THE UNIVERSITY OF MANITOBA

THE EFFECT OF TIME AND METHOD OF PHOSPHORUS APPLICATION ON YIELD OF WHEAT AND SOIL PHOSPHORUS LEVELS

By

Gregg Wayne Morden

A Thesis

Submitted to the Faculty of

Graduate Studies in Partial Fulfillment

for the Degree

Master of Science

Department of Soil Science

Winnipeg, Manitoba

 May, 1986

ISBN Ø-315-33958-6

THE EFFECT OF TIME AND METHOD OF PHOSPHORUS APPLICATION ON YIELD OF WHEAT AND SOIL PHOSPHORUS LEVELS

BY

GREGG WAYNE MORDEN

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

Field plots were initiated to study the effect of time and method of phosphorus fertilizer application on yield of wheat at four Manitoba sites over four years. Yields with deep banded phosphorus (phosphorus banded at about 7 to 10 cm soil depth and in 17.5 cm spacings prior to seeding) were superior to those of with seed application. With seed application was superior to broadcast applications. Phosphorus broadcast in the fall was as effective in increasing yields as phosphorus broadcast in the spring. In contrast, deep banded applications of phosphorus in the fall were not as effective as phosphorus deep-banded in spring.

A single addition of 50 kg $P.ha^{-1}$ was less effective than four annual seed row applications of 12.5 kg $P.ha^{-1}$ but superior to annual broadcast applications in increasing yields over the four years of the study. Yields with a single addition of 100 kg $P.ha^{-1}$ were similar to annual applications of 25 kg $P.ha^{-1}$ added in the seed row or broadcast. Single applications of P at 50 or 100 kg $P.ha^{-1}$ supplemented by annual applications did not increase yields above that obtained with only annual applications of 25 kg $P.ha^{-1}$ with the seed.

The amount of H_2O or $NaHCO_3$ extractable phosphorus was plotted versus % yield. Although the relationships were poor, the data indicated that a response to applied phosphorus could occur on soils previously treated with relatively large amounts of P and which have

high values of $NaHCO_3$-ext. P.

A laboratory experiment was conducted to observe the rate of hydrolysis of Dicalcium Phosphate Dihydrate (DCPD) to less soluble reaction products such as Octacalcium Phosphate (OCP). Samples were incubated at pH values of 6, 7 and 8, temperatures of 10, 20 and 30 C and calcium concentrations of 0.01, 0.001, and 0.0001 M. There was little or no hydrolysis of the DCPD at a pH of 6 and the hydrolysis was slow at a temperature of 10 C. Rates of hydrolysis increased with increases in temperature, pH and calcium concentration.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to:

Dr. G. Racz, Professor, Department of Soil Science, University of Manitoba, under whose immediate supervision this study was conducted, for his helpful advice and constructive criticism of the work.

Val Huzel, for her appreciated assistance in the lab.

Sid Glufka, for his expertise in the field work.

Mary Melnychuk, my future wife, for her patience.

And, of course, for their financial support, Western CO-OP Fertilizers and NSERC.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Placement of phosphorus fertilizers with or near the seed is considered to be the best method of supplying phosphorus to plants grown on phosphorus deficient soils and is the traditional method of applying phosphorus fertilizers to annual crops grown on the Canadian Prairies. This method of fertilizer placement involves handling relatively large quantities of fertilizer by the farmer at time of seeding which can cause delays in seeding and reduced potential yields. Thus, farmers are interested in applying phosphorus fertilizers at a time other than seeding.

Field experiments were initiated at four locations in October 1978 to compare the effects of time and method of phosphorus fertilizer application on yield of wheat. The objectives of the study were to compare: annual broadcast versus annual seed row applied phosphorus, fall versus spring applied phosphorus, phosphorus deep banded into the soil prior to seeding versus seed row and broadcast phosphorus, a single large application of phosphorus versus small annual applications, and a single large application of phosphorus versus a large application plus annual seed row and broadcast applications.

Dicalcium phosphate dihydrate (DCPD) is an initial reaction product formed in calcareous and base saturated soils when fertilizers of high water solubility, particularly superphosphates, are applied. DCPD, however, is metastable and hydrolyses to octacalcium phosphate (OCP) which eventually hydrolyzes to an apatite (usually hydroxyapatite, HA). The solubility and thus the plant availability of phosphorus from these sources decreases in the order: DCPD > OCP > HA. Hence, the rate at which DCPD hydrolyses to OCP or less soluble phosphates influences the residual value of the applied phosphate. A laboratory experiment was conducted to determine the rate of change of DCPD to less soluble reaction products as a function of pH, temperature and calcium concentration.

Chapter II

REVIEW OF LITERATURE

A. Effect of Time and Method of Phosphorus Application on Yield

There has been much work reported on the effectiveness of various methods of applying phosphate fertilizers. Since immobile nutrients such as phosphorus are not accessible unless they are physically placed where roots can grow to them, the proper location of fertilizer placement is important for maximum root access (Klepper et al, 1983) and hence plant growth. Essentially, methods of placement can be seen as variations of broadcasting and banding. These two methods have been explained by, among others, Bailey et al.(1980), Engelstad and Terman (1980), and Tisdale et al.(1985). In broadcasting, the fertilizer is uniformly distributed over a field before planting, either in the spring or in the fall, and is usually incorporated by either shallow or deep cultivation; although broadcasting may also include topdressing on growing crops. Banding refers to the placement of a concentrated source of nutrient in a restricted soil volume in the vicinity of plant roots. This would include for example: seed placed (placed in direct contact with the seed), side banding (applied in bands to one or both sides of the seed or plant), and placement directly below the seed at a prescribed depth.

Olsen and Dreier (1956) found the efficiency of applied phosphate was greater when applied with the seed than when broadcasted and recommended placement of P fertilizer with the seed of small grains in the drier regions. Fertilizer in proximity with a germinating seed was rapidly translocated and concentrated in the moisture imbibing seed and thus available to the plant. Nyborg and Hennig (1969) compared placement of P in the seed row with placement in different positions away from the seed row using barley as a test crop and triple superphosphate as a fertilizer. They showed that with low rates of P, 7 kg $P.ha^{-1}$, yields of barley were greatest when the P was placed directly in the seed row. However, at a higher rate of P, 29 kg $P.ha^{-1}$, yield with seed row P and P placed 2.5 cm below the seed were equal. They noted that phosphorus should not be placed far from the seed row. In contrast, Lutz et al (1973) found an advantage in placing P away from the seed.

Ridley and Tayakepisuthe (1974) compared the effect of broadcast P and seed row P on yield of wheat. Wheat responded well to the applied P, with seed row being the most effective method of application. Phosphorus applied in the seed row was found to be about twice as effective as P broadcast at time of seeding in an Australian experiment (Rudd and Barrow, 1973). They noted that phosphate applied with the seed at time of seeding has been regarded as the standard treatment and the effectiveness of other treatments compared with it.

The importance of P placement has also been shown in experiments with other crops. Garg and Welch (1966), in greenhouse experiments with corn, indicated that P placed with the seed was more available for plant absorption, as reflected by plant yields, than P banded or broadcast and incorporated. Bates (1970), in a field experiment using corn, found that the best yields were obtained with seed placed P in combination with either broadcast and incorporated P or side- banded P.

Bullen (1983) studied various P placement methods for soybeans. On soils low in $NaHCO_3$ ext-P, yield responses were greatest with P banded 2.5 cm below the seed. Sidebanding P at 2.5 cm below and 2.5 cm beside the seed was less effective than placing P directly below the seed. Placing P with the seed or broadcast application in spring or fall were not as effective in increasing grain yields as were the previous methods.

Kinra et al.(1963) found that yields of winter wheat were significantly lower on plots with seed placed P than on plots with side banded P (no broadcast treatments were used). Peterson et al.(1980), compared seed row applied P with broadcast and incorporated P, and found that at low initial soil P values, as much as three times the amount of broadcast P was necessary to give a similar yield to seed row applied P. However, at medium soil P values, yields were similar for both placements. Crop response to broadcast or seed row applied P may be variable due to climatic conditions such as moisture, or to the initial level of soil P. Several workers (Power et al.1961, Ferguson 1963, Read and Warder 1974, Bailey et al.1977) found a strong relationship between moisture levels and P uptake. Powers et al. (1961), working with spring wheat in Montana, found a linear function between P uptake and four moisture regimes. Bailey et al.(1977) found that in years of high water supply, yield and P uptake were generally higher than in years of low water supply. Powers et al (1961) and

Strong and Soper (1973) noted an inverse relationship between the availability of soil P and the utilization of P from a fertilizer band.

Whether P is added to the soil as annual additions, single large additions or a combination of the two methods, it has been found that the crop uptake of P is relatively low compared to the amount of P added (Maclean, 1963, Read et al, 1977, Halvorson and Black, 1985). This P accumulates in the soil and may be utilized by succeeding crops dependent upon the degree of migration from the rooting zone and the extent of change to non-available forms (Maclean, 1963). Therefore, one objective of several experiments conducted by various researchers has been to determine the effect of this residual P on crop yields as a function of time.

Bailey et al (1977) broadcasted P at rates of 0, 100, 200 and 400 kg P per ha^{-1} and cropped the soils over a period of eight years in a continuous wheat-flax rotation. They found the addition of 100 kg P per ha^{-1} to be the most efficient treatment over the eight year period in increasing yields, but by the eighth year the soil P was reduced to about 8 kg $P.ha^{-1}$ which was considered inadequate for maximum crop production. The 200 and 400 kg P per ha^{-1} additions were no more effective than the 100 kg $P.ha^{-1}$ in increasing yields over the eight year period. However, even after eight years of cropping there was about 20 and 50 kg $P.ha^{-1}$ of $NaHCO_3$-ext. P in the soils treated with 200 and 400 kg $P.ha^{-1}$. Halvorson and Black (1985), broadcasted and incorporated 0, 22, 45, 90, and 180 kg P ha^{-1} and found over ten or eleven crops that a one time application of P at rates of 90 kg P ha-1 was an effective way of meeting crop needs. Wagar et al (1985) measured the effectiveness of residual P and found that over a period of five years, a single broadcast application of 40 kg $P.ha^{-1}$ produced yields comparable to those produced by seed placed treatment of 20 kg $P.ha^{-1}$ yr^{-1}. These results, however, appeared to be biased by an excellent response to P in only the first year of study. Jansen et al (1985) found that it made little difference in the total yield of grain sorghum when the P fertilizer was applied every year, every two years or every four years.

The enhancement of yield with small amounts of P applied in the seed row ("starter effect") is also of importance. Results on "starter effects" have been variable among experiments.

Poulet (1985) found that, on a soil low in $NaHCO_3$, placing P at 17 kg $P.ha^{-1}$ in the seed row increased yields even on plots previously treated with 100 kg $P.ha^{-1}$. He found that both broadcast and with seed applications were necessary to achieve maximum yield on soils very low in plant available P.

Read et al (1977) found a general lack of response to P applied with the seed on soils that had received a large application of P. Ridley and Tayakepisuthe (1974) found seed row P tended to increase yields of wheat when applied to plots that had received 50 or 100 kg $P.ha^{-1}$ but found reduced yields when seed row P was applied to plots which had received 200 kg $P.ha^{-1}$. Alessi and Power (1980) concluded that banded P may be beneficial for spring wheat since yield increases were obtained from banding P with the seed even when soil test levels were high.

A number of researchers have attempted to predict the duration of the beneficial effects of large applications of P based on the idea that phosphate fertilizer should be reapplied when soil tests reach 15 ppm and large yield increases are expected when soil tests are below 10 ppm (Spratt and Read, 1980). Spratt et al (1980) derived linear equations for $NaHCO_3$-ext. P values versus time and predicted that 100, 200, 400 kg $P.ha^{-1}$ would provide sufficient P to wheat for about 6, 9, and 13 years, respectively, before further application would be needed. Fixen and Ludwick (1982) developed a methodology for determining residual P in Colorado soils based on the level of $NaHCO_3$-ext. P, the percentage clay and the percentage of lime in the soil (residual P was defined as the amount of P removed from the soil by plant uptake until the $NaHCO_3$-ext. P level dropped to 10 ppm).

$$\begin{aligned}\text{Residual P, mg/2kg soil} = \; & -17.02 + 2.062\ (NaHCO_3\text{-ext. P,ppm}) \\ & +0.058\ (NaHCO_3\text{-ext. P, * clay,\%}) \\ & -0.187\ (\text{lime,\% * clay})\end{aligned}$$

B. Reaction Products of P in soil

1. Fate of Applied Fertilizer

Water soluble P fertilizers are either precipitated or absorbed by soil constituents. However, the majority of P near a granule is precipitated. Numerous researchers have shown the initial reaction product to be DCPD and DMPT in calcareous or base saturated neutral soils. Cole et al (1953) studied the adsorption of soluble phosphate fertilizers by calcium carbonate and found that DCPD was precipitated. Moreno et al (1960) noted that DCPD was an initial reaction product formed in soils when fertilizers of high water solubility, particularly superphosphates, were applied. DCPD forms both at the site of application due to hydrolysis of monocalcium phosphate, and in the soil immediately surrounding it. Beaton and Read (1963), added water soluble phosphate fertilizers to soil and found that the major initial reaction product was DCPD, as did Larsen and Widdowsin (1970) and Strong and Racz (1969). These products are metastable and undergo hydrolysis to less soluble, and hence less plant available, forms of P. The general sequence of hydrolysis for DCPD in neutral and calcareous soils, as outlined by Lehr and Brown (1958) is:

$$\text{DCPD} \longrightarrow \text{OCP} \longrightarrow \text{HA}$$

The solubilities of these compounds are, pKsp = 6.56 (DCPD), pKsp = 93.81 (OCP), pKsp = 111.82 (HA). (Sample et al, 1980)

2. Products Present in Soil

Weir and Soper (1963) found that phosphate in nonphosphated Manitoba soils was more soluble than HA but less soluble than DCPD. They also found that in most fertilized soils the solubility of P was quite close to the solubility isotherm of OCP. Ridley and Tayakepisuthe (1974) working with Manitoba soils, also found that in an untreated soil the soil was undersaturated with respect to OCP but supersaturated with respect to HA. This suggested that either HA or OCP governed the P concentration in the soil solution. In soils treated with 50 kg $P.ha^{-1}$, the solubilities of P were also between that of OCP and HA, but were very close to that of OCP, indicating a higher solubility of phosphate in the fertilized soil than in the unfertilized soil. Similarly Sadler and Stewart (1976) found that in control soils phosphate concentration was controlled by impure HA while after phosphate addition the solution concentration was controlled by either OCP or HA. Fixen (1979) indicated, however, that fertilized soils from Colorado appeared buffered near the solubility isotherm of tricalcium phosphate (TCP) which has a solubility isotherm between that of OCP and HA. Fixen and Ludwick (1982) found that for 27 of 28 Colorada soils, OCP was probably not an important residue although they pointed out that its importance may have been greater if soils of a high $NaHCO_3$-ext. P content had been selected. Griffin and Juriak (1973) studied absorption isotherms of phosphate as described by a two region Langmuir equation. Their studies indicated that in region one of the isotherm (at low phosphate concentrations) the soil solution was supersaturated with respect to HA while in region two (at higher phosphate concentrations, >0.6 ppm P) the soil solution was supersaturated with respect to OCP.

3. Factors Influencing Hydrolysis of DCPD

DCPD hydrolyses to less soluble phosphate compounds such as OCP or HA. In laboratory experiments the rate of hydrolysis has been shown to be affected by soil parameters such as pH, organic matter, presence of calcium carbonate, temperature, moisture and time (Sample et al, 1980)

Time: Bell and Black (9170) incubated soils with DCPD for 4, 16 and 44 weeks and found that transformation of DCPD to OCP increased with time of incubation, but they found no evidence of conversion of OCP to more basic phosphates. This is in agreement with results obtained by Moreno et al (1960a) who investigated the equilibrium of DCPD with a neutral soil and noted the hydrolysis of DCPD to OCP over a period of 60 days. However, Strong (1969) incubated pellets of DCPD for periods of up to 8 months and found that the samples had reached equilibrium with respect to DCPD and remained so for considerable lengths of time. Values plotted on a solubility isotherm diagram remained between OCP and DCPD. Racz and Soper (1967) studied the hydrolysis of DCPD in 4 Manitoba soils (0.1 g of phosphorus was placed between filter paper separating layers of soil in plastic cylinders) for up to 6 months. No OCP was detected in any of the four soils.

Temperature: Bell and Black (1970) incubated DCPD at temperatures of 25 C and 35 C and found the hydrolysis of DCPD to OCP increased with increased temperature. Probert and Larsen (1970), investigated the dissolution of DCPD incorporated in moist soil and found that over a temperature range of 15 C to 33 C the rate of dissolution increased.

Beaton et al (1965), found that the water soluble phosphorus concentration was relatively unaffected by temperature in reaction zones of 15 mg of P as DCPD placed in cavities in the surface of two soils incubated at 5, 20 and 30 C. This indicated that the solubility of DCPD was not greatly affected by temperature.

pH: Bell and Black (1970) found that hydrolysis of DCPD to OCP in incubated soils was confirmed after 4 weeks in soils having a pH values between 6.9 and 7.9, whereas for soils with a pH value higher than 6.9 the new phase was found only after incubation for 44 weeks. They concluded that the transformation of DCPD increased with increasing pH (in neutral to basic soils). Moreno et al. (1960b) found that OCP was found to precipitate when the pH of the solution (DCPD in dilute phosphoric acid and water) was higher than 6.38. The extent of the hydrolysis was larger the higher the initial pH of the solution.

Moisture: Probert and Larsen (1970) found the rate of dissolution of DCPD to increase with moisture content over the range of 12 to 32 percent.

Organic matter: Moreno et al (1960a) noted that there was a decrease in the rate of hydrolysis of DCPD as the level of organic matter increased. They suggested that organic matter interfered in some way with the formation of OCP. Solubilized organic matter complexed calcium in appreciable quantities at pH values above 6, introducing apparent supersaturation with respect to DCPD, which may shift the equilibrium of the reaction to favour DCPD.

Calcium carbonate: Racz and Soper (1967) incubated 4 soils and $CaCO_3$ and $MgCO_3$ treated with DCPD at room temperature for up to six months. OCP was formed after one month of incubation when DCPD was placed into calcium carbonate but no OCP was found in any of the 4 soils.

Surface area of DCPD: Probert and Larsen (1970), used small and coarse crystals of DCPD and found that the rate of dissolution was greater for the small than for the large crystals incorporated in moist soil. Similarly, Bouldin and Sample (1959), using different mesh sizes of fertilizer, reported that the availability coefficients of different granular sizes of DCPD were primarily dependent upon the geometric surface area of the granules, the smaller the granular size the higher the availability of phosphorus. Moreno et al (1960b) found that if OCP was mixed with DCPD prior to the addition of phosphoric acid (in a solution experiment to study precipitation products of DCPD in dilute phosphoric acid) equilibrium was obtained slowly because the DCPD crystals become coated with OCP. These results indicate that a coating of OCP, which may occur on surfaces of DCPD crystals as they undergo congruent dissolution, would reduce the solubility and perhaps the rate of hydrolysis of DCPD crystals.

Chapter III

METHODS AND MATERIALS

1) Field Studies - Effect of Time and Method of Phosphorus Application on Yield of Wheat

The soils selected varied in $NaHCO_3$-ext. P (6 to 24 ppm), pH (6.5 to 7.5), $\%CO_3$ (.1 to 6.2) as well as texture and organic matter content. The basic criteria used in the selection of the soils was the level of $NaHCO_3$-ext. P. A wide range was selected in order that the effects of time and method of placement of P on efficacy be determined at both low and high levels of plant available P.

Field studies were initiated on four sites in South-Central Manitoba in the fall of 1978. Some chemical and physical characteristics of these sites are shown in table 1.

Wheat (Triticum aestivium, var Neepawa) was seeded at 110 $kg.ha^{-1}$ for all sites and years of the study. Treatments, shown in table 2, were arranged in a randomized block design with 21 treatments replicated 5 times. Each plot was 3.25 m by 7.23 m and replicates were separated by 1.81 m roadways.

A small plot seeder was used for seeding and fertilizer placement. Phosphorus applied as a broadcast treatment in the

Table 1. Physical and Chemical Characteristics of the Soils Used in the Field Studies

	Purvis	Kaleida	Portage	Carman
Soil Type	Orthic Black	Orthic Black	Cumulic Regosol	Orthic Black
Association	Snowflake	Manitou	Elm River	Willowcrest
Texture	L	CL	L	LFS
sand (%)	30	36	33	85
silt (%)	43	36	46	5
clay (%)	27	28	21	10
C.E.C. ($cmoles.kg^{-1}$)	29.2	30.6	16.1	13.5
O.M. (%)	6.3	8.0	3.4	3.3
CO_3(%)	0.3	0.2	moderate	0.1
pH	7.0	6.5	7.5	7.0
H_2O-ext. P (ppm)	0.6	7.9	0.7	3.1
$NaHCO_3$-ext. P (ppm)	6.3	23.9	6.9	6.3

Table 2. Fertilizer Treatments for Field Plots

Treat. No.	Broadcast P Applied at Initiation of Exp.	Annual Application and Time and Method of Application	
1	0		0
2	0	12.5	kg $P.ha^{-1}$, seed row in spring
3	0	25	kg $P.ha^{-1}$, seed row in spring
4	0	12.5	kg $P.ha^{-1}$ broadcast & incorporated in spring
5	0	25	kg $P.ha^{-1}$, broadcast & incorporated in spring
6	0	12.5	kg $P.ha^{-1}$, broadcast & incorporated in fall
7	0	25	kg $P.ha^{-1}$, broadcast & incorporated in fall
8*	0	12.5	kg $P.ha^{-1}$, banded in soil in spring
9*	0	25	kg $P.ha^{-1}$, banded in soil in spring
10*	0	12.5	kg $P.ha^{-1}$, banded in soil in fall
11*	0	25	kg $P.ha^{-1}$, banded in soil in fall
12	50 kg $P.ha^{-1}$		0
13	50 kg $P.ha^{-1}$	12.5	kg $P.ha^{-1}$, seed row in spring
14	50 kg $P.ha^{-1}$	25	kg $P.ha^{-1}$, seed row in spring
15	50 kg $P.ha^{-1}$	12.5	kg $P.ha^{-1}$, broadcast & incorporated in spring
16	50 kg $P.ha^{-1}$	25	kg $P.ha^{-1}$, broadcast & incorporated in spring
17	100 kg $P.ha^{-1}$		0
18	100 kg $P.ha^{-1}$	12.5	kg $P.ha^{-1}$, seed row in spring
19	100 kg $P.ha^{-1}$	25	kg $P.ha^{-1}$, seed row in spring
20	100 kg $P.ha^{-1}$	12.5	kg $P.ha^{-1}$, broadcast & incorporated in spring
21	100 kg $P.ha^{-1}$	25	kg $P.ha^{-1}$, broadcast & incorporated in spring

Notes:

(1) * Phosphorus fertilizer banded into soil at depths of 7 to 10 cm in fall after cultivation or in spring prior to seeding

(2) Phosphorus, when broadcast, was incorporated to a depth of 10 cm immediately after application using a rotory cultivator

fall was spread by hand. The phosphorus fertilizer was incorporated into the soil to a depth of 7.5 to 10 cm using a rotary cultivator. Phosphorus applied in bands in the fall was placed at depths of 8 to 10 cm at 17.5 cm spacings using a small plot seeder equipped with a fertilizer dispenser. Band application of the fertilizer was conducted after the tillage operation. In spring, broadcast and preplant band applications were applied as described above immediately prior to seeding. Nitrogen fertilizer, as ammonium nitrate, was applied at the rate of 100 kg $N.ha^{-1}.yr^{-1}$. The nitrogen fertilizer was applied prior to the spring tillage operation.

Plots were maintained weed free using the herbicides Buctryl M and Hoegrass at recommended application rates.

In 1980, a severe drought resulted in poor emergence and growth. Plant growth at the Portage and Carman sites were reasonably satisfactory and adequate for yield measurements. In contrast, at the Purvis and Kaleida sites, growth was very poor and harvesting was not conducted.

At maturity, the total above ground portion of the plant in 7.22 m of row from the center of each plot, was harvested. Samples were dried, threshed and ground and yields of grain and straw determined. The samples from each replicate were bulked by treatment prior to analysis.

Soil samples were taken from the 0 to 15 cm depth of all treatments in fall after tillage operations. Each plot was sampled at four locations and samples from the various locations and from all replicates bulked by treatment. Samples were air dried and ground prior to analysis.

2) Laboratory Studies - Hydrolysis of DCPD as affected by pH, calcium concentration and temperature.

Two experiments were conducted in the laboratory.

(a) Solution study: A solution experiment was conducted to observe changes in DCPD with time at different pH values, calcium concentrations, and temperatures.

One g of DCPD was enclosed in Whatman filter paper and incubated in flasks containing solutions of varying concentrations of calcium (0.01 M, 0.001 M and 0.0001 M) and maintained at various pH values (pH 6, pH 7 and pH 8). The samples were incubated at temperatures of 10, 20 or 30 C for a period of up to 24 months. Solutions were changed at regular monthly intervals and the pH values of the solutions adjusted when necessary. After incubation, the DCPD was removed from the solution and air dried. Subsamples were subjected to X - ray diffraction analysis and analyzed for calcium and phosphorus content.

(b) Soil studies: An experiment was conducted to observe the hydrolysis of DCPD in various soils.

Incubation of DCPD for each soil was as follows: Two plexiglass cylinders (4 cm I.D. and 5 cm high) were each filled with about 100 g of dry soil. The ends of the cylinders were sealed with polyethylene mesh with a mesh opening of 157 u. One g of DCPD was placed as uniformly as possible between the two halves which were then taped together with electrical tape. The samples were placed in containers with free water at the bottom and the soils allowed to wet to field capacity by capillarity. The samples were removed from the wetting container and incubated at temperatures of 0, 10, 20 and 30 C for periods of up to 30 months. During incubation the samples were periodically inverted to assure uniform water content and assure aerobic conditions. Some chemical characteristics of the 12 soils used are shown in Table 3.

After incubation, the DCPD was removed and dried prior to analysis. Subsamples were subjected to X - ray diffraction analysis, and analyzed for calcium and phosphorus content.

3) Analytical Procedures

Organic matter content of the soils was determined by the Walkley-Black method as described by Allison (1965). Titrations were conducted using an automated potentiometer.

Particle size analysis was performed by the standard pipette method described by Kilner and Alexander (1949).

Soil pH was determined on a 1 : 1 soil to water paste using a combination glass - calomel electrode.

Table 3. Some Physical and Chemical Properties of Soils Used for the Incubation Studies

Soil Name	Texture	%CO_3	pH
Elm River	SiL	6.2	7.8
Lakeland	SiCL	18.2	7.9
Stockton	LFS	0.0	6.8
Wellwood	L	0.4	7.1
Newdale	CL	1.8	7.5
Plumridge	LFS	8.0	8.1
Snowflake	CL	0.3	7.1
Willowcrest	LFS	0.1	6.9
Balmoral	SiC	10.6	8.1
Lundar	L	3.4	7.7
Manitou	CL	0.2	6.8
Inwood	CL	12.0	7.9

The inorganic carbonate content of the soil samples was determined by reacting a 0.5 g sample of soil with 40 ml of 0.1 M HCL. The CO_2 evolved was collected in a Nesbett tube containing ascarite and the percentage calcium carbonate equivalent was calculated from the change in weight of the ascarite.

Cation exchange capacity was determined by ammonium saturation and displacement of exchangeable cations using NH_4OAc at pH 7 (Chapman, 1965).

$NaHCO_3$ extractable phosphorus was determined by a modified Olsen et al (1954) method. Five g of air dried soil was extracted with 100 ml of 0.5 M $NaHCO_3$ at a pH of 8.5 for 30 minutes. After equilibration, the solutions were either centrifuged or refiltered until a clear extract was obtained. Water extractable phosphorus was determined by shaking 5 g of soil with 100 ml of water for 30 minutes. The concentration of phosphorus in solution was determined by the acid - molybdate procedure as described by Murphy and Riley (1962).

DCPD was prepared by a slow addition of a $CaCl_2$ solution and a phosphorus solution ($Na_2HPO_4.2H_2O$ + KH_2PO_4) into a phosphate solution (KH_2PO_4) maintained at pH 4 to 5. When the precipitation was complete the liquid was decanted and the precipitate washed, first with a dilute solution of phosphoric acid then with ethanol and air dried (Racz 1966).

The calcium and phosphorus content of the phosphorus reaction products was determined as follows: 0.1 g of sample was dissolved in concentrated HCL and diluted to concentrations appropriate for analysis. Phosphorus was measured as mentioned previously. Calcium was determined by Atomic Absorption spectrophotometry.

The phosphorus content of plant tissues was determined as follows: one gm of plant material was digested using a HNO_3-$HClO_3$ acid mixture. The digests were filtered, diluted and the phosphorus content determined colourimetrically (Murphy and Riley 1962).

X - ray diffraction analysis was conducted on the phosphorus reaction products using a Philips X - ray Defractometer, model PW 1051. The sample was finely ground and placed in the target area. The samples were mechanically rotated from 00 to 500 . The lines were measured from the chart output and the "d" spacing corresponding to each major peak was calculated. The phosphorus reaction products were identified by comparison of the "d" spacings obtained for the samples to those listed for the various phosphorus reaction products in Crystallographic Properties of Fertilizer Compounds (Lehr et al. 1967).

Chapter IV

RESULTS AND DISCUSSION

A. Field Studies - Effect of Time and Method of Phosphorus Fertilizer Application on Yield of Wheat

1. Purvis

Yield measurements were taken in only three of the four years of the study at Purvis. Due to drought, the crop was not harvested in 1980. Analysis of variance, ANOVA, was conducted on the yield data to test for significant differences in yields; a) among years and treatments, b) between rates, and c) between methods of application (Appendix A). This analysis showed that there were significant differences in yields among years of the study and among treatments. Yield of wheat, between the rates of 12.5 kg $P.ha^{-1}$ and 25 kg $P.ha^{-1}$, was significantly different when no P was added in the first year of the study and when 50 kg $P.ha^{-1}$ was broadcast. Methods of application significantly affected yield only for those treatments which had no initial large application of P.

Yield of wheat grown at Purvis was significantly increased by phosphorus (P) fertilization in all years of study (Table 4). Grain yields among plots treated with annual applications of P but without an initial large application of broadcast P were not significantly different except in 1982 when yield with P applied in a preplant band in spring at 12.5 kg $P.ha^{-1}$ was higher than yield with broadcast P application in fall or spring at the same rate of application. Despite the lack of significant differences in yield among most of these treatments, various yield trends were evident. Yields with P applied in the seed-row at 12.5 kg $P.ha^{-1}$ were always superior to yields with P applied broadcast at 12.5 kg $P.ha^{-1}$. At the higher rate of application (25 kg $P.ha^{-1}$), although yields with P applied in the seed-row were higher than those with broadcast P applications in two of three years, the mean yield for all years of study for these two treatments were equal. Yield increase (kg grain per kg P added) for all years of study was 65, 50, 38, and 38 for P applied in the seed row at 12.5 and 25 kg $P.ha^{-1}$ and P applied broadcast at 12.5 and 25 kg $P.ha^{-1}$, respectively.

The average yields with P banded into the soil prior to seeding at 12.5 kg $P.ha^{-1}$ (3227 kg) were higher than with P broadcast in the spring and P applied in the seed row (respectively, 2932 kg and 3182 kg). Yield of wheat with 25 kg $P.ha^{-1}$ applied as a preplant band were also slightly greater than with broadcast or seed row application. It should be noted, however, that in these experiments the spacing of

Table 4. Effect of Time and Method of Phosphorus Application on Yield of Wheat At Purvis

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Yield (kg P.ha^{-1}) 1979	1981	1982	average	Yield increase (kg grain per kg P added)
0	no P applied		--	2451 G	1930 C	1926 E	2102	--
0	seed row - sp	12.5	50	3245 ABCDEF	3033 AB	3268 ABCD	3182	65
0	seed row - sp	25.0	100	3627 ABCDE	3151 AB	3345 ABC	3374	38
0	broadcast - sp	12.5	50	2992 E	2935 AB	2869 CD	2932	50
0	broadcast - sp	25.0	100	3487 ABCDEF	3048 AB	3587 A	3374	38
0	broadcast - f	12.5	50	3140 CDEF	2795 AB	2915 BCD	2950	51
0	broadcast - f	25.0	100	3191 ABCDEF	2965 AB	3314 ABC	3157	32
0	banded - sp	12.5	50	3164 BCDEF	3027 AB	3491 A	3227	68
0	banded - sp	25.0	100	3476 ABCDEF	3214 A	3596 A	3429	40
0	banded - f	12.5	50	3064 EF	2778 AB	3093 ABCD	2978	53
0	banded - f	25.0	100	3120 DEF	3121 AB	3379 ABCD	3207	33
50	no P applied		50	3723 ABC	2725 B	2788 D	3079	59
50	seed row - sp	12.5	100	3528 ABCDEF	3040 AB	3404 AB	3324	37
50	seed row - sp	25.0	150	3616 ABCDE	3208 AB	3452 A	3425	26
50	broadcast - sp	12.5	100	3478 ABCDEF	2900 AB	3148 ABCD	3175	32
50	broadcast - sp	25.0	150	3747 AB	2963 AB	3539 A	3416	26
100	no P applied		100	3729 AB	2966 AB	3229 ABCD	3308	36
100	seed row - sp	12.5	150	3780 A	2976 AB	3301 ABC	3352	25
100	seed row - sp	25.0	200	3572 ABCDEF	2992 AB	3548 A	3371	19
100	broadcast - sp	12.5	150	3574 ABCDEF	3258 A	3414 AB	3415	26
100	broadcast - sp	25.0	200	3675 ABCD	2919 AB	3364 ABC	3319	18

* Duncans Multiple Range Test, numbers followed by the same letter are not significantly different at p = 0.05

the preplant P bands was 17.5 cm (a relatively narrow spacing) and thus the P band was no more than about 9 cm from the seed row. The excellent response of wheat to P applied in preplant bands suggests that this method of P application may be a suitable alternative to P applied in the seed-row.

P broadcast in fall at 12.5 kg $P.ha^{-1}$ was as effective in increasing yields as P broadcast in spring. P broadcast in fall at 25 kg $P.ha^{-1}$ was less effective in increasing yields than P broadcast in spring in all years of study. None of these differences in yield, however, were significantly different in any year of study.

P applied in preplant bands in fall were less effective in increasing yields than P applied in preplant bands in spring at both application rates and all years of study. In these studies, the P bands placed in the fall were disturbed by spring tillage operations. This would reduce the plant availability of the P banded in the fall. Plant availability of P banded in the fall approximated that of broadcast P applications.

A single large application of P, with the idea of eliminating annual application, was compared to annual applications. As noted previously, differences in yield among treatments were usually not significantly different but several trends were evident. Broadcasting 50 kg $P.ha^{-1}$ in year one of the study resulted in lower yields than four annual applications of 12.5 kg $P.ha^{-1}$ in the seed row or preplant bands in spring. A single large application of 50 kg $P.ha^{-1}$, however, was on average more effective in increasing yields than four annual broadcast applications at 12.5 kg $P.ha^{-1}$. It should be noted, however that the application of 50 kg P.ha^{-1} increased yields mainly in only the first and second year of the study. Yield increases tended to decline with cropping in years three and four of the study with the single application of 50 kg P.ha^{-1} and yields with the annual broadcast P application at 12.5 kg P.ha^{-1} were slightly higher in years three and four than with the single large application. Additional P was required in years three and four of the study to obtain maximum yields when 50 kg P.ha^{-1} was broadcast in year one. Both seed-row and annual broadcast P applications at 12.5 and 25 kg P.ha^{-1} increased yields on these plots, seed-row applications of P were more effective in increasing yields than broadcast P.

Broadcasting 100 kg P.ha^{-1} in year one of the study resulted in high yields in all years. However, four annual applications of 25 kg P.ha^{-1} in the seed-row, spring broadcast or applied preplant in a band in spring were slightly more effective in increasing yields. Annual application, in addition to the single large application, was required for maximum yield only in the last year of study when a slight yield response to annual application was noted.

Although it is important to consider the efficacy of P use (ie. yield increase per unit of P added) it is also important to study methods of P application which result in maximum yields. At this site, annual applications of 25 kg P.ha^{-1} applied in the seed-row, applied in preplant bands in spring or broadcast in the spring resulted in yields equal to yields obtained from treatments in which much greater amounts of P was added.

Uptake of P by wheat at Purvis was greatly increased by P fertilization and usually increased with increases in the amount of P added (Table 5). Samples from the various replicates were bulked prior to analysis and thus a statistical evaluation of the data could not be conducted. Uptake of P as affected by time and method of placement followed the trends noted for yield. Uptake of P by wheat grown on plots without a single large application of P varied from about 8 to 14 kg $P.ha^{-1}$ with annual applications of P. Since most of the P in the above ground portion of the plant is contained in the seed (Racz et al 1965) relatively large quantities of P (6 to 10 kg $P.ha^{-1}$) would be removed each year. Thus producers would need to add about 6 to 10 kg $P.ha^{-1}$ per year in order to replace P removed by cropping. P uptakes were greatest on plots with the single large P application supplemented with annual applications. These treatments usually did not result in higher yields than those with annual seed-row placed P or P applied in a preplant band in spring at 25 kg $P.ha^{-1}$. Thus luxury consumption of P occurred on these plots, particularly on plots treated with 100 kg $P.ha^{-1}$.

Percent utilization of added P (amount of P in treated plants minus amount of P in nontreated plants divided by amount of P added) decreased with increases in amount of P applied. Percent utilization of applied P as affected by time and method of P placement followed trends noted for yields.

It should be noted that the difference method used for calculating fertilizer usage:

(P uptake from a treated plot minus P uptake from the control plot) / (total P added) * 100.

Table 5. Effect of Time and Method of Phosphorus Applications on Uptake of Phosphorus at Purvis

P Initial (Kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (Kg P.ha^{-1})	Total P added (Kg P.ha^{-1})	Total P Uptake (kg P.ha^{-1}) 1979	1981	1982	total	Total - Tr 1	% utilization
0	no P applied		--	6.1	6.4	5.9	18.4	----	---
0	seed row - sp	12.5	50	8.4	11.8	13.0	33.2	14.8	30
0	seed row - sp	25.0	100	10.9	13.2	12.4	36.5	18.1	18
0	broadcast - sp	12.5	50	9.0	11.9	11.7	32.6	14.2	28
0	broadcast - sp	25.0	100	10.5	12.2	13.9	36.6	18.2	18
0	broadcast - f	12.5	50	9.3	11.4	11.1	31.8	13.4	27
0	broadcast - f	25.0	100	9.7	11.7	13.8	35.2	16.8	17
0	banded - sp	12.5	50	10.9	12.6	14.8	38.3	19.9	40
0	banded - sp	25.0	100	9.4	12.6	14.8	36.8	18.4	18
0	banded - f	12.5	50	9.0	11.3	11.7	32.0	13.6	27
0	banded - f	25.0	100	10.1	13.4	13.8	37.3	18.9	19
50	no P applied		50	12.7	10.4	10.9	34.0	15.6	31
50	seed row - sp	12.5	100	11.8	12.3	13.4	37.5	19.1	19
50	seed row - sp	25.0	150	12.9	13.3	15.1	41.3	22.9	15
50	broadcast - sp	12.5	100	11.6	12.6	12.6	36.8	18.4	18
50	broadcast - sp	25.0	150	13.7	12.5	14.4	40.6	22.2	15
100	no P applied		100	12.7	12.8	12.7	38.2	19.8	20
100	seed row - sp	12.5	150	14.1	12.7	12.9	39.7	21.3	14
100	seed row - sp	25.0	200	12.9	14.1	15.1	42.1	23.7	12
100	broadcast - sp	12.5	150	13.3	13.9	13.4	40.6	22.2	15
100	broadcast - sp	25.0	200	13.2	14.7	14.3	42.2	23.8	12

could lead to an underestimation of fertilizer use. Adding P fertilizer can at times reduce soil P uptake resulting in an underestimation of the amount of fertilizer P used. It is also possible that under certain circumstances the addition of fertilizer P results in a much larger plant and a larger and deeper root system, which results in an increased soil P uptake. The use of a tracer such as ^{32}P is required to separate these effects.

2. Kaleida

Yields were measured in three of the four years of the study. Due to drought, the crop was not harvested in 1980. Statistical analysis. ANOVA, showed that there were significant differences in the yields among years of the study and among treatments. Yields with 12.5 and 25 kg $P.ha^{-1}$ were not significantly different. The method of application affected yield with the 0 and 100 kg $P.ha^{-1}$ broadcast applications.

Response to P fertilization at Kaleida was not as great as at Purvis (Table 6). Yield of wheat at Kaleida was significantly increased by P fertilization only in the last year of the study. Grain yields among plots without an initial large application of P were not significantly different in any year except in 1981 when 12.5 kg $P.ha^{-1}$ applied in a band prior to seeding resulted in higher yields than the same amount of P applied broadcast in the spring. In spite of the lack of significant differences various yield trends were evident. Yields with P at 12.5 kg $P.ha^{-1}$ applied in the seed row were on average higher than yields with the same quantity of P broadcast in spring. In contrast, yields with P broadcast in spring at 25 kg $P.ha^{-1}$ were slightly higher than when the same quantity of P was applied with the

Table 6. Effect of Time and Method of Phosphorus Application on Yield of Wheat at Kaleida

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Yield (kg P.ha-1)				Yield increase (kg grain per kg P added)
				1979	1981	1982	average	
0	no P applied			2993 A*	2511 ABC	2637 D	2714	---
0	seed row - sp	12.5	50	3210 A	2710 ABC	3379 BC	3100	23
0	seed row - sp	25.0	100	3109 A	2542 ABC	3419 ABC	3023	9
0	broadcast - sp	12.5	50	3391 A	2312 C	2982 CD	2895	11
0	broadcast - sp	25.0	100	3234 A	2456 ABC	3893 AB	3194	14
0	broadcast - f	12.5	50	3360 A	2814 ABC	3327 BC	3167	27
0	broadcast - f	25.0	100	3463 A	2432 BC	3606 ABC	3167	14
0	banded - sp	12.5	50	3533 A	3097 AB	3864 AB	3498	47
0	banded - sp	25.0	100	3411 A	2950 ABC	3790 AB	3384	20
0	banded - f	12.5	50	3605 A	2902 ABC	3674 ABC	3394	41
0	banded - f	25.0	100	3072 A	2682 ABC	3373 BC	3042	10
50	no P applied		50	3002 A	2248 C	3224 BCD	2825	7
50	seed row - sp	12.5	100	3717 A	2518 ABC	3451 ABC	3229	15
50	seed row - sp	25.0	150	3146 A	2706 ABC	3547 ABC	3133	8
50	broadcast - sp	12.5	100	3090 A	2742 ABC	3877 AB	3236	16
50	broadcast - sp	25.0	150	3463 A	2830 ABC	3668 ABC	3320	12
100	no P applied		100	2947 A	2852 ABC	3329 BC	3043	10
100	seed row - sp	12.5	150	3682 A	3145 AB	3716 AB	3514	16
100	seed row - sp	25.0	200	3605 A	2780 ABC	4085 A	3490	12
100	broadcast - sp	12.5	150	3341 A	2625 ABC	3454 ABC	3140	9
100	broadcast - sp	25.0	200	3199 A	3160 A	3630 ABC	3330	9

* Duncans Multiple Range Test, numbers followed by the same letter are not significantly different at p = 0.05

seed. Preplant banding of P in spring resulted in higher yields than P placed in the seed-row at all times and at both rates of added P, and was superior to spring broadcast P three of three years at 12.5 kg $P.ha^{-1}$ and two of three years at 25 kg $P.ha^{-1}$. The excellent response of wheat to P applied in preplant bands in spring, as was noted for the Purvis site, indicates that this method is an alternative to P applied in the seed row.

Yields with P broadcast in the fall at 12.5 kg $P.ha^{-1}$ were slightly higher than yields with P applied in the seed row or applied broadcast in spring. At 25 kg $P.ha^{-1}$, yields with P broadcast in the fall were higher than yields with P banded in spring but lower than yields with P applied in the seed row. Yields with P applied in preplant bands in the fall were lower than yields with P applied in preplant bands in the spring at 12.5 kg $P.ha^{-1}$. P applied at 25 kg $P.ha-^{1}$ in preplant bands in the fall was less effective in increasing yields than P preplant banded in spring. Again, it should be noted that none of these differences in yield were significantly different in any year of the study.

Yield increase per unit of P applied (kg grain per kg P added) was highest when 12.5 kg $P.ha^{-1}$ was applied in preplant bands in spring. Yield increase per unit of P applied was also high when 12.5 kg $P.ha^{-1}$ was banded into the soil in fall. The highest yield increase per unit of P applied when 25 kg $P.ha^{-1}$ was applied occurred when the P was applied in a preplant band in spring.

A single large application of P was compared to annual applications. Differences in yield were usually not statistically significant but some trends were evident. Broadcasting 50 kg $P.ha^{-1}$ in year one of the study resulted in lower yields than four annual applications of 12.5 kg $P.ha^{-1}$ by any other application method in all years of the study. Additional P was required to obtain maximum yields in all years of the study; both seed row and annual broadcast applications increased yields, yield increases being similar for the two methods of application.

Broadcasting 100 kg $P.ha^{-1}$ in year one of the study also usually resulted in lower yields than four annual applications of 25 kg $P.ha^{-1}$. Additional P was required to obtain maximum yields and P applied in the seed row was more effective than broadcast P in enhancing yields.

As was noted for the Purvis site, maximum or near maximum yields could be obtained with annual P applications. Applying P in preplant bands in spring, generally resulted in as high a yield as when larger amounts were broadcast followed by annual applications.

Uptake of P by wheat at Kaleida was greatly increased by P fertilization and usually increased with increases in the amount of P added (Table 7). Uptake of P as affected by time and method of placement generally followed the trends noted for yields. The relationship between yield and P uptake, however, was not as close as noted for the results obtained at Purvis. Luxury consumption of P occurred on plots treated with a single large application of P particularly when supplemented with annual applications. Percent utilization of added P was highest when 12.5 kg $P.ha^{-1}$ was applied in preplant bands.

Table 7. Effect of Time and Method of Phosphorus Applications on Uptake of Phosphorus at Kaleida

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Total P Uptake (kg P.ha^{-1}) 1979	1981	1982	total	Total - Tr 1	% utilization
0	no P applied		--	11.2	8.8	10.5	30.5	---	---
0	seed row - sp	12.5	50	12.8	11.2	14.2	38.2	7.7	15
0	seed row - sp	25.0	100	13.7	11.2	14.1	39.0	8.5	9
0	broadcast - sp	12.5	50	13.2	9.7	11.2	34.1	3.6	7
0	broadcast - sp	25.0	100	14.8	12.0	16.2	43.0	12.5	13
0	broadcast - f	12.5	50	12.7	11.2	13.7	37.6	7.1	14
0	broadcast - f	25.0	100	16.6	10.8	13.2	40.6	10.1	10
0	banded - sp	12.5	50	13.7	11.2	15.6	40.5	10.0	20
0	banded - sp	25.0	100	15.7	12.7	16.7	45.1	14.6	15
0	banded - f	12.5	50	16.1	11.9	15.0	43.0	12.5	25
0	banded - f	25.0	100	14.7	11.8	15.1	41.6	11.1	11
50	no P applied		50	16.6	8.8	11.3	36.7	6.2	12
50	seed row - sp	12.5	100	20.4	12.1	13.9	46.4	15.9	16
50	seed row - sp	25.0	150	17.5	12.4	15.5	45.4	14.9	10
50	broadcast - sp	12.5	100	15.8	12.0	16.3	44.1	13.6	14
50	broadcast - sp	25.0	150	17.5	12.7	16.3	46.5	16.0	11
100	no P applied		100	17.4	12.5	13.4	43.3	12.8	13
100	seed row - sp	12.5	150	18.5	14.9	16.3	49.7	19.2	13
100	seed row - sp	25.0	200	17.5	13.5	18.5	49.5	19.0	10
100	broadcast - sp	12.5	150	20.1	12.7	15.5	48.3	17.8	12
100	broadcast - sp	25.0	200	19.1	14.6	18.0	51.7	21.2	11

3. Portage

Yields were measured in all four years of study at Portage. An analysis of variance, ANOVA, was conducted on the data. Yield among years were significantly different, however, all other comparisons were not significant.

Yield of wheat grown at Portage was significantly increased by P fertilization only in 1981 (Table 8). Grain yields among plots treated with annual applications of P but without an initial large application of broadcast P were not significantly different.

On average, yields with P banded into the soil prior to seeding were similar to yields obtained when the P was placed in the seed row and when P was applied broadcast. P broadcast in the fall was about as effective in increasing yields as P broadcast in spring and P applied in preplant bands in the fall were about as effective in increasing yields as P applied in preplant bands in spring.

A single large application of P was compared to annual applications. Differences in yield, although not significantly different, did show some trends. In contrast to the previous sites, broadcasting 50 kg $P.ha^{-1}$ in year one of the study resulted in yields equal to or slightly better than yields with four annual applications of 12.5 kg $P.ha^{-1}$. Yields were usually not increased by annual additions, thus P in addition to the single application of 50 kg $P.ha^{-1}$ was not needed to obtain maximum yields.

Table 8. Effect of Time and Method of Phosphorus Application on Yield of Wheat at Portage

P initial (kg $P.ha^{-1}$)	Method & Time of Annual Application	Annual P added (kg $P.ha^{-1}$)	Total P added (kg $P.ha^{-1}$)	Yield (kg $P.ha^{-1}$) 1979		1980		1981		1982		average	Yield increase (kg grain per kg P added)
0	no P applied		0	3038	AB*	1667	B	2708	D	2388	B	2450	--
0	seed row - sp	12.5	50	3511	AB	1791	B	3363	ABC	2593	AB	2815	29
0	seed row - sp	25.0	100	3647	AB	1803	B	3605	ABC	2548	AB	2901	18
0	broadcast - sp	12.5	50	3459	B	1671	B	3109	CD	2770	AB	2752	24
0	broadcast - sp	25.0	100	3651	AB	1688	B	3575	ABC	2620	AB	2884	17
0	broadcast - f	12.5	50	3074	AB	1743	B	3212	BC	2661	B	2673	18
0	broadcast - f	25.0	100	3375	AB	1978	AB	3463	ABC	2696	AB	2878	17
0	banded - sp	12.5	50	3365	AB	1762	B	3365	ABC	2694	AB	2797	28
0	banded - sp	25.0	100	3113	AB	1963	AB	3625	ABC	2838	AB	2885	17
0	banded - f	12.5	50	3421	AB	2059	AB	3311	ABC	2938	AB	2932	39
0	banded - f	25.0	100	3052	AB	1952	AB	3142	CD	2543	AB	2672	9
50	0		50	3651	AB	1985	AB	3426	ABC	2600	AB	2916	37
50	12.5 seed-row	12.5	100	3741	AB	2073	AB	3463	ABC	2570	AB	2962	20
50	25 seed-row	25.0	150	3105	AB	1744	B	3774	A	2842	AB	2866	11
50	12.5 brdcast	12.5	100	3367	AB	2114	AB	3227	ABC	2662	AB	2843	16
50	25 brdcast	25.0	150	3531	AB	1696	B	3352	ABC	2415	AB	2749	8
100	0		100	3814	A	2055	AB	3726	AB	2506	AB	3025	23
100	12.5 seed-row	12.5	150	3220	AB	2073	AB	3582	ABC	2856	AB	2933	13
100	25 seed-row	25.0	200	3196	AB	2428	AB	3512	ABC	2489	AB	2906	9
100	12.5 brdcast	12.5	150	2789	AB	2077	AB	3468	ABC	2718	AB	2763	8
100	25 brdcast	25.0	200	3547	AB	2625	A	3435	ABC	3091	A	3175	14

* Duncans Multiple Range Test, numbers followed by the same letter are not significantly different at $p = 0.05$

Broadcasting 100 kg P.ha^{-1} in year one of the study gave results similar to those for the 50 kg P.ha^{-1} addition. On average, the single large application was more effective in increasing yields than all annual treatments of 25 kg P.ha^{-1}. In contrast to the previous sites, yield was usually not increased when additional P was added. The data also shows that the residual effects of the single large applications may have diminished slightly by the fourth year.

Uptake of P by wheat at Portage was increased by P fertilization and usually increased with increases in the amount of P added (Table 9). Uptake of P as affected by time and method of placement followed the trends noted for yield. Percent utilization of added P decreased with increases in P applied, the highest utilization occurred on plots with the highest yield increases.

Table 9. Effect of Time and Method of Phosphorus Applications on Uptake of Phosphorus at Portage

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Total P uptake (kg P.ha^{-1}) 1979	1980	1981	1982	total	Total - Tr 1	% utilization
0	no P applied		--	10.7	5.8	9.1	10.8	36.4	---	---
0	seed row - sp	12.5	50	12.3	6.8	11.9	14.0	45.0	8.6	17
0	seed row - sp	25.0	100	13.8	6.8	13.7	14.6	48.9	12.5	13
0	broadcast - sp	12.5	50	13.3	6.1	10.6	15.3	45.3	8.9	18
0	broadcast - sp	25.0	100	15.2	6.7	13.9	15.6	51.4	15.0	15
0	broadcast - f	12.5	50	12.5	6.8	11.2	13.4	43.9	7.5	15
0	broadcast - f	25.0	100	14.1	7.2	14.5	17.5	53.3	16.9	17
0	banded - sp	12.5	50	12.8	6.9	12.0	14.1	45.8	9.4	19
0	banded - sp	25.0	100	13.2	7.6	13.3	15.9	50.0	13.6	14
0	banded - f	12.5	50	15.2	8.0	12.6	13.6	49.4	13.0	26
0	banded - f	25.0	100	12.9	7.9	13.0	16.6	50.4	14.0	14
50	no P applied		50	16.5	8.6	12.6	14.1	51.8	15.4	31
50	seed row - sp	12.5	100	16.4	8.6	13.5	15.8	54.3	17.9	18
50	seed row - sp	25.0	150	13.7	7.0	15.9	16.3	52.9	16.5	11
50	broadcast - sp	12.5	100	15.8	8.7	13.5	15.6	53.6	17.2	17
50	broadcast - sp	25.0	150	15.4	6.9	14.4	14.4	51.1	14.7	10
100	no P applied		100	18.1	7.9	15.8	15.2	57.0	20.6	21
100	seed row - sp	12.5	150	14.8	9.5	15.9	16.5	56.7	20.3	14
100	seed row - sp	25.0	200	14.7	10.9	16.2	15.5	57.3	20.9	10
100	broadcast - sp	12.5	150	13.8	9.1	15.2	15.9	54.0	17.6	12
100	broadcast - sp	25.0	200	16.3	11.7	15.5	18.4	61.9	25.5	13

4. Carman

Carman was harvested in all four years of the study, however, due to drought and poor emergence in 1980, statistical analysis could only be done on three years of the study. An analysis of variance, ANOVA, was conducted on the data. Yields among years were significantly different, however, all other comparisons were not significant.

Yield of wheat grown at Carman was significantly increased by P fertilization only in 1982 (Table 10). Grain yields among plots treated with annual applications of P but without an initial large application of broadcast P showed some significant differences in 1981 and 1982 (statistical analysis was not conducted in 1980 due to missing plots as a result of drought and poor emergence). Although not statistically significant, yields with P applied in the seed row at 12.5 kg $P.ha^{-1}$ were always superior to yields with P broadcast in spring. Yields with P applied at 25 kg $P.ha^{-1}$ were higher than yields with P broadcast at the same rate in three of the four years of study. Yield increase (kg grain per kg P added) for all years of study was 29, 22, 12 and 8 for seed row applied P at 12.5 and 25 and P applied broadcast at 12.5 and 25 kg $P.ha^{-1}$, respectively.

Yields with P banded into the soil prior to seeding were slightly higher than with P applied in the seed row. These differences, however, were not statistically significant.

P broadcast in the fall was more effective in increasing yields

Table 10. Effect of Time and Method of Phosphorus Application on Yield of Wheat at Carman

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Yield (kg P.ha^{-1}) 1979	1980	1981	1982	average	Yield increase (kg grain per kg P added)
0	no P applied			2738 ABCD*	1140 **	2459 C	3050 B	2347	
0	seed row - sp	12.5	50	3197 ABC	1365	3193 A	3087 B	2711	29
0	seed row - sp	25.0	100	3336 A	1970	2830 AB	3463 AB	2900	22
0	broadcast - sp	12.5	50	2963 ABCD	1170	3000 AB	2836 B	2492	12
0	broadcast - sp	25.0	100	3033 ABCD	1162	2989 AB	3019 B	2551	8
0	broadcast - f	12.5	50	3135 ABCD	1282	2799 B	3214 B	2608	21
0	broadcast - f	25.0	100	3129 ABCD	1159	2843 AB	3301 AB	2608	10
0	banded - sp	12.5	50	3149 ABCD	1674	2677 BC	4010 A	2878	42
0	banded - sp	25.0	100	3352 A	2362	2880 AB	3403 AB	2999	26
0	banded - f	12.5	50	2854 ABCD	1258	2806 B	3443 AB	2590	19
0	banded - f	25.0	100	3144 ABCD	1651	3026 AB	3058 AB	2720	15
50	0		50	3269 AB	1420	2784 B	3185 B	2665	25
50	seed-row - sp	12.5	100	2985 ABCD	1420	3046 AB	3286 AB	2684	13
50	seed row - sp	25.0	150	2736 ABCD	1787	3197 A	3312 AB	2758	11
50	broadcast - sp	12.5	100	2882 ABCD	1374	2874 AB	3225 B	2589	10
50	broadcast - sp	25.0	150	3214 AB	1688	2981 AB	2941 B	2706	10
100	0		100	2920 ABCD	1420	2804 B	3467 AB	2653	12
100	seed-row - sp	12.5	150	2685 BCD	1918	2989 AB	3523 AB	2779	12
100	seed row - sp	25.0	200	2593 CD	1928	3000 AB	3238 B	2690	7
100	broadcast - sp	12.5	150	2554 D	1575	2839 AB	3500 AB	2617	7
100	broadcast - sp	25.0	200	2697 BCD	1830	2823 B	2777 B	2532	4

* Duncans Multiple Range Test, numbers followed by the same letter are not significantly different at p = 0.05

** statistical tests not conducted due to missing plots from drought and poor emergence than P broadcast in spring. None of these differences in yield were significantly different in any year of study.

P applied in preplant bands in the fall were less effective than P applied in preplant bands in spring at both application rates in three of four years. It should be noted that the fall bands were most likely disturbed by spring tillage operations. P banded in the fall resulted in yields that were approximently equal to that obtained with P broadcast in spring when 12.5 kg $P.ha^{-1}$ was added.

A single large application of P was compared to annual applications, differences in yield were not significant but several trends were evident. Broadcasting 50 kg $P.ha^{-1}$ in year one of the study resulted in higher yields than four annual applications of 12.5 kg $P.ha^{-1}$ applied broadcast in fall or spring. Yields with a single application of 50 kg $P.ha^{-1}$, however, were less than that with four annual applications of 12.5 kg $P.ha^{-1}$ applied in preplant bands or in the seed row. Average yields increased in three of four instances, when annual applications of P were made to plots initially treated with 50 kg $P.ha^{-1}$. However the yield increases were not as large as those obtained at Purvis and Kaleida.

Broadcasting 100 kg $P.ha^{-1}$ in year one of the study gave yields that were on average higher than four annual applications of 25 kg P.ha-1 applied broadcast in fall or spring, but lower than annual applications in preplant bands or in the seed row. On average, when additional P was added annually in the seed row, yields were increased over the single large addition, however additional P broadcast annually resulted in lower yields. This is similar to the results at Portage.

Uptake of P by wheat at Carman was increased by P fertilization and usually increased with increases in the amount of P added (Table 11). Uptake of P as affected by time and method of placement followed the trends noted for yield, the highest percent utilization occurred when the P was applied in preplant bands in spring at 12.5 kg $P.ha^{-1}$, which corresponded to the highest yield increase at this site.

Table 11. Effect of Time and Method of Phosphorus Applications on Uptake of Phosphorus at Carman

P Initial (kg P.ha^{-1})	Method & Time of Annual Application	Annual P added (kg P.ha^{-1})	Total P added (kg P.ha^{-1})	Total P uptake (kg P.ha^{-1}) 1979	1980	1981	1982	total	Total - Tr 1	% utilization
0	no P applied		--	10.9	5.4	8.6	11.7	36.6	---	---
0	seed row - sp	12.5	50	13.3	7.0	12.2	12.7	45.2	8.6	17
0	seed row - sp	25.0	100	14.0	9.8	11.5	12.7	48.0	11.4	11
0	broadcast - sp	12.5	50	12.3	6.7	11.8	12.0	42.8	6.2	12
0	broadcast - sp	25.0	100	13.0	6.4	12.6	15.3	47.3	10.7	11
0	broadcast - f	12.5	50	13.3	6.1	11.2	12.0	42.6	6.0	12
0	broadcast - f	25.0	100	13.4	8.5	11.3	15.4	48.6	12.0	12
0	banded - sp	12.5	50	13.5	8.3	11.3	19.0	52.1	15.5	31
0	banded - sp	25.0	100	13.9	13.0	12.2	16.6	55.7	19.1	19
0	banded - f	12.5	50	11.8	6.1	11.2	16.3	45.4	8.8	18
0	banded - f	25.0	100	13.6	6.9	11.9	17.7	50.1	13.5	14
50	no P applied		50	14.1	6.9	11.3	14.2	46.5	9.9	20
50	seed row - sp	12.5	100	14.1	7.5	12.9	16.7	51.2	14.6	15
50	seed row - sp	25.0	150	13.2	9.0	13.7	16.5	52.4	15.8	11
50	broadcast - sp	12.5	100	12.9	7.4	12.4	17.2	49.9	13.3	13
50	broadcast - sp	25.0	150	15.0	8.4	13.0	15.5	51.9	15.3	10
100	no P applied		100	14.9	6.6	12.0	17.5	51.0	14.4	14
100	seed row - sp	12.5	150	12.4	8.8	13.8	17.4	52.4	15.8	11
100	seed row - sp	25.0	200	13.2	10.3	13.8	17.6	54.9	18.3	9
100	broadcast - sp	12.5	150	13.1	8.3	12.1	18.0	51.5	14.9	10
100	broadcast - sp	25.0	200	13.2	10.0	13.0	18.7	54.9	18.3	9

Summary

In Table 12, the averages from all sites and years of study were used to compare the time and method of phosphorus fertilizer application. For purposes of comparison, the yield with P applied in the seed row was assigned a relative value of 100. At the 12.5 kg $P.ha^{-1}$ application rate, yield with deep danded P was superior to those with broadcast P applications and to seed row application. P broadcast in the fall was more effective than P broadcast in the spring in increasing yields. In contrast, banded application of P in the fall was not as effective as deep banding application in spring. At the 25 kg $P.ha^{-1}$ application rate, yield with deep banded P was superior to those with broadcast applications and to seed row application. P broadcast in the fall was less effective in increasing yields than P broadcast in the spring. Similarly, P banded in the fall was less effective than P deep banded in the spring. For both rates of application, deepbanding in the spring was the most effective method of increasing yields, seed row application was always the next most effective. In this study, the P bands placed in the fall were disturbed by spring tillage operations. This would reduce the plant availability of the P deep banded in the fall, giving it an intermediate degree of fertilizer and soil mixing compared to broadcast and banded application.

Table 12. Effect of Time and Method of Phosphorus Application on Yield of Wheat (data are means of all sites and years of study)

Method and Time of Application	Rate per year ($kg.ha^{-1}$)	Yield ($kg.ha^{-1}$)	Yield Increase ($kg.ha^{-1}$)	* Relative Value of Increase
no P	0	2403	0	0
seed row	12.5	2952	549	100
broadcast (spring)	12.5	2768	365	66
broadcast (fall)	12.5	2850	447	81
banded (spring)	12.5	3100	697	127
banded (fall)	12.5	2974	571	104
Broadcast (initial) (50 kg $P.ha^{-1}$)	0	2874	465	85
seed row	25	3050	647	100
broadcast (spring)	25	3001	598	92
broadcast (fall)	25	2953	550	85
banded (spring)	25	3174	771	119
banded (fall)	25	2910	507	78
Broadcast (initial) (100 kg $P.ha^{-1}$)	0	3007	604	93

* Relative Value, seed row set to 100 at each rate

Fall deep baned application gave a lower yield than broadcast applications at 12.5 kg $P.ha^{-1}$ but when more P was applied at 25 kg $P.ha^{-1}$ the reverse was true.

A single large application of phosphorus, with the idea of eliminating annual application, was compared to annual applications (Table 12). Each treatment was cropped four times to wheat (except in 1980 when only Carman and Portage were harvested) and after four years the same quantity of phosphorus was added to each treatment. The information obtained showed that, for a 50 kg $P.ha^{-1}$ addition, a single large application was less effective than annual seed row applications but superior to annual broadcast applications in increasing yields. It was found that the single large application of 50 kg $P.ha^{-1}$ resulted in good yield increases in the first few years of study whereas the annual application of small amounts of broadcast phosphorus (12.5 kg $P.ha^{-1}$) usually did not give large increases in any year. Yields with a single large application of 100 kg $P.ha^{-1}$ were similar to annual applications of 25 kg $P.ha^{-1}$ added in the seed row or broadcast. In this instance, due to the large amount of phosphorus added, the plants obtained sufficient phosphorus regardless of the method of placement.

A response to annual applications of phosphorus (broadcast or seed row) was usually obtained on plots initially treated with 50 or 100 kg $P.ha^{-1}$ (Table 13). Phosphorus applied in the seed row was usually more

Table 13. Effect of Annual Applications of Phosphorus on Yield of Wheat Grown on Plots Treated With a Single Large Application of Phosphorus (data are means of all sites and years of study)

P initial ($kg.ha^{-1}$)	P annual ($kg.ha^{-1}$)	Yield ($kg.ha^{-1}$)	Yield Increase ($kg.ha^{-1}$)
50	0	2871	---
50	12.5 seed row	3050	179
50	25 seed row	3048	174
50	12.5 broadcast	2961	90
50	25 broadcast	3048	177
100	0	3007	---
100	12.5 seed row	3145	135
100	25 seed row	3114	107
100	12.5 broadcast	2984	-23
100	25 broadcast	3089	82

effective in enhancing yields on these plots than phosphorus applied broadcast.

B. Relationship between Soil Extractable Phosphorus and Time and Method of Application of Phosphorus

Water extractable P and $NaHCO_3$ extractable P were determined on soil samples obtained in the fall for all sites and treatments. Samples from the various replicates were bulked for each treatment prior to analysis and thus a statistical evaluation of the data could not be conducted.

$NaHCO_3$-ext. P values obtained for the control and plots treated with an annual application of 12.5 kg $P.ha^{-1}$ are shown in figures 1 to 4. Ext. P values were relatively constant with time except at Carman where ext. P values increased with time particularly in the first year of the study. The $NaHCO_3$-ext. P content of the treated plots were greater than for untreated plots for all sites during years 3 and 4 of the study. This suggests that application of 12.5 kg $P.ha^{-1}$ was sufficient to maintain the original available P status of these soils. Differences in ext. P values as affected by time and method of application were very small.

$NaHCO_3$-ext. P values obtained for the control and plots treated with an annual application of 25 kg $P.ha^{-1}$ are shown in figures 5 to 8. Ext. P values increased during the first year but were relatively constant thereafter. These values were higher than those at the lower

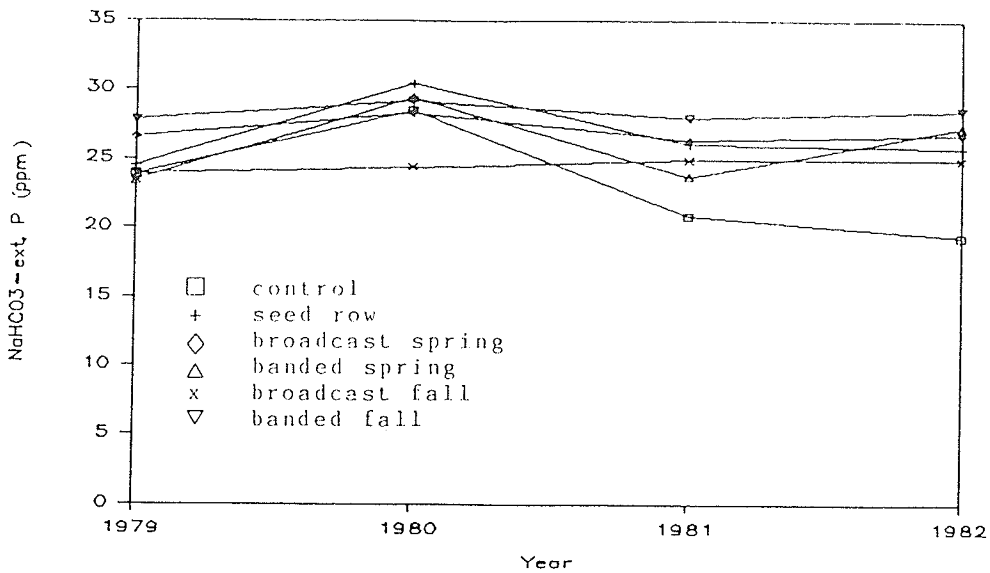


Figure 1. Kaleida. $NaHCO_3$-ext. P for the control plot plus annual applications of 12.5 kg $P.ha^{-1}$

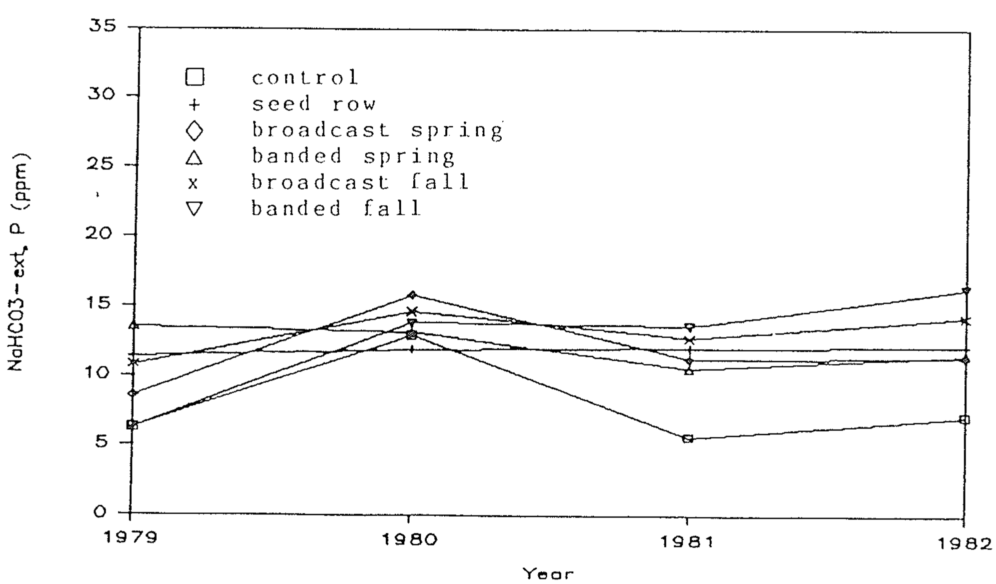


Figure 2. Purvis. $NaHCO_3$-ext. P for the control plot plus annual applications of 12.5 kg $P.ha^{-1}$

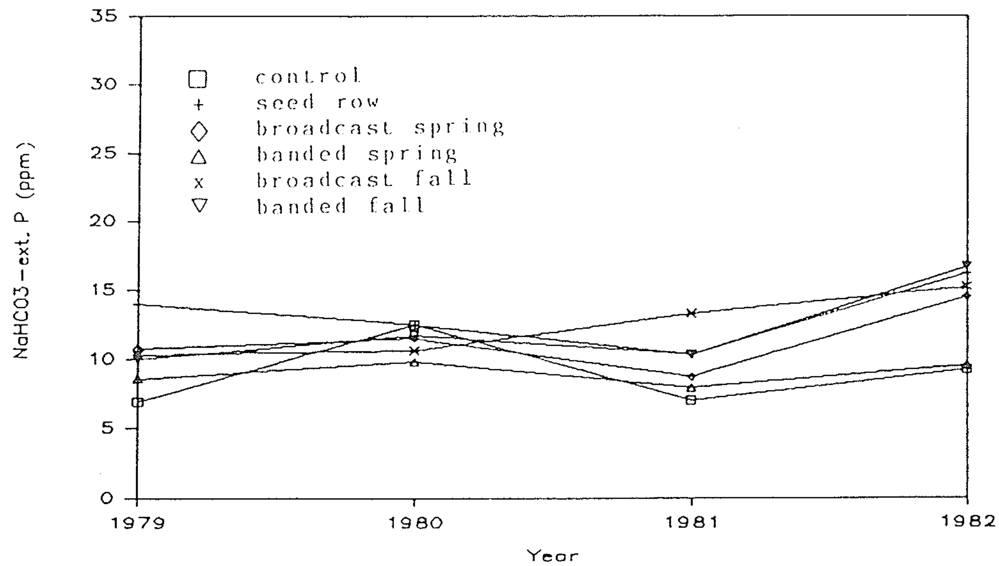


Figure 3. Portage. $NaHCO_3$-ext. P for the control plot plus annual applications of 12.5 kg $P.ha^{-1}$

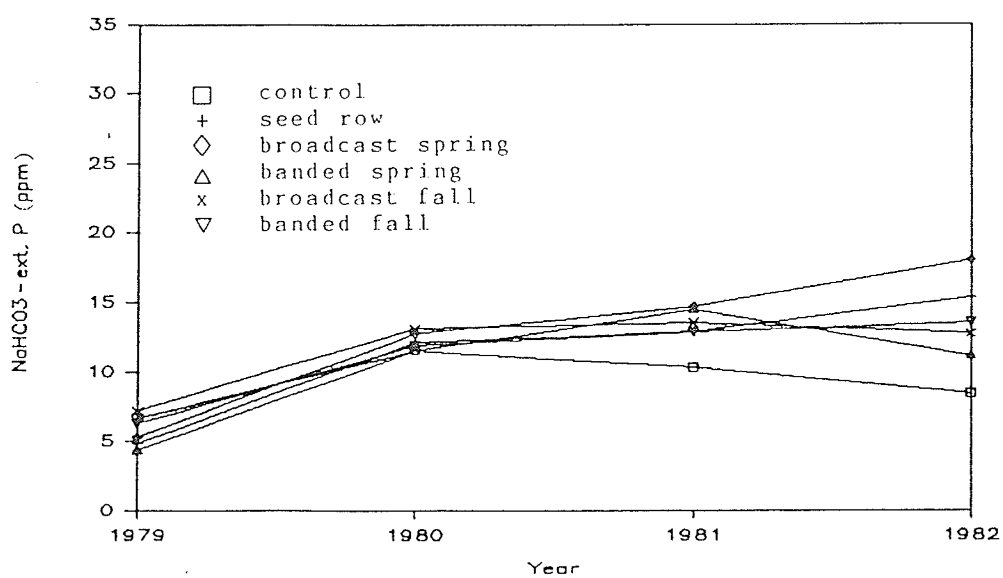


Figure 4. Carman. $NaHCO_3$-ext. P for the control plot plus annual applications of 12.5 kg $P.ha^{-1}$

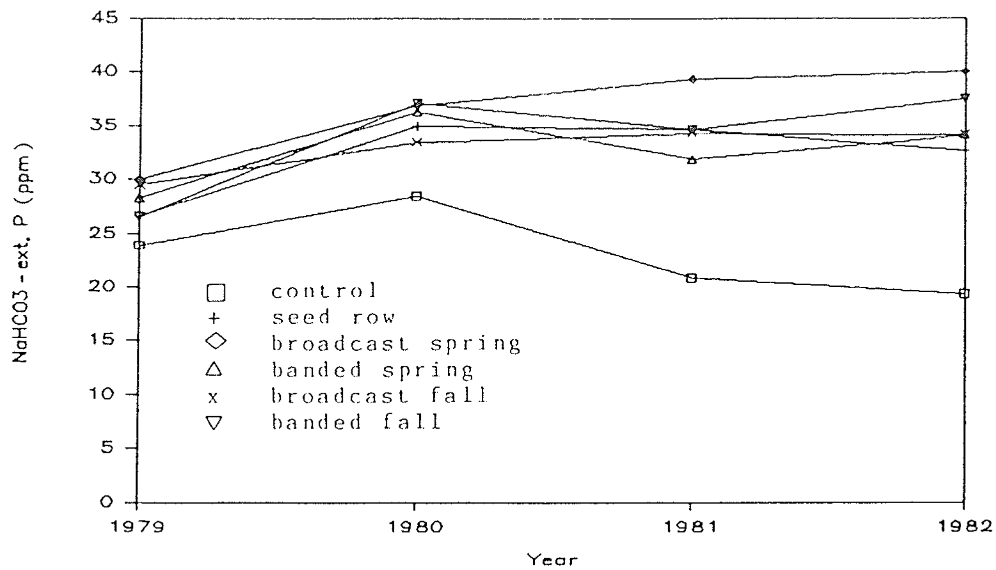


Figure 5. Kaleida. $NaHCO_3$-ext. P for the control plot plus annual applications of 25 kg $P.ha^{-1}$

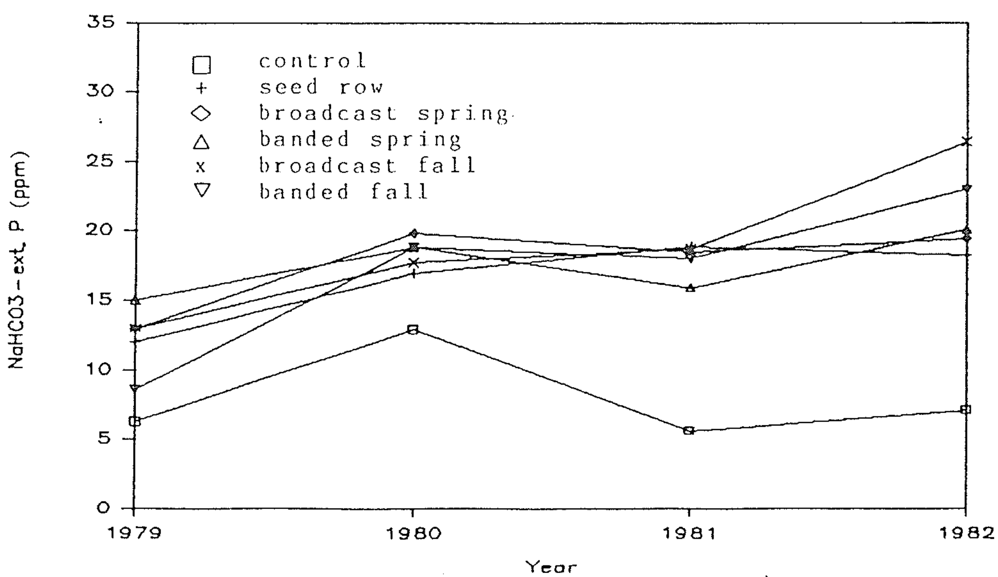


Figure 6. Purvis. $NaHCO_3$-ext. P for the control plot plus annual applications of 25 kg $P.ha^{-1}$

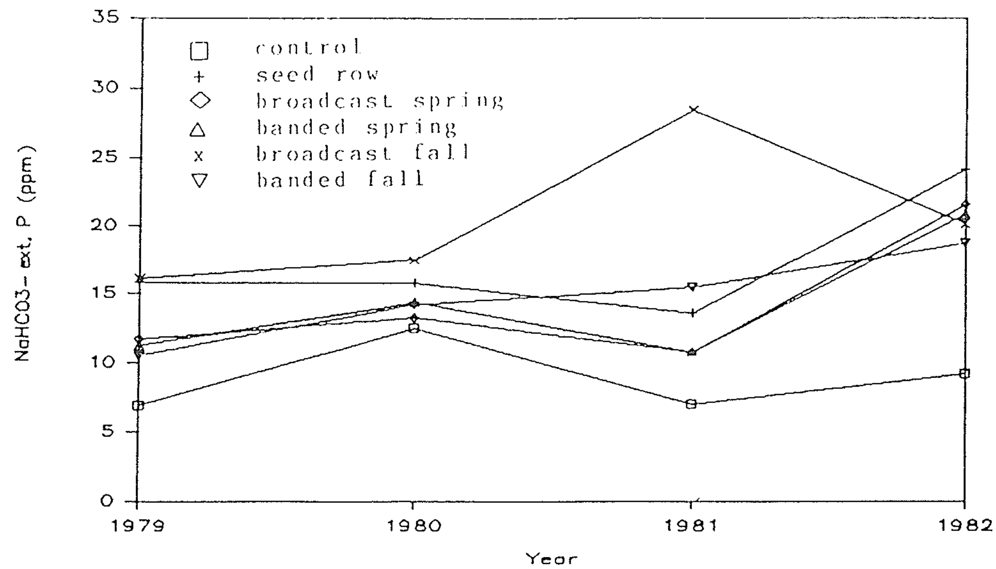


Figure 7. Portage. $NaHCO_3$-ext. P for the control plot plus annual applications of 25 kg $P.ha^{-1}$

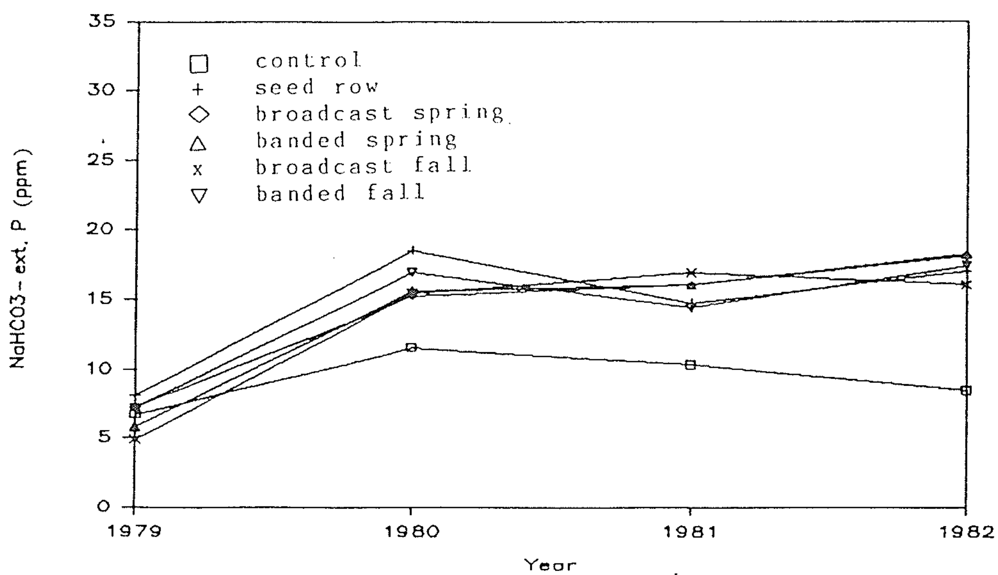


Figure 8. Carman. $NaHCO_3$-ext. P for the control plot plus annual applications of 25 kg $P.ha^{-1}$

rate of P applied and sufficient for maintenance of soil available P at moderate levels. The differences among times and methods of application were not large and were not consistent from plot to plot.

$NaHCO_3$-ext. P values for the plots treated with an initial application of 50 kg P.ha^{-1} and values for plots treated with the initial application of 50 kg P.ha^{-1} plus annual applications are shown in figures 9 to 12. Application of 50 kg P.ha^{-1} in year one of the study increased ext. P values above that of nontreated soils at all sites and years of study with two exceptions, Portage in 1982 and Carman in 1980. Annual applications of P increased ext. P above that of the untreated plots and the 50 kg P.ha^{-1} at all sites and years. In general, ext. P was higher with 25 kg P.ha^{-1} than with 12.5 kg P.ha^{-1} added annually. The method of P application did not affect the value of $NaHCO_3$-ext. P. Ext. P levels were maintained at moderately high levels for all sites when P was added annually in addition to the initial application of 50 kg P.ha^{-1}.

$NaHCO_3$-ext. P values for the plots treated with an initial application of 100 kg P.ha^{-1} and ext. P values for plots treated with the initial application of 100 kg P.ha^{-1} plus annual applications are shown in figures 13 to 16. Application of 100 kg P.ha^{-1} in year one of the study increased ext. P above that of the nontreated plots in all

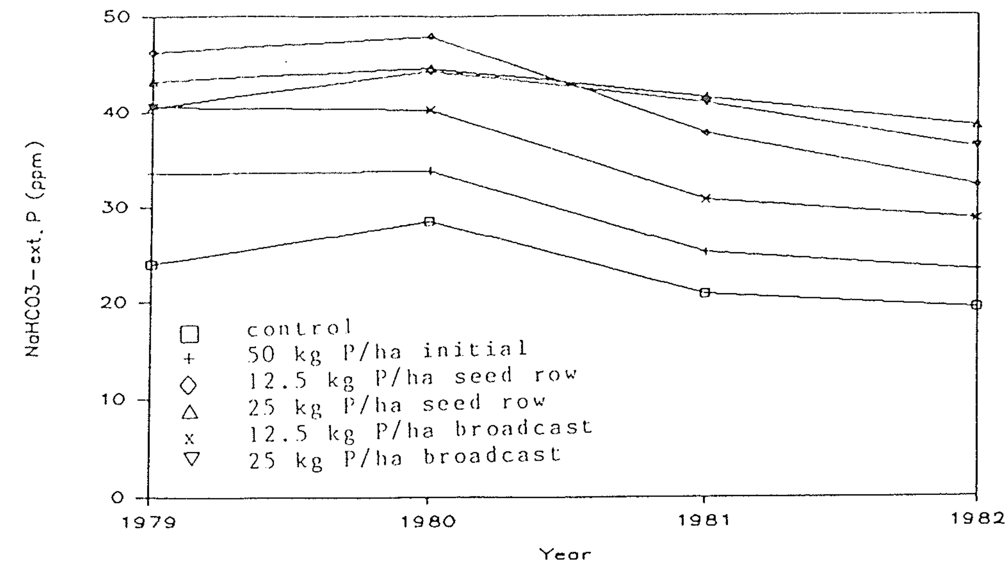


Figure 9. Kaleida. $NaHCO_3$-ext. P for the control plot, the initial application of 50 kg P.ha^{-1} and 50 kg P.ha^{-1} plus annual additions

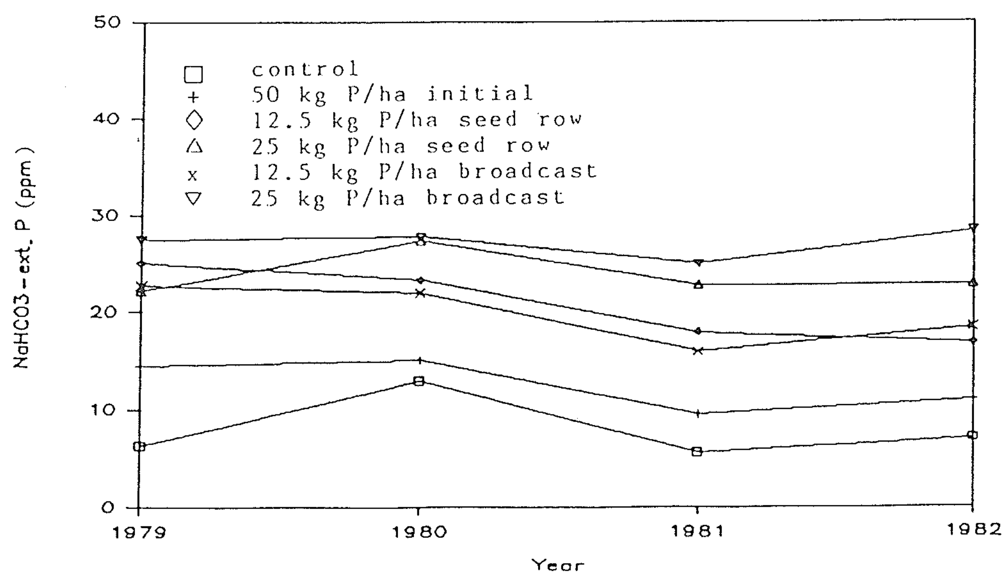


Figure 10. Purvis. $NaHCO_3$-ext. P for the control plot, the initial application of 50 kg P.ha^{-1} and 50 kg P.ha^{-1} plus annual additions

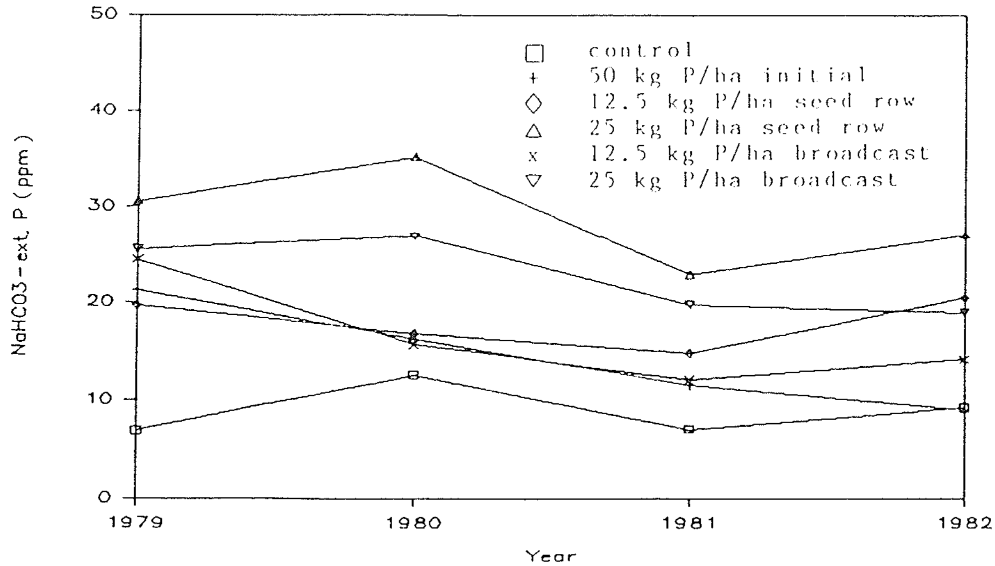


Figure 11. Portage. $NaHCO_3$-ext. P for the control plot, the initial application of 50 kg $P.ha^{-1}$ and 50 kg $P.ha^{-1}$ plus annual applications

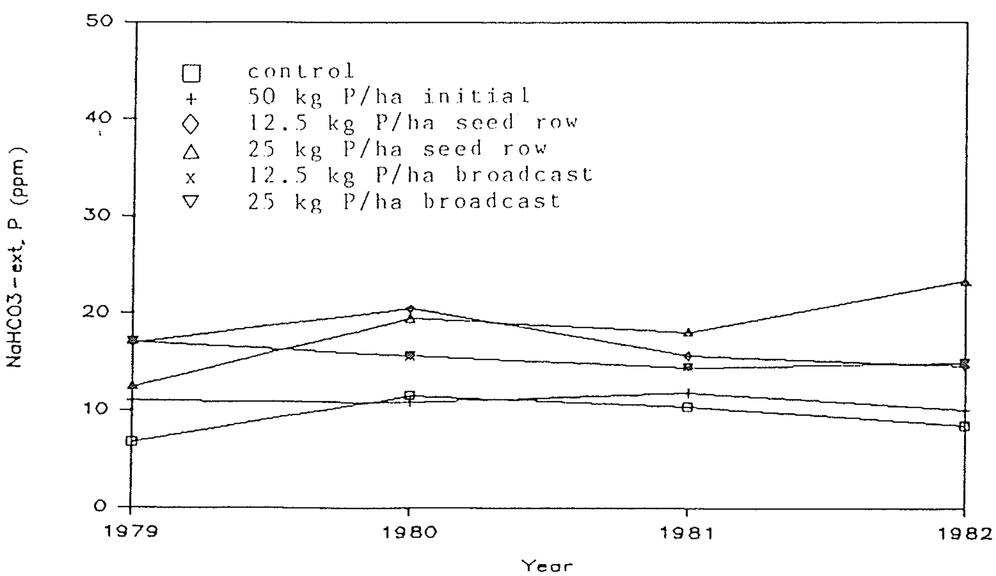


Figure 12. Carman. $NaHCO_3$-ext. P for the control plot, the initial application of 50 kg $P.ha^{-1}$ and 50 kg $P.ha^{-1}$ plus annual additions

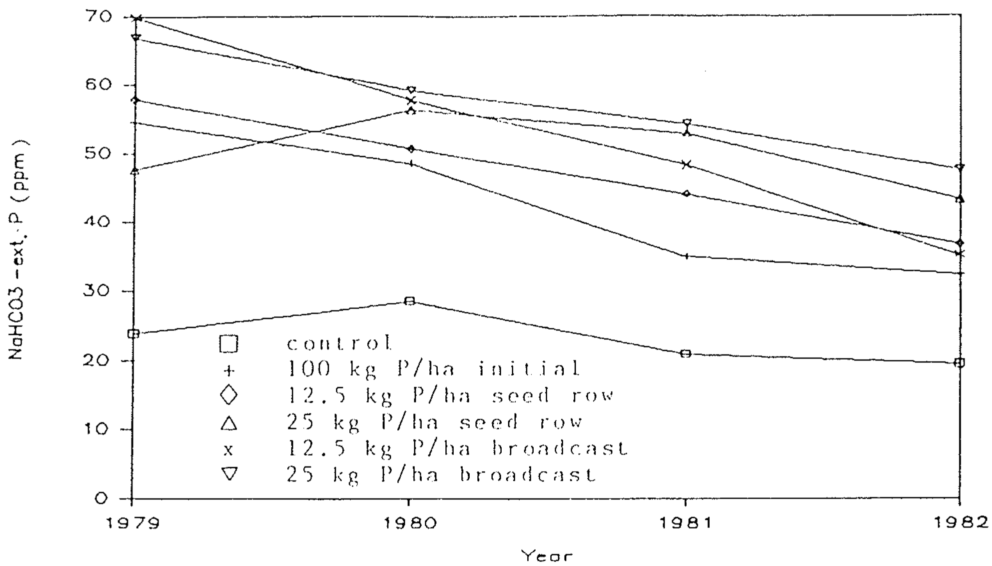


Figure 13. Kaleida. $NaHCO_3$-ext. P for the control plot, the initial application of 100 kg $P.ha^{-1}$ and 100 kg $P.ha^{-1}$ plus annual additions

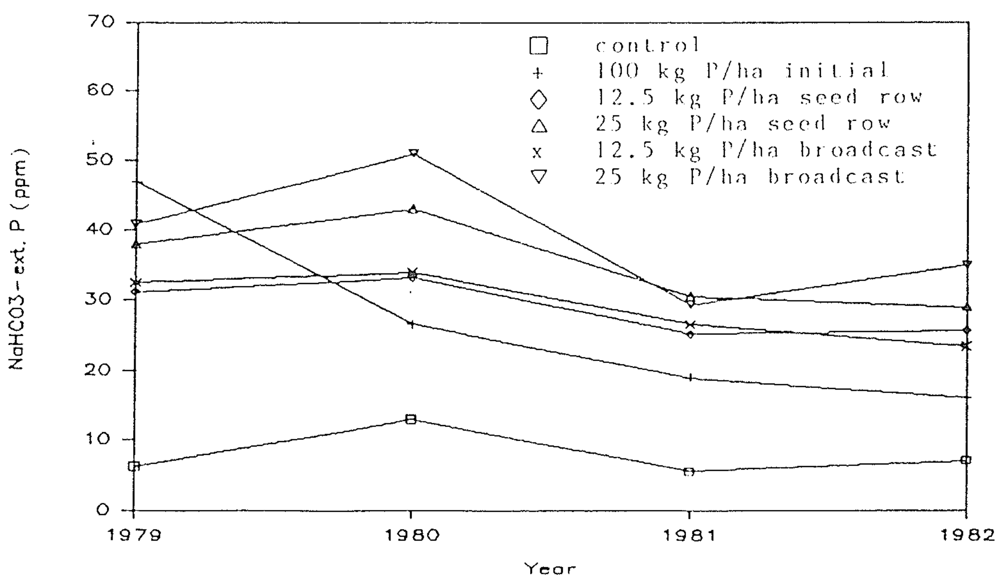


Figure 14. Purvis. $NaHCO_3$-ext. P for the control plot, the initial application of 100 kg $P.ha^{-1}$ and 100 kg $P.ha^{-1}$ plus annual additions

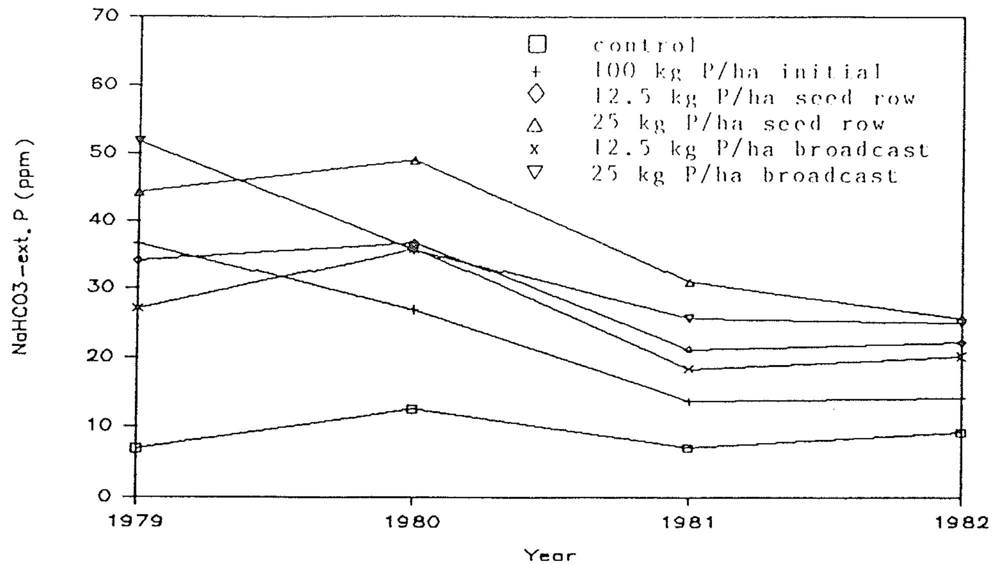


Figure 15. Portage. $NaHCO_3$-ext. P for the control plot, the initial application of 100 kg $P.ha^{-1}$ and 100 kg $P.ha^{-1}$ plus annual additions

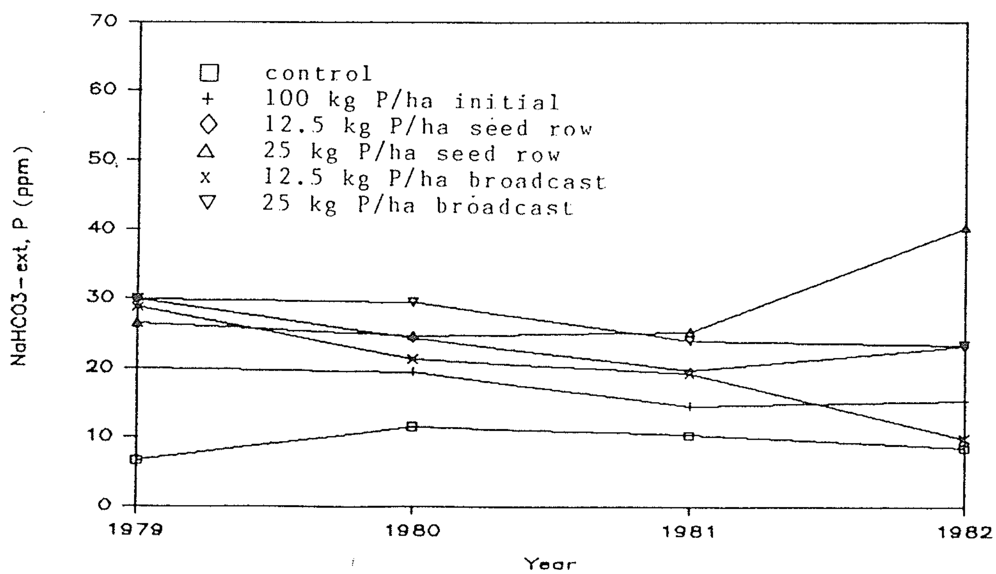


Figure 16. Carman. $NaHCO_3$-ext. P for the control plot, the initial application of 100 kg $P.ha^{-1}$ and 100 kg $P.ha^{-1}$ plus annual additions

years of study and at all sites. $NaHCO_3$-ext. P declined with time, thus, the increases in $NaHCO_3$ ext. P was greatest during the first two to three years after application. The decline in ext. P with time was at a rate greater than was shown for the 50 kg $P.ha^{-1}$ initial addition. The rate of decline was greatest at Kaleida, which had the highest initial level of ext. P, and least at Carman. Annual applications of P increased ext. P above that of the untreated plots and the 100 kg $P.ha^{-1}$ single addition at all sites for the last three of the study. In general, ext. P was higher with 25 than with 12.5 kg $P.ha^{-1}$ added annually. The method of P application did not consistently affect the value of $NaHCO_3$-ext. P. Ext. P levels were maintained at moderately high levels for all sites when P was added annually in addition to the initial application of 100 kg $P.ha^{-1}$.

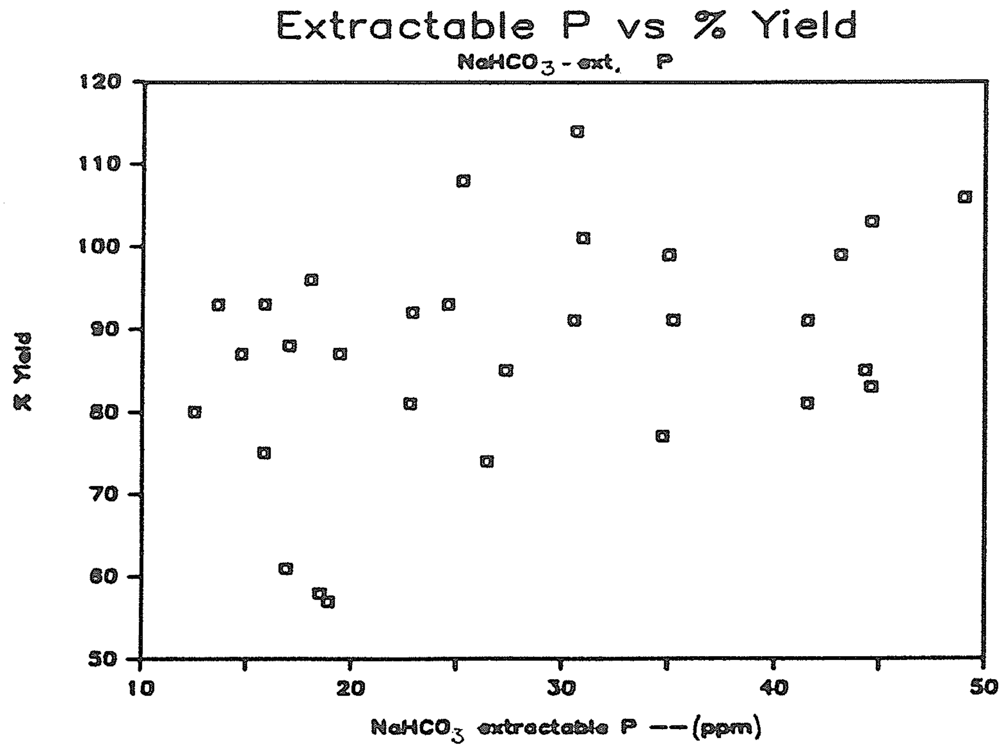
The water ext. P contents of the soils as affected by the various phosphorus fertilizer applications followed the trends noted for $NaHCO_3$-ext. P and thus the data was not included. It was noted, however, that water extracted about one-half as much P as $NaHCO_3$.

C. Relationship Between Extractable Phosphorus and Yield

The amount of H_2O and $NaHCO_3$ extractable phosphorus, in the various soil samples, was plotted versus yield for the 0, 50 and 100 kg $P.ha^{-1}$ additions (where there was no applied P in the spring). There was, however, no clear relationship (plots not shown).

$NaHCO_3$-ext. P and H_2O-ext. P values were plotted verus % yield for the plots initially treated with 50 and 100 kg $P.ha^{-1}$ and for the control plot (Figure 17). Percent yield values were calculated for each site and year of study, using the following yield ratios multiplied by 100: T1/T3, T12/T14 and T17/T19. Treatments 1, 12 and 17 represent plots initially treated with 0, 50 and 100 kg $P.ha^{-1}$. Treatments 3, 14 and 19 represent the same plots but with an annual application of 25 kg $P.ha^{-1}$ applied with the seed at time of seeding. These plots were constructed to evaluate soil-ext. P levels at which additional P has to be added to obtain maximum yields.

The relationships between ext. P and % yield were generally weak (r value of .375 for % yield versus $NaHCO_3$). Despite the weak relationship several observations are evident. Wheat, in three of seven observations, responded well to P applied in the seed row even at $NaHCO_3$-ext. P levels of 40 to 45 ppm. This is in contrast to the work of Spratt and Read (1980) who suggested that seed row P needed to be applied to soils previously treated with a large amount of P only when $NaHCO_3$-ext. P levels decreased to a value of about 15 ppm.



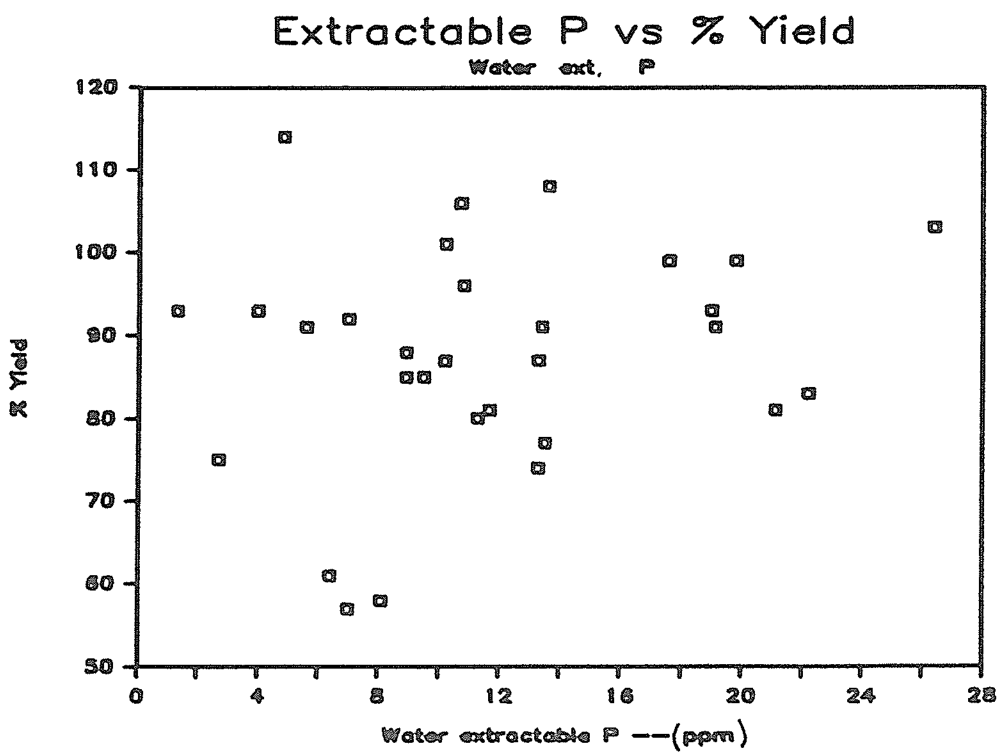


Figure 17. $NaHCO_3$-ext. P and H_2O-ext. P versus % yield.

The relationship between H_2O-ext. P and % yield was also weak. Generally water extracted about half as much P from the soil as did $NaHCO_3$.

The results of this study generally indicate that the present soil test recommendations for phosphorus application are reasonably sound. Present soil test guidelines suggest relatively large amounts of P (up to 22 kg $P.ha^{-1}$ for cereals) be added to soils testing very low and suggest that about 5 kg $P.ha^{-1}$ be added to cereals even at very high levels of $NaHCO_3$-ext. P. This study confirmed the relatively high requirement for fertilizer P on soils testing very low in $NaHCO_3$-ext. P and the need for "starter P" for maximum yield on soils testing high in $NaHCO_3$-ext. P.

D. Laboratory Studies - Hydrolysis of DCPD as Affected by pH, Temperature and Calcium Concentration

An experiment was conducted to determine the rate of change of dicalcium phosphate dihydrate (DCPD) to less soluble reaction products such as octacalcium phosphate (OCP) as a function of the effects of pH, temperature and calcium concentration. X-ray diffraction analysis was used to identify the phosphorus reaction products. Since only DCPD and/or OCP was detected by X-ray diffraction analysis, the amounts of calcium and phosphorus in the samples was used to calculate the percentage of each phosphate present.

The results of the X-ray diffraction analysis is shown in table 15. DCPD and OCP were the only solid phases identified by X-ray diffraction analysis. OCP was detected in samples incubated at 20 and 30 C after 4 months of incubation, whereas OCP was detected in samples incubated at 10 C only after 10 months of incubation. The hydrolysis of DCPD was slow at 10 C and increased as the temperature increased to 20 or 30 C. OCP was not detected in samples incubated at pH 6, whereas OCP was detected in samples incubated at pH 7 and 8, indicating that there was little or no hydrolysis of DCPD to OCP at pH of 6. Calcium concentration also affected hydrolysis of DCPD to OCP. OCP was detected in samples incubated in solutions of 0.01 M Ca after 2 months, whereas in 0.001 and 0.0001 M calcium concentrations OCP was detected only after 4 months of incubation.

Table 14. Effect of pH, Temperature and Calcium Concentration on hydrolysis of DCPD

	Time of Incubation					
	1 mo	2 mo	4 mo	10 mo	18 mo	24 mo
Temp. 1						
10	DCPD	DCPD	DCPD	DCPD,OCP	DCPD,OCP	DCPD,OCP
20	DCPD	DCPD	DCPD,OCP	OCP	OCP	OCP
30	DCPD	DCPD	OCP	OCP	OCP	OCP
pH 2						
6	DCPD	DCPD	DCPD	DCPD	DCPD	DCPD
7	DCPD	DCPD	DCPD,OCP	OCP	OCP	OCP
8	DCPD	DCPD	OCP	OCP	OCP	OCP
[Ca] 3						
0.01	DCPD	DCPD,OCP	OCP	OCP	OCP	OCP
0.001	DCPD	DCPD	DCPD,OCP	OCP	OCP	OCP
0.0001	DCPD	DCPD	DCPD,OCP	OCP	OCP	OCP

1. Effects of temperature studied with pH maintained at 7.0 and at a calcium concentration of 0.001 M
2. Effects of ph studied with temperature maintained at 20 C and at a calcium concentration of 0.001 M
3. Effects of calcium concentration studied with pH maintained at 7.0 and at a temperature of 20 C

DCPD was not detected in several of the samples. This indicates that in several of the samples DCPD hydrolysed completely to OCP. DCPD was not present in samples incubated at temperatures of 20 and 30 C after 10 months and 4 months, respectively. DCPD was present for a period of 24 months for samples incubated at a temperature of 10 C. DCPD was detected at 24 months at a pH of 6 but was not detected after 4 and 2 months for a pH of 7 and 8, respectively. DCPD was not detected in solutions of calcium concentrations of 0.0001 M and 0.001 M after 4 months of incubation and was not detected when the calcium concentration was 0.01 M after only 2 months of incubation.

An indirect analysis was used to calculate the percent OCP in the reaction products. Since the calcium content in DCPD is 23.5% and the calcium content in OCP is 32.0%, the percent OCP can be interpolated from the calcium content of the sample (Table 16). The rate of hydrolysis increased with increases in pH, temperature and calcium concentration. The rate of hydrolysis as measured by the percent OCP in the sample was negligible at a pH of 6 whereas the rate of hydrolysis was similar at pH's of 7 and 8, with the formation of OCP complete at about 10 months. The rate of hydrolysis of the sample incubated at 10 C was slow with the formation of OCP not complete after 24 months. However, at temperatures of 20 and 30 C, the formation of OCP was complete by 10 to 18 months. The samples incubated at calcium concentrations of 0.001 M and 0.0001 M hydrolysed more slowly than the sample incubated at a calcium concentration of 0.01 M. In many instances the calcium concentrations were higher than that for pure OCP

Table 15. Hydrolysis of DCPD Expressed as % OCP

	Time of Incubation					
	1 mo	2 mo	4 mo	10 mo	18 mo	24 mo
Temp. 1						
10	0	12	12	71	49	85
20	0	53	65	97	113	112
30	6	18	88	82	105	119
pH 2						
6	12	0	0	12	12	6
7	0	53	65	97	113	112
8	0	23	71	107	121	82
[Ca] 3						
0.01	18	36	100	113	131	134
0.001	0	53	65	97	113	112
0.0001	0	18	47	115	105	119

1. Effects of temperature studied with pH maintained at 7.0 and at a calcium concentration of 0.001 M
2. Effects of ph studied with temperature maintained at 20 C and at a calcium concentration of 0.001 M
3. Effects of calcium concentration studied with pH maintained at 7.0 and at a temperature of 20 C

(values in excess of 100%). It is possible that a product other than OCP was present. For example, it is possible that OCP was hydrolysed to a compound such as HA. It should be noted,however, that HA was not detected by X-ray diffraction.

The Ca/P ratios for the various samples were calculated and are shown in figure 18. The Ca/P ratio for DCPD is 1.30 and the Ca/P ratio for OCP is 1.69. An increase in the Ca/P ratio represents a change from DCPD to OCP and the rate of change of the ratio represents the rate of hydrolysis of DCPD to OCP. Rates of hydrolysis were relatively rapid during the first few months of incubation except for the system held at a pH of 6 and for the system incubated at 10 C. Rates of hydrolysis at 20 and 30 C were much more rapid than at 10 C. Rate of hydrolysis was also a function of pH, the rate of hydrolysis at pH 7 and 8 were similar and much greater than at a pH of 6. Calcium concentration had minor effects on rates of hydrolysis , the hydrolysis rate at a calcium concentration of 0.01 M tended to be greater than at the lower calcium concentrations.

The results of this experiment generally indicate that DCPD, the initial reaction product of water soluble phosphate fertilizers in base saturated soils, will hydrolyze at a greater rate in soils of high pH, high calcium concentration and at higher temperatures. DCPD is more water soluble than OCP and thus is a better source of plant available P than OCP. Since the residual effect of P fertilizer is a function of the solubility of the solid phase present in the soil, residual P effects would be more pronounced and last for a longer period of time in soils of lower pH and lower calcium concentration than in soils of

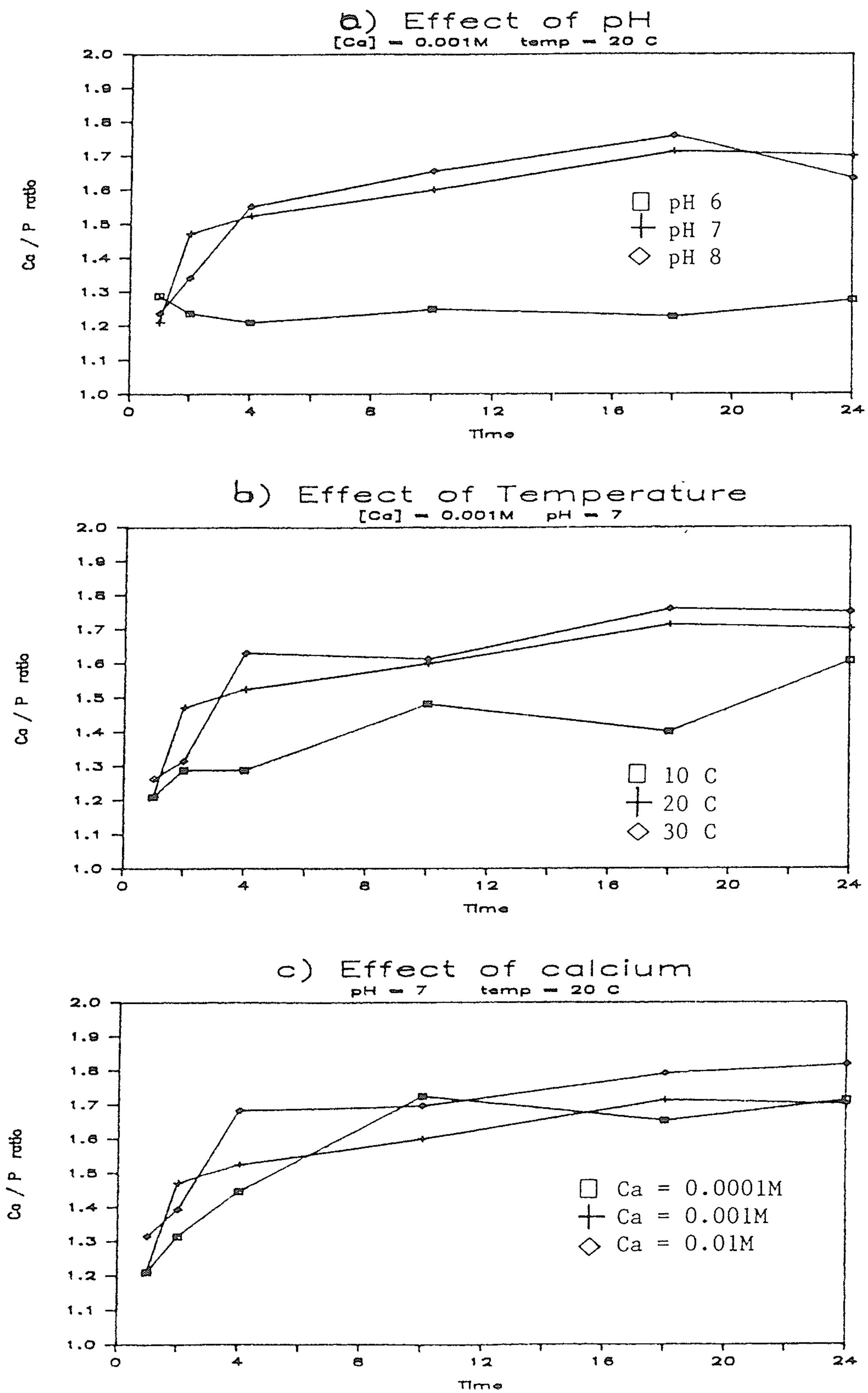


Figure 18. The hydrolysis of DCPD, measured by the Ca/P ratio, as affected by pH, temperature and calcium concentration.

higher pH and higher soil solution calcium concentration.

An experiment was conducted to study the rate of change of DCPD in soils as affected by soil properties such as pH and CaCO3 content. In this experiment 1 g of DCPD was placed between two layers of soil. Twelve soils varying in pH, texture and percent carbonate were incubated at temperatures of 0, 10, 20 and 30 C for up to 30 months. Hydrolysis of DCPD to OCP was detected in only one soil, Balmoral, incubated at 20 C for 30 months. The presence of OCP was confirmed by both chemical and X-ray diffraction analysis. Hydrolysis of DCPD to OCP was not detected in other samples. The reasons for the lack of change in the reaction products is unknown at this time.

The differences in rate of hydrolysis noted for the solution and soil studies may be a result of the experimental techniques used. In the solution studies, the solutions were replaced regularly. Thus, the P which dissolved was continually being removed, creating a very large sink for the dissolution of P from the reaction products. In contrast, in the studies using soil, the sink for dissolution was confined to the layers of soil immediatly adjacent to the reaction product. Saturation of this soil with P would occur, and, since the P was not removed, the sink for dissolved P would be small. This may have reduced hydrolysis rates as compared to those obtained for the solution studies.

CHAPTER V

SUMMARY AND CONCLUSIONS

Field plots were initiated to study the effect of time and method of phosphorus fertilizer application on yield of wheat at four Manitoba sites over four years. Yields with deep banded phosphorus ,phosphorus banded at about 7 to 10 cm soil depth and in 17.5 cm spacings prior to seeding, were superior to those of with seed application. With seed application was superior to broadcast applications. Phosphorus broadcast in the fall was as effective in increasing yields as phosphorus broadcast in the spring. In contrast, deep banded applications of phosphorus in the fall were not as effective as spring deep banded operations. The data generally indicated that the most effective method of applying P fertilizer was to place the P in narrow preplant bands in spring or place the P with the seed at time of seeding.

A single addition of 50 kg $P.ha^{-1}$ was less effective than annual seed row application but superior to annual broadcast application, with an equivalent amount of P, in increasing yields over the four years of the study. Yields with a single large addition of 100 kg $P.ha^{-1}$ were similar to annual applications of 25 kg $P.ha^{-1}$ added in the seed row or broadcast. Single large applications of P supplemented by annual applications did not increase yields above that obtained with only annual applications with the seed at relatively high rates, that is, near maximum yields could be obtained with annual seed row applications. However, a response to annual applications of phosphorus was obtained on plots initially treated with a single large addition of phosphorus on two of the experimental sites.

The amount of H_2O and $NaHCO_3$ extractable phosphorus was plotted versus % yield. Although the relationships were poor, the data indicated that a response to applied phosphorus could occur even on soils previously treated with relatively large amounts of P and which have high values of $NaHCO_3$-ext. P.

A laboratory experiment was conducted to observe the rate of hydrolysis of DCPD to less soluble reaction products such as OCP. One g of DCPD was enclosed in Whatman filter paper and incubated in flasks containing solutions of varying concentrations of calcium (0.01 M, 0.001 M, 0.0001 M) and maintained at various pH values (pH 6, pH 7, pH 8). The samples were incubated at temperatures of 10, 20 and 30 C for a period of up to 24 months. Rates of hydrolysis increased with increases in temperature, pH and calcium concentration. These results indicate that DCPD would hydrolyse at a greater rate in soils of high pH, high calcium concentration and at higher temperatures. Residual P effects would be less pronounced and last for a shorter period of time in soils of higher pH and higher calcium concentrations.

An experiment was also conducted using 12 soils to study the rate of hydrolysis of DCPD as affected by soil pH, temperature and carbonate content. Hydrolysis of DCPD to OCP was detected in in one soil incubated at 20 C for 30 months. This soil had a high pH and contained

10.6 $\%CO_3$. No change was detected in the other samples.

Appendix A. Analysis of Variance, ANOVA

* 1% level
** 5% level
ns not significant

1. Purvis

a) comparison among years and treatment

	df	F
years	2	34.17 **
treatment	20	8.29 **
error	40	

b) comparison between rates of 12.5 and 25 kg P.ha^{-1} at 0, 50 and 100 kg P.ha^{-1}

	df	F
0	1	15.23 **
50	1	2.78 *
100	1	ns
error	40	

c) comparison among methods of application at 0, 50 and 100 kg P.ha^{-1}

	df	F
0	4	2.64 *
50	1	ns
100	1	ns
error	40	

2. Kaleida

a) comparison among years and treatment

	df	F
years	2	83.00 **
treatment	20	3.18 **
error	40	

b) comparison between rates of 12.5 and 25 kg P.ha^{-1} at 0, 50 and 100 kg P.ha^{-1}

	df	F
0	1	ns
50	1	ns
100	1	ns
error	40	

c) comparison among methods of application at 0, 50 and 100 kg P.ha^{-1}

	df	F
0	4	3.44 **
50	1	ns
100	1	4.82 *
error	40	

3. Portage

a) comparison among years and treatment

	df	F
years	2	90.00 **
treatment	20	ns
error	40	

b) comparison between rates of 12.5 and 25 kg $P.ha^{-1}$ at 0, 50 and 100 kg $P.ha^{-1}$

	df	F
0	1	ns
50	1	ns
100	1	
error	40	

c) comparison among methods of application at 0, 50 and 100 kg $P.ha^{-1}$

	df	F
0	4	ns
50	1	ns
100	1	ns
error	40	

4. Carman

a) comparison among years and treatment

	df	F
years	2	12.90 **
treatment	20	ns
error	40	

b) comparison between rates of 12.5 and 25 kg $P.ha^{-1}$ at 0, 50 and 100 kg $P.ha^{-1}$

	df	F
0	1	ns
50	1	ns
100	1	
error	40	

c) comparison among methods of application at 0, 50 and 100 kg $P.ha^{-1}$

	df	F
0	4	ns
50	1	ns
100	1	ns
error	40	

CHAPTER VI

BIBLIOGRAPHY

Alessi, J. and J.F. Power. 1980. Effects of Banded and Residual Fertilizer on Dryland Spring Wheat Yield in the Northern Plains. Soil Science Society of America Journal, Volume 44: 792 - 796.

Bailey, L.D., E.D. Spratt, D.W.L. Read, F.G. Warder and W.S. Ferguson. 1977. Residual Effects of Phosphorus Fertilizer. II. For Wheat and Flax Grown on Chernozemic Soils in Manitoba. Canadian Journal of Soil Science, Volume 57: 263 - 270.

Bates, T.E. 1971. Response of Corn to Small Amounts of Fertilizer Placed With the Seed: III. Relation to P and K Placement and Tillage. Agronomy Journal, Volume 63: 372 - 375.

Beaton, J.D. and D.W.L. Read. 1963. Distribution of Monocalcium and Monoammonium Phosphate Reaction Products in a Calcarous Saskatchewan Soil. Nature, Volume 198: 813 - 814.

Beaton, J.D. and D.W.L. Read. 1963. Effects of Temperature and Moisture on Phosphorus Uptake from a Calcareous Soil Treated with Several Pelleted Sources of Phosphate. Soil Science of America Proceedings, Volume 27: 61 - 65.

Beaton, J.D., R.C. Speer, and G. Brown. 1965. Effect of Soil Temperature and Length of Reaction Period on Water Solubility of Phosphorus in Soil Fertilizer Reaction Zones. Soil Science Society Proceedings 1965, Volume : 194 - 198.

Bell, L.C. and C.A. Black. 1970. Transformation of Dibasic Calcium Phosphate Dihydrate and Octacalcium Phosphate in Slightly Acid and Alkaline Soils. Soil Science Society Proceedings, Volume 34: 583 - 587.

Bouldin, D.R. and E.C. Sample. 1959. Calcium Phosphate Fertilizers: III The Effect of Surface Area on the Availability Coefficients of the Dicalcium Phosphates. Soil Science Society Proceedings, Volume 23:276 - 281.

Bullen, C.W., R.J. Soper and L.D. Bailey. 1983..Phosphorus Nutrition of Soybeans as Affected by Placement of Fertilizer Phosphorus. Canadian Journal of Soil Science 63:199-210.

Cole, C.V., Sterling R. Olsen, and C.O. Scott. 1952. The Nature of Phosphate Sorption by Calcium Carbonate. Soil Science Society Proceedings 1953, Volume : 352 - 356.

Engelstad, O.P. and G.L. Terman. 1980. Agronomic Effectiveness of Phosphate Fertilizers in The Role of Phosphorus in Agriculture. Khasawneh, Sample and Kamprath, Ed. pp. 311 - 332.

Ferguson, W.S. 1964. Effect of Rainfall on Plant Response to Phosphorus. Canadian Journal of Soil Science, Volume 44: 180 - 186.

Fixen, P.E. and A.E. Ludwick. 1981. Residual Available Phosphorous in Near-Neutral and Alkaline Soils: I. Solubility and Capacity Relationships. Soil Science Society of America Journal, Volume 46: 332 - 334.

Fixen, P.E. and A.E. Ludwick. 1981. Residual Available Phosphorous in Near-Neutral and Alkaline Soils: II. Persistence and Quantitative Estimation. Soil Science Society of America Journal, Volume 46: 335 - 338.

Garg, K.P. and L.F. Welch. 1966. Growth and Phosphorus Uptake by Corn as Influenced by Phosphorus Placement. Agronomy Journal, Volume 59: 152 - 154.

Griffin, R.A., and J.J. Jurinak. 1973. The Interaction of Phosphate with Calcite. Soil Science Society of America Proceedings, Volume 37: 847 - 850.

Halvorson, A.D. and A.L. Black. 1985. Long-Term Dryland Crop Responses to Residual Phosphorus Fertilizer. Soil Science Society of America Journal, Volume 49: 928 - 937.

Kinra, K.L., H.D. Foth, L.S. Robertson and H.M. Brown. 1963. Effect of Seeding Rate , Row Spacing and Rate and Placement of Fertilizer on Winter Wheat Performance in Michigan. Agronomy Journal, Volume 55: 24 - 27.

Klepper, B., P.E. Rasmussen and R.W. Rickman. 1983. Fertilizer Placement for Cereal Root Access. Journal of Soil and Water Conservation, Volume 38: 250 - 252.

Larsen, Sigurd. 1966. The Solubility of Phosphate in a Calcareous Soil. Journal of Soil Science, Volume 17: 121 - 126.

Larsen, S., and A.E. Widdowson. 1970. Evidence of Dicalcium Phosphate Precipitation in a Calcareous Soil. Journal of Soil Science, Volume 21: 364 - 367.

Lehr, J.R. and W.E. Brown. 1958. Calcium Phosphate Fertilizers: II A Petrograhic Study of Their Alterations in Soils. Soil Science Society Proceedings, Volume 22: 29 - 30.

Lehr, J.R., E.H. Brown, A.W. Frazier, J.P. Smith and R.D. Thrasher.

1967. Crystallographic Properties of Fertilizer Compounds. Chemical Engineering Bulletin Number 6.

Lutz, J.A., G.L. Terman, and J.L. Anthony. 1961. Rate and Placement of Phosphorus for Small Grains. Agronomy Journal, Volume 58: 303 - 305.

Maclean, A.A. 1964. The Evaluation of the Residual Effect of Fertilizer in Long-Term Fertility Plots. Canadian Journal of Soil Science, Volume 44: 223 - 227.

Moreno, E.C., W.E. Brown and G. Osborn. 1960. Solubility of Phosphate Dihydrate in Aqueous Systems. Soil Science Society Proceedings, Volume 24: 94 - 99.

Moreno, E.C., W.L. Lindsay, and G.Osborn. 1960. Reactions of Dicalcium Phosphate Dihydrate in Soils. Soil Science, Volume 90: 58 - 68.

Murphy, J. and J.P. Riley. 1962. A Modified Single Solution Method for Determination of Phosphate in Natural Waters. Analy. Chem. Acta, Volume 27: 31 - 36.

Nyborg, Marvin and A.M.F. Hennig. 1969. Field Experiments with Different Placement of Fertilizer for Barley, Flax and Rapeseed. Canadian Journal of Soil Science, Volume 49: 79 - 88.

Olson, R.A. and A.F. Dreier. 1956. Fertilizer Placement for Small Grains in Relation to Crop Stand and Nutrient Efficiency in Nebraska. Soil Science Society Proceedings, Volume 20:19 - 24.

Peterson, G.A., D.H. Sander, P.H. Grabouski and M.L. Hooker. 1981. A New Look at Row and Broadcast Phosphate Recommendations for Winter Wheat. Agronomy Journal, Volume 73: 13 - 17.

Power, J.F., G.A. Reichman and D.L. Grunes. 1961. The Influence of Phosphorus Fertilization and Moisture on Growth and Nutrient Absorption by Spring Wheat: II. Soil and Fertilizer P Uptake in Plants. Siol Science Society Proceedings, Volume 25: 210 - 213.

Probert, M.E. and S. Larsen. 1970. The Stability of Dicalcium Phosphate Dihydrate in Soil. Journal of Soil Science, Volume 21: 353 - 363.

Racz, G.J. 1966. Reaction Products in Soils Containing Varying Amounts of Calcium and Magnesium. PhD. Thesis, University of Manitoba.

Racz, G.J. and R.J. Soper. 1967. Reaction Products of Orthophosphates in Soils Containing Varying Amounts of Calcium and Magnesium. Canadian Journal of Soil Science, Volume 47: 223 - 230.

Read, D.W.L., E.D. Spratt, L.D. Bailey, and F.G. Warder. 1977. Residual Effects of Phosphorus Fertilizer. I. For Wheat Grown on Four Chernozemic Soil Types in Saskatchewan and Manitoba. Canadian Journal of Soil Science, Volume 57: 255 - 262.

Read, D.W.L., E.D. Spratt, L.D. Bailey, and F.G. Warder. 1977. Residual Effects of Phosphorus Fertilizer. II. For Wheat and Flax Grown on Four Chernozemic Soil Types in Manitoba. Canadian Journal of Soil Science, Volume 57: 263 - 270.

Read, D.W.L., F.G. Warder and D.R. Cameron. 1982. Factors Affecting Fertilizer Response of Wheat in Southwestern Saskatchewan. Canadian Journal of Soil Science, Volume 62: 577 - 586.

Ridley, A.O. and S. Tayakepisuthe. 1974. Residual Effects of Fertilizer Phosphorus as Measured by Crop Yields, Phosphorus Uptake and Soil Analysis. Canadian Journal of Soil Science, Volume 54: 265 - 272.

Rudd, C.L. and N.J. Barrow. 1973. The Effectiveness of Several Methods of Applying Superphosphate on Yield Response by Wheat. Australian Journal of Experimental Agriculture and Animal Husbandry, Volume 13: 430 - 433.

Sadler, J.M. and J.W.B. Stewart. 1977. Labile Residual Fertilizer Phosphorus in Chernozemic Soils. I. Solubility and Quantity/Intensity Studies. Canadian Journal of Soil Science, Volume 57: 65 - 73.

Sample,E.C., R.J. Soper and G.J. Racz. 1980. Reactions of Phosphate Fertilizers in Soils in The Role of Phosphorus in Agriculture. Khasawneh, Sample and Kamprath, Ed. pp. 263 - 310.

Spratt, E.D., F.G. Warder, L.D. Bailey, and D.W.L.Read. 1980. Measurement of Fertilizer Phosphorus Residues and Its Utilization. Soil Science Society of America Journal, Volume 44:1200 - 1204.

Strong, W.M. and R.J. Soper. 1974. Phosphorus Utilization by Flax, Wheat, Rape, and Buckwheat from a Band or Pellet-like Application. II. Influence of Reaction Zone Phosphorus Concentration and Soil Phosphorus Supply. Agronomy Journal, Volume 66: 601 - 605.

Tisdale, S.L., W.L. Nelson and J.D. Beaton. 1985. Soil Fertility and Fertilizers. MacMillan Publishing Company.

Wagar, B.I., J.O. Moir and J.W.B. Stewart. 1985. Broadcast and Residual P Versus Annual Seed Placed P. Proceedings of the Soils and Crops Workshop, University of Saskatchewan: 100 - 122.

Walkley, A. and Black, T.A. 1934. An Examination of the Degljareff method for Determining Soil Organic Matter and a Proposed

Modification of the Chromic Acid Titration Method. Soil Science, Volume 37: 29 - 38.

Weir, C.C. and R.J. Soper. 1963. Solubility Studies of Phosphorus in Some Calcareous Manitoba Soils. Journal of Soil Science, Volume 14: 256 - 261.