drilled phosphorus on the yields of barley.

TABLE 6

EFFECT OF PREVIOUSLY BROADCAST AND SEED DRILLED PHOSPHORUS ON BARLEY YIELD AND PHOSPHORUS UPTAKE AT SIX WEEKS AFTER SEEDING (1968 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast-Drilled	Emergence (%)	Plant material (cwt./acre) (average of 4 replicates)	P content (%)	P uptake (lb.P/acre)
0- 0	100	7.56	0.24	1.81
0-10	103	11.38	0.25	2.85
0-20	101	14.10	0.24	3.38
0-40	98	15.24	0.26	3.96
0-80	104	13.99	0.30	4.20
100- 0	98	9.09	0.24	2.18
100-10	98	11.41	0.26	2.97
100-20	95	11.08	0.26	2.88
100-40	100	13.92	0.27	3.76
100-80	94	13.25	0.28	3.71
200- 0	99	12.70	0.28	3.56
200-10	100	16.05	0.31	4.98
200-20	98	14.09	0.31	4.37
200-40	96	15.83	0.31	4.91
200-80	103	18.29	0.34	6.22
400- 0	91	16.80	0.33	5.54
400-10	103	17.20	0.36	6.19
400-20	88	19.28	0.33	6.36
400-40	102	19.85	0.36	7.15
400-80	102	19.13	0.34	6.50
L.S.D. Broadcast (5%)		6.63		
L.S.D. Broadcast (1%)	NS	9.52	-	-
Drilled (5%)		2.29		
Drilled (1%)	NS	3.06	-	-
Broadcast x Drilled	NS	NS	-	-

The phosphorus uptake by barley at six weeks after seeding as affected by previously broadcast and seed drilled phosphorus is also shown in Table 6. The phosphorus content of barley at this early growth stage was increased by previously broadcast phosphorus except for the 100 lb. P_2O_5 per acre treatment where results were similar to those on plots which received no broadcast phosphorus. This suggests that there was, if any, little residual effect from the 100 lb. P_2O_5 per acre rate. Applications of phosphorus with the seed also increased the phosphorus content of young barley. Total phosphorus uptake by barley, at six weeks after seeding, as affected by previously broadcast and seed drilled phosphorus followed the same trends as the phosphorus content.

The yields of barley at maturity as affected by previously broadcast and seed drilled phosphorus are shown in Table 7. Both grain and straw yields are means of four replicates.

The grain yields of barley obtained in 1968 show a good response to the phosphorus broadcast in 1966 (Figure IV). The grain yields of barley progressively increased with increasing rates of previously broadcast phosphorus. However, the increase in grain yields by the 100 lb. P_2O_5 per acre treatment was not statistically significant, indicating that this rate of monocalcium phosphate broadcast in 1966 had little residual effect on barley, the second crop grown in the third year after application. This result agrees very well with that obtained for barley at six weeks after seeding. When the yields from the 200 lb. P_2O_5 per acre treatment were compared to those from the 100 lb. P_2O_5 per acre treatment, the yield increase was relatively large and was statistically highly significant. The previously broadcast phosphorus at the rate of 400 lb. P_2O_5 per acre produced only a slight additional yield increase which was not significantly greater than that

TABLE 7

BARLEY YIELD AND PHOSPHORUS UPTAKE AS AFFECTED BY PREVIOUSLY BROADCAST AND SEED DRILLED PHOSPHORUS (1968 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast-Drilled	Yield (cwt./acre)		P content (%)		P uptake (lb. P/acre)		
	Grain	Straw	Grain	Straw	Grain	Straw	Total
0- 0	19.67	22.44	0.22	0.06	4.33	1.35	5.68
0-10	23.78	21.72	0.24	0.06	5.71	1.30	7.01
0-20	24.44	24.52	0.25	0.06	6.11	1.47	7.58
0-40	32.08	27.29	0.25	0.06	8.02	1.64	9.66
0-80	37.36	30.48	0.28	0.07	10.46	2.13	12.59
100- 0	23.68	24.82	0.31	0.09	7.34	2.23	9.57
100-10	26.20	23.96	0.33	0.08	8.65	1.92	10.57
100-20	28.38	25.07	0.33	0.08	9.37	2.01	11.38
100-40	32.02	28.19	0.31	0.07	9.93	1.97	11.90
100-80	34.98	30.21	0.37	0.08	12.94	2.42	15.36
200- 0	29.94	24.52	0.34	0.09	10.18	2.21	12.39
200-10	36.19	30.25	0.37	0.09	13.39	2.72	16.11
200-20	36.33	30.97	0.40	0.09	14.53	2.79	17.32
200-40	37.28	31.77	0.38	0.09	14.17	2.86	17.03
200-80	36.13	32.57	0.39	0.10	14.09	3.26	17.35
400- 0	31.52	28.40	0.42	0.11	13.24	3.12	16.36
400-10	34.35	29.58	0.42	0.12	14.43	3.55	17.98
400-20	33.77	28.13	0.42	0.15	14.18	4.22	18.40
400-40	37.89	27.39	0.39	0.11	14.78	3.01	17.79
400-80	38.64	31.01	0.39	0.11	15.07	3.41	18.48
L.S.D. Broadcast	10.04 14.42	NS	-	-	-	-	-
5% 1% Drilled	2.22 2.96	2.24 3.00	-	-	-	-	-
Broadcast x Drilled	4.43 5.92	NS	-	-	-	-	-

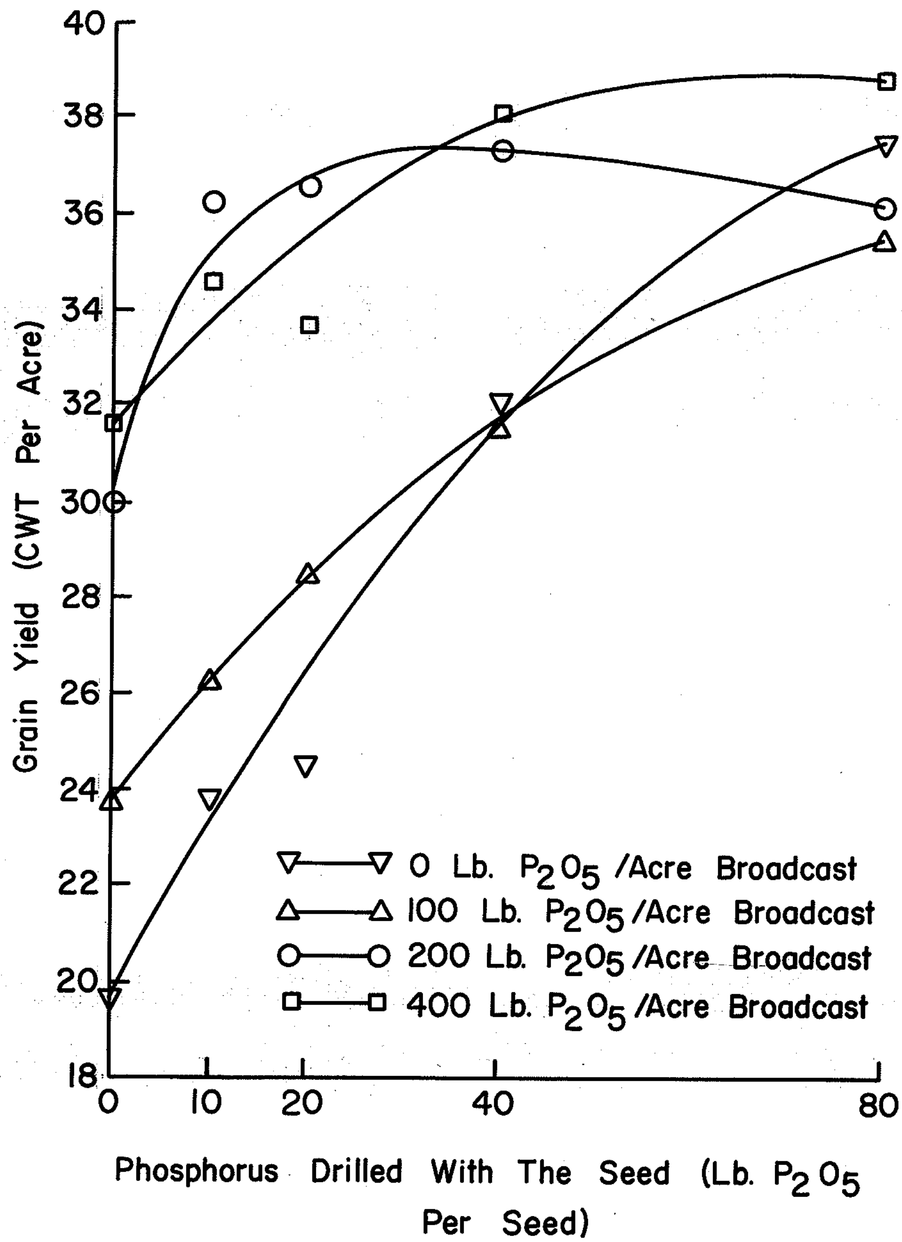

Figure IV. Effect of Previously Broadcast and Seed Drilled Phosphorus on Yield of Barley (1968 Field Experiment) produced by the 200 lb. P_2O_5 per acre treatment. It would appear from this experiment that the residual effects of fertilizer phosphorus broadcast in 1966 at the rates of 200 and 400 lb. P_2O_5 per acre were similar as indicated by the yields of barley grown in 1968.

The grain yield data also show that some phosphorus has to be added with the seed even on the plots treated with large amounts of broadcast phosphorus in order to obtain maximum yields. Applications of monoammonium phosphate with the seed consistently increased the yields on all previously broadcast phosphorus treated plots. The yields produced by applications of 10 and 20 lb. P_2O_5 per acre with the seed were about the same, and the increases over that produced by the check was statistically highly significant. Addition of 40 lb. P_2O_5 per acre with the seed produced further significant yield increases over those obtained from the 10 and 20 lb. P_2O_5 per acre rates on the plots where no phosphorus or 100 lb. P_2O_5 per acre was broadcast. A little additional yield increase was obtained from 80 lb. P_2O_5 per acre with the seed on all plots except those treated with 400 lb. P_2O_5 per acre broadcast. The greatest magnitude of yield increases as affected by seed drilled phosphorus appeared on the 0 lb. P_2O_5 per acre broadcast phosphorus treated plots, indicating the low supply of native phosphorus in the soils receiving no broadcast phosphorus in 1966. A relatively high yield increase with respect to seed drilled phosphorus also occurred on the 100 lb. P_2O_5 per acre treatment, suggesting that phosphorus broadcast at the rate of 100 lb. P_2O_5 per acre in 1966 was insufficient for optimum yields of barley grown in 1968. The yields obtained from the application of 40 lb. P_2O_5 per acre with the seed to the plots receiving no broadcast phosphorus were slightly higher than those obtained from the plots previously broadcast with phosphorus at the rate of 400 lb. P_2O_5 per acre with no phosphorus drilled with the seed, indicating the effectiveness of seed drilled phosphorus. The maximum yield of barley obtained with only seed drilled phosphorus was 37.36 cwt. per acre, whereas the maximum yield obtained with previously broadcast plus seed drilled phosphorus was 38.64 cwt. per acre, indicating that relatively large amounts of phosphorus with the seed of barley can result in near maximum yields.

Statistical analyses showed that there was a significant interaction between previously broadcast and seed drilled phosphorus on the production of barley grain yields. The interaction was not found at six weeks after seeding (Table 6), suggesting its occurrence during the later stage of growth.

The yields of barley straw were not significantly increased by previously broadcast phosphorus. Applications of phosphorus with the seed consistently increased the straw yields. However, there was no significant interaction between previously broadcast and seed drilled phosphorus on the production of straw yields of barley.

The phosphorus uptake by barley at maturity as affected by previously broadcast and seed drilled phosphorus is also shown in Table 7. The phosphorus content of both grain and straw was increased by previously broadcast phosphorus. Seed drilled phosphorus increased the phosphorus content of barley grain except on the plots which received 400 lb. P_2O_5 per acre broadcast. Seed drilled phosphorus had little effect on the phosphorus content of the straw.

The total amount of phosphorus in the barley grain increased considerably with increasing rates of previously broadcast phosphorus. Applications of fertilizer phosphorus with the seed also increased the amount of phosphorus accumulated in the grain. The amount of phosphorus in the straw was increased by previously broadcast phosphorus, but remained relatively constant with respect to the effect of seed drilled phosphorus. The total phosphorus uptake by barley, however, increased progressively with increasing rates of either previously broadcast or seed drilled phosphorus.

Barley accumulated considerably greater amounts of phosphorus in the grain than in the straw, which is similar to that noted for wheat. The total amount of phosphorus utilized by barley to complete its growth was higher than that utilized by wheat, indicating the greater requirement of barley for this element.

Table 8 shows the calculated data of the % recovery of previously broadcast and seed drilled phosphorus by barley. The results for the early stage of growth are also included.

The efficiency or % recovery of previously broadcast phosphorus by barley at six weeks after seeding was extremely low, increasing with increasing rates of previously broadcast phosphorus. This indicates that very little residual phosphorus was absorbed by barley at the early stage of growth. The % recovery of previously broadcast phosphorus by barley at maturity was relatively low but considerably higher than that at the early stage of growth, confirming that most of the residual phosphorus utilized by barley was absorbed during the growth period after six weeks after seeding. At maturity, however, the % recovery decreased with increased rates of previously broadcast phosphorus.

The % recovery of seed drilled phosphorus by barley either at six weeks after seeding or at maturity was consistently high and decreased with increased rates of seed drilled phosphorus. The efficiency calculated at maturity was higher than at the early growth stage. The % recovery of seed drilled

TABLE 8

EFFICIENCY OF PREVIOUSLY BROADCAST AND SEED DRILLED PHOSPHORUS AS INDICATED BY THE PHOSPHORUS UPTAKE BY BARLEY (1968 FIELD EXPERIMENT)

Treatment (lb. P_2O_5/acre) Broadcast(1)-Drilled(2)	Efficiency of applied phosphorus (%) Six weeks after seeding	Maturity
0- 0	-	-
0-10	23.83	30.48
0-20	17.99	21.77
0-40	12.32	22.80
0-80	6.85	19.79
100- 0	0.85(3)	8.91(3)
100-10	18.10	22.91
100-20	8.02	20.74
100-40	9.05	13.35
100-80	4.38	16.58
200- 0	2.00(3)	7.69(3)
200-10	32.54	85.24
200-20	9.28	56.48
200-40	7.73	26.58
200-80	7.62	14.21
400- 0	2.14(3)	6.12(3)
400-10	14.89	37.12
400-20	9.39	23.37
400-40	9.22	8.19
400-80	2.75	6.07

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

(2) Monoammonium phosphate (11-48-0) drilled with the seed.

(3) Efficiency of residual (previously broadcast) phosphorus.

phosphorus by barley at maturity varied greatly, depending on previous phosphorus treatments, i.e. the levels of available phosphorus in soils. The averages were 43.94, 30.59, 17.73, and 14.16% for the rates of 10, 20, 40, and 80 lb. P_2O_5 per acre, respectively. The considerably high efficiency of seed drilled phosphorus on the 200 and 400 lb. P_2O_5 per acre treatments emphasizes the need of adding small amounts of fertilizer phosphorus with the seed even on the soils previously treated with large amounts of broadcast phosphorus.

3. Effect of Applied Phosphorus on $NaHCO_3$-Extractable Phosphorus in Soils

Since it has been found that the availability of fertilizer phosphorus applied to calcareous soils can be reflected by the amount of $NaHCO_3$-extractable phosphorus, the availability of monocalcium phosphate (0-45-0) originally applied broadcast in May, 1966 to the soils on which the field experiments were conducted was evaluated using the $NaHCO_3$-extraction method. The data for the $NaHCO_3$-extractable phosphorus fraction of the top 6 inches of soil are shown in Table 9. The data in 1966 were obtained from analyses of the composite soil samples; consequently, no statistical analysis was performed. The data in 1967 and 1968 are the averages of four replicates.

The amount of $NaHCO_3$-extractable phosphorus in the 0 to 6 inches of soils at the beginning of the experiment averaged 6.5 ppm (Table 1). After the fertilizer phosphorus was broadcast, the experimental plots A and B were cropped to wheat and flax, respectively. The data for the fall of 1966 indicate the amounts of $NaHCO_3$-extractable phosphorus in soils at harvest time. Although the amounts of extractable phosphorus in soils were variable, presumably due to sampling errors, the data reflect well the effects of

TABLE 9

$NaHCO_3$-EXTRACTABLE PHOSPHORUS IN SOILS AS AFFECTED BY APPLIED PHOSPHORUS

Treatment (1) ($lb. P_2O_5$/acre)	$NaHCO_3$-extractable P in 0-6 in. depth soils (ppm.)						
	Fall 1966		Spring 1967		Fall 1967	Spring 1968	Fall 1968
	plot A	plot B	plot A	plot B	plot B	plot B	plot A
0	2.5	3.5	4.4	5.6	4.7	5.3	3.8
100	16.8	9.4	29.2	13.6	12.5	10.2	8.1
200	18.9	26.4	22.6	15.3	17.2	17.9	13.0
400	65.4	41.0	39.2	30.4	34.6	26.6	20.9
L.S.D. 5%	-	-	NS	13.3	9.3	12.6	6.4
L.S.D. 1%				19.1	13.3	19.5	9.2

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

broadcast phosphorus on the $NaHCO_3$-extractable phosphorus fraction of the soils. It is obvious that after one crop was grown and harvested, the $NaHCO_3$-extractable phosphorus in the fertilized soils remained high, and increased with increased rates of the broadcast phosphorus. The extractable phosphorus levels in the nonfertilized soils decreased considerably, when compared to that of the original level. This is difficult to explain since the decreases are more than can be accounted for by crop removals. The lack of data for the extractable phosphorus in the fertilized soils at seeding time has made it impossible to compare the levels of extractable phosphorus before and after cropping. It is reasonable, however, to assume a somewhat higher level of extractable phosphorus for the treated soils at seeding time.

In 1967 the experimental plots were fallowed. The soils were sampled in the spring for evaluation of the $NaHCO_3$-extractable phosphorus. The data again show consistently large extractable phosphorus contents of the fertilized soils. The variability of the results is great, particularly on the 100 lb. P_2O_5 per acre treatment on the experimental plots A. The abnormally high amount of extractable phosphorus in this treatment was undoubtedly due to sampling errors. The data for the plots A were so variable that no significant differences were obtained on statistical analysis. However, less variable results were obtained from the experimental plots B. On these plots the $NaHCO_3$-extractable phosphorus levels increased with increased rates of applied phosphorus; a significant increase above that of the plot not fertilized resulted only when 400 lb. P_2O_5 per acre was added.

In the fall of 1967, only the soil samples from the experimental plots B were collected for determination of $NaHCO_3$-extractable phosphorus. The results were surprisingly similar to those found in the spring. The amounts of extractable phosphorus in the soils on all treatments remained relatively constant during the fallow period.

Plots A and B were sown to barley and flax, respectively in 1968. Only the plots B were sampled in the spring. It was found that the levels of extractable phosphorus in the soils remained similar to those in the fall of 1967, except on the 400 lb. P_2O_5 per acre broadcast phosphorus treated soils in which a decrease in the extractable phosphorus occurred. The $NaHCO_3$-extractable phosphorus increased with increased rates of applied phosphorus. Statistically significant differences were obtained with the 200 and 400 lb. P_2O_5 per acre treatments.

Since the flax plots (plots B) were plowed down in July due to serious weed problems, only the soils from the barley plots (plot A) were sampled in the fall of 1968. The $NaHCO_3$-extractable phosphorus content of these soils indicated that after the originally treated soils of these plots were cropped to wheat in 1966, were fallowed in 1967, and were cropped to barley in 1968, the extractable phosphorus in the soils remained relatively high, and increased with increased rates of previously broadcast phosphorus. The increases due to the 200 and 400 lb. P_2O_5 per acre treatments were statistically significant.

The amounts of $NaHCO_3$-extractable phosphorus in the fertilized soils decreased with continued cropping. The extractable phosphorus content of the non-fertilized soil was usually lower at harvest time than before cropping but increased to approximately the original level before cropping if time for equilibration was allowed. These agree with the results obtained by Campbell (11).

It would therefore appear from the studies that a single high rate of fertilizer phosphorus applied broadcast to a calcareous soil could consistently increase the amount of $NaHCO_3$-extractable phosphorus in the soil for years in spite of its gradual reduction with continued crop removal. The results are similar to those reported by Campbell (11), Hunter et al. (28), Leamer (33), Olsen et al. (53), Ridley and Hedlin (63), and Spratt and McCurdy (68). The yields of barley grown on these treated soils responded well to the previous treatments, particularly when the soils tested high in $NaHCO_3$-extractable phosphorus in the top six inches of soils. This indicates not only the residual value of previously broadcast phosphorus, but also the significance of $NaHCO_3$ as an extractant in reflecting the availability of applied phosphorus.

4. Phosphorus Balance Sheet

Since the experimental plots A in the field were continuously under investigation, the amounts of phosphorus applied, recovered by crops, extracted by $NaHCO_3$, and accumulated in soils can be related. The data are shown in Table 10.

The differences between the amounts of phosphorus applied and the amounts of fertilizer phosphorus taken up by the two crops were the amounts of applied phosphorus accumulated in the soils in the fall of 1968, which were 35.83, 76.05, and 156.96 lb. P per acre on the 100, 200, and 400 lb. P_2O_5 per acre broadcast phosphorus treated plots, respectively. Thus, it is obvious that large amounts of applied phosphorus remained in the soils since the cumulative phosphorus recovery by the two crops was extremely low, accounting for only 10-18% of the amount applied.

The amount of fertilizer phosphorus accumulated in soils was divided

TABLE 10

PHOSPHORUS BALANCE SHEET

Treatment(1) ($lb.P_2O_5$/acre)	Total P applied (lb.P/acre)	Phosphorus uptake by 2 crops (lb.P/acre)			Fertilizer P taken up (lb.P/acre)	Fall-1968 $NaHCO_3$-ext.P (2) (lb.P/acre)	Residual P soluble in $NaHCO_3$ (lb.P/acre)	Residual P insoluble in $NaHCO_3$ (lb.P/acre)
		1966 wheat	1968 barley	Total P uptake				
0	0	4.81	5.68	10.49	0	6.73	0	0
100	43.64	8.73	9.57	18.30	7.81	14.34	7.61	28.22
200	87.28	9.33	12.39	21.72	11.23	23.01	16.28	59.77
400	174.57	11.74	16.36	28.10	17.61	36.99	30.26	126.70

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

(2) Calculated on the basis of 1 acre to 6-inch depth = 1.77×10^6 lb. soil.

into $NaHCO_3$-soluble and $NaHCO_3$-insoluble phosphorus fractions. The amount of phosphorus soluble in $NaHCO_3$ was very low, accounting for approximately one-fifth of the total amount accumulated. This $NaHCO_3$-soluble phosphorus fraction, however, increased with increased rates of broadcast phosphorus, suggesting that yield response to the residual phosphorus would be obtained for subsequent crops. Some of the $NaHCO_3$-insoluble phosphorus would also be expected to be available to plants.

In fact, the crop yield data obtained in 1969 from these experimental plots, which have not been included in this report, showed a good response to the previously broadcast phosphorus, supporting the above-mentioned conclusion.

5. Solubility of Previously Broadcast Phosphorus in Soils

The solubility of phosphorus in the soils collected from the experimental plots was determined in order to characterize the phosphorus compounds present in the soils treated with different rates of monocalcium phosphate (0-45-0). The phosphorus, calcium and magnesium concentrations in the soil extracts are shown in Table 11. The calculated lime and phosphate potentials are also included.

In all soil extracts the concentration of calcium was much higher than the concentration of magnesium. The concentration of calcium in the soil extracts increased with increased rates of applied phosphorus whereas the concentration of magnesium remained relatively constant, indicating that phosphorus applied to these soils reacted primarily with calcium.

The phosphorus concentration in the soil extracts increased with increased rates of applied phosphorus, and decreased gradually with time, except on the

TABLE 11
IONIC CONCENTRATIONS AND ACTIVITIES, AND LIME AND PHOSPHATE POTENTIALS OBTAINED BY EQUILIBRATING SOILS WITH WATER AT 25 ± 1°C

Sampling date	Treatment[1] lb. P_2O_5/acre	pH	Ca $\times 10^3$M	Mg $\times 10^3$M	P $\times 10^3$M	$\frac{1}{2}$pCa	$\frac{1}{2}$pMg	pH_2PO_4	pH$-\frac{1}{2}$pCa	pH$-\frac{1}{2}$pMg	$pH_2PO_4+\frac{1}{2}$pCa	$pH_2PO_4+\frac{1}{2}$pMg
Fall 1966	Original soil	7.60	0.58	0.23	0.010	1.66	1.86	5.71	5.94	5.74	7.37	7.57
	0	7.72	0.58	0.23	0.007	1.66	1.86	5.97	6.06	5.86	7.63	7.83
	100	7.80	0.70	0.25	0.025	1.62	1.85	5.50	6.18	5.95	7.12	7.35
	200	7.85	0.75	0.27	0.046	1.61	1.83	5.29	6.24	6.02	6.90	7.12
	400	7.75	1.89	0.28	0.066	1.58	1.83	5.06	6.17	5.92	6.64	6.89
Spring 1967	0	7.62	0.81	0.23	0.005	1.59	1.87	6.06	6.03	5.75	7.65	7.93
	100	7.52	0.75	0.23	0.022	1.61	1.87	5.33	5.91	5.65	6.94	7.20
	200	7.79	0.83	0.24	0.043	1.59	1.86	5.27	6.20	5.93	6.86	7.13
	400	7.78	1.80	0.37	0.050	1.44	1.78	5.30	6.34	6.00	6.74	7.08
Fall 1967	0	7.58	0.82	0.19	0.005	1.59	1.91	6.02	5.99	5.67	7.61	7.93
	100	7.76	0.93	0.25	0.016	1.57	1.85	5.69	6.19	5.91	7.26	7.54
	200	7.80	0.93	0.27	0.030	1.57	1.84	5.45	6.23	5.96	7.02	7.29
	400	7.61	1.50	0.38	0.042	1.47	1.77	5.21	6.14	5.84	6.68	6.98
Spring 1968	0	7.77	0.92	0.30	0.004	1.57	1.81	6.30	6.20	5.96	7.87	8.11
	100	7.82	0.80	0.34	0.016	1.60	1.78	5.73	6.22	6.04	7.33	7.51
	200	7.72	0.85	0.50	0.022	1.59	1.70	5.53	6.13	6.02	7.12	7.23
	400	7.75	1.70	0.43	0.040	1.45	1.75	5.37	6.30	6.00	6.82	7.12
Fall 1968	0	7.78	0.96	0.30	0.004	1.56	1.81	6.31	6.22	5.97	7.87	8.12
	100	7.80	0.85	0.28	0.016	1.59	1.83	5.71	6.21	5.97	7.30	7.54
	200	7.79	0.88	0.45	0.020	1.58	1.73	5.63	6.21	6.06	7.21	7.36
	400	7.75	1.65	0.38	0.036	1.46	1.77	5.41	6.29	5.98	6.87	7.18

(1) Monocalcium phosphate (0-45-0) was broadcast in May, 1966.

0 and 100 P_2O_5 per acre treatment in which the phosphorus concentration in the soil extracts remained relatively constant after the sampling date of the spring of 1967.

Since it was found that calcium predominated in these soils, only the lime and phosphate potentials in terms of pH $- \frac{1}{2}$ p Ca and p $H_2PO_4 + \frac{1}{2}$ p Ca, respectively, were used to evaluate the solubility of applied phosphorus in the soils. The solubility of phosphorus was determined by plotting the lime and phosphate potentials on a diagram with isotherms representing the solubilities of the pure phosphorus compounds. The results are shown in Figure V.

The solubility of phosphorus in the original soil on which the field experiments were originated was approximately half way in between that of octacalcium phosphate and hydroxyapatite, indicating that the soil was undersaturated with respect to octacalcium phosphate and supersaturated with respect to hydroxyapatite. This suggests that either hydroxyapatite or octacalcium phosphate governed the solution concentration in this calcareous soil. This is in agreement with the results obtained by Weir and Soper (79). The solubility of phosphorus in the nonfertilized soils sampled in the fall of 1966 and the later sampling dates also remained between that of octacalcium phosphate and hydroxyapatite. The values of the lime and phosphate potentials, however, were slightly higher than for the original soil.

The solubility of phosphorus in the soils treated with 100 lb. P_2O_5 per acre was also in between that of octacalcium phosphate and hydroxyapatite but very close to that of octacalcium phosphate, indicating a higher solubility of phosphorus in these soils than that in the nonfertilized soils. The solubility values did not change appreciably with time and remained close to that of octacalcium phosphate.

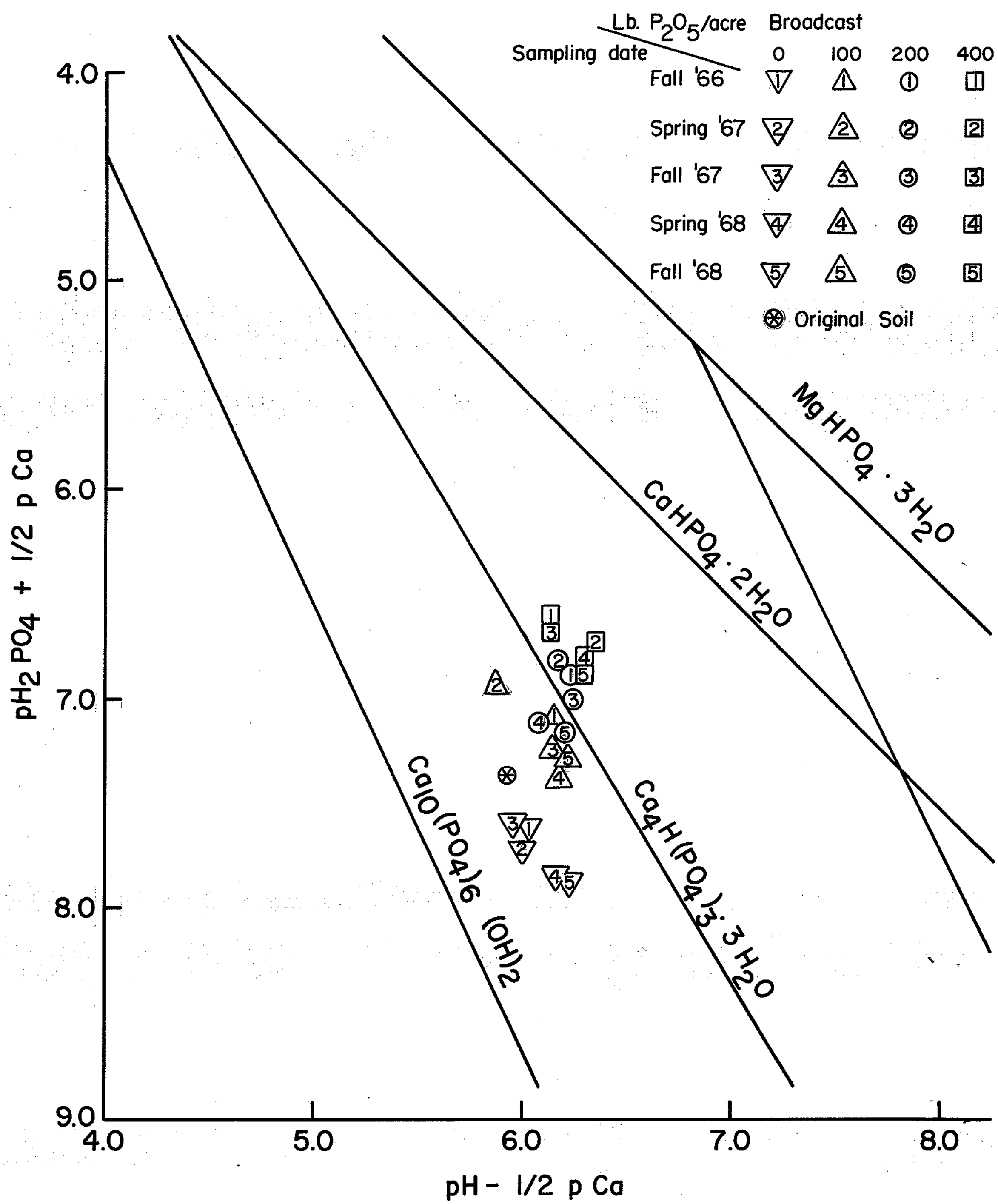

Figure V. Solubility of Phosphorus in Soils Broadcast With Different Rates of Monocalcium Phosphate (Monocalcium Phosphate (0-45-0) Was Broadcast in May 1966)

The solubility of phosphorus in the soils treated with 200 lb. P_2O_5 per acre and obtained in the fall of 1966 and the spring of 1967 was in between that of dicalcium phosphate dihydrate and octacalcium phosphate but close to that of octacalcium phosphate, indicating that during these periods these soils were slightly supersaturated with respect to octacalcium phosphate. The solubility of phosphorus in the soils obtained in the fall of 1967 approximated that of octacalcium phosphate, indicating the presence of this compound as a major reaction product. In the spring and fall of 1968, however, the solubility values dropped to that of the soils treated with 100 lb. P_2O_5 per acre. This suggests a slow reversion of applied phosphorus from relatively soluble compounds to rather insoluble forms.

The solubility of phosphorus in the soils treated with 400 lb. P_2O_5 per acre was in between that of dicalcium phosphate dihydrate and octacalcium phosphate throughout the entire sampling period, and was greater than that in the soils treated with 200 lb. P_2O_5 per acre. The soil solution was therefore supersaturated with respect to octacalcium phosphate at all times.

The solubility studies indicate that after a season of cropping, octacalcium phosphate was probably the prominent reaction product in the calcareous soil used in this investigation. The solubility of added phosphorus, particularly the higher rates, was in between that of dicalcium phosphate dihydrate and octacalcium phosphate, indicating the presence of small amounts of dicalcium phosphate dihydrate or some phosphorus compounds slightly more soluble than octacalcium phosphate. The solubility of the reaction products was always greater than the solubility of phosphorus in the untreated soils. Plant growth studies on these soils showed a good response to previously applied phosphorus, suggesting that these reaction products are relatively available to plants.

Strong (70) studying the effect of soil calcium and magnesium content and time of incubation on the reaction products of applied orthophosphate in Manitoba soils, found dicalcium phosphate dihydrate and octacalcium phosphate as the prominent reaction products throughout the entire incubation period of 450 days. These reaction products were reported to be available to plants. The availability of octacalcium phosphate was estimated to be about 80% of that of monocalcium phosphate.

B. GREENHOUSE EXPERIMENTS

1. First Greenhouse Experiment

The $NaHCO_3$-extractable phosphorus content of the soils which were previously and newly treated with fertilizer phosphorus is shown in Table 12. The data for the extractable phosphorus in the previously treated soils collected in the spring of 1968 are higher than those shown in Table 9, probably due to the use of a spade instead of an auger as was used in the earlier samplings. The use of the spade resulted in obtaining a sample that was representative of a depth less than six inches. Since most of the broadcast phosphorus would be present in the top few inches of soil, the samples taken with the spade would be expected to have a higher level of $NaHCO_3$-extractable phosphorus than would the samples taken with an auger.

The $NaHCO_3$-extractable phosphorus in the previously treated soils increased with increased rates of previously broadcast monocalcium phosphate. For each corresponding treatment, the amount of $NaHCO_3$-extractable phosphorus in the newly treated soils was approximately twice that in the previously treated soils, and also increased with increased rates of applied monoammonium phosphate. By subtracting the amount of the extractable

TABLE 12

$NaHCO_3$-EXTRACTABLE P IN SOILS PREVIOUSLY AND NEWLY TREATED WITH PHOSPHORUS (FIRST GREENHOUSE EXPERIMENT)

Treatment (lb. P_2O_5 per acre)	$NaHCO_3$-extractable P (ppm.)	
	Previously treated soils (1)	Newly treated soils (2)
0	7.4	-
100	13.2	28.7
200	19.2	37.1
400	42.5	82.7

(1) Soils were collected in spring 1968 from the experimental plots broadcast with monocalcium phosphate (0-45-0) in May, 1966.

(2) The nonfertilized soils were mixed with pelleted monoammonium phosphate (11-48-0). Rate of phosphorus addition calculated on the basis of 1 acre to 6-inch depth = 1.77×10^6 lb. soil.

phosphorus in the check from that in the newly treated soils, it is evident that the $NaHCO_3$-extraction method extracted from 60 to 86% of the added monoammonium phosphate.

The average yields of barley, rape, and flax are presented in Table 13.

Barley and rape responded well to either previously or newly applied phosphorus. The yields of plant material of both crops increased progressively with increased rates of either previously or newly applied phosphorus. However, yield increases were considerably greater in all fertilizer treatments for rape than for barley, indicating that rape is more responsive to previously and newly applied phosphorus than barley. For both crops, yield increases were consistently greater with the newly applied phosphorus than with the previously applied phosphorus. This suggests that the newly applied phosphorus was more readily available to plants than the residual phosphorus. Significant residual effects were obtained from previously broadcast phosphorus with rates higher than 100 lb. P_2O_5 per acre for barley and with all rates for rape, indicating a greater ability of rape to utilize the residual phosphorus. The previous treatment of 400 lb. P_2O_5 per acre produced as much yield of rape as those produced by each newly applied phosphorus treatment.

Among the three crops, flax was the poorest with respect to response to added phosphorus. It is obvious that flax did not respond to either previously or newly applied phosphorus with rates lower than 400 lb. P_2O_5 per acre. The flax yields obtained from the check, the previous treatment of 100 lb. P_2O_5 per acre and the newly applied phosphorus treatments of 100 and 200 lb. P_2O_5 per acre were about the same. For rates higher than 100 lb. P_2O_5 per acre, the yields of flax were greater for the previously applied phosphorus than for the newly applied. This seems to indicate that for

TABLE 13
CROP YIELDS AND PHOSPHORUS UPTAKE AS AFFECTED BY PREVIOUSLY AND NEWLY APPLIED PHOSPHORUS[1] (FIRST GREENHOUSE EXPERIMENT)

Treatment ($lb. P_2O_5$/acre)	Plant material (g. per pot[2])			P content (%)			Total P uptake (mg. per pot)		
	barley	rape	flax	barley	rape	flax	barley	rape	flax
0	5.24	6.56	0.82	0.30	0.25	0.23	15.6	16.6	1.9
100	5.75	7.82	0.86	0.35	0.33	0.30	20.1	25.9	2.6
200	6.11	9.10	0.96	0.42	0.40	0.38	25.9	37.3	3.7
400	6.48	10.04	1.32	0.45	0.52	0.41	29.5	52.6	5.5
100*	6.77	10.46	0.87	0.43	0.42	0.31	29.3	44.0	2.7
200*	7.06	10.59	0.88	0.48	0.46	0.33	33.9	48.8	2.9
400*	7.65	10.68	1.07	0.58	0.56	0.42	44.8	60.1	4.5
L.S.D. 5%	0.53	0.87	0.25	0.053	0.071	0.033	5.75	9.99	1.12
L.S.D. 1%	0.72	1.18	0.35	0.072	0.096	0.045	7.83	13.59	1.52

(1) Previously applied phosphorus was monocalcium phosphate (0-45-0). Newly applied phosphorus was pelleted monoammonium phosphate (11-48-0).

(2) Oven dry weight. Four plants were grown in each pot.

* Newly applied phosphorus treatments calculated on the basis of 1 acre to 6-inch depth = 1.77×10^6 lb. soil.

flax the residual phosphorus is more important as a source of phosphorus supply than the newly applied phosphorus. It would therefore appear from the studies that increasing phosphorus levels in soils by fertilizing other crops with sufficiently large amount of fertilizer phosphorus might serve as an indirect method of supplying adequate phosphorus for flax grown in subsequent years.

The effect of previously and newly applied phosphorus on the phosphorus uptake by barley, rape, and flax is also shown in Table 13. The phosphorus content of all crops increased with increased rates of either previously or newly applied phosphorus. The percentages of phosphorus in the plant tissue decreased in the order of barley, rape, flax. For barley and rape, the phosphorus content was higher for the newly applied phosphorus treatments than for the previously applied phosphorus. This was not true for flax which contained almost the same percentage of phosphorus for the corresponding treatments.

The total amount of phosphorus taken up by all crops also increased with increased rates of applied phosphorus. The total amount of phosphorus utilized by the crops was greatest for rape and smallest for flax. Barley and rape utilized more phosphorus from the newly applied phosphorus than from the residual phosphorus. Flax, on the other hand, utilized more phosphorus from the residual source, especially from the 200 and 400 lb. P_2O_5 per acre treatments.

The efficiency or % recovery of previously and newly applied phosphorus as indicated by the phosphorus uptake by barley, rape, and flax is shown in Table 14. The efficiency differed greatly, depending on crops. The efficiency of either previously or newly applied phosphorus was highest for rape and lowest for flax. This indicates the ability of the crops to utilize the

TABLE 14

EFFICIENCY OF PREVIOUSLY AND NEWLY APPLIED PHOSPHORUS AS INDICATED BY THE PHOSPHORUS UPTAKE BY VARIOUS CROPS

Treatment ($lb. P_2O_5$ per acre)	Efficiency or % recovery		
	Barley	Rape	Flax
0	-	-	-
100	8.94	19.06	1.40
200	10.08	20.28	1.79
400	6.82	18.15	1.79
100*	27.15	55.82	1.65
200*	18.42	32.76	1.03
400*	14.53	22.00	1.32

* Newly applied phosphorus treatments calculated on the basis of 1 acre to 6-inch depth = 1.77×10^6 lb. soil.

residual and the newly applied phosphorus, which was in the order: rape > barley > flax. The efficiency of residual phosphorus did not vary to any great degree with treatments, while that of newly applied phosphorus as determined by the phosphorus uptake by barley and rape decreased considerably with increased rates of applied phosphorus. The efficiency of applied phosphorus as determined by the phosphorus uptake by flax was almost the same for all treatments. The utilization of phosphorus by flax from the previously applied 200 and 400 lb. P_2O_5 per acre was slightly greater than that from the newly applied 200 and 400 lb. P_2O_5 per acre treatments.

2. Second Greenhouse Experiment

Since flax showed little response to pelleted monoammonium phosphate added to the soils in the first greenhouse experiment, an investigation was conducted to find out if it would respond to the same phosphate carrier added to these soils in the powdered form. The data for yield and phosphorus uptake are shown in Table 15. The yields of plant material obtained from this experiment were higher than those obtained from the first experiment due to an increase in number of plants per pot. However, insofar as the degree of response to added phosphorus is concerned, the results obtained were similar to those of the first greenhouse experiment. The data for the phosphorus content of flax in this experiment are similar to those in the first experiment, indicating that there was no difference in availability of pelleted and powdered monoammonium phosphate added to a calcareous soil sown to flax. The phosphorus uptake data also show that flax utilized more phosphorus from the residual phosphorus than from the newly added phosphorus.

Table 16 shows the efficiency of applied phosphorus. The efficiency was also increased by the increase in number of plants per pot. The efficiency

TABLE 15

FLAX YIELD AND PHOSPHORUS UPTAKE AS AFFECTED BY PREVIOUSLY AND NEWLY APPLIED PHOSPHORUS(1)

(SECOND GREENHOUSE EXPERIMENT)

Treatment (lb. P_2O_5 per acre)		Plant Material (g. per pot(2))	P content (%)	P uptake (mg. per pot)
0		1.52	0.21	3.2
100		1.82	0.28	5.1
200		1.90	0.35	6.8
400		2.42	0.40	9.9
100*		1.71	0.31	5.3
200*		1.78	0.34	6.1
400*		1.95	0.44	8.6
L.S.D.	5%	0.39	0.039	1.97
	1%	0.53	0.053	2.69

(1) Previously applied phosphorus was monocalcium phosphate (0-45-0). Newly applied phosphorus was ground monoammonium phosphate (11-48-0).

(2) Oven dry weight. Twelve plants were grown in each pot.

* Newly applied phosphorus treatments calculated on the basis of 1 acre to 6-inch depth = 1.77×10^6 lb. soil.

TABLE 16

EFFICIENCY OF PREVIOUSLY AND NEWLY APPLIED PHOSPHORUS AS INDICATED BY THE PHOSPHORUS UPTAKE BY FLAX (1)

(SECOND GREENHOUSE EXPERIMENT)

Treatment (lb. P_2O_5 per acre)	Efficiency or % recovery
0	-
100	3.87
200	3.52
400	3.29
100*	4.28
200*	2.91
400*	2.73

(1) Twelve flax plants were grown in each pot.

* Newly applied phosphorus treatments calculated on the basis of 1 acre to 6-inch depth = 1.77 x 10^6 lb. soil.

of residual phosphorus remained relatively constant with increased rates of previous treatments, whereas that of newly applied phosphorus decreased slightly with increased rates.

According to the two greenhouse studies, flax showed better response to previously applied phosphorus than to newly applied phosphorus. It is therefore essential that soils sown to flax contain high levels of available phosphorus. Better yields might be obtained if flax is grown as a succeeding crop on the field previously cropped and fertilized with large amounts of fertilizer phosphorus. Further field studies, however, are needed to confirm the above conclusion.

V. SUMMARY AND CONCLUSIONS

Field and greenhouse experiments were undertaken with the following objectives:

1. To study the effects of broadcast and seed drilled phosphorus on crop yields and phosphorus uptake.

2. To evaluate the residual effects of large amounts of added phosphorus on crop yields, phosphorus uptake, and water and $NaHCO_3$-extractable phosphorus.

The field studies were conducted on a calcareous Altona soil at Winkler. Monocalcium phosphate (0-45-0) at rates of 0, 100, 200, and 400 lb. P_2O_5 per acre was broadcast in 1966. Additional monoammonium phosphate (11-48-0) at rates of 0, 10, 20, 40, and 80 lb. P_2O_5 per acre was drilled with the seed on each of the broadcast phosphorus treated plots. Wheat and flax were grown in 1966. After having been fallowed in 1967, the experimental plots were cropped to barley in 1968. Greenhouse studies were conducted to investigate the availability of previously and newly applied phosphorus to barley, rape, and flax. The previously applied phosphorus treatments were represented by the soils collected from the experimental plots in the spring of 1968. The newly applied phosphorus treatments were obtained by mixing monoammonium phosphate (11-48-0) with the non-fertilized soils from the experimental plots.

Under the conditions of the investigation, the results obtained can be summarized as follows:

1. Wheat responded well to either broadcast or seed drilled phosphorus. With respect to the efficiency, seed drilled phosphorus was found to be more effective in increasing the yields of wheat than broadcast phosphorus. It was also found that in order to obtain maximum yields of wheat grown on a

calcareous soil low in soil available phosphorus, small amounts of phosphorus at rates of 10 to 20 lb. P_2O_5 per acre had to be added with the seed even on the plots treated with large amounts of broadcast phosphorus. Phosphorus uptake by wheat increased with increased rates of either broadcast or seed drilled phosphorus.

2. Flax was not responsive to either broadcast or seed drilled phosphorus. Broadcast applications of 200 and 400 lb. P_2O_5 per acre consistently decreased the yields of flax, probably due to deficiencies of other nutrient elements. Phosphorus drilled with the seed significantly reduced flax germination. Phosphorus uptake by flax, however, was increased by applied phosphorus.

3. Barley grown as the second crop showed good response to phosphorus applied broadcast three years before. Significant residual effects were obtained with previously broadcast phosphorus at rates of 200 and 400 lb. P_2O_5 per acre. However, applications of 10 to 40 lb. P_2O_5 per acre with the seed were needed even on the plots previously broadcast with large amounts of phosphorus in order to obtain maximum yields of barley. Phosphorus uptake by barley was increased consistently by either previously broadcast or seed drilled phosphorus.

4. The greenhouse studies indicated that the degree of yield responses to previously and newly applied phosphorus increased in the order of flax, barley, rape. Barley and flax showed a better response to newly applied phosphorus than to the previously added phosphorus. Flax, however, showed better a response to previously applied phosphorus than to the newly added phosphorus.

5. Analyses of the soils collected from the experimental plots showed that the $NaHCO_3$-extractable phosphorus content of the soils was increased by

broadcast phosphorus for a number of years.

6. Solubility studies indicated that the prominent reaction product of monocalcium phosphate applied broadcast to a calcareous soil was probably octacalcium phosphate. This reaction product was found to exist in soils for a period of at least three years, and was available to plants.

The results of the studies conducted show that phosphorus added to soils in large amounts not only benefits the crop fertilized but remains available for succeeding crops as well. Since the experiment was conducted for a period of three years only and yield increases of some crops were obtained three years after adding the phosphorus, further cropping would be required to thoroughly evaluate the residual effects of the added phosphorus. Also experiments conducted on soils other than used in this study would further help to evaluate the residual effects of fertilizer phosphorus.

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