

THE EFFECT OF UREA ON THE SOLUBILITY AND PLANT UPTAKE OF
MONOAMMONIUM PHOSPHATE

by



Donald Norman Flaten

A thesis presented to
the Faculty of Graduate Studies
at the University of Manitoba
in partial fulfillment of the
degree of

Doctor of Philosophy
in
Soil Science

Winnipeg, Manitoba, 1989

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ABSTRACT

Laboratory, growth chamber and field experiments were conducted between 1981 and 1984 to determine the effect of urea on the solubility and plant uptake of banded monoammonium phosphate (MAP).

In a diffusion study MAP was applied with or without cosolutes to soil columns. After incubation, sections of the column were extracted by water, then 0.5M H₂SO₄. Adding urea with MAP increased the quantity of water-extractable P by 20% and 60% after 1 and 5 wk of incubation, respectively. Similar treatments were utilized in an elution study where the columns were incubated, then leached with water for 48 h. Adding urea with MAP increased the quantity of P eluted by 10% and 40% from columns incubated for 1 and 5 wk, respectively.

Plant uptake studies were conducted using spring wheat (Triticum aestivum). In the growth chamber, in vivo monitoring of ³²P intensities indicated that adding urea with MAP (dual banding) delayed the initiation of fertilizer P uptake at the seedling stage, likely due to high concentrations of ammonia preventing root growth into dual bands. However, scintillation counting and further monitoring at the heading and mature stages revealed that adding urea with MAP eventually increased the uptake of fertilizer P from MAP bands that were not close to the seed row. Field experiments showed that grain yields and early season uptake of P were generally greater for P placed in the seed row, 18 cm dual bands or 36 cm separate bands than for P in 36 cm dual bands. Further evidence of delayed initiation of uptake of fertilizer P during the seedling stage was obtained with the use of ³²P at one field site.

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1. INTRODUCTION

Most research on the placement of P fertilizers has been directed towards studying the behavior of P fertilizers alone, not in combination with other fertilizers. However, in order to save labor, the placement of P and N fertilizers in the same band (commonly referred to as "double shooting" or "dual banding") has become increasingly popular in Western Canada (Harapiak and Penny 1984). This has led to an increased need to understand more fully the interactions between fertilizers and subsequent effects on yield and P uptake by the crop.

The purpose of this thesis was to investigate the effects of dual banded urea and monoammonium phosphate (MAP) on P solubility and P utilization by spring wheat and to compare P placement in dual bands to conventional placement of P in the seed row. Urea and MAP were chosen because they are popular forms of N and P fertilizers in Western Canada. A potential advantage of adding urea to MAP bands is that ammonium-N in the same zone as P fertilizer can stimulate uptake of fertilizer P (Rennie and Soper 1958; Miller 1974). This "ammonium ion effect" is one of the reasons why MAP has generally been regarded as superior to calcium phosphate sources of P in Western Canada (Dion et al. 1949a; Dion et al. 1949b; Mitchell 1957). One potential disadvantage of applying P and N together in bands before seeding compared to placing P in the seed row is the delayed uptake of fertilizer P caused by the increased distance between the P fertilizer and the seed.

To more fully understand the reactions in dual bands and plant uptake

of P from dual bands, a literature review and a series of laboratory, growth chamber and field experiments were conducted between 1980 and 1984. The objectives of these studies were to describe the effects of urea and placement on the solubility, movement and plant uptake of MAP.

2. REVIEW OF LITERATURE

2.1 Introduction

Most soils in Western Canada are deficient in P and require the addition of P fertilizer for maximum crop production. The traditional recommendation for wheat has been to place P fertilizer in the seed row to allow rapid, early uptake (Faculty of Agriculture, University of Manitoba 1977; Bailey et al. 1980). However, preplant application of P fertilizer with large quantities of N fertilizer in the same band (dual banding) has recently become a popular alternative to placing P in the seed row (Leikam et al. 1979; Harapiak 1980; Leikam et al. 1983; Harapiak and Penny 1984).

A potential advantage of dual banding may be stimulation of fertilizer P uptake due to the presence of additional ammonium-N, a phenomenon referred to as the "ammonium ion effect" (Rennie and Soper 1958; Miller 1974). Unfortunately, dual banding prior to seeding also results in increased distance between the seed and P fertilizer, which may delay the uptake of fertilizer P. Therefore, the efficiency of MAP placed in dual bands compared to MAP placed in the seed row depends on the relative importance of these two factors.

2.2 Role of P as a Nutrient

The role of P in plant nutrition has been reviewed comprehensively by Bielecki (1973) and Bielecki and Ferguson (1983). In general, plant tissues contain 0.2 to 0.4% P on a dry matter basis or 5 to 10 mM expressed in terms of concentration in living tissue (Bielecki 1976).

All P in higher plants is found in the fully oxidized state as inorganic orthophosphate or organic forms such as DNA, RNA, phospholipids and ester-P (Bielecki 1973, 1976; Bielecki and Ferguson 1983). Concentrations of metabolically active P are less variable with respect to time, environment and species than inorganic P (Bielecki 1973; Loughman 1978; Chisolm et al 1981; Lefebvre and Glass 1982). The inorganic P fraction serves as a form for storing P in the plant. It increases sharply in response to improved P status and accumulates in the vacuole (Bielecki 1973; Loughman 1978; Chapin and Bielecki 1982). This "luxurious uptake" of P is likely an ecological adaptation to survive between pulses of P availability.

The benefits of P fertilization include more than a simple nutritional correction for improved yields. Other agronomic benefits include increased resistance to frost (Nelson 1956) and common root rot (Verma et al. 1975). P fertilization also hastens maturity (Coe 1926; Nelson 1956), which may increase yields by compensating for the detrimental effect of late seeding (Anderson and Hennig 1964; Ciha 1983).

2.3 Factors Influencing the Effectiveness of Different Methods of Placing P Fertilizers

The method of placing P fertilizer affects its effectiveness by influencing the degree to which soil retains the added P, root accessibility and timeliness of uptake.

2.3.1 Retention of P Fertilizer by Soil

When soluble P fertilizer is added to soil it rapidly becomes

significantly less mobile and less available to the plant, due primarily to adsorption and precipitation reactions. The two processes are difficult to separate because they involve similar chemical bonds (Larsen 1967; Veith and Sposito 1977). However, the adsorption mechanism predominates only at low P concentrations, conditions quite different from those near a fertilizer band or granule.

In base saturated soils, fertilizer P is precipitated initially as dicalcium phosphate or dimagnesium phosphate which gradually changes to less soluble forms such as octacalcium phosphate (Lindsay et al. 1962; Strong and Racz 1969; Racz and Soper 1970; Sample et al. 1980; Freeman and Rowell 1981; Talibudeen 1981). In general, higher concentrations of added P appear to result in more soluble reaction products (Larsen and Widdowson 1970). This has led some researchers to speculate that reduced retention of P by soil is one of the reasons why P fertilizer is more effective when banded rather than broadcast (Prummel 1957).

Although immobilization of P by microbial activity does not account for the rapid retention of fertilizer P, organic P accounts for 20-80% of total P in soil (Larsen 1967). Recent evidence indicates that added P can be immobilized during the degradation of crop residues low in P (Singh and Jones 1976). Therefore, P fertilizer placed underneath crop residues may be less likely to be immobilized.

The release of retained P to plants via diffusion is controlled by several environmental factors, most notably, soil moisture and soil temperature. Increases in soil water content enlarge the cross sectional area of water films around soil particles, decreasing path length and tortuosity (Barber 1962, 1980). The increase in thickness of water films

also reduces resistance to diffusion caused by negative ion attraction and viscosity changes (Olsen and Kemper 1968). Therefore, P fertilizer will diffuse slowly if placed at a depth in the soil where drying is likely to occur. Increases in soil temperature generally increase the solubility and diffusion rates of inorganic P in soil (Sutton 1969, Nielsen 1971). However, low soil temperature and low soil water content discourage conversion of fertilizer P to insoluble forms (Beaton and Read 1963; Beaton et al. 1965).

2.3.2 Root Access to P Fertilizer

The zone of P depletion near plant roots is very small due to retention of P by the soil. Therefore, configuration and length of the root system are important determinants of P supply to the plant (Barley 1970; Newman and Andrews 1973) and placement of P fertilizer relative to the root system is critical.

For cereals in the relatively dry environment of Western Canada, seminal roots are at least as important as nodal roots (Pavlychenko 1937; Boatwright and Ferguson 1967). Seminal roots grow outward only 10-20 cm away from the vertical axis of the plant before growing mainly downwards (Klepper et al. 1983). Therefore, root proliferation and rate of P uptake are usually greatest when P is placed near the base of the plant (McClure 1972).

Roots are capable of proliferating in zones rich in P near fertilizer granules or bands. This has been demonstrated in solution culture and pot experiments with both barley (Drew 1975; Drew and Saker 1975; Drew and Saker 1978) and wheat (McClure 1972; Strong and Soper 1973). Root

proliferation in P fertilizer zones has also been observed in field experiments with barley (Bohm 1973, 1974).

The moisture content and temperature of the soil affect the ability of the root to absorb P. Temporary drying of the root system disrupts the cortex, resulting in a drastic reduction of uptake and translocation of P (Clarkson et al. 1968). Cool temperatures allow for sustained P uptake along a greater proportion of root length, although overall root growth and P uptake decline (Bowen 1970b).

2.3.3 Timeliness of Uptake of P Fertilizer

The method of placing P fertilizer affects the time at which the fertilizer can be utilized by the plant. Although it is often assumed that P fertilizer must be accessible to the plant early in its growth it is uncertain how early this access needs to be. There are some contradictions in the literature especially between evidence reported in terms of yield and that reported in terms of P uptake.

Part of the reason for these contradictions is a feedback mechanism that allows a plant to regulate its ability to take up P, depending on its need for P. Boatwright and Viets (1966) found that if wheat was starved initially for P and then transferred to a solution containing P, the plants accumulated more P than plants grown continuously in a solution containing P. Others have also found that cereal seedlings are capable of faster uptake of P after an initial starvation period (Bowen 1970a; Green et al. 1973; Clarkson et al. 1978; Drew and Saker 1978). Abnormally high tissue P concentrations, as high as 3%, have been observed in plants transferred from P deficient to P sufficient solutions (Green and Warder 1973). P

deficient plants are also capable of increased rates of uptake per unit length of root when roots are trimmed (Jungk and Barber 1974) or when only part of the root system is exposed to P (Drew and Saker 1978).

The kinetic explanation for this physiological compensation is not quite clear. It appears that inorganic P allosterically inhibits P uptake (Lefebvre and Glass 1982). As mentioned previously, inorganic P concentrations are very low in plants deficient in P, with most of the P being in the organic form (Loughman 1978; Chapin and Bielecki 1982).

Although plants initially starved for P may accumulate P rapidly once P is supplied, final yields of grain may be reduced. Field studies in the Northern Great Plains have shown that most of the P accumulated by spring wheat is taken up before heading (Spinks and Barber 1947; Boatwright and Haas 1961; Racz et al. 1965). Fertilizer P, especially, is taken up by wheat early in the growing season (Spinks and Barber 1947). However the accumulation of P early in the season is not, by itself, sufficient proof that large amounts of P are necessary at this time. As mentioned previously, large amounts of inorganic P may be stored in the vacuole during periods of "luxurious" uptake.

Unfortunately, much of the early research examining the effect of the time at which P is made available to plants has little practical value. For example, Gericke has been quoted as having proven the nutritive value of P early in the season (Dion et al. 1949b; Sutton et al. 1983). Yet, Gericke's original hypothesis was that late season depletion of most nutrients increased wheat growth and grain yield. In Gericke's experiments yields increased when plants were deprived of not only P, but also Mg and S after only 4 wk growth (Gericke 1924a, 1924b, 1925). Part of the reason

for these peculiar results may have been due to the lack of Cu, Zn and aeration in his crude solution cultures. Brenchley (1929) also used crude solution culture techniques but found that barley could not be deprived of P beyond the first 2 wk of growth before there was an irreversible loss of tillers. There was evidence that the most acute demand for P occurred between 2 and 4 wk after starting growth. Brenchley referred to research by Pember in 1917 that showed an early, temporary restriction in P supply was not detrimental to the yield of the main shoot. However, in Pember's experiment tillers were all removed as they appeared.

In pot experiments with wheat, Saskatchewan researchers found that delaying P application up to 4 wk after planting reduced midseason dry matter yields, although it increased the uptake of fertilizer P (Barber 1947; Dion et al. 1949b). Unfortunately, no harvests of grain were taken. Other researchers found that the rapid, early vegetative growth associated with early uptake of fertilizer P (the "popup" effect) did not always result in higher final grain yield (Wallingford 1978; McConnell et al. 1986). Hamid and Sarwar (1977) found that higher wheat yields and fertilizer uptake were obtained from broadcasting P at the tillering stage than from placing P in or near the seed row, in spite of an obvious growth advantage early in the season for the latter treatments.

In solution culture experiments, Boatwright and Viets (1966) found that withholding P from spring wheat for the first 2 wk of growth reduced grain and dry matter yields by 58% and 20% respectively. However, initial starvation of P increased the total amount of P taken up. In solution culture experiments with barley, Drew and Saker (1978) found that placing the zone of P supply further away from the base of the shoot reduced the

initial relative growth rate due to lack of P. Although the relative growth rate resumed later, absolute growth remained retarded. Unfortunately, these solution culture experiments generally do not reflect field conditions where P may be low in supply but not completely absent and where the early development of a vigorous, healthy plant is essential for further root exploration for soil P.

In contrast to the importance of early season uptake of P, the withdrawal of the plant's P supply late in the growing season appears to have little effect on yield (Boatwright and Viets 1966; Chapman and Keay 1971; Sutton et al. 1983).

2.4 The Effectiveness of Different Methods of Placing P Fertilizer

For reasons that relate to the factors previously discussed, placing P fertilizer in a band in or near the seed row of wheat often results in the greatest yield and/or nutrient uptake (Hanway and Olson 1980; Bailey et al. 1980). P which is banded in or near the seed row increases cereal yields more than broadcasted P especially if fertilization rates and levels of available P are low (Coe 1926; Lawton et al. 1956; Vavra and Bray 1959; Ridley and Tayakepisuthe 1974; MacLeod et al. 1975). When P is broadcasted, two to three times as much P is required to produce grain yield responses equivalent to those from P placed in the seed row (Coe 1926; Lutz et al. 1961; Rudd and Barrow 1973; Peterson et al. 1981). For example, Prummel (1957) conducted 100 field experiments in the Netherlands and found that two and a half times as much broadcasted P was required to match yields from sidebanded P. He attributed the advantage to less

retention by soil, a more favorable position beneath the dry surface soil and better P uptake and vigor early in the season. Brandon and Mikkelsen (1979) reached similar conclusions from field experiments in California. Recent research on irrigated soils also demonstrated the advantage of banded P when the surface soil dries (Vig and Singh 1983). Cool soil temperatures may also enhance the superiority of localized versus broadcast placement of low rates of P (Ketcheson 1957; Knoll et al. 1964; Englestad and Allen 1971a; Alessi and Power 1980; Sheppard 1982). In contrast, high rates of P application and high levels of available P in the soil may reduce or eliminate the advantage of placement near the seed row (Peterson et al. 1981; Sheppard 1982).

Banding P at high rates in the seed row may injure seedlings, reducing the nutritional benefit of this method of placement. Olson and Dreier (1956a) found that P placed in the seed row produced higher grain yields of wheat and oats compared to broadcasted P at moderate rates. The opposite was true at high rates where P in the seed row damaged seedlings and reduced emergence. Seedling damage is most likely to occur when diammonium phosphate is used as a P source (Olson and Dreier 1956a; Stevenson and Bates 1968; MacLeod et al. 1975) and/or when the spacing between seed rows is wide (Kinra et al. 1963). As a result, although P placed in the seed row may be more effective than sidebanded P at moderate rates and in soils with low levels of available P, sidebanded P is more effective at high rates and in soils with high levels of available P (Sherrell et al. 1965; Nyborg and Hennig 1969).

For sidebanded P, increasing the distance between the P band and the seed row can reduce yields. Prummel (1957) found that placing P 8 cm

rather than 4 cm to the side of the seed row reduced early growth and final grain yield of oats grown in the field. Nyborg and Hennig (1969) found that placing P 5 cm rather than 2.5 cm to the side of the seed reduced barley growth and yield. Sherell et al. (1965) found that increasing the horizontal distance between P bands and the seed row reduced fertilizer P uptake and the grain yield of oats. In contrast, McConnell et al. (1986) found no consistent differences in grain yield of winter wheat, whether ammonium polyphosphate was banded in the seed row or 15 cm away and 5 cm below the seed row.

P applied in bands before planting may not produce grain yields as high as those from placing P in the seed row because of the likelihood of increased distance between seed and fertilizer (Coe 1926). In more recent field studies with wheat, Alston (1980) found a significant decline in grain yield when preplant P bands were spaced 50 cm instead of 18 cm apart.

Placing P fertilizer below the depth of the seed row may have some advantages over seed row placement. No P can be absorbed by wheat roots in a dry layer of soil (Boatwright et al. 1964). Even temporary drying destroys the ability of that portion of the root system to take up P (Clarkson et al. 1968). Therefore, banding P a few cm below the seed depth may allow greater P uptake and yield during periods when the surface soil is dry (Murdock and Engelbert 1958; Power et al. 1961; Singh 1962; McConnell et al. 1986).

The supply of moisture to the crop does not, however, always account for the response of cereals to depth of placement. In field studies with drought-stressed wheat in Saskatchewan, Mitchell (1957) found no advantage to placing fertilizer deeper than the seed. Meanwhile in the Netherlands,

where soil moisture supplies were excellent, Prummel (1957) found that placing P 4 cm below the seed was superior to placement with the seed or 2 cm below the seed. In deep pot studies Alston (1976) found that placement of N and P at 25 cm below the surface resulted in higher wheat yields and greater P accumulation compared to placement at a depth of 5 cm. However, there was no interaction between the effect of placement and moisture supply. Later, in a field study he found no benefit from placing P at 15 cm versus 5 cm deep with wheat grown in dryland or irrigated conditions (Alston 1980). The inconsistent relationship between moisture supply and depth of placement may be due to variations in the pattern of adding and extracting water from the soil profile. The surface soil may be drier or wetter than deeper soil, depending on the balance between evaporation and transpiration losses combined with the pattern of rainfall or irrigation.

2.5 Effects of N on P Fertilizer

Several authors have reviewed the literature describing the effect of N, especially in the ammonium form, on P uptake (Grunes 1959; Fried and Broeshart 1967; Miller 1974; Miller and Ohlrogge 1977; Sheppard and Racz 1980). Most of this literature describes the effect of adding small amounts of N fertilizer to calcium phosphates. There is very little information about the effect of adding large amounts of urea to MAP bands.

Some of the earliest research into the ammonium ion effect was done in Saskatchewan where researchers found that cereal yield responses to P fertilizer were greater with MAP than with calcium phosphates (Mitchell 1946; Dion et al. 1949a, 1949b; Mitchell 1957; Rennie and Soper 1958;

Beaton and Read 1963). The superiority of MAP was especially obvious in early growth stages and on alkaline soils. Olson et al. (1956a) found similar results in field and greenhouse experiments with small grains in Nebraska. Recent research with wheat and barley in California also demonstrated the superiority of MAP (Brandon and Mikkelsen 1979).

Since the superiority of MAP was attributed to the ammonium ion one might wonder if the higher ammonium content of diammonium phosphate (DAP) would be of further benefit. One might also speculate that the higher ammonium content and alkaline pH in the DAP reaction zone may resemble the effect of urea on the otherwise acidic MAP reaction zone. Unfortunately the performance of DAP compared to MAP is inconsistent. Bouldin and Sample (1959) and Hashimoto and Lehr (1973) extracted more water soluble P from acidic soils incubated with DAP compared to MAP. Bouldin and Sample (1959) found the opposite trend in a calcareous soil. Beaton et al. (1965) extracted similar amounts of water soluble P from DAP and MAP treated soils, regardless of carbonate content. However, in earlier pot experiments Beaton and Read (1963) found that oats took up less fertilizer P from DAP compared to MAP. Lindsay et al. (1962) found large differences between DAP and MAP in the nature of their reaction products, but Racz and Soper (1967) found that dicalcium phosphate was the major reaction product for both DAP and MAP. Bell and Black (1970) found some differences in reaction products from DAP compared to MAP, but dicalcium phosphate predominated in both cases. Lewis and Racz (1969) found that P moved less extensively from DAP compared to MAP pellets, but others have reported the opposite trend (Read and Beaton 1963; Bell and Black 1970).

Early research using ammonium sulfate or ammonium nitrate plus

ordinary superphosphate showed that placing ammonium-N within rather than beside the P band increased the uptake of fertilizer P in a variety of crops grown under field and greenhouse conditions (Volk 1944; Robertson et al. 1954; Olson and Dreier 1956b; Olson et al. 1956b; Miller and Ohlrogge 1958). Increases in yield were less frequent, especially after the early growth stage.

Similar observations were reported using ammonium fertilizers plus triple superphosphate or monocalcium phosphate on grain crops (Rennie and Mitchell 1954; Duncan and Ohlrogge 1957; Rennie and Soper 1958; Grunes et al. 1958; Miller and Ashton 1960; Werkhoven and Miller 1960; Englestad and Allen 1971b). Conversely, for cool season forage crops, adding ammonium-N to monocalcium phosphate bands gave no consistent benefit (Sheard 1974, 1980).

Rennie and Soper (1958) examined the influence of additional ammonium-N on the uptake of monocalcium, monopotassium and monoammonium phosphate. In one of their experiments, N fertilizers and MAP were placed in the seed row and a relatively low rate of N was applied (33 kg/ha). They found increased uptake of fertilizer P by wheat after 53 d of growth when urea or ammonium sulfate was mixed with the P fertilizers. The ammonium ion effect was most obvious at an early growth stage and N had relatively little influence on fertilizer P uptake when applied separate from the P band or in a nitrate form.

Over the years there have been many hypotheses put forth to explain how ammonium-N stimulates the uptake of P fertilizer. The factors cited fall into two primary groups: those that are directly related to chemical reactions of the fertilizers within the soil and those that are related to

plant physiology or root morphology.

2.5.1 Effects of N on Movement and Solubility of P Fertilizer

The two principle chemical effects of adding ammonium salts to P fertilizers are changes in the pH and ionic strength of the soil solution.

The availability of P is usually greatest at neutral pH (Cho and Caldwell 1959). At higher pH, the solubility of precipitated calcium phosphates is decreased and the strength of adsorption is greater (Olsen and Kemper 1968). At low pH, the solubility of iron and aluminum phosphates is restricted.

Acidification of alkaline soils can release soil P, allowing higher P uptake by plants (Ryan and Stroehlein 1979). Part of this increase in P uptake may result from the plant's physiological preference for H_2PO_4^- versus $\text{HPO}_4^{=}$ ions (Hagen and Hopkins 1955). Volk (1944) found that the addition of lime to the fertilizer layer reduced the stimulatory effect of ammonium sulfate on superphosphate uptake. He hypothesized that the acid-forming nature of ammonium sulfate was, therefore, the principle factor involved. Rennie and Mitchell (1954) also attributed the ammonium ion effect to the acidifying effect of nitrification, based upon greenhouse experiments in which the oxidation of elemental S had increased the uptake of dicalcium phosphate by wheat (Mitchell et al. 1952; Lorenz and Johnston 1953). However, in a later paper, Rennie and Soper (1958) disproved the nitrification theory. They found that the addition of acidic salts to bands of P fertilizer had an adverse effect, if any, on the uptake of fertilizer P. Rennie and Soper then postulated that ammonium increased the ability of plants to take up P and did not increase directly the

availability of P. Olson and Dreier (1956b) and Grunes et al. (1958) also found that the acidification of a P band was not beneficial, especially in calcareous soils. In both papers, the authors postulated that acidification increased the concentration of soluble calcium allowing greater precipitation of the P fertilizer, counteracting the positive influence of the lower pH on P solubility.

More recent research using nitrification inhibitors provided further evidence that nitrification was an unlikely factor in the ammonium-ion effect. In several experiments, inhibition of nitrification increased fertilizer P uptake from bands of ammonium phosphates or ammonium plus phosphate fertilizers (Nielsen et al. 1967; Miller et al. 1970; Engelstad and Allen 1971b; Spratt 1973; Leikam et al. 1983).

One must question the general premise that acidification of alkaline soils always increases the solubility of soil and fertilizer P. Although Isensee and Walsh (1971, 1972) reported that adding urea to monocalcium phosphate depressed the solubility of fertilizer P, Hanson and Westfall (1985, 1986) added ammonium hydroxide to ammonium polyphosphate and increased the levels of sodium bicarbonate- and Bray-extractable P. The common extractants used to assess plant available P in alkaline soils are, themselves, alkaline. And, although Starostka and Hill (1955) are often cited for their observation of the increase in solubility of dicalcium phosphate upon the addition of ammonium sulfate, they also noted that the solubility of dicalcium phosphate was enhanced by alkaline salts such as sodium carbonate and potassium carbonate more than any of the other 15 cosolutes tested. In the same short term experiment, urea did not enhance P solubility, although the urea may not have hydrolyzed.

Bouldin and Sample (1958) found that a wide variety of salts, including both ammonium and potassium salts, increased the uptake of concentrated superphosphate by oats grown in acidic soils. Most of this effect was explained by an increase in P solubility. In this and subsequent studies with concentrated superphosphate (Bouldin et al. 1960; Taylor and Gurney 1965) researchers found that the addition of ammonium and potassium salts reduced the proportion of granule residue at the site of application. Similarly, Blanchar and Caldwell (1966a, 1966b) found that both ammonium and potassium chloride increased the solubility of monocalcium phosphate. However, in pot studies, corn took up much more fertilizer P from the ammonium chloride treatment. Therefore, they concluded that most of the ammonium ion effect was due to physiological factors. Other researchers have found that adding ammonium salts to monocalcium phosphate reduces P solubility while still allowing plants to take up more fertilizer P (Miller and Vij 1962).

In an early review, Grunes (1959) noted that an increase in ionic strength caused by adding salt to soil solution may decrease the activity coefficients of a slightly soluble salt, such as dicalcium phosphate, resulting in an apparent increase in solubility. However, he also noted that at high ionic strengths, such as those in a fertilizer reaction zone, the activity coefficients may actually increase, reducing the apparent solubility of a slightly soluble salt. Another potentially deleterious effect of adding large amounts of salt with P fertilizer is displacement of calcium from cation exchange sites allowing it to react with the P (Grunes 1959; Isensee and Walsh 1972). The benefit of any so-called "salt effect" is further diminished when one considers that placing nitrate or potassium

fertilizers in the P band has little, if any, positive effect on fertilizer P uptake (Robertson et al. 1954; Olson et al. 1956b; Grunes et al. 1958; Rennie and Soper 1958; Leonce and Miller 1966; Bhandari and Virmani 1972).

2.5.2 Effects of N on Ability of Plants to Take Up P Fertilizer

Chemical reactions in the fertilizer reaction zone do not, by themselves, account for most of the increase in fertilizer P absorption caused by the ammonium ion (Rennie and Soper 1958; Miller 1974; Miller and Ohlrogge 1977). Plant-related factors cited in explanations of the ammonium ion effect include physiological acidification of the rhizosphere, cation/anion balance, root morphology and metabolic influences of ammonium.

The acidic rhizosphere of plants fed ammonium is a result of the excretion of hydrogen ions in exchange for the uptake of ammonium ions (Kirkby and Mengel 1967; Kirkby 1968). Conversely, nitrate uptake results in the excretion of bicarbonate.

Many years ago Chapman (1936) proposed that physiologically acid N fertilizers would increase the availability of P. Lorenz and Johnston (1953) reinforced this hypothesis during experiments that compared the addition of ammonium sulfate versus calcium nitrate to bands of P fertilizer. Unfortunately, much of these data are inconclusive because of the confounding factors of added calcium and changes in the pH of the fertilizer reaction zone that were unrelated to plant activity.

Leonce and Miller (1966) observed that labelled P fertilizer accumulated on the surface of corn roots when plants were supplied with concentrated superphosphate plus potassium nitrate but not when supplied with concentrated superphosphate plus ammonium chloride. Although they

hypothesized initially that ammonium affected P carrier activity within the plant root. Miller and his colleagues proved later that the absence of P accumulation on the root surface was due to a reduction in the pH of the rhizosphere (Miller et al. 1970). Riley and Barber (1971) arrived at a similar conclusion in experiments with soybeans. The pH of the rhizosphere of plants fed with ammonium was significantly lower than that of the bulk soil. Conversely, the pH of the rhizosphere of plants fed with nitrate was higher than that of the bulk soil. There was a significant, negative correlation between fertilizer P uptake and rhizocylinder pH. In the same year, Miller and his associates showed that the degree of ammonium enhancement of P fertilizer uptake was relatively greater at higher soil pH (Blair et al. 1971). Later, Soon and Miller (1977) isolated the rhizocylinder of corn plants fed with monocalcium phosphate plus nitrate or ammonium-N and found that the lower pH of plants fed ammonium was accompanied by increased solubility and uptake of fertilizer P. Although the aforementioned research was done with corn and soybeans, there is no reason to expect that wheat would respond differently. The lowering of pH in the rhizosphere of wheat fed ammonium-N has been observed both in the greenhouse and in the field (Smiley 1974; Marschner and Romheld 1983).

Changes in the pH of the rhizosphere not only influence retention of P by the soil, they also affect the physiology of P uptake. Hagen and Hopkins (1955) found that excised barley roots absorbed the greatest amount of P from solution cultures at pH 4 to 5. They attributed reduced uptake of P at higher pH to competition with hydroxyl ions. Recent research suggests that an electrogenic ion pump drives the P uptake system and that the pH influence may be due to the role of the hydrogen ion gradient in

that system (Ullrich-Eberius et al. 1981; Bielecki and Ferguson 1983; Pitman and Luttge 1983). Centripetal passage of P through the roots is also enhanced at lower pH (Emmert 1983).

There are other differences between ammonium and nitrate nutrition, as pointed out in recent reviews (Haynes and Goh 1978; Runge 1983). Besides changing the pH of the rhizosphere, the form of N also affects the balance of other cations and anions taken up. Ammonium uptake encourages the absorption of anions. Nitrate uptake, on the other hand, encourages cation absorption (Mengel and Kirkby 1979). This observation is not new. Arnon (1939) observed that barley fed with ammonium in nutrient solution contained more P and had a lower content of cations compared to plants fed with nitrate. He found that the pH of the shoot sap was lower in plants fed with ammonium and attributed the response to the "well-known physiological acidity" of ammonium nutrition. More recently, Blair et al. (1970) found that plants fed with ammonium took up more P and S from nutrient solutions, even though the pH of the solutions was kept constant. Also, Cox and Reisenauer (1973) found that adding ammonium to a flowing nutrient solution containing adequate nitrate increased the uptake of P and S by wheat.

The practical importance of these studies is unclear. In soil where nitrate is available to the plant the influence of ammonium fertilizers on the balance between cations and anions in the plant may not play as great a role. In pot experiments with soil, ammonium fertilizer increased the uptake of fertilizer P, but had no influence on the uptake of S (Mamaril and Miller 1970). Also, Dogar and Van Hai (1979) found that the enhancement of P uptake by ammonium in nutrient solutions reached a maximum

at approximately 1 mM NH_4 , a low concentration compared to that within a fertilizer band.

Several reseachers have noted that seedlings pretreated with nitrate or ammonium take up more P from nutrient solutions than untreated seedlings during short term experiments (Cole et al. 1963; Taber and McFee 1974). The effect has been attributed to the formation of a nitrogenous metabolite which aids P uptake. Recently, Barneix and co-workers found that wheat seedlings pretreated with ammonium sulfate or urea were able to take up more P from flowing nutrient solutions than plants pretreated with calcium nitrate (Barneix and Arnozis 1980; Barneix 1981). Barneix also suggested that a nitrogenous intermediate related to the P uptake mechanism was responsible. However, because the unique role of ammonium relative to nitrate is rather poorly defined and inconsistent, it is unlikely that nitrogenous metabolites account for the ammonium ion effect.

Root proliferation by a cereal crop is stimulated by a localized supply of nitrate or ammonium provided that the concentration of salts, ammonia or nitrite is not high enough to be toxic (Passioura and Wetselaar 1972; Drew 1975). Root proliferation is enhanced further when both N and P are supplied in the same zone (Grunes et al. 1958; Duncan and Ohlrogge 1958a; Drew 1975; Alston 1976; Drew and Saker 1978). Therefore, the ammonium ion effect has occasionally been attributed to the increased root proliferation in the P band when N is added (Miller and Ohlrogge 1958; Miller and Vij 1962).

However, root proliferation, alone, cannot explain the ammonium ion effect. Root proliferation is also stimulated by KNO_3 and KCl without much subsequent effect on P uptake (Duncan and Ohlrogge 1958a; Blanchar and

Caldwell 1966b; Blair et al. 1971). The ammonium ion effect has also been observed where there was little or no increase in root proliferation (Miller and Vij 1965; Leonce and Miller 1966; Mamaril and Miller 1970; Riley and Barber 1971). Therefore one must agree with earlier authors that there are physiological factors other than a physical increase in root proliferation which are responsible for the ammonium ion effect (Olson and Dreier 1956b).

In summary, after reviewing the wide variety of hypotheses, one concludes that the ammonium ion effect is likely not due to only a single factor (Miller 1974). Rather, there is likely a combination of several factors that are responsible, with root proliferation and physiological acidification being the primary ones.

2.5 Research Needs

There are many research papers that describe either the effect of placing P in different positions relative to the seed row or the interaction between N and P. Unfortunately there is little information about the relative efficiency of MAP applied in the seedrow versus MAP placed with urea in dual bands prior to planting, especially for cereals grown under Western Canadian conditions. Although researchers in Kansas recently investigated preplant dual banding, they used ammonium polyphosphate as a P source and winter wheat as a test crop (Leikam et al. 1979; Leikam et al. 1983). Leikam et al. (1983) reported that dual banded P resulted in higher P concentrations in plant tissue and higher grain yields than P banded in the seed row. Lately, though, Kansas researchers

have suggested that some seed row P may be advantageous when N and P are banded before seeding, especially if band spacings exceed 20 cm (Maxwell et al. 1984; Cabrera et al. 1986). In Colorado, although ammonium polyphosphate was applied in conjunction with N, different placements were not compared (Hanson and Westfall 1985).

Also, there is very little information that describes the effect of using ratios of N to P as high as those applied typically in Western Canada. Duncan and Ohlrogge (1958b) found that increasing the N:P₂O₅ ratio from 1:1 to 3:1 depressed fertilizer P uptake. Miller and Ohlrogge (1977) suggested that an N:P₂O₅ ratio of 1:4 is optimum, meaning they would not expect enhancement of P uptake from adding more N to a band of MAP. Yet Rennie and Soper (1958) found that adding 33 kg/ha of urea-N to 26 kg/ha of P₂O₅ in an MAP band increased the uptake of P fertilizer by wheat after 33 and 53 d of growth. Unfortunately, no grain harvest was taken.

3. EXPERIMENTAL PROCEDURES AND RESULTS

3.1 Diffusion Experiment

As mentioned in the literature review, the ammonium ion effect is caused by several factors (Miller 1974). And, although most of the research to date indicates that the predominant factors are root proliferation in the fertilized zone and pH reduction in the rhizosphere, there is evidence that ammoniacal fertilizers may also enhance the chemical availability of fertilizer P (Hanson and Westfall 1985, 1986). Therefore, laboratory studies were conducted with incubated soil columns to investigate the effects of urea on the chemical nature of the fertilizer reaction zone and, specifically, the effects on MAP movement and solubility. Some of the effects of urea on the ionic environment of the fertilizer reaction zone include an initially high pH, elevated concentrations of salt and, in particular, higher concentrations of ammonium. Therefore, K_2CO_3 , KCl and NH_4Cl , respectively were added to the MAP reaction zone in an attempt to imitate those individual characteristics.

Experimental Procedures

The soil used in this experiment was obtained from the Ap horizon of a Gleyed Rego Black Chernozem loamy fine sand, Almasippi series, collected near Graysville, Manitoba, SE 24-7-6 W1 (Table 1). Prior to use, the soil was air dried, mixed and passed through a 1 mm sieve.

The soil was moistened with 0.24 kg water/kg soil and thoroughly mixed in a polyethylene bag immediately prior to being packed gently into acrylic cylinders (the experimental procedures are described in greater detail in

Table 1. Some Properties of the Soil Used in the Diffusion and Elution Flow Experiments

Texture	loamy fine sand
pH (1:1, soil:water)	7.8
NaHCO ₃ -extractable P	10 mg/kg
NO ₃ -N	5.4 mg/kg
NH ₄ Ac-extractable K	92 mg/kg
SO ₄ -S	1.1 mg/kg
Carbonates (CaCO ₃ equiv.)	less than 1 g/kg
Organic C (Walkley-Black)	7.2 mg/kg
CEC (1M NH ₄ Ac, pH 7)	9.4 cmol (+)/kg
Exch. Ca	8.2 cmol (+)/kg
Exch. Mg	1.7 cmol (+)/kg
Exch. Na	0.02 cmol (+)/kg
Exch. K	0.15 cmol (+)/kg
Field Capacity (33 kPa)	28%

Appendix A). The soil was packed layer by layer with a long tined fork to a bulk density of 1.33 g/cm³. The cylinders were 5.1 cm in diameter, 10 cm long and were formed by stacking 20 - 0.5 cm acrylic rings and taping them together using vinyl tape. The bottom ring was glued to an acrylic plate which had been drilled with approximately 15 - 3 mm holes for aeration. Polyethylene mesh (Spectramesh with .150 mm openings) was placed between the bottom ring and the plate to cover the aeration holes.

Chemical treatments were applied as reagent grade, finely ground crystals or granules to the surface of the moist soil columns. The treatments included 226 mg MAP, 226 mg MAP plus 521 mg urea, 226 mg MAP plus 929 mg NH₄Cl, 226 mg MAP plus 1295 mg KCl, 226 mg MAP plus 1198 mg K₂CO₃ and a control with no salts added. The rates of P and N application

were equivalent to those in a fertilizer band if 25 kg P/ha and 100 kg N/ha were applied in a band width of 2.5 cm and at a spacing of 30 cm between bands. Potassium salts were applied at a rate equivalent to the moles of N added. A protective acrylic collar, 3 cm long and 5.1 cm in diameter was then taped to the top of each column and covered with parafilm which was punctured with small holes to allow air exchange. The soil columns were incubated in an upright position inside a humidified chamber for 1 or 5 wk at 20°C. Each treatment was replicated twice.

After the incubation period, the 0.5 cm sections of the soil columns were separated with a sharpened putty knife. An 8.3 g sample or approximately half of each moist disk of soil was weighed and placed into an Erlenmeyer flask for extraction; the other half was placed into a moisture tin for moisture content determination. Both the construction and dismantling of the soil columns was done in a fully humidified room to avoid dehydration.

Samples were shaken in 135 mL of distilled water for 30 min (soil:solution ratio approximately 1:20) and then centrifuged at 6000 rpm for 10 min. One 12 mL sample of supernatant was collected for pH and electrical conductivity analysis; another 12 mL was acidified with .05 mL conc. H_2SO_4 and analysed for P, $(\text{NO}_3+\text{NO}_2)$, NH_4 , Ca, Mg and K. The soil was then extracted with 135 mL of 0.5M H_2SO_4 for 30 min. The acid extracts were filtered using Whatman #42 filter paper and the filtrate collected for chemical analysis.

Water extracts were analysed for pH using a Fisher Accumet 620 pH meter equipped with a pencil thin polymer body combination electrode. Electrical conductivity was measured using a Radiometer CDM 2e conductivity

meter. Water and acid extracts were analysed manually for P using the ascorbic acid-molybdate blue method (Appendix B, Murphy and Riley (1962)). The concentration of combined (NO_3+NO_2)-N in water extracts was determined using a modification of the automated procedure of Kamphake et al. (1967). NH_4 -N in water extracts was determined by the Nessler method (Jackson 1958). Ca and Mg in water extracts and K in water and acid extracts were determined using a Perkin Elmer 560 Atomic Absorption Spectrophotometer.

Results

The concentration profiles of pH, water-extractable ions and total (acid plus water) extractable P were drawn by hand through data points that represent the mean data from duplicate soil columns (Figures 1 to 16). Although the data from individual replicates are not shown, the variation in water-extractable ions between duplicate soil columns was generally small (Appendix B). The total amounts of P, N, K and Ca extracted from individual sections of the soil columns were summed together and are presented in Table 2, 3, 4 and 5. Considering the large ratio of water to soil (20:1) used in the water extraction, these data may not be a quantitatively accurate description of the amount of water soluble ions within the soil solution of intact soil columns, but the data are still very useful for comparisons among treatments.

Water-Extractable P

The amount of water-extractable P in the fertilized soil columns after 1 wk of incubation varied substantially with treatment (Table 2). The amount of water-extractable P recovered from the soil columns fertilized with MAP increased 20% with the addition of urea and more than 60% with the

Table 2. Effects of Cosolutes Plus MAP on Extractable P in Incubated Soil Columns - Diffusion Experiment.

Treatment	Water- Extractable P	0.5 M H ₂ SO ₄ - Extractable P	Total P ¹ Extracted
	mg/column	mg/column	mg/column
<u>1 Wk Incubation</u>			
Control	1.1 ± 0.02 ²	92 ± 0.5	93 ± 0.5
MAP (only)	31.1 ± 0.5	121 ± 0.5	152 ± 1
Urea + MAP	37.9 ± 2.8	118 ± 4	156 ± 7
NH ₄ Cl + MAP	29.2 ± 0.1	123 ± 1	153 ± 2
KCl + MAP	30.0 ± 0.5	125 ± 0.5	155 ± 2
K ₂ CO ₃ + MAP	50.9 ± 1.1	106 ± 0.5	157 ± 2
<u>5 Wk Incubation</u>			
Control	1.1 ± 0.04	92 ± 0.8	93 ± 0.7
MAP (only)	20.8 ± 0.8	134 ± 3	155 ± 4
Urea + MAP	33.3 ± 1.8	123 ± 2	156 ± 0
NH ₄ Cl + MAP	18.7 ± 0.7	137 ± 2	155 ± 2
KCl + MAP	20.2 ± 0.1	133 ± 3	153 ± 3
K ₂ CO ₃ + MAP	44.5 ± 0.1	113 ± 1	157 ± 1

¹ Sum of water- and 0.5 M H₂SO₄-extractable P (fertilized soil columns received 61 mg of P as MAP).

² Plus or minus figures indicate the range between the mean and the two replicates.

addition of K₂CO₃. Adding KCl or NH₄Cl had very little effect on the solubility of P.

After 1 wk of incubation, fertilizer P had diffused 3 to 4 cm from the site of application (Figure 1). Differences in extent of fertilizer P movement were small. Water-extractable P was detected furthest from the site of application in soil columns treated with K₂CO₃ + MAP. Distance of movement for the other treatments decreased in the order: MAP (only), NH₄Cl + MAP, KCl + MAP and urea + MAP. Differences in concentration of

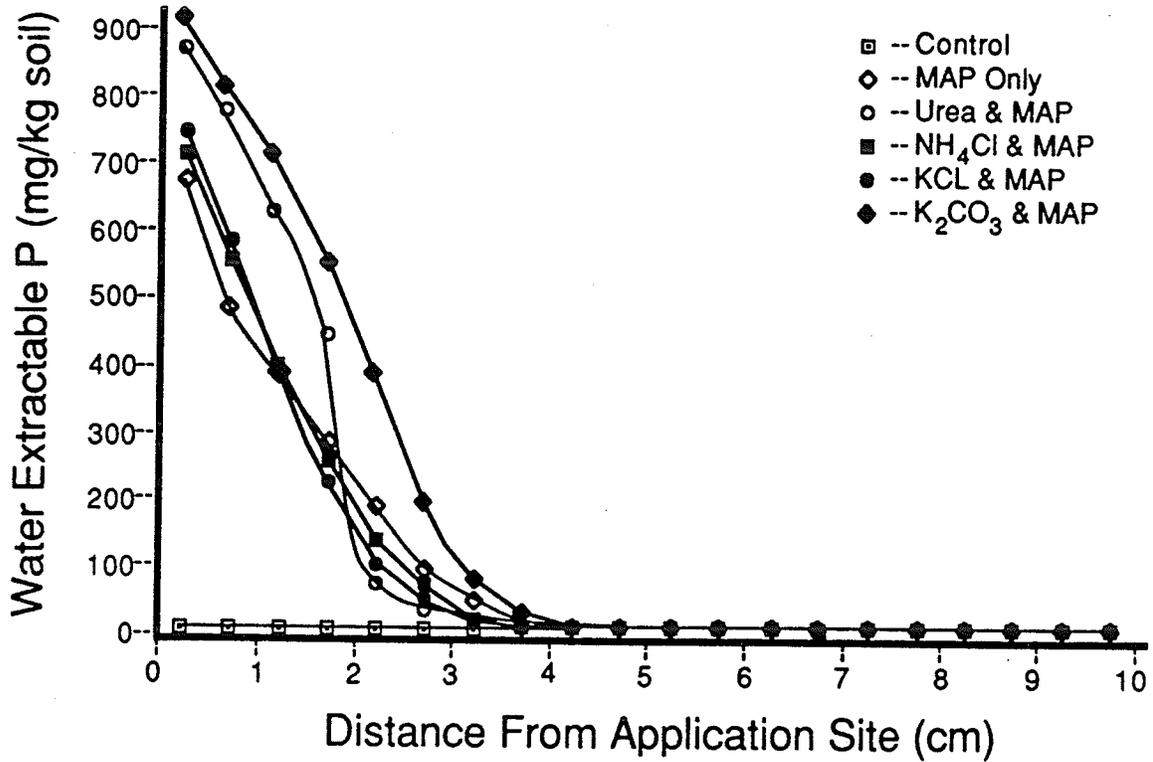


Figure 1. Water-extractable P from sections of soil columns 1 wk after treatment.

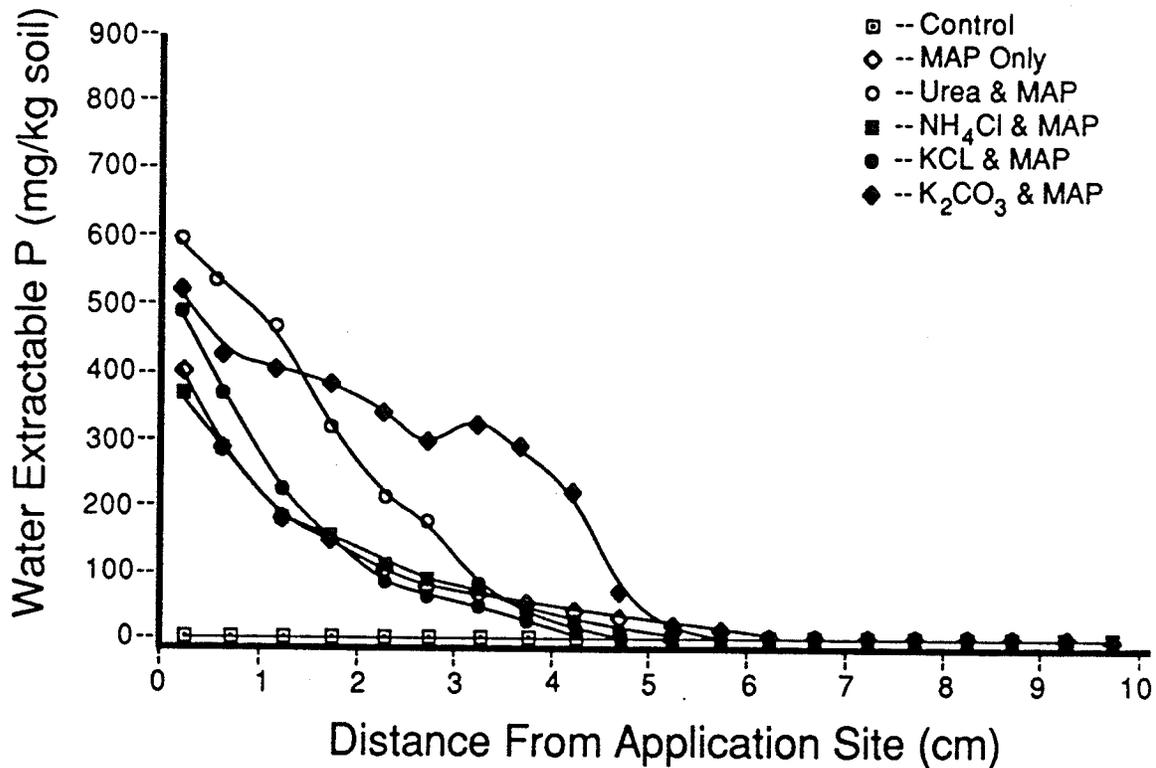


Figure 2. Water-extractable P from sections of soil columns 5 wk after treatment.

water-extractable P were quite large. The concentration of water-extractable P in the control and beyond the MAP reaction zone of the fertilized soil columns was extremely low and consistent. Therefore, one can assume that the differences in concentration are due to differences in the behavior of MAP and not due to the effect of the cosolute on soil P. For all treatments, the concentration of water-extractable P was highest near the application site. Comparing treatments, the concentration of water-extractable P throughout the MAP reaction zone was highest with K_2CO_3 + MAP. The urea + MAP treatment also resulted in a high concentration of water-extractable P within 2 cm of the application site, but the concentration dropped sharply beyond that distance. At a distance of 0 to 1.25 cm from the application site, the concentration of water-extractable P in soil columns treated with KCl + MAP was slightly higher than in those treated with NH_4Cl + MAP or MAP (only), respectively. However, the ranking among the latter three treatments was reversed at distances beyond 1.25 cm from the application site.

The amount of water-extractable P in the fertilized soil columns after 5 wk of incubation was less than after 1 wk of incubation, but the ranking of the treatments was quite similar (Table 2). The amount of water-extractable P recovered from the soil columns fertilized with MAP increased 60% with the addition of urea and over 100% with the addition of K_2CO_3 . Solubility of P was not increased and may, have been decreased slightly by the addition of KCl or NH_4Cl to MAP.

After 5 wk of incubation, fertilizer P had apparently diffused 4 to 6 cm from the application site (Figure 2). Differences in extent of fertilizer P movement were generally similar to those after 1 wk of

incubation but were less easily differentiated. Fertilizer P diffused furthest with the K_2CO_3 + MAP and MAP (only) treatments. The extent of fertilizer P movement was less with the other fertilizer treatments but no obvious differences among them were observed. The concentration of water-extractable P was highest near the application site with urea + MAP. However, the K_2CO_3 + MAP treatment resulted in concentrations of water-extractable P higher than those of the urea + MAP treatment at distances between 2 and 6 cm from the application site. The MAP (only) and KCl + MAP treatments resulted in similar amounts of water-extractable P but, as noted after 1 wk of incubation, the negative slope of the concentration profile was steeper for the KCl + MAP treatment. The concentration of water-extractable P with NH_4Cl + MAP did not appear to exceed that of MAP (only) at any location in the soil columns.

Acid-Extractable P

Extraction with 0.5 M H_2SO_4 removed any fertilizer P that remained in the soil after the water extraction, resulting in similar totals of P extracted for the various fertilizer treatments and incubation periods (Table 2).

The extent of fertilizer P movement as described by acid-extractable P for the various treatments was similar to that observed for water-extractable P, although the higher concentrations of acid-extractable soil P made interpretation of the data more difficult (Figures 3, 4).

For both incubation periods, the concentration of acid-extractable P within 1 or 2 cm of the application site was lower when urea or K_2CO_3 were added with MAP than when MAP was added alone, indicating less water-insoluble fertilizer P was retained at the application site. In

contrast, the profiles of acid-extractable P concentration of the other treatments were similar in shape and hierarchy to those of the water extraction. The peak concentration of extractable P and rate of decline with distance from the application site were greater with KCl + MAP than with NH_4Cl + MAP or MAP (only).

Total (Water + Acid) Extractable P

As mentioned previously, the total amount of P extracted with water and 0.5 M H_2SO_4 was similar for all fertilized soil columns and accounted for the total amount of P fertilizer added (Table 2).

Fertilizer P diffused furthest in the K_2CO_3 + MAP and MAP (only) treatments for both incubation periods (Figures 5, 6). This observation was similar to the observations made on the basis of the water-extractable P concentrations.

After 1 wk of incubation the distribution of total extractable P within the fertilizer reaction zone varied substantially with the cosolute added. Adding urea or K_2CO_3 to MAP resulted in P concentration profiles which were concave to the origin for part of the distance from the application site. The P distribution profiles for other treatments, including MAP (only) were convex to the origin with a large proportion of fertilizer P retained near the application site. Although the concentration of P with urea + MAP was the highest of any treatment at a distance of 1.5 cm from the application site, the concentration of P dropped dramatically beyond that point and was the lowest of any fertilized treatment at a distance of 2.5 cm. The concentration of P at distances greater than 2 cm from the application site was highest with K_2CO_3 + MAP.

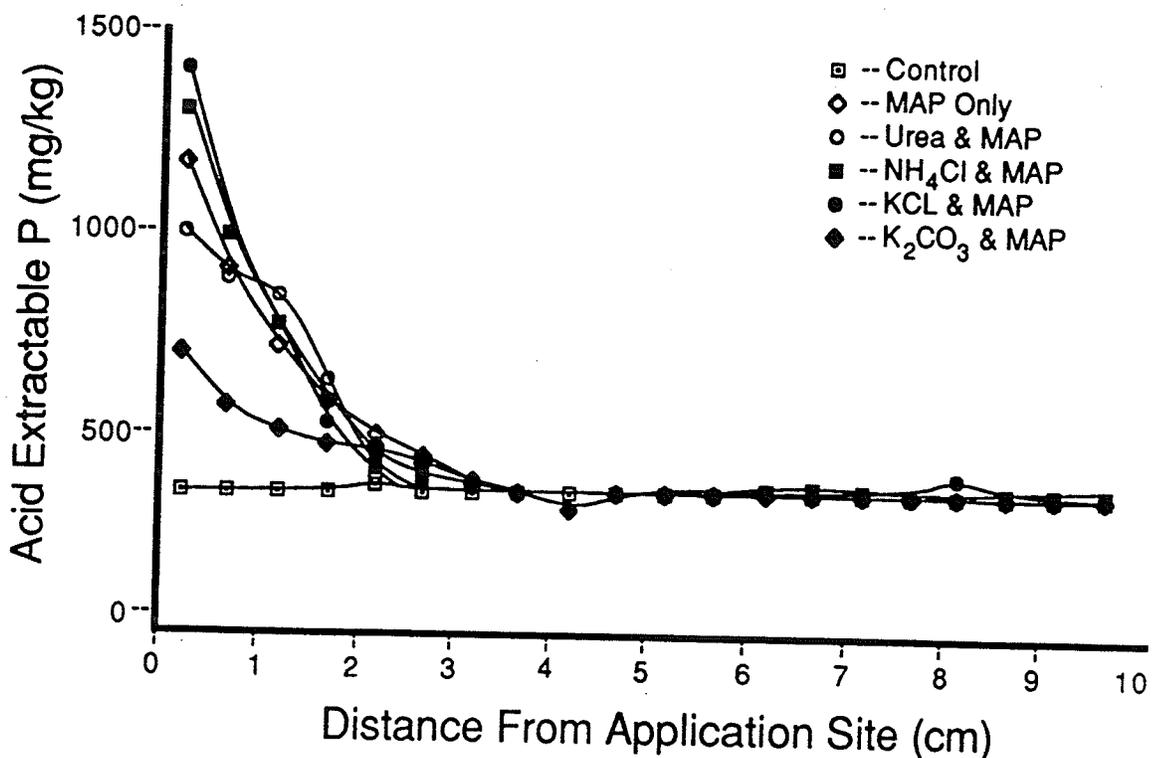


Figure 3. Acid-extractable P from sections of soil columns 1 wk after treatment.

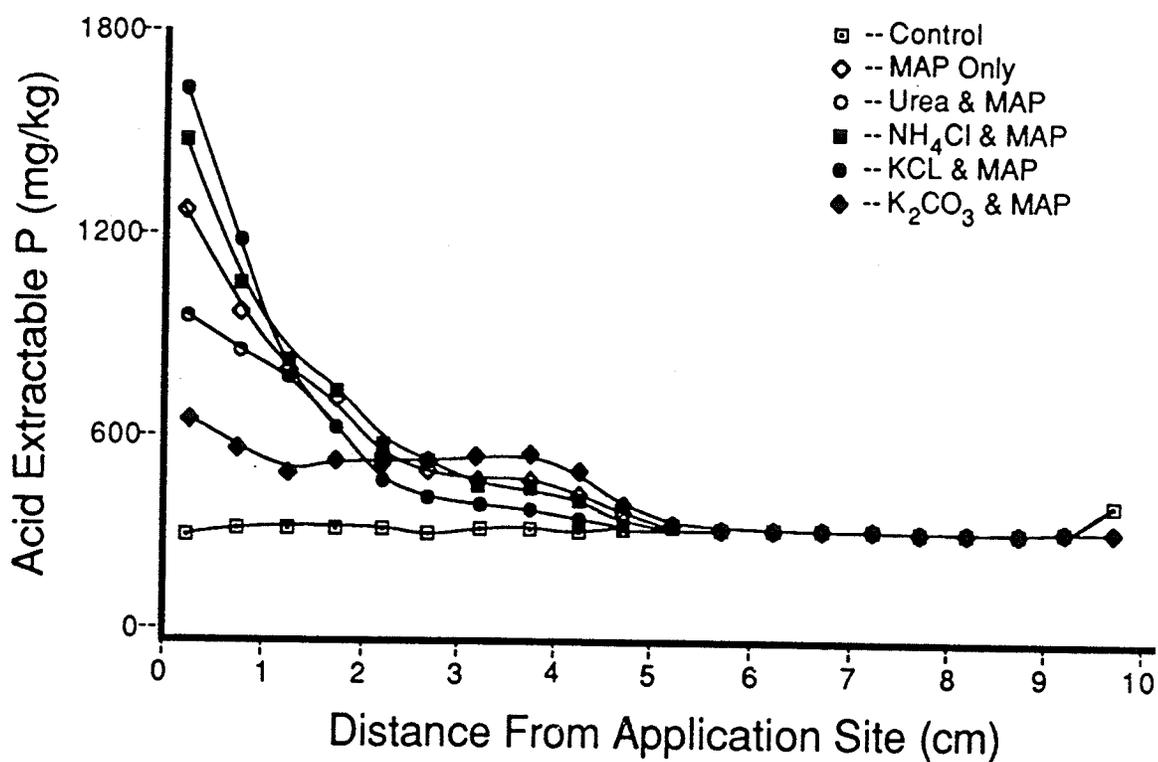


Figure 4. Acid-extractable P from sections of soil columns 5 wk after treatment.

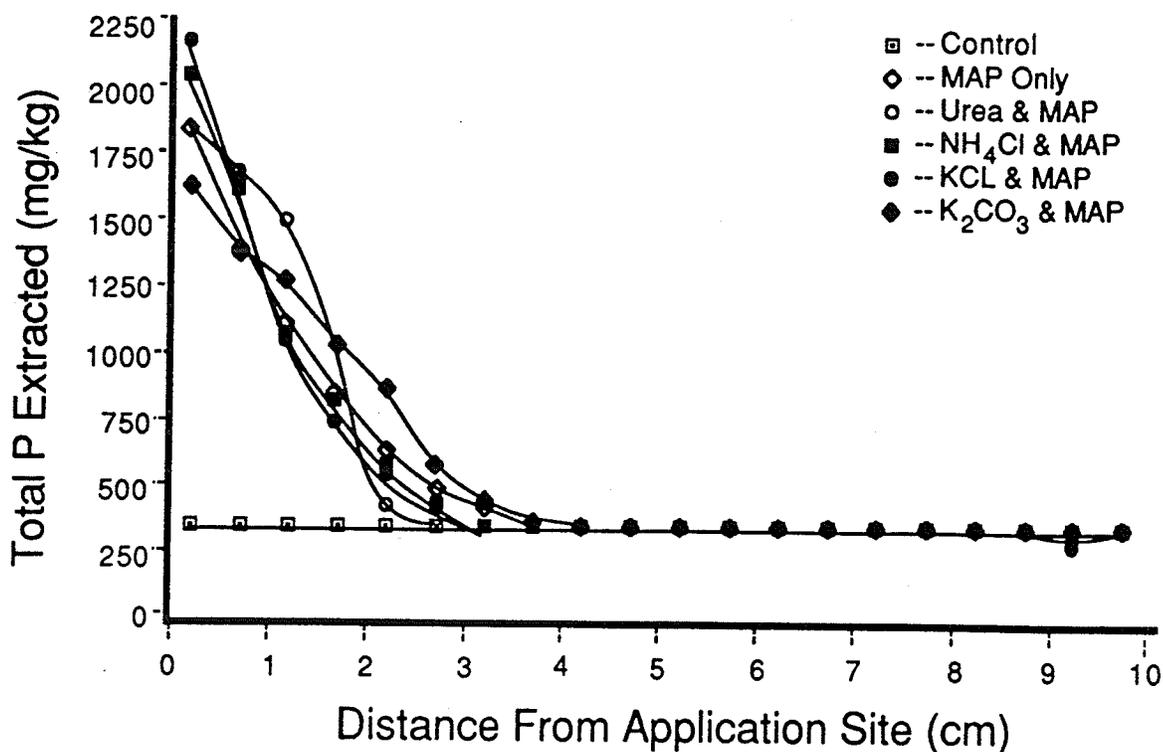


Figure 5. Total (acid plus water)-extractable P from sections of soil columns 1 wk after treatment.

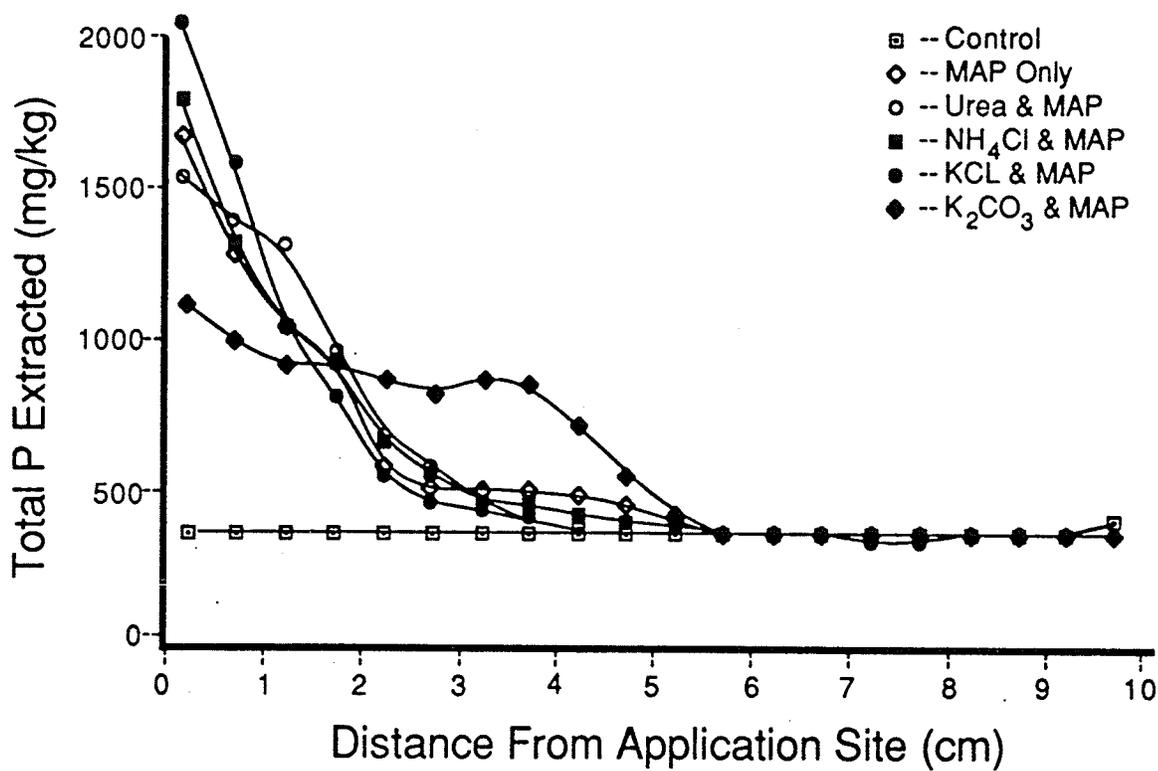


Figure 6. Total (acid plus water)-extractable P from sections of soil columns 5 wk after treatment.

During the 1 to 5 wk incubation period substantial amounts of fertilizer P diffused from the application site in the soil columns treated with urea + MAP or K_2CO_3 + MAP. Total P concentrations near the application site in the other soil columns were relatively similar for both incubation periods. After 5 wk of incubation the P concentration with urea + MAP was the highest of any treatment at a distance of 1.5 cm from the application site, but at distances beyond 2 cm, the concentration with K_2CO_3 + MAP was highest. Beyond 3 cm from the application site, the P concentration with urea + MAP was less than that with MAP (only).

Water-Extractable NH_4 -N

Most of the fertilizer N was still in the NH_4 form after 1 wk of incubation (Table 3). Adding KCl or NH_4Cl rather than alkaline cosolutes to MAP resulted in somewhat higher amounts of water-extractable NH_4 -N. The extent of NH_4 movement varied between 3.5 and 8 cm from the application site, distances that were considerably greater than for P movement, especially for treatments where NH_4Cl or urea was added with MAP (Figure 7). The extent of NH_4 movement from the application site was greatest with NH_4Cl + MAP and decreased in the order: urea + MAP, KCl + MAP, K_2CO_3 + MAP and MAP only for other treatments.

The highest concentrations of NH_4 -N occurred with NH_4Cl + MAP followed by urea + MAP. Differences in concentration of NH_4 -N among other treatments were quite small although the addition of KCl with MAP resulted in slightly higher concentrations of NH_4 -N than with MAP (only), perhaps due to some exchange with soil- NH_4 or reduced fixation of fertilizer- NH_4 . Adding K_2CO_3 to MAP appeared to enhance movement of NH_4 -N from the application site, although the total amount of NH_4 -N extracted was similar

Table 3. Effects of Cosolutes Plus MAP on Extractable N in Incubated Soil Columns - Diffusion Experiment.

Treatment	Water- Extractable NH ₄ -N	Water- Extractable (NO ₃ +NO ₂)-N	Total Water- ¹ Extractable N
	mg/column	mg/column	mg/column
<u>1 Wk Incubation</u>			
Control	2.7 ± 0.1 ²	8.4 ± 1.8	11 ± 2
MAP (only)	23.8 ± 1.9	9.2 ± 0.0	33 ± 2
Urea + MAP	191 ± 8	7.2 ± 0.3	198 ± 8
NH ₄ Cl + MAP	251 ± 1	6.9 ± 1.6	258 ± 1
KCl + MAP	34.3 ± 1.8	8.5 ± 0.3	43 ± 2
K ₂ CO ₃ + MAP	22.8 ± 0.1	9.0 ± 0.4	32 ± 1
<u>5 Wk Incubation</u>			
Control	8.6 ± 4.0	15.7 ± 0.1	24 ± 4
MAP (only)	22.8 ± 1.8	36.2 ± 2.2	59 ± 0.5
Urea + MAP	100 ± 3	95.3 ± 3.0	195 ± 5
NH ₄ Cl + MAP	192 ± 1	64.0 ± 0.2	256 ± 1
KCl + MAP	20.9 ± 0.5	34.5 ± 0.5	55 ± 1
K ₂ CO ₃ + MAP	12.4 ± 2.2	28.3 ± 1.0	41 ± 3

¹ Sum of water-extractable NH₄ plus (NO₃+NO₂)-N (fertilized soil columns received 25 mg of N as MAP. Soil columns treated with urea or NH₄Cl received an additional 240 mg of N).

² Plus or minus figures indicate the range between the mean and the two replicates.

to that with MAP (only).

Between the first and fifth wk of incubation the total amount of water-extractable NH₄-N extracted from the fertilized soil columns declined, presumably due to nitrification (Table 3). The largest declines occurred with urea + MAP and NH₄Cl + MAP where the amounts of NH₄ extracted declined by approximately 50 and 25%, respectively during the additional 4 wk of incubation.

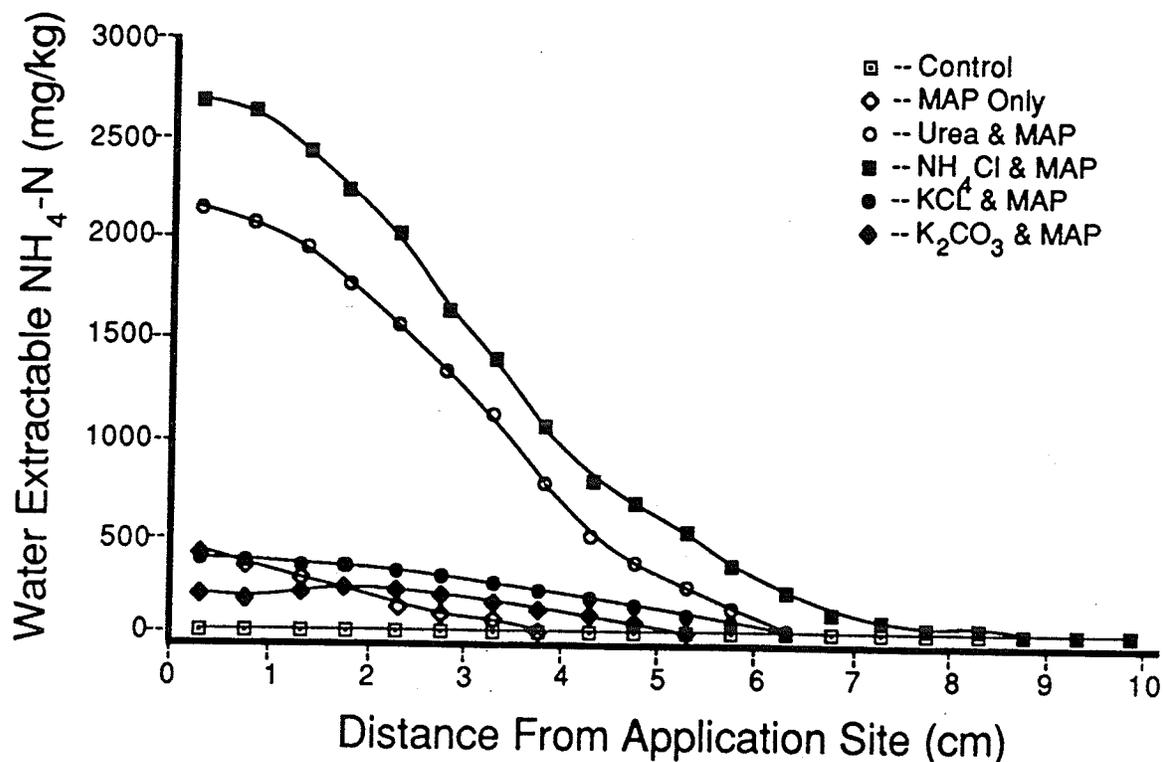


Figure 7. Water-extractable $\text{NH}_4\text{-N}$ from sections of soil columns 1 wk after treatment.

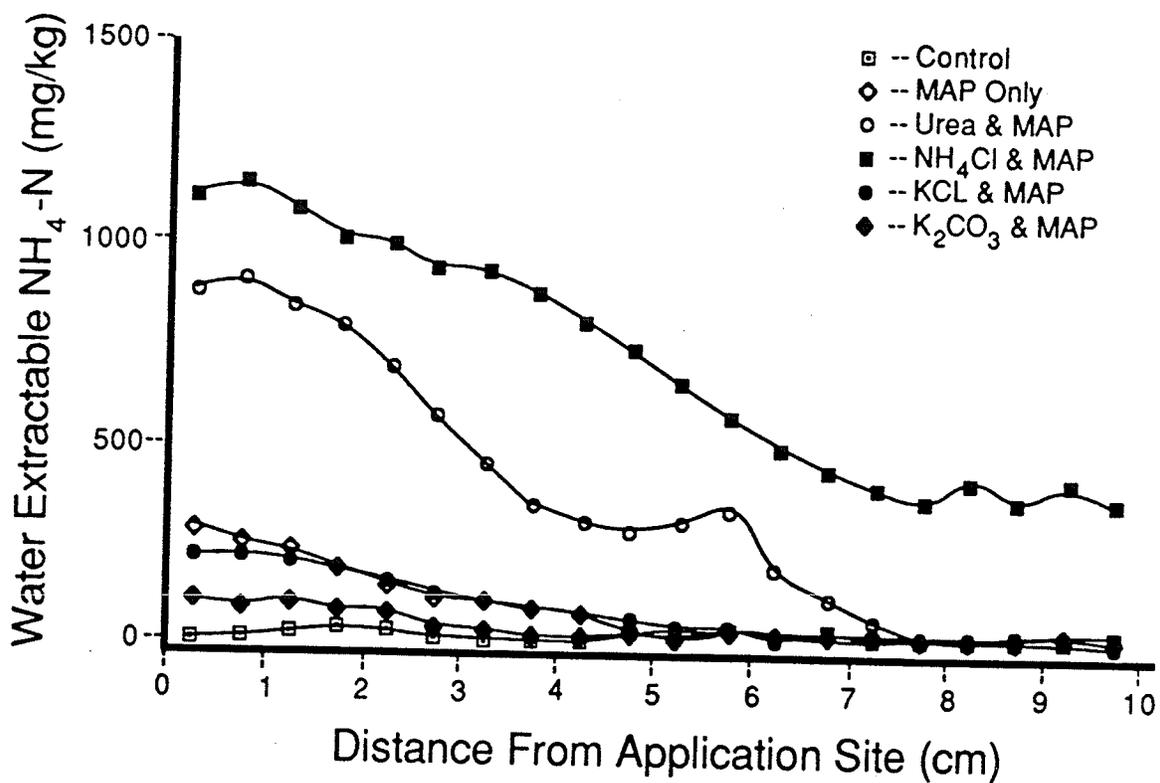


Figure 8. Water-extractable $\text{NH}_4\text{-N}$ from sections of soil columns 5 wk after treatment.

The distribution of water-extractable $\text{NH}_4\text{-N}$ in the soil columns changed only slightly between 1 and 5 wk after treatment (Figure 8). NH_4 had diffused to the end of the soil columns with $\text{NH}_4\text{Cl} + \text{MAP}$ and 7.5 cm from the application site with urea + MAP. The extent of NH_4 diffusion with other treatments was quite similar to that after 1 wk of incubation. Concentrations of water-extractable $\text{NH}_4\text{-N}$ near the application site of the $\text{NH}_4\text{Cl} + \text{MAP}$ and urea + MAP treatments had declined over 50%. Generally the concentration of NH_4 declined with increasing distance from the application site. However, a small increase in concentration of NH_4 was observed in both replicates of the urea + MAP treatment, between 5 and 6 cm from the application site.

Water-Extractable K

Soil columns treated with K_2CO_3 contained less water-extractable K than soil columns treated with KCl for both incubation periods (Table 4). In this regard, the behavior of K with respect to carrier is similar to that of NH_4 . Less K or NH_4 was extracted from soil columns where the carrier was or became an alkaline carbonate salt than where the carrier was an acidic or neutral chloride salt. Comparing the effect of urea to that of NH_4Cl one might be tempted to attribute the difference in extractable NH_4 to ammonia volatilization. However, the same behavior was noted with extractable K where K salts were applied. Considering this fact plus the observation that the acid extraction accounted for most of the K in the K_2CO_3 treatment which was not extractable with water (Table 4), one must conclude that applying alkaline rather than neutral or acid salts resulted in stronger retention of NH_4 and K by the soil.

Table 4. Effects of Cosolutes Plus MAP on Extractable K in Incubated Soil Columns - Diffusion Experiment.

Treatment	Water- Extractable K	0.5 M H ₂ SO ₄ - Extractable K	Total K ¹ Extracted
	mg/column	mg/column	mg/column
<u>1 Wk Incubation</u>			
Control	11.6 ± 0.6 ²	30.9 ± 0.9	42.5 ± 0.3
MAP (only)	13.9 ± 0.7	26.5 ± 0.3	40.3 ± 0.4
Urea + MAP	16.8 ± 1.4	25.9 ± 0.7	42.6 ± 4.6
NH ₄ Cl + MAP	18.2 ± 1.0	21.3 ± 0.4	39.5 ± 0.6
KCl + MAP	599 ± 3	148 ± 9	747 ± 6
K ₂ CO ₃ + MAP	501 ± 14	211 ± 9	736 ± 23
<u>5 Wk Incubation</u>			
Control	10.1 ± 1.3	28.2 ± 0.9	38.3 ± 3.2
MAP (only)	12.6 ± 1.8	26.2 ± 0.8	38.8 ± 3.4
Urea + MAP	14.6 ± 1.8	22.6 ± 2.9	37.2 ± 1.1
NH ₄ Cl + MAP	22.3 ± 1.3	16.7 ± 4.2	38.9 ± 6.4
KCl + MAP	533 ± 17	160 ± 2	693 ± 15
K ₂ CO ₃ + MAP	419 ± 2	280 ± 8	699 ± 10

¹ Sum of water- plus 0.5 M H₂SO₄-extractable K (soil columns treated with KCl or K₂CO₃ received an additional 680 mg of K).

² Plus or minus figures indicate the range between the mean and the two replicates.

The distribution of water-extractable K in soil columns treated with KCl and K₂CO₃ was quite similar to the distribution of water-extractable NH₄ in soil columns treated with NH₄Cl or urea, respectively (Figures 7 to 10). K or NH₄ added in the form of a chloride salt appeared to diffuse further than when added in the form of a compound that was or became a carbonate salt. As explained earlier, it is likely that the alkaline compounds resulted in stronger retention of NH₄ and K by the soil.

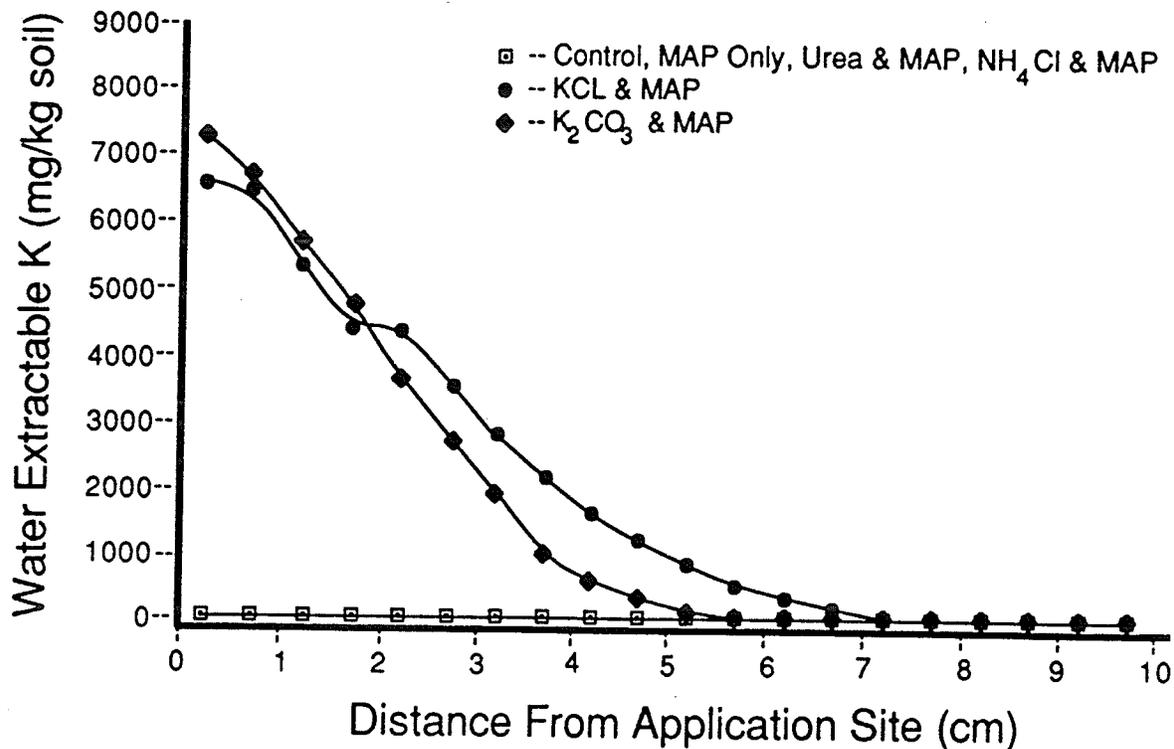


Figure 9. Water-extractable K from sections of soil columns 1 wk after treatment.

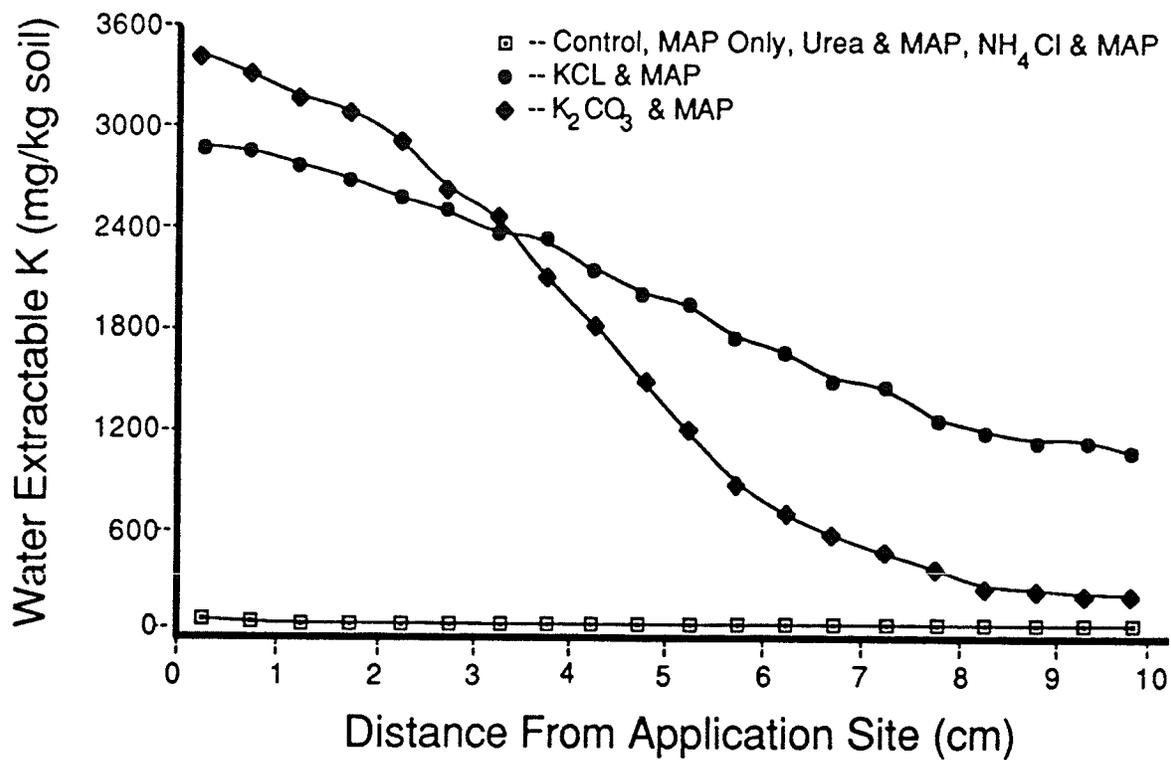


Figure 10. Water-extractable K from sections of soil columns 5 wk after treatment.

Water-Extractable (NO₃+NO₂)

Small total amounts of (NO₃+NO₂) were extracted from the soil columns after 1 wk of incubation (Table 3). No substantial differences among treatments were observed. Considering that a large quantity of NH₄ was added and subsequently extracted after 1 wk of incubation, these data indicate that very little nitrification of fertilizer N had taken place during the first wk. However, the concentration profiles showed that the local concentration of (NO₃+NO₂) varied within the soil columns (Figure 11). The concentration of (NO₃+NO₂) near the application site of the fertilized soil columns was less than that of the control. Apparently the high concentration of fertilizer in this zone had severely restricted nitrification. Concentrations of (NO₃+NO₂) in fertilized soil columns increased above that of the control at distances of 2 to 8 cm from the site of fertilizer application. It was also noted that (NO₃+NO₂) concentrations in fertilized soil columns was higher than that of the control at a distance of approximately 3 cm from the furthest extent of NH₄ movement. The maximum concentration of (NO₃+NO₂) occurred with K₂CO₃ + MAP, not with urea + MAP or NH₄Cl + MAP. At the distal end of the soil column the concentration of (NO₃+NO₂) with NH₄Cl + MAP and KCl + MAP appeared to be lower than with the control or other fertilizer treatments.

The total amount of (NO₃+NO₂) extracted from the soil columns increased dramatically between 1 and 5 wk of incubation, primarily due to nitrification (Table 3). The largest amount of (NO₃+NO₂) was extracted from the soil columns treated with urea + MAP and decreased in the order: NH₄Cl + MAP, MAP (only), KCl + MAP, K₂CO₃ + MAP and the control.

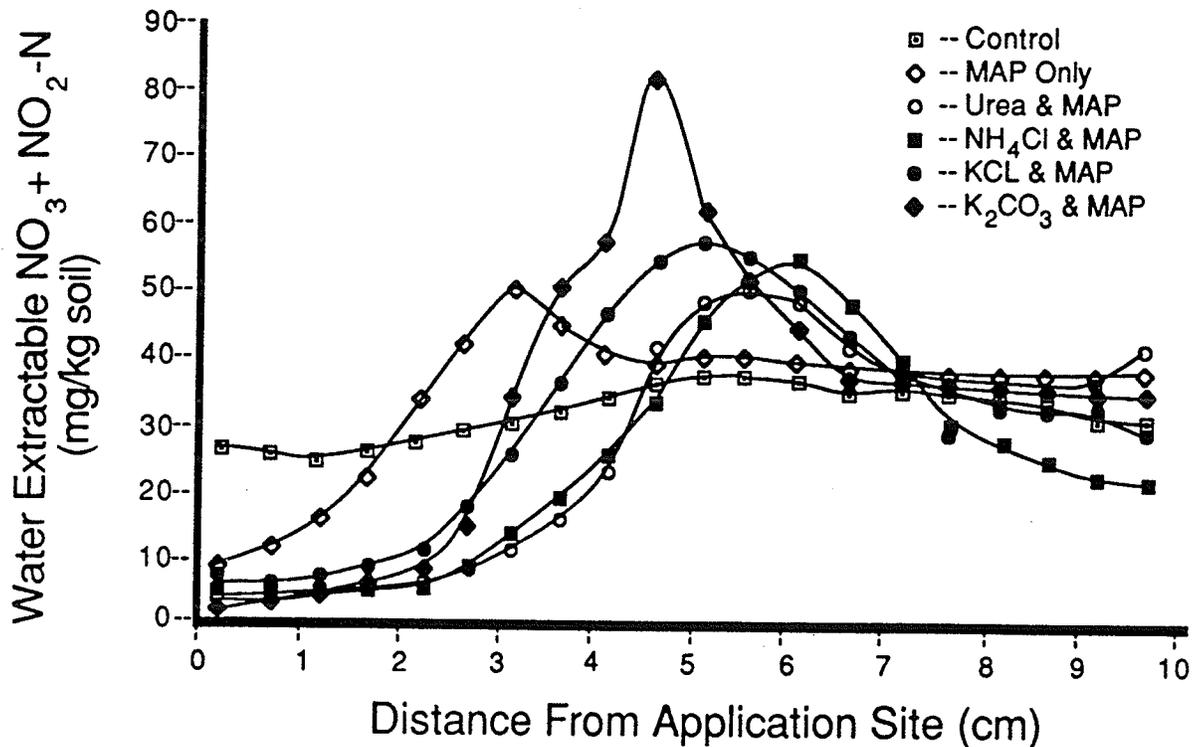


Figure 11. Water-extractable ($\text{NO}_3 + \text{NO}_2$) from sections of soil columns 1 wk after treatment.

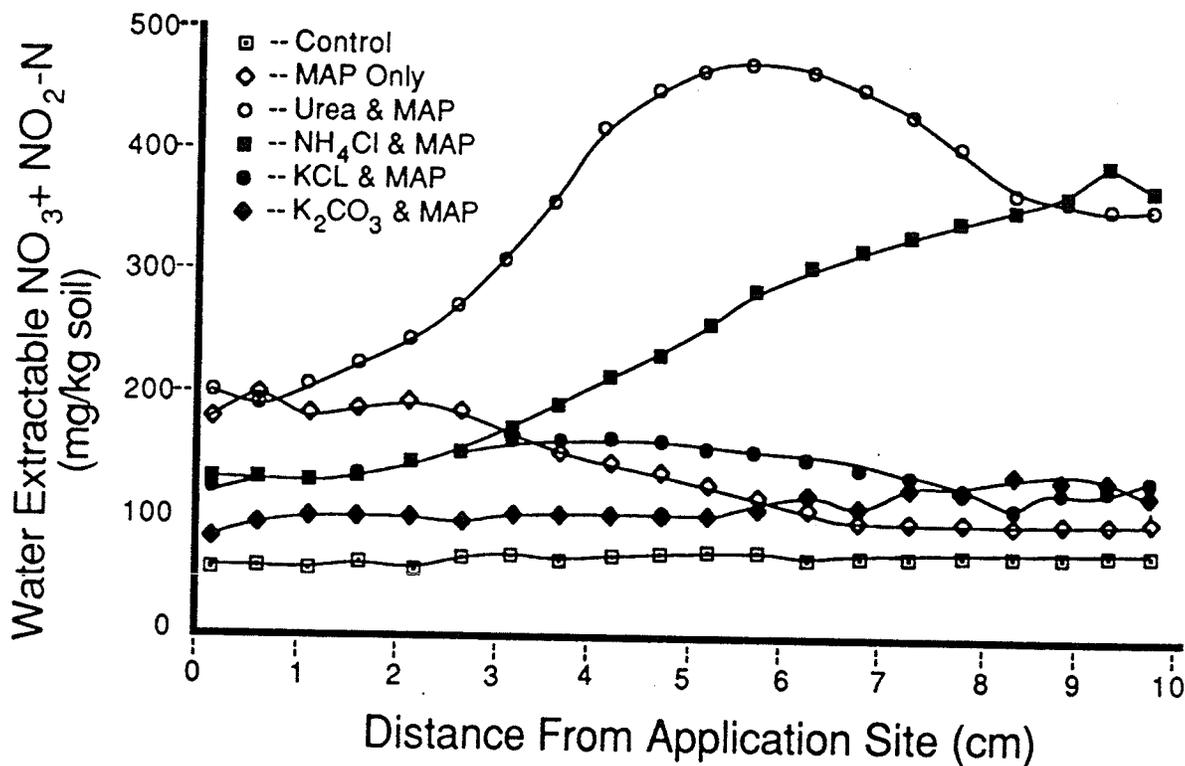


Figure 12. Water-extractable ($\text{NO}_3 + \text{NO}_2$) from sections of soil columns 5 wk after treatment.

After 5 wk of incubation, the distribution of $(\text{NO}_3+\text{NO}_2)$ in the soil columns was much different than after 1 wk (Figure 12). The maximum concentration of $(\text{NO}_3+\text{NO}_2)$ occurred with urea + MAP followed by NH_4Cl + MAP. The concentration of $(\text{NO}_3+\text{NO}_2)$ in soil columns with K_2CO_3 + MAP was generally lower than with any other fertilizer treatment. Also, peaks in the concentration of $(\text{NO}_3+\text{NO}_2)$ were much less defined and less consistent than after 1 wk of incubation. The profile of $(\text{NO}_3+\text{NO}_2)$ concentration with urea + MAP was a broad curve, concave to the x-axis and peaked at 6 cm from the application site. The profile for NH_4Cl + MAP was a relatively straight line, increasing towards the distal end of the soil column. Restricted nitrification of fertilizer N due to high concentrations of ammonium salts near the application site was likely responsible for the decline in concentration of $(\text{NO}_3+\text{NO}_2)$ towards the site of application of urea or NH_4Cl . The difference in distribution of $(\text{NO}_3+\text{NO}_2)$ between the urea and NH_4Cl treatments may have been due to the more extensive movement of NH_4 in the case of the latter. The profile of $(\text{NO}_3+\text{NO}_2)$ in soil columns treated with MAP (only) was also a relatively straight line, but decreased towards the distal end, similar to the distribution of water-extractable NH_4 .

pH of Water Extracts

The pH of water extracts from the soil columns after 1 wk of incubation varied substantially with treatment (Figure 13). The pH of the untreated soil columns was approximately 8.5. Adding K_2CO_3 + MAP or urea + MAP to the soil columns increased the pH within 4 cm of the application site to 9.9 and 9.0, respectively. In contrast, the addition of MAP (only), NH_4Cl + MAP or KCl + MAP decreased the pH of extracts by as much as

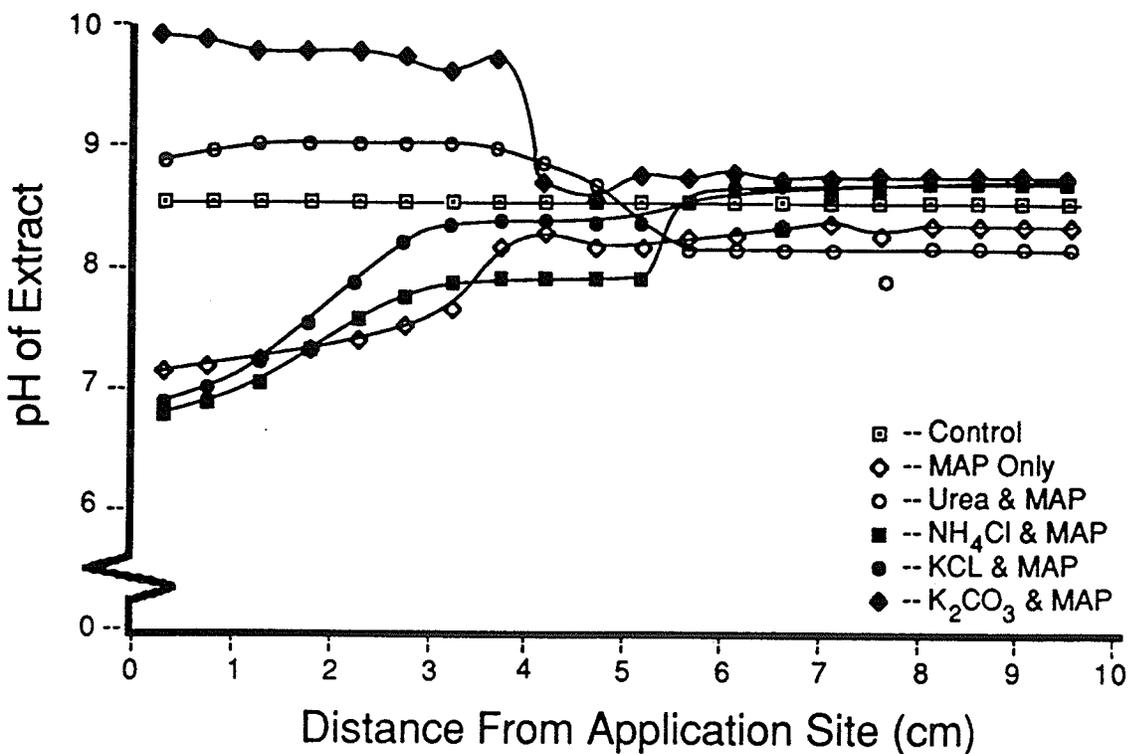


Figure 13. pH of extracts from sections of soil columns 1 wk after treatment.

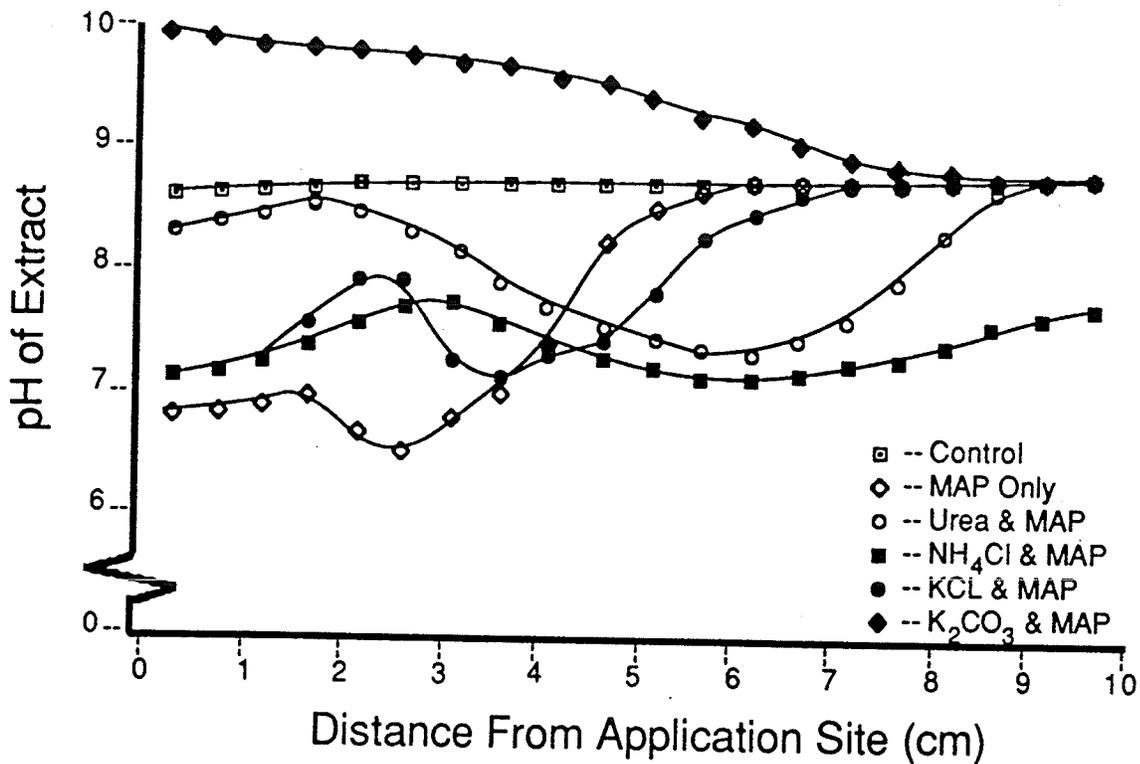


Figure 14. pH of extracts from sections of soil columns 5 wk after treatment.

1.5 units below that of the control, presumably due to the acidity of MAP and/or NH_4Cl , the salt effects of cosolutes and a localized zone of nitrification at the distal end of the reaction zone. The effect of fertilizer treatment on pH extended approximately the same distance as the furthest movement of added NH_4 or K.

After 5 wk of incubation, the pH differences among treatments were greater than those observed after 1 wk (Figure 14). The pH of the untreated soil columns was approximately 8.7. The only soil columns more alkaline than the untreated soil columns were those treated with K_2CO_3 + MAP. All other treated soil columns, including those with urea + MAP, were considerably more acidic than the untreated soil columns. The acidifying effect of these fertilizer treatments extended further into the soil columns than after 1 wk, presumably due to further diffusion of the fertilizer and much more nitrification of added NH_4 . Similar to the results after 1 wk of incubation, the effect of fertilizer treatment on pH extended as far as the furthest movement of added NH_4 from the application site, but slightly less than the furthest movement of added K.

Water-Extractable Mg and Ca

Water-extractable Mg concentrations paralleled those for water-extractable Ca, although concentrations of Mg were much less than concentrations of Ca (Appendix B). Since the behavior of these two ions was essentially the same, only the Ca data is discussed.

The amount of water-extractable Ca in the soil columns varied inversely with the pH of the various soil columns (Table 5). After 1 wk of incubation, soil columns treated with K_2CO_3 + MAP or urea + MAP contained the lowest amounts of water-extractable Ca, whereas the untreated soil

Table 5. Effects of Cosolutes plus MAP on Extractable Ca in Incubated Soil Columns - Diffusion Experiment.

Treatment	Water-Extractable Ca	
	mg/column	
	1 Wk Incubation	5 Wk Incubation
Control	102 ± 17 ¹	124 ± 4
MAP (only)	66 ± 15	128 ± 7
Urea + MAP	47 ± 5	141 ± 1
NH ₄ Cl + MAP	96 ± 7	212 ± 2
KCl + MAP	93 ± 6	191 ± 2
K ₂ CO ₃ + MAP	51 ± 3	95 ± 9

¹ Plus or minus figures indicate the mean and the two replicates.

columns and soil columns treated with NH₄Cl + MAP or KCl + MAP contained the greatest amount of water-extractable Ca. The high pH and high concentration of HCO₃ in the reaction zone of urea or K₂CO₃ likely decreased the solubility of basic calcium compounds which may have been present. The soil used in the soil column study contained no measurable calcium carbonate. Therefore much of the extractable Ca must have come from exchange sites. The displacement of Ca from exchange sites by added salts caused less Ca to be extracted from soil columns treated with MAP (only), than from those to which KCl salt had been added, in spite of similarities in pH. Less Ca was extracted from soil columns treated with MAP (only) than from untreated soil columns, indicating that the degree to which Ca remained soluble was influenced not only by the various cosolutes added but also by the availability of P.

The distribution of water-extractable Ca within the fertilized soil columns after 1 wk also illustrates the effects of the cosolutes added with MAP (Figure 15). Much less Ca was extracted from the first 8 cm of soil columns treated with K_2CO_3 or urea than from soil columns treated with NH_4Cl or KCl . Peak concentrations of water-extractable Ca were observed at distances of 5 to 6 cm from the application site. The peaks were particularly obvious with the chloride salt treatments. However, the reason for these peaks is uncertain. The peaks may be due to an accumulation of Ca displaced by diffusing NH_4 or K, causing Ca to be "snowplowed" off exchange sites (Olsen and Kemper 1968; Cho 1985). The displaced Ca, if at least slightly soluble, would have been partially extractable with water, considering the large dilution effect of the 1:20,

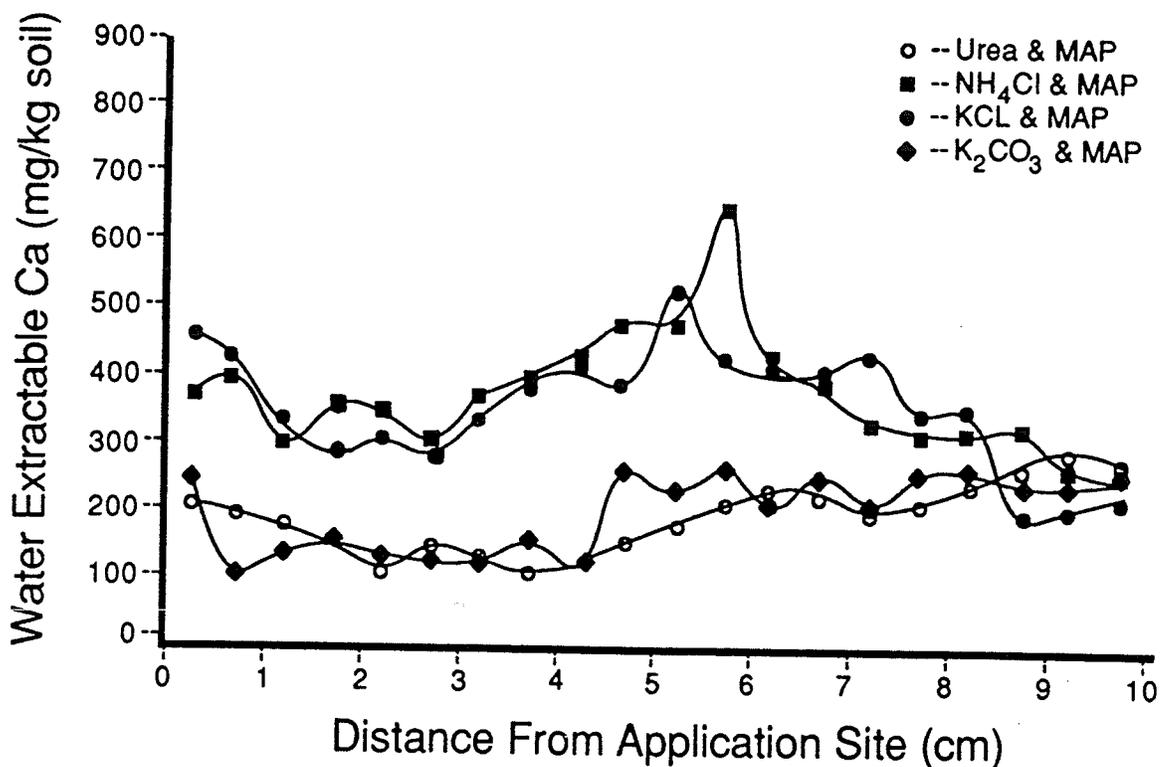


Figure 15. Water-extractable Ca from sections of soil columns 1 wk after treatment.

soil:solution ratio used for extraction. Also, the peaks occur in a region where nitrification, and therefore, acidification were also occurring. Therefore it is uncertain whether the high concentrations of water-extractable Ca were due to displacement or to an increase in solubility of Ca compounds in situ.

After 5 wk of incubation, the least amount of Ca was extracted from soil columns treated with K_2CO_3 + MAP (Table 5). Soil columns treated with K_2CO_3 were also the only fertilized soil columns from which less Ca was extracted than from those treated with MAP (only). The solubility of Ca had increased dramatically between the first and fifth wk in soil columns treated with urea + MAP, likely due to the decline in pH associated with nitrification of the urea. This observation agrees with that of Isensee and Walsh (1972) who observed a similar increase in solubility of Ca during the incubation of soil columns treated with urea + monocalcium phosphate.

The distribution profiles of water-extractable Ca within the soil columns after 5 wk paralleled the observations made from the data on total amount of Ca in the entire columns (data not shown). However, the profiles were considerably more erratic than after 1 wk of incubation and contained no obvious peaks of water-extractable Ca.

Discussion and Conclusions

The solubility of P in the MAP fertilizer reaction zone was increased for both incubation periods when urea or K_2CO_3 was added with MAP. This increase in solubility was likely due to reduced Ca activity and greater anionic competition caused by high pH and high concentrations of HCO_3 in the fertilizer reaction zone.

Alkaline bicarbonate compounds are well known for their ability to solubilize P. For example, a common extractant for determining the available P in alkaline soils is NaHCO_3 solution, buffered at pH 8.5. Jackson (1958) attributed most of the increase in P solubility during NaHCO_3 extraction to a lowering of Ca activity, due to the effects of pH and HCO_3^- (as a common ion) on the solubility of CaCO_3 . Increases, either in pH or HCO_3^- concentration, greatly increase the ability of NaHCO_3 to extract P from soil (Barrow 1976). Barrow also noted that the extractability of P from a soil treated with monocalcium phosphate was inversely proportional to the ability of the extractant to displace calcium (Barrow and Shaw 1979). The diffusion of NH_4^+ or K and the high pH with the urea or K_2CO_3 treatments extended well beyond the limits of movement of P fertilizer, allowing a large portion of P fertilizer to remain water soluble. As a result, there was a strong, inverse relationship between the total amount of water-extractable Ca and the total amount of water-extractable P for entire columns where MAP was added with a cosolute (Figure 16). However, it should be noted that for alkaline carbonate extractions, the reduced activity of Ca may not be the only factor which enhances the solubility of P. There may also be significant competitive anionic displacement of P by the HCO_3^- ion (Mott 1981).

Increases in P solubility upon adding K_2CO_3 have been observed before. Das (1930) proposed the use of 1% K_2CO_3 as an extracting solution for available P after finding that it dissolved substantial quantities of P in alkaline soils. Starostka and Hill (1955) reported that the solubility of dicalcium phosphate was increased by K_2CO_3 more than any other cosolute tested. In fact, Jackson (1958) reported that the major fault with using

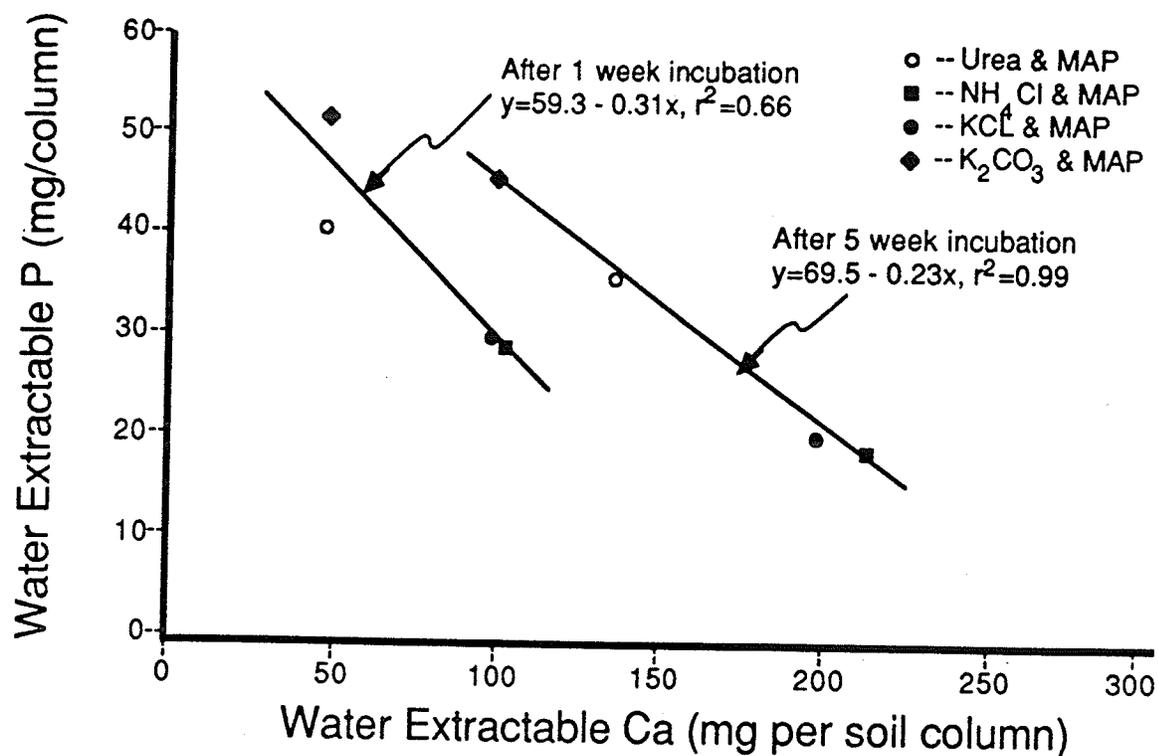


Figure 16. The effect of added salts on total water-extractable P and Ca from entire soil columns in the diffusion experiment.

K₂CO₃ as a P extractant was that it dissolved too much of the alkali-soluble P and was relatively insensitive to the availability of P to plants. Ammonium bicarbonate, a compound which is likely to form upon the hydrolysis of urea, has also been used to extract P during soil testing (Soltanpour and Schwab 1977).

The practical implications of the results of the diffusion experiment are not clear. Normally one would expect that the increase in P solubility as a result of adding urea to the MAP reaction zone would benefit plant growth. However, only one soil type was examined and the incubation period was short relative to the growing season of a crop. Because of the eventual decline in pH of the urea + MAP reaction zone, one can surmise that, eventually, the greater activity of calcium in a nitrified urea + MAP

band may encourage greater retention of fertilizer P by the soil.

Experiments with other fertilizers have shown that the nitrification of ammonium applied with P fertilizers does, indeed, eventually decrease the uptake of fertilizer P by plants (Spratt 1973; Leikam et al. 1983). And, regarding the correlation between P solubility and P uptake by plants, one must also consider that adding ammonium salts to P fertilizer may decrease P solubility while still allowing plants to take up more P (Miller and Vij 1962).

In addition, the implications of high ammoniacal N and high pH in the reaction zone of urea + MAP, although positive with respect to chemical availability of P, may be negative with respect to root growth in the band. These conditions are favourable to the generation of free ammonia which, even at low concentrations, is toxic to roots (Bennett 1974).

3.2 Elution Experiment

Most of the movement of P to plant roots is by diffusion rather than mass flow. However, elution techniques are useful for studying the movement and retention of P fertilizer added to soil (Cho et al. 1970). Therefore an elution experiment was conducted, using soil columns which were treated with MAP plus various cosolutes and incubated for 1 or 5 wk, similar to the diffusion experiment.

Experimental Procedures

The soil used in the elution experiment was the same soil used in the diffusion experiment (Table 1). Prior to use, the soil was air dried, mixed and passed through a 1 mm sieve. The soil columns were formed using acrylic cylinders 15 cm long with an inside diameter of 2.54 cm. The bottom ends of the cylinders were fitted with perforated acrylic discs. The cylinders were assembled by placing polyethylene mesh ("Spectramesh", 0.150 mm opening) and Whatman #42 filter paper over top of the discs and friction fitting the discs into the base of the cylinders.

The cylinders were then filled to a 10 cm height with 67.5 g of dry soil. A disc of filter paper, 2.5 cm in diameter was placed on top of the soil column to protect the soil surface while 25 mL of water was added slowly to the soil columns. After 5 min the soil columns were placed into a humidified vacuum apparatus where 9 mL of water was extracted, resulting in a final water content of 23.7%. The columns were incubated for 24 h in a humidified chamber at 20°C before adding the fertilizer treatments (Appendix A).

Treatments were similar per unit of surface area to those in the diffusion experiment. The tops of the acrylic cylinders were covered with

parafilm which was then punctured with small holes to allow air exchange. The soil columns were incubated in an upright position inside a humidified chamber for 1 or 5 wk at 20°C. Each treatment was replicated twice.

After the incubation period the soil columns were eluted with distilled water over a 45 h period. The surface of each column was covered with 5 mm of moist, washed sand and a filter paper disc to distribute the water and to protect the soil surface during elution. Water was then applied to the soil columns at a rate of 3 mL/h using an LKB 2132 Microperpex peristaltic pump. Eluate was extracted from the soil columns using a Masterflex 7553-10 pump (Cole-Parmer, Chicago, Illinois). Eluate fractions were collected on an hourly basis into preweighed test tubes using an Instrumentation Specialties model 560 fraction collector.

Eluate samples were weighed and measured for pH. One mL of 1.0 M HCl was then added to each sample to precipitate dissolved organic matter and to maintain the solubility of eluted P. Samples of eluate were analysed for Mg, Ca and K by atomic absorption and for P by an automated ascorbic acid-molybdate blue method (Murphy and Riley 1962, Appendix A). The concentration of (NO₃+NO₂) - N in the eluate was determined using an automated procedure modified from Kamphake et al. (1967, Appendix A). NH₄-N was determined by modified Nessler method (Jackson 1958, Appendix A).

The intervals between fractions were recalculated in units of pore volume. During the elution period there was some variability in flow rate through the soil columns. Therefore the water filled pore volume in each soil column was estimated on an hourly basis assuming it would be 16 mL plus or minus the net inflow or outflow of eluate measured in each fraction collected. Although the absolute volume of water eluted through each soil

column was similar, the differences in flow behaviour among the columns resulted in differences in apparent total eluate volume when expressed as pore volumes. Therefore all totals of eluted ions were adjusted to describe the eluate accumulated after an equivalent of 6.8 pore volumes.

One day after elution, 1 cm sections of the soil column were sequentially extracted with water and then 0.5 M NaHCO_3 buffered at pH 8.5. Both extractions were conducted for 30 min at 20°C , using a soil:solution ratio of 1:20. The water extract was clarified by centrifugation. The NaHCO_3 extract was decolorized by the addition of 0.5 g prewashed charcoal and filtered through Whatman #42 filter paper. Water extracts were analysed for P using a manual ascorbic acid-molybdate blue method (Appendix E). Sodium bicarbonate extracts were analysed for P using an automated ascorbic acid-molybdate blue method (Appendix A).

Results

Elution of P

The total amount of P eluted varied substantially with treatment, but the results were quite different from those for the diffusion experiment (Table 6). After 1 wk of incubation, the greatest amount of P was eluted from soil columns treated with K_2CO_3 + MAP, followed by those treated with NH_4Cl + MAP, KCl + MAP, urea + MAP and MAP (only). This contrasts with the results of the diffusion experiment where the addition of KCl or NH_4Cl with MAP had a negligible, if any, effect on the amount of water-extractable P (Table 2).

Table 6. Effects of Cosolutes Plus MAP on the Elution of P from Incubated Soil Columns.

Treatment	P Eluted ¹ mg/column	Ca Eluted mg/column
<u>1 Wk Incubation</u>		
Control	0.02 ± 0.01 ²	3.62 ± 0.24
MAP (only)	5.22 ± 0.05	7.34 ± 0.63
Urea + MAP	5.88 ± 0.16	6.90 ± 0.28
NH ₄ Cl + MAP	9.62 ± 0.17	51.72 ± 0.19
KCl + MAP	8.29 ± 0.41	35.17 ± 3.75
K ₂ CO ₃ + MAP	10.43 ± 0.01	10.79 ± 1.92
<u>5 Wk Incubation</u>		
Control	0	4.28 ± 0.01
MAP (only)	4.48 ± 0.06	9.23 ± 0.24
Urea + MAP	6.25 ± 0.67	27.15 ± 4.0
NH ₄ Cl + MAP	7.59 ± 0.78	57.62 ± 0.32
KCl + MAP	7.02 ± 0.08	40.97 ± 0.76
K ₂ CO ₃ + MAP	6.84 ± 0.18	9.54 ± 0.10

¹ All quantities are based on amount of P eluted with an equivalent of 6.8 pore volumes of water (fertilized soil columns received 15.2 mg of P as MAP).

² Plus or minus figures indicate the range between the mean and the two replicates.

After 5 wk of incubation, the greatest amount of P was eluted from soil columns treated with NH₄Cl + MAP, opposite to the results of the diffusion study where adding NH₄Cl to MAP had resulted in the least water-extractable P of any fertilizer treatment. In contrast to the diffusion experiment, adding MAP with K₂CO₃ or urea resulted in less water-extractable P than with NH₄Cl. There was, however, considerable variation between replicates of similar treatments, so the effect of the various cosolutes was not distinguishable. Considerably less P, though,

was eluted from soil columns treated with MAP (only). This contrasts with the diffusion experiment where soil columns treated with MAP (only) contained at least as much water-extractable P as those treated with NH_4Cl + MAP or KCl + MAP.

The elution profiles for P differed substantially for the various fertilizer treatments (Figures 17 and 18). For both incubation periods, the highest peak in P concentration was observed with NH_4Cl + MAP and decreased in the order: KCl + MAP, K_2CO_3 + MAP and MAP (only) which was similar to urea + MAP. The position of concentration maxima for the various treatments increased from approximately 1.5 to 4 pore volumes in the same order. However, the position of the maximum concentration of P with urea + MAP was much more retarded than with the other treatments. The distinctively dispersed elution profile for P with the urea + MAP treatment was surprising. One would have expected the profile to resemble at least one of the other treatments based upon the salt, NH_4 or pH effect of the added urea. The dispersed and retarded elution profile with urea + MAP compared to that with MAP (only) might suggest that the addition of urea caused greater retention of MAP. However, more P was eventually eluted from the soil columns where urea was added with MAP. Therefore, it is likely that although the addition of urea with MAP had increased retention of P, the degree of retention was moderate.

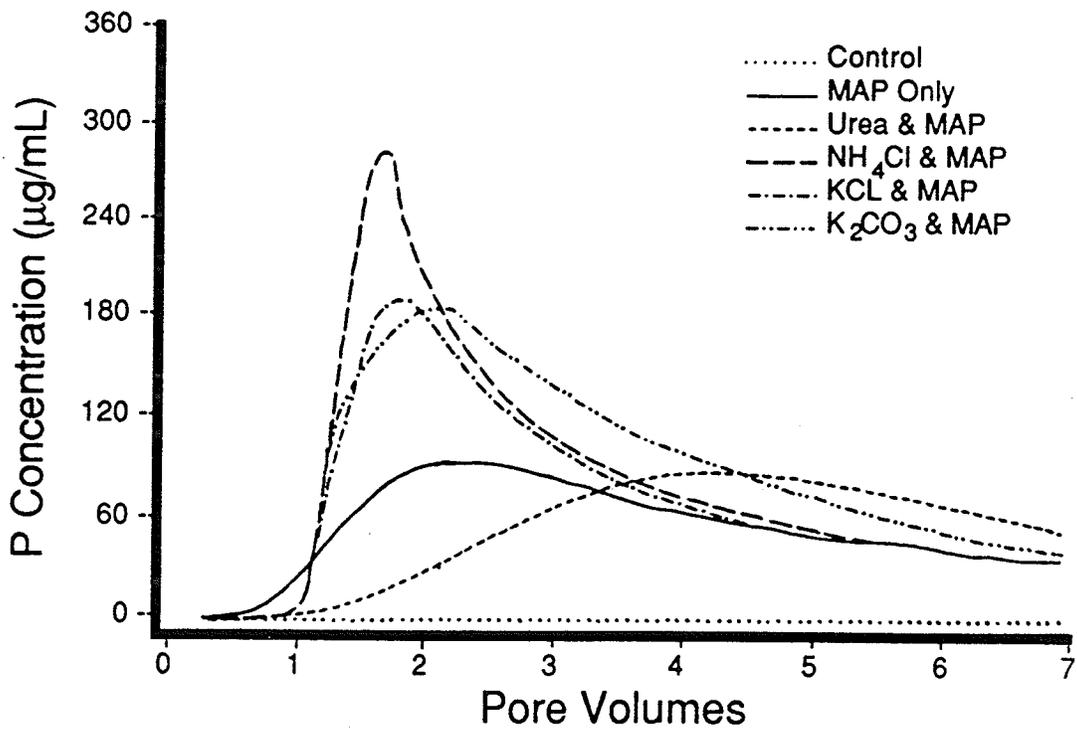


Figure 17. Elution of P from soil columns incubated for 1 wk.

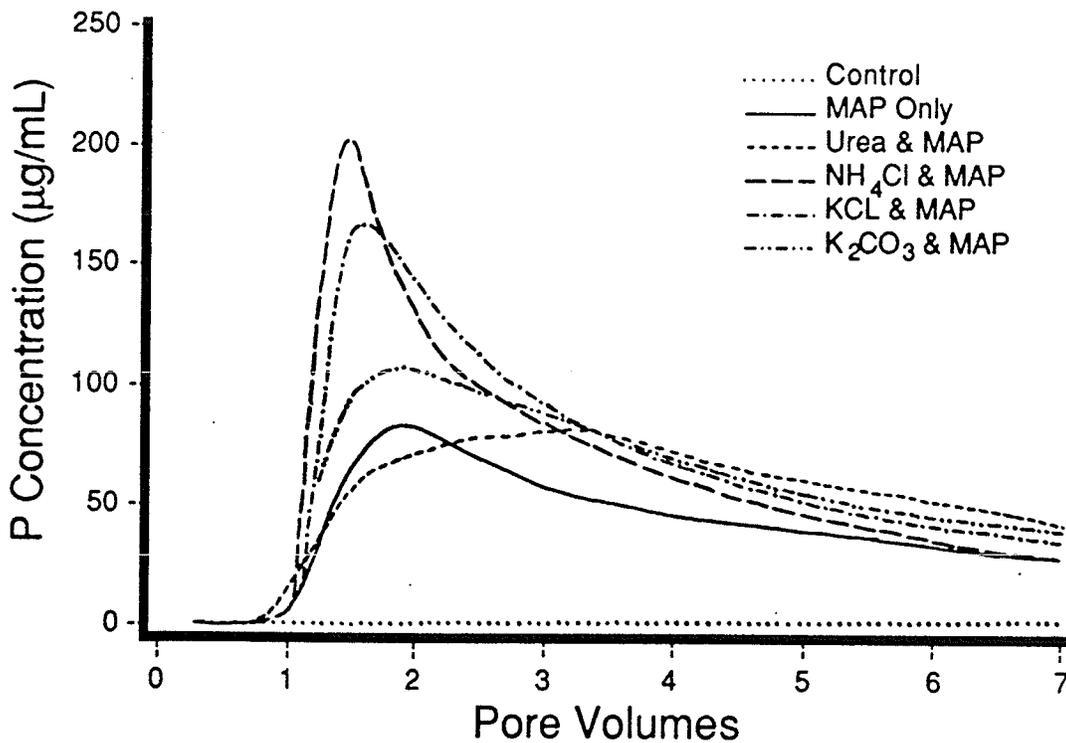


Figure 18. Elution of P from soil columns incubated for 5 wk.

Elution of Ca and Mg

Concentrations of Mg eluted from the various treatments followed the trends noted for Ca although the concentrations of Mg were much less than those of Ca (Appendix C). Since the behavior of these two cations was so similar, only the elution of Ca is discussed.

Differences among treatments in the total amount of Ca extracted from soil columns were much greater in the elution experiment than in the diffusion experiment (Tables 5, 6). It should be noted that the columns used in the diffusion study contained four times as much soil as those used in the elution experiment. In the diffusion experiment the amount of Ca extracted from the soil columns treated with NH_4Cl + MAP or KCl + MAP was approximately twice that from columns treated with urea + MAP or K_2CO_3 + MAP. In the elution experiment the amount of Ca extracted from columns treated with MAP plus NH_4Cl or KCl was up to seven times as great as that from columns treated with MAP plus urea or K_2CO_3 . One reason for this is the low water content maintained during extraction by elution. By comparison, the higher solution:soil ratio of the batch extraction in the diffusion experiment increased the dissolution of Ca compounds of moderately low solubility in soil. This factor is likely responsible for the 85% reduction in efficiency of extraction of Ca per g of soil for the control treatment when the soil was eluted rather than extracted by a batch method. The large effect of cosolute on extractable Ca in the elution experiment was due also to the elution process allowing Ca which was displaced by KCl or NH_4Cl to freely exit the soil columns. This allowed considerably more Ca per g of soil to be eluted rather than batch extracted from columns treated with NH_4Cl or KCl and incubated for 1 wk, for example.

The largest amount of Ca eluted from soil columns incubated for 1 wk was from columns treated with NH_4Cl + MAP followed by those treated with KCl + MAP, K_2CO_3 + MAP, MAP (only), urea + MAP and the control. In contrast, in the diffusion experiment the K_2CO_3 + MAP and urea + MAP treatments resulted in the lowest amount of water-extractable Ca of all treatments. Thus, it appears that pH was a less dominant factor determining the extractability of Ca in the elution study than in the diffusion study. In contrast to the data obtained from the diffusion experiment, no inverse relationship between Ca and P extractable with water was noted for data from the elution studies. There was no consistent relationship between water-extractable Ca and P in the elution study. More Ca and P were eluted from soil columns treated with MAP plus NH_4Cl or KCl than from those treated with MAP added alone or with urea. However, comparing the effect of K_2CO_3 to that with KCl , K_2CO_3 allowed considerably more P to be eluted while allowing more Ca to be retained.

The elution profiles of Ca for soil columns incubated for 1 wk indicated that nearly all the eluted Ca was extracted before the P was leached, with maximum concentrations consistently occurring within the first pore volume followed by a decrease to low concentrations at 1 to 2 pore volumes (Figure 19). This indicates that the highest concentration of eluted Ca was already some distance away from the surface of the soil column. The Ca had been in an exchangeable form which was displaced or "snowplowed" by NH_4 or K. The distribution pattern of the Ca concentration profile was similar for all treatments. Therefore, the concentration maxima reflected the ranking of the total amounts of Ca eluted for the various treatments.

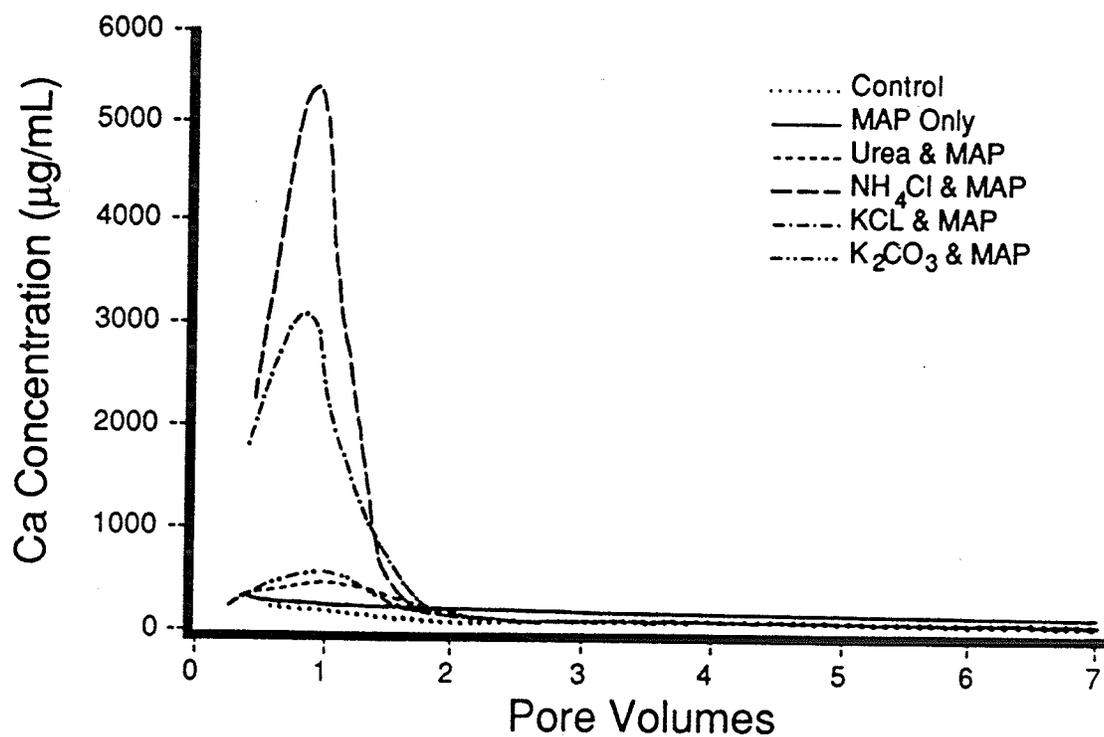


Figure 19. Elution of Ca from soil columns incubated for 1 wk.

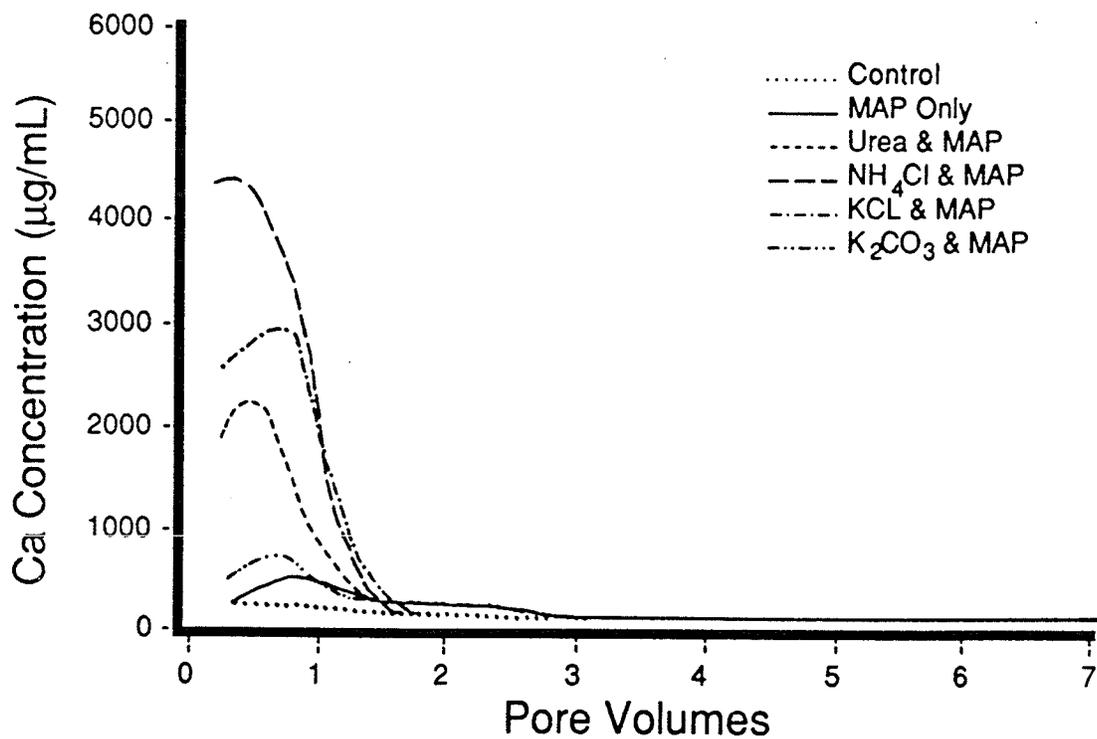


Figure 20. Elution of Ca from soil columns incubated for 5 wk.

Elution of Ca from soil columns which had been incubated for 5 wk revealed trends similar to those for the 1 wk incubation, except that substantially more Ca was eluted from columns treated with urea + MAP after 5 wk (Table 6). Presumably, the acidifying effect of nitrification was responsible for an increase in solubility of Ca compounds in the soil.

The elution profiles of Ca for soil columns incubated for 5 wk were generally similar to those after 1 wk of incubation (Figure 20). However, the peak concentrations of Ca after 5 wk occurred earlier in the elution period and the peak concentration with urea + MAP was much greater than after 1 wk.

Elution of NH_4 , K, (NO_3+NO_2) and H

The maximum concentration of NH_4 or K eluted from soil columns treated with NH_4Cl or KCl , respectively, occurred at 1 pore volume after 1 wk of incubation and at 0.75 pore volume after 5 wk of incubation (Figures 21 to 24). These maxima occurred after those observed for Ca and before those observed for P. Peak concentrations were much higher for NH_4Cl or KCl than for urea or K_2CO_3 . The greater mobility of the chloride salts compared to their alkaline counterparts was also observed in the diffusion experiment. The displacement of Ca from the soil columns by the cosolutes added with MAP was likely responsible for more P being extracted from all columns treated with cosolutes than from columns treated with MAP (only).

The decline in NH_4 concentration between the first and fifth wk was accompanied by a dramatic increase in (NO_3+NO_2) (Figures 25 and 26). As expected, the (NO_3+NO_2) was eluted within the first pore volume. The amount of (NO_3+NO_2) produced for the various treatments and incubations

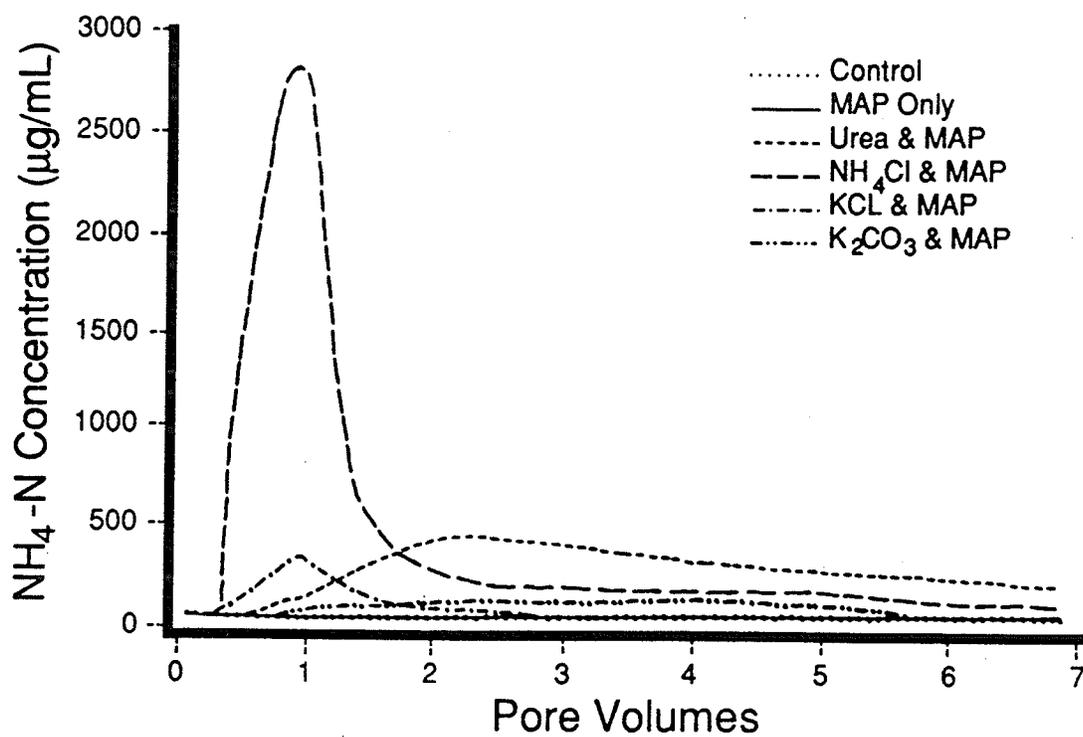


Figure 21. Elution of NH_4 from soil columns incubated for 1 wk.

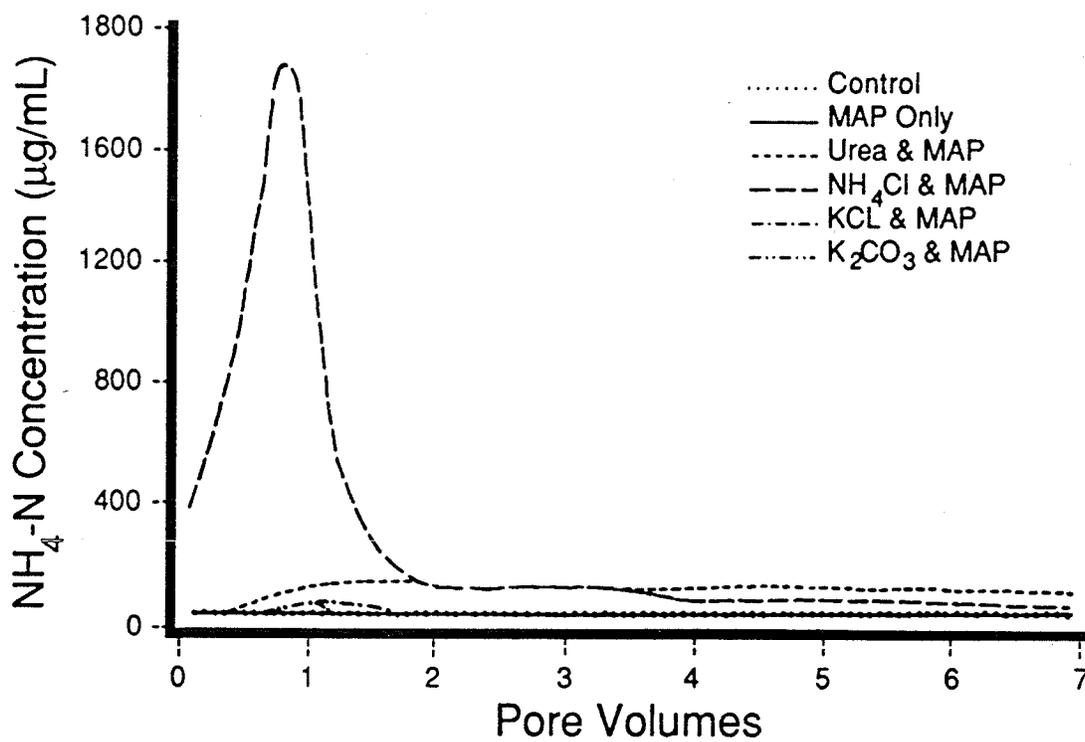


Figure 22. Elution of NH_4 from soil columns incubated for 5 wk.

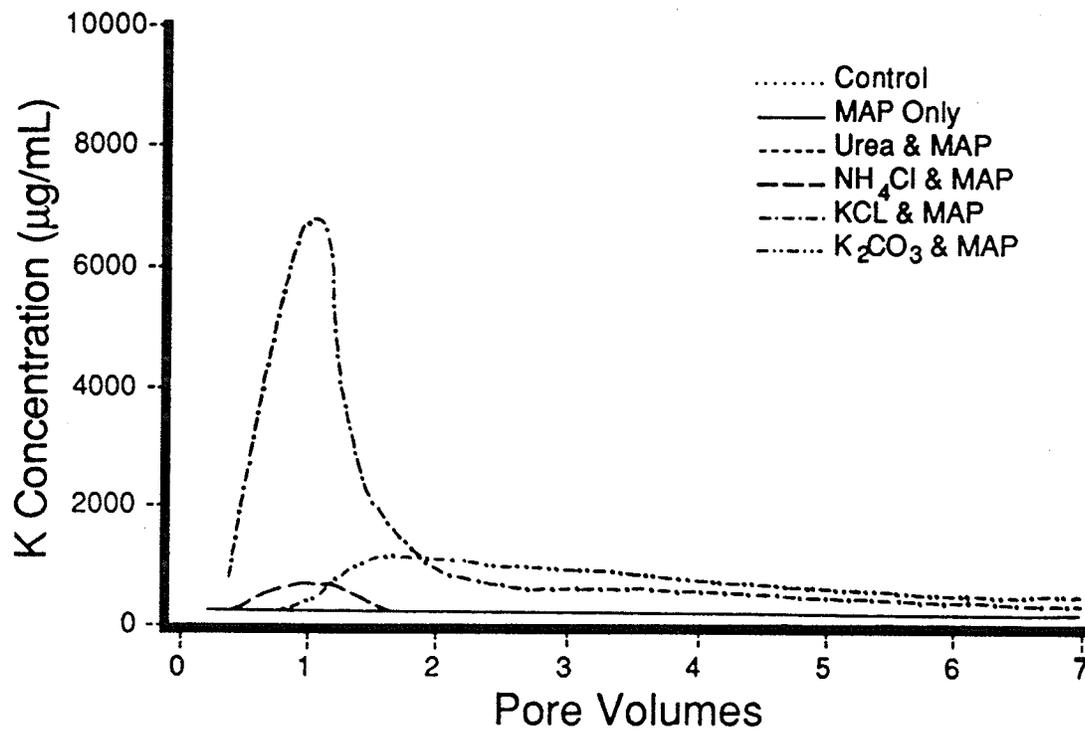


Figure 23. Elution of K from soil columns incubated for 1 wk.

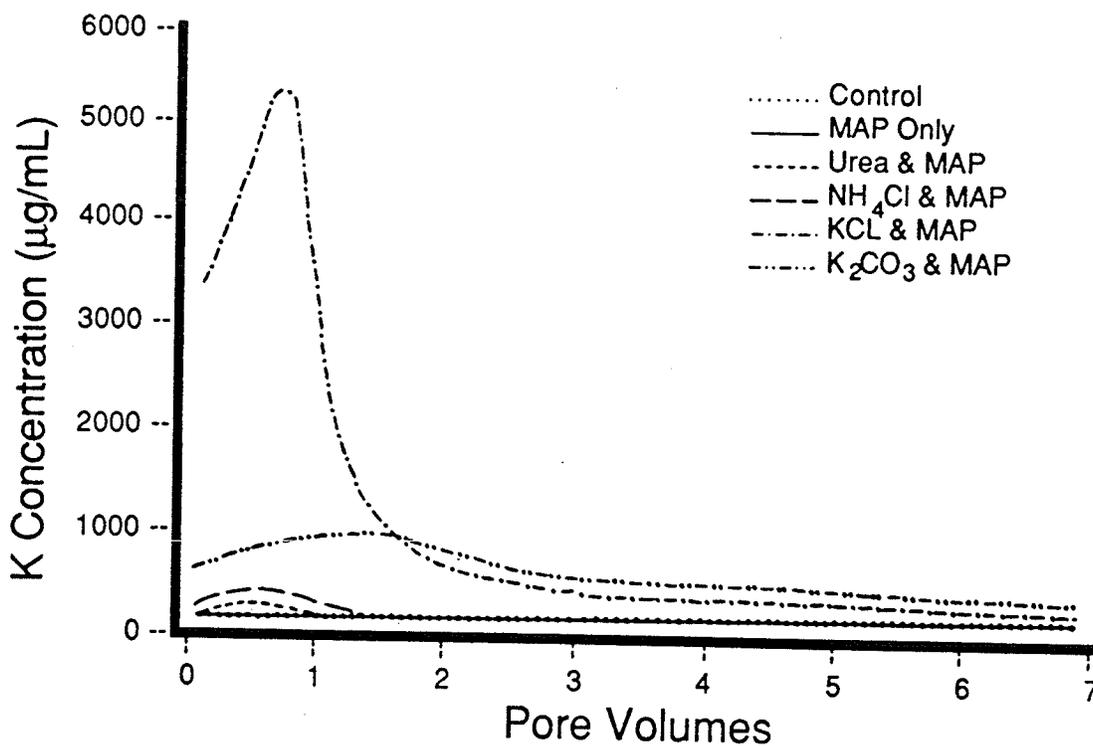


Figure 24. Elution of K from soil columns incubated for 5 wk.

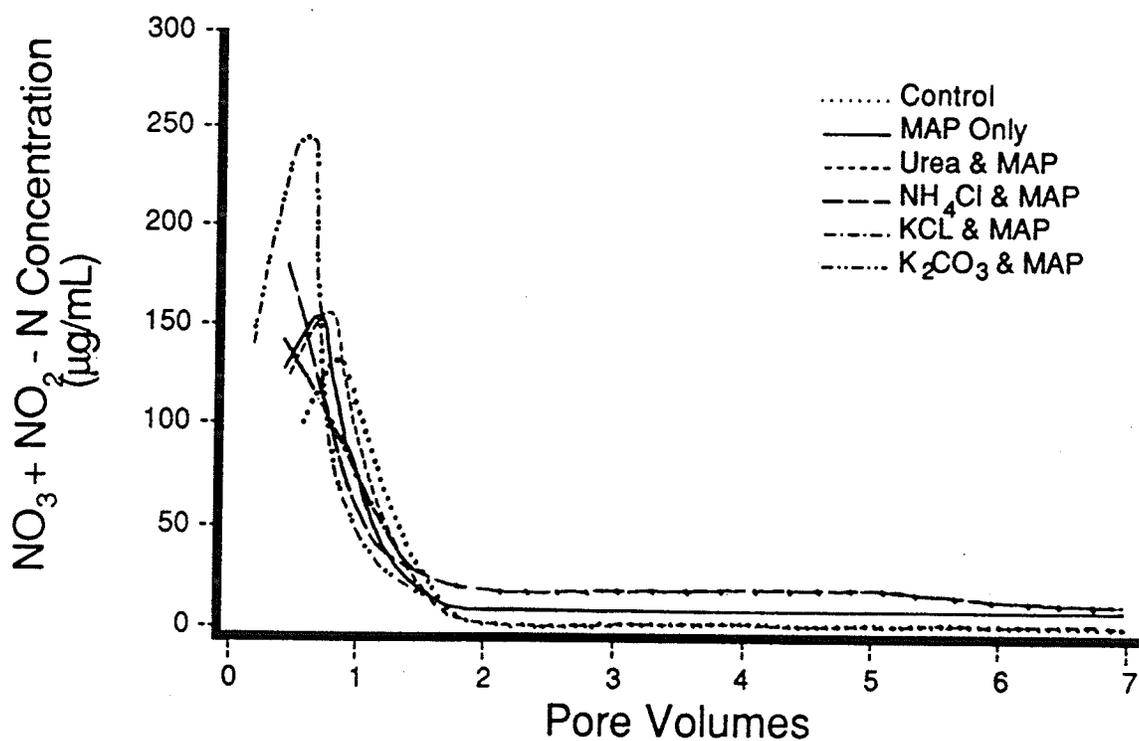


Figure 25. Elution of $(\text{NO}_3 + \text{NO}_2)$ from soil columns incubated for 1 wk.

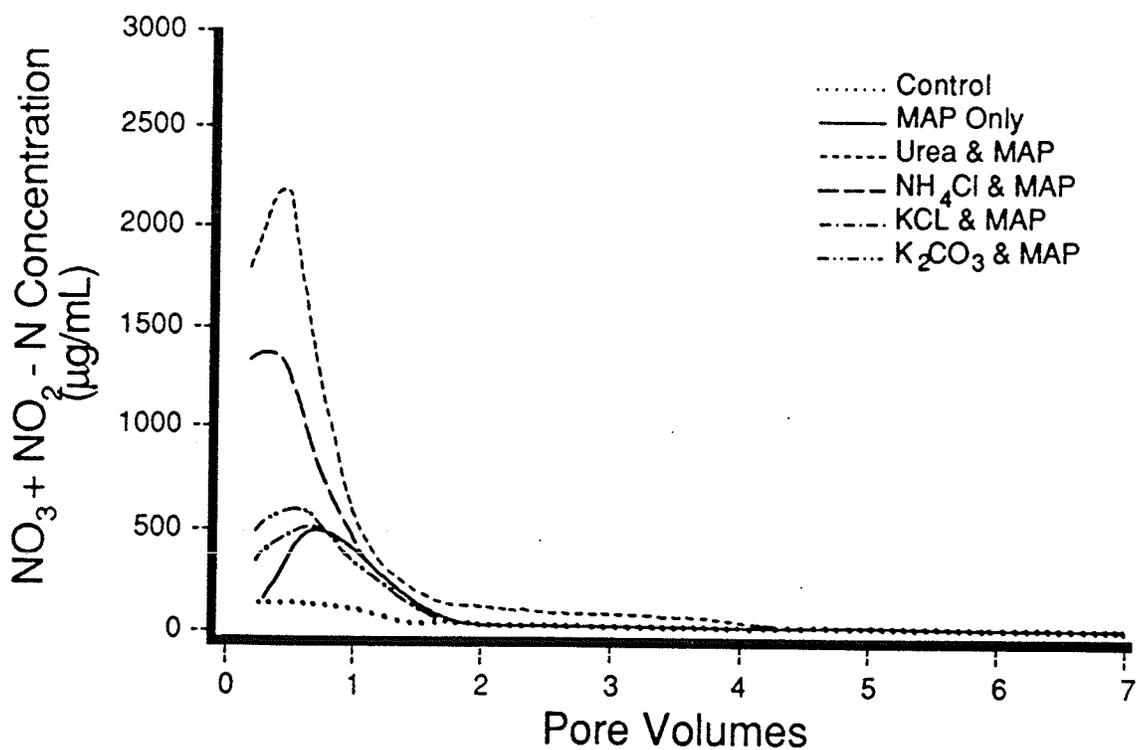


Figure 26. Elution of $(\text{NO}_3 + \text{NO}_2)$ from soil columns incubated for 5 wk.

was similar to that observed in the diffusion experiment. Very little nitrification of fertilizer N occurred during the first wk of incubation. After 5 wk of incubation, the greatest amount of ($\text{NO}_3 + \text{NO}_2$) was eluted from soil columns treated with urea + MAP, followed by those treated with NH_4Cl + MAP. Soil columns treated with MAP (only), KCl + MAP and K_2CO_3 + MAP contained similar quantities of ($\text{NO}_3 + \text{NO}_2$).

Differences in pH among treatments followed a pattern similar to that observed in the diffusion study (Figures 27 and 28). After 1 wk of incubation, the eluate from soil columns treated with MAP plus K_2CO_3 or urea was considerably more alkaline than that from the control, whereas eluate from columns treated with KCl + MAP, NH_4Cl + MAP or MAP (only) was more acidic. After 5 wk of incubation, the only eluate more alkaline than that for the control was that for K_2CO_3 + MAP. All other fertilized soil columns including those treated with urea + MAP were more acidic than the control. Presumably, nitrification resulted in the eluate from soil columns treated with MAP plus urea or NH_4Cl being considerably more acidic than those with MAP (only) or KCl + MAP.

Batch Extraction of Column Sections After Elution

The residual P extracted by water and NaHCO_3 from eluted soil columns was generally greatest for treatments that had resulted in the least P extracted during elution (Table 7). As a result, the total amount of P extracted by water during the elution plus batch extractions was relatively similar for all treatments.

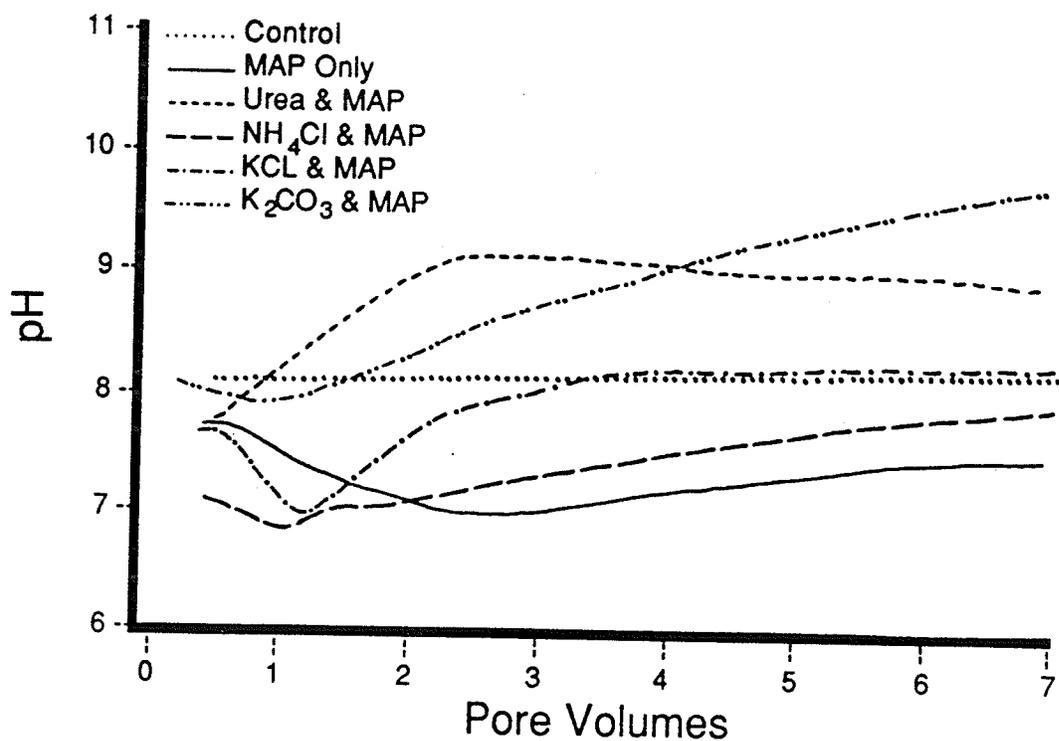


Figure 27. pH of eluate from soil columns incubated for 1 wk.

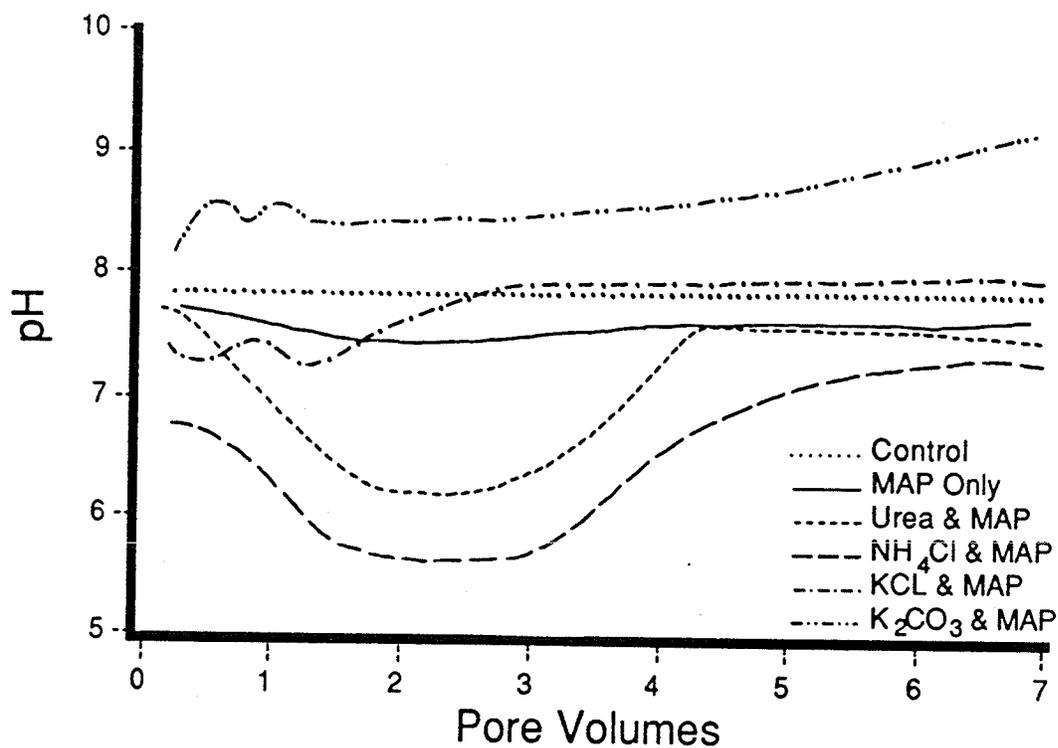


Figure 28. pH of eluate from soil columns incubated for 5 wk.

The concentration profiles of residual P extracted with water from individual soil column sections were generally parallel to those for the NaHCO_3 extraction. Thus the totals of the two extractions are plotted (Figures 29 and 30). The highest concentration of residual P was extracted near the surface of soil columns treated with MAP (only). The distribution profile of residual P in soil columns treated with NH_4Cl + MAP or KCl + MAP was similar in overall shape to those with MAP (only), except the concentrations were lower. The distribution profile with K_2CO_3 + MAP was much different than for other treatments. The concentration of extractable

Table 7. Residual P Extracted with Water then NaHCO_3 from Eluted Soil Columns.

Treatment	Water- Extractable P	NaHCO_3 - Extractable P	Total P Extracted ¹
	mg/column	mg/column	mg/column
<u>1 Wk Incubation</u>			
Control	0.16 ± 0.01^2	0.32 ± 0.10	0.05 ± 0.1
MAP (only)	3.01 ± 0.10	2.75 ± 0.29	11.9 ± 0.7
Urea + MAP	3.86 ± 0.77	2.11 ± 0.23	12.7 ± 0.7
NH_4Cl + MAP	1.98 ± 0.01	1.45 ± 0.03	13.2 ± 0.1
KCl + MAP	1.96 ± 0.13	1.35 ± 0.02	11.8 ± 0.4
K_2CO_3 + MAP	2.30 ± 0.16	1.45 ± 0.02	14.5 ± 0.1
<u>5 Wk Incubation</u>			
Control	0.17 ± 0.0	0.47 ± 0.07	0.6 ± 0.1
MAP (only)	2.74 ± 0.17	3.30 ± 0.31	11.0 ± 0.5
Urea + MAP	2.95 ± 0.17	1.76 ± 0.01	11.4 ± 0.2
NH_4Cl + MAP	2.11 ± 0.01	1.91 ± 0.03	11.9 ± 0.7
KCl + MAP	2.44 ± 0.02	2.31 ± 0.15	12.3 ± 0.1
K_2CO_3 + MAP	3.59 ± 0.17	2.40 ± 0.05	13.1 ± 0.2

¹ Includes water-extractable P eluted over entire 45 h elution period plus P extracted with water and NaHCO_3 from soil columns during batch extractions of sections of eluted columns.

² Plus or minus figures indicate the range between the mean and the two replicates.

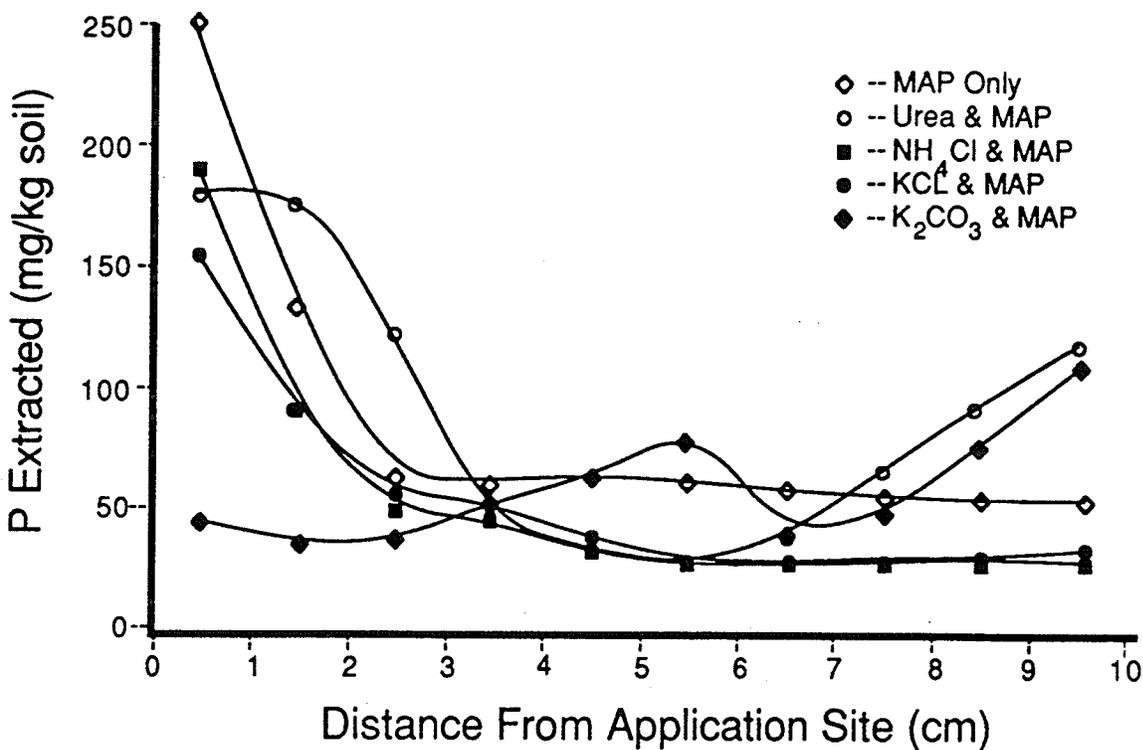


Figure 29. Residual P extracted with water then NaHCO₃ from sections of eluted soil columns which had been incubated for 1 wk prior to elution.

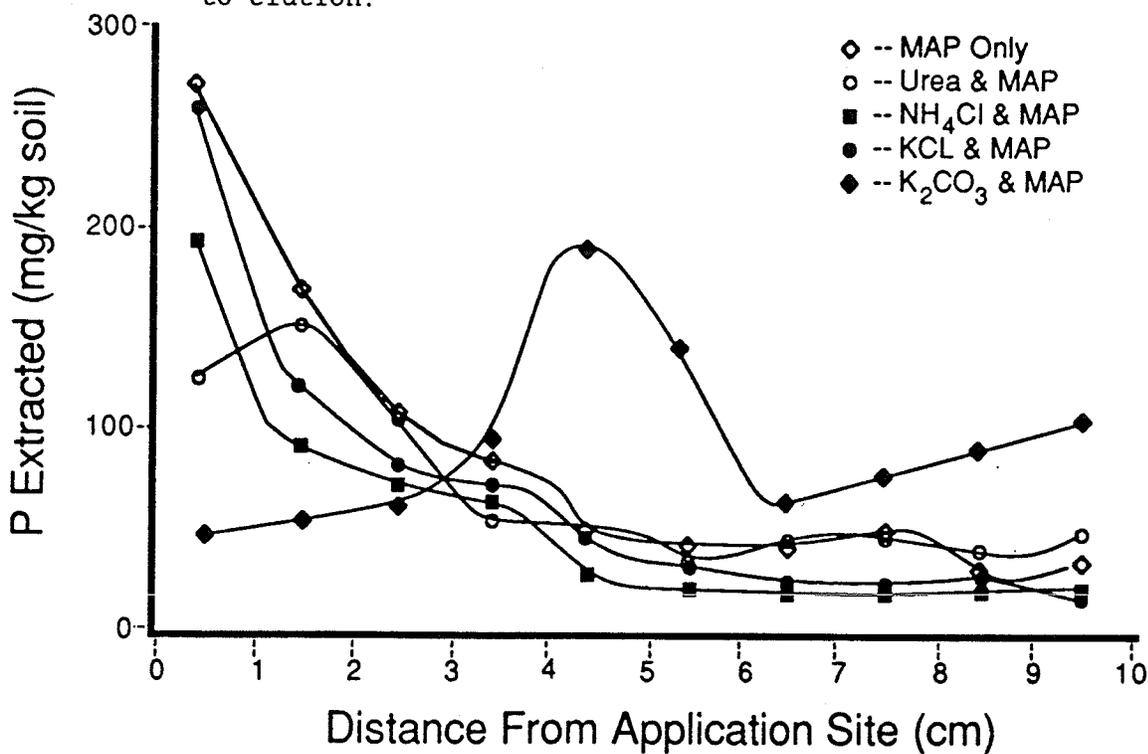


Figure 30. Residual P extracted with water then NaHCO₃ from sections of eluted soil columns which had been incubated for 5 wk prior to elution.

P was very low near the application site in soil columns treated with K_2CO_3 + MAP with maximum concentrations near the middle and towards the distal end of the soil columns. Reasons for this distinctive behaviour are not clear. The P concentration profiles observed in the diffusion experiment (Sec. 3.1, Figures 1-6) reveal that the low concentration of residual P near the application site was likely due to increased mobility of fertilizer P. However, there is little information from the diffusion studies that would explain the increased concentrations of residual P at the middle or end of the soil columns. A similar increase in the concentration of P at the distal end of soil columns was observed for urea + MAP (another alkaline treatment) when incubated for 1 wk. No such increase was observed after 5 wk of incubation in soil columns treated with urea + MAP, perhaps due to nitrification having acidified the columns. One possible explanation for this profile of residual P is that Ca may have been excluded from the application site because of the diffusion of other cations. The excluded Ca may then have precipitated as $CaCO_3$ in the middle of the column. During elution this region may then have retained P in a moderately soluble form which was solubilized during the subsequent batch extractions with water and $NaHCO_3$.

For both incubation periods there was a broad peak in the concentration profile of residual P near the application site for soil columns treated with urea + MAP. There was no indication of the reason for the unique concentration profile of residual P for this treatment.

Discussion and Conclusions

Results of the elution experiment were often quite different from those of the diffusion experiment. Although there had been an inverse relationship between water-extractable Ca and water-extractable P in the diffusion studies, no such relationship occurred in the elution studies. Adding KCl or NH_4Cl with MAP increased water-extractable Ca in both experiments and increased water-extractable P in the elution columns, but did not increase water-extractable P in the diffusion columns. In the elution study, the Ca displaced by the KCl or NH_4Cl was quickly forced out of the soil columns, lessening P retention during elution. In the diffusion study the displacement of Ca by KCl or NH_4Cl offered no such advantage in terms of enhancing P solubility because the Ca had no means of leaving the soil column. Without elution, much of the Ca displaced by the chloride salts likely diffused back to its original position (Cho 1985). Under the conditions for the diffusion study alkaline cosolutes added with MAP resulted in the most water-extractable P, likely due to their low pH reducing the activity of Ca within the confined system.

The conditions selected for the elution experiment were not very representative of soil in the field where a fertilizer band is unlikely to encounter a continuous leaching event. The diffusion studies are likely somewhat more useful for estimating the chemical availability of a dual band of urea + MAP under field conditions.

However, it is important to remember that chemical availability, alone, is not the sole factor influencing the plant uptake of P from localized placements of P with other fertilizers (Blanchar and Caldwell 1966b).

3.3 Initial N and P Placement Study

The distance between plants and P fertilizer in preplant dual NP bands is variable. In instances where the distance between the seed row and fertilizer band is great, young seedlings are less likely to initiate utilization of fertilizer P as soon as where the P is applied in or near the seed row. Also, the utilization of fertilizer P applied far from the seed row may be reduced because the root density away from the crown is not as great as that near the crown. The distance factor is especially great when there is a wide spacing between preplant bands (Alston 1980; Maxwell et al. 1984).

The addition of ammonium-N to P fertilizer bands often increases fertilizer P uptake (Miller 1974). This "ammonium-ion effect" may counteract the negative influence of the distance factor. Monoammonium phosphate (MAP), the most common P fertilizer in Western Canada, has an ammonium-N:P₂O₅ ratio of 1:5. This ratio is near the optimum 1:4 suggested by Miller and Ohlrogge (1977) but much less than the 1.5:1 ratio at which Rennie and Soper (1958) found urea stimulated MAP uptake early in the growing season.

A growth chamber study was conducted in 1981 to examine the influence of urea and distance between the P band and the seed row on the uptake of MAP by spring wheat. ¹⁵N was used to label the urea and ³²P was used to label the MAP. Large soil containers were used to allow bands to be placed far from the seed row and to more nearly represent field conditions, such as minimized root confinement and increased time intervals between waterings which reduced leaching of fertilizer bands. A soil with a typical, but moderately low concentration of available P was selected for

the experiment. Although soils extremely low in P provide a greater yield response to added P, unusually low P soils also provide an atypical advantage for near-row P placement (Peterson et al. 1981).

Experimental Procedures

The soil used in this experiment was obtained from the Ap horizon of a Gleyed Rego Black Chernozemic loamy fine sand, Willowcrest series, collected near Carman, Manitoba, NW 25-5-5 W1 (Table 8). Prior to use the soil was air dried, mixed and passed through a 10 mm sieve.

Large wooden boxes (45x25x28cm deep) lined with polyethylene bags were used as soil containers (Figure 31). Each box contained 36 kg soil, 25 cm deep. The soil was placed in the boxes in layers according to the depth at which the N and P bands were to be applied. The appropriate depth of soil, either 17.5 or 20 cm, was added to the box and moistened prior to applying the fertilizer bands.

The fertilizer treatments consisted of a control with urea only and eight placements of urea and MAP applied in bands at rates of 0.92 g N/box (80 kg N/ha) and 0.23 g P/box (20 kg P/ha). The fertilizer bands were placed across the shorter dimension of the boxes. Therefore, the concentration of N and P fertilizer was equivalent to that of bands placed at 45 cm spacings. Nitrogen application was equalized in all treatments to account for the N added as MAP. MAP was placed in one of four positions relative to the seed row:

- (1) 2.5 cm below and 2.5 cm beside
- (2) 7.5 cm below and 2.5 cm beside
- (3) 7.5 cm below and 7.5 cm beside
- (4) 7.5 cm below and 12.5 cm beside

Table 8. Some Properties of the Soil Used in the Initial N and P Placement Study

pH (1:1, soil:water)	6.4
NaHCO ₃ -extractable P	12.2 mg/kg
NO ₃ -N	10.6 mg/kg
NH ₄ Ac-extractable K	34.5 mg/kg
SO ₄ -S	2 mg/kg
Carbonates	none detected
Texture	loamy fine sand
% water, field capacity	25 %

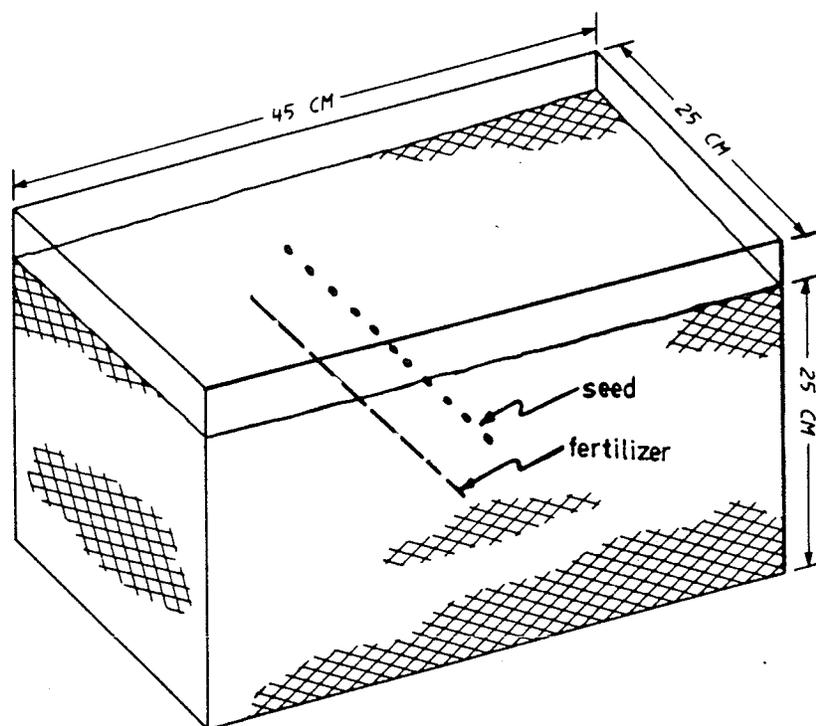


Figure 31. Orientation of fertilizer band and seed row for initial N and P study.

Urea was placed either with MAP in the same band (dual band) or separate from the MAP on the opposite side of the seed row (separate band). Where urea and MAP were placed separately, the bands were an equal distance from the seed row. There were three replicates of each treatment. Urea and MAP were each applied in 10 mL of solution pipetted onto the soil. Where dual bands were placed, the urea solution was applied first, followed by MAP. The MAP solution consisted of reagent grade MAP dissolved in distilled water and was labelled with 74 kBq $\text{H}_3^{32}\text{PO}_4/\text{mL}$. The urea solution contained 2.061 atom percent excess ^{15}N , prepared from reagent grade urea, distilled water and 50 atom percent excess ^{15}N -urea. After the bands were placed, the top layer of soil was added and moistened to field capacity. Sulphur was applied to all treatments at a rate of 30 kg $\text{SO}_4\text{-S}/\text{ha}$ in the form of K_2SO_4 broadcast onto the soil surface prior to watering.

One d after banding the fertilizer, 20 seeds of spring wheat (Triticum aestivum cv. Neepawa) were planted in a row 2.5 cm below the soil surface perpendicular to the midpoint of the length of the box (Figure 31). The boxes were arranged in randomized complete blocks on growth benches and rotated weekly. Lighting was from a mixture of fluorescent and incandescent lamps giving an average intensity of $350 \mu\text{Em}^{-2}\text{s}^{-1}$ at the top of the canopy (measured with a Licor LI-185B Quantum meter and Q4027 Quantum sensor). Daylength was 16 h. Day and night air temperatures averaged 25°C and 18°C , respectively. The plant stand was thinned to 12 plants per box 4 d after emergence. The soil was watered to field capacity once per wk in the initial stages of growth and twice per wk near the end of the experiment.

Radioactive phosphorus intensity in the plants was monitored during the first 6 wk of plant growth using a handheld Nuclear Chicago 2652 survey meter with an end-window Geiger-Mueller probe. The probe was moved steadily back and forth along the row of plants, taking care to survey the boxes consistently and to estimate the average intensity from the analog meter. In vivo readings were corrected for radioactive decay. Quantitative estimates of fertilizer phosphorus uptake were not obtained using this method due to such problems as variable geometry and biological dilution. However, especially for measuring differences between treatments in the juvenile plant stages, this simple, non-destructive technique provided a useful, semi-quantitative estimate of ^{32}P uptake.

The shoot portion of plants was harvested 58 d after emergence when the wheat was fully headed. Samples were dried at 70°C , weighed and ground. Subsamples to be analysed for total and fertilizer phosphorus were wet-ashed using a nitric-perchloric acid mixture, (Appendix D). Total P concentrations in the digests were determined using the ascorbic acid-molybdate blue method (Appendix E, Murphy and Riley (1962)). Fertilizer P contents of digests were determined directly using the Cerenkov counting method and a Beckman 7500 liquid scintillation counter. Correction for differences in counting efficiency between samples was made using a modification of the sample channels ratio procedure provided in the data reduction accessory of the scintillation counter (Appendix F). Subsamples were also analysed for total and fertilizer N content using a modified Kjeldahl procedure (Appendix G) and a VG-Micromass 602C mass spectrometer (Cho and Sakdinan 1978).

Statistical analyses were performed using the ANOVA procedures of the Statistical Analysis System (SAS 1982).

Results and Discussion

MAP Uptake During Growth

In vivo monitoring of the ^{32}P intensities revealed that plants contained fertilizer P on the day of emergence where urea and MAP were placed separately and near the seed row (Figure 32). The uptake of fertilizer P was delayed for at least 1 wk in all other treatments. The delay in P uptake was slightly greater for dual NP bands than for separate NP bands when the P bands were placed away from the seed row. Distance between the plants and fertilizer band was the likely cause of delayed MAP uptake from the urea and MAP bands placed separately. However, for dual bands placed near the seed row the delay in uptake of MAP was most likely due to ammonia from the urea preventing root penetration into the dual bands (Figure 33). Delayed P uptake from dual bands placed far from the seed row was likely due to a combination of ammonia toxicity in the bands and the distance between the fertilizer band and the seed row.

Although the shoots showed no visible signs of ammonia toxicity, the roots were likely impaired by an incipient ammonia toxicity (Bennett 1974). Bennett noted that the root tip is especially sensitive to fertilizer toxicities because it is the most physiologically active part of the plant. Urea bands contain not only high concentrations of ammoniacal nitrogen, they also contain a large proportion of N in the form of ammonia instead of ammonium because of the initially high pH of the band. The threshold concentration of aqueous ammonia that is toxic to root growth is only 0.15

mM and 6 mM has been found to be lethal (Bennett 1974). Concentrations within the bands almost certainly exceeded those levels. Laboratory studies using a soil type and fertilizer concentrations similar to those of this growth chamber study indicated that ammonia plus $\text{NH}_4\text{-N}$ concentrations in the band were in excess of 2000 mg/kg of soil and the pH of the water extract was approximately 9 (section 3.1). At a pH of 9, approximately 40 percent of this nitrogen would be in the form of ammonia (Court et al. 1964). Thus, the concentration of ammonia in the band could have been approximately 250 mM, assuming a moisture content of 25% in the soil. Although roots may not have penetrated the interior of the urea band, roots may have grown normally in the bulk soil and, in fact, may have proliferated around the periphery of the band (Passioura and Wetselaar 1972). Hence, the toxicity of ammonia which may have prevented root growth into the fertilizer band need not have resulted in any obvious symptoms on the shoot portion of the plants.

Ammonia toxicity is most likely to occur when ammoniacal fertilizers such as urea are confined to a small volume, such as in widely spaced bands (Wetselaar et al. 1972) and when it is applied immediately prior to planting (Colliver and Welch 1970) such as in this experiment. Ammonia toxicity is also most likely to occur on soils with low clay and organic matter content (Nyborg 1961; Allred and Ohlrogge 1964; Toews and Soper 1978), characteristics that also describe the soil used in this experiment. The release of free ammonia is also more likely when the soil contains free lime and/or the pH is alkaline (Allred and Ohlrogge 1964; Fenn and Kissell 1973). Although the latter characteristics do not pertain to the soil used in this experiment, the low buffering capacity of this soil would likely

allow the fertilizer reaction zone to be very alkaline.

The adverse effect of urea on early uptake of fertilizer P was also observed by Liegel and Walsh (1975), using banded urea ammonium polyphosphate. Urea toxicity was also likely responsible for the poor performance of superphosphate placed with 264 kg of urea/ha in experiments conducted by Starostka and Hill (1955). Salt toxicity to root growth has also been observed in very highly concentrated bands of ammonium chloride plus monocalcium phosphate (Blanchar and Caldwell 1966b).

Rapid uptake of ^{32}P from dual bands followed the initial delay period (Figure 32). After 30 to 40 d of growth, fertilizer P uptake from the all dual bands equalled or exceeded fertilizer P uptake from the separately banded MAP nearest the seed and was much superior to that from separately banded MAP further from the seed row. Placing urea with MAP did not increase MAP uptake substantially when the MAP was banded near the seed row. Minor delays in phenological development were noted for treatments in which fertilizer P uptake was delayed.

The lag in fertilizer P uptake followed by the very rapid uptake of fertilizer P from dual bands has been observed previously. Duncan and Ohlrogge (1957) noted that urea did not enhance fertilizer P uptake in the first 10 d after emergence but enhanced fertilizer P uptake greatly thereafter. The interaction between band position and the uptake of P from dual bands compared to separate bands has also been observed previously. Werkhoven and Miller (1960) observed that placing phosphate fertilizer bands further from the seed row decreased fertilizer P uptake by sugarbeets, except when ammonium nitrate was banded with the phosphate. Maxwell et al. (1984) observed uptake of P from ammonium polyphosphate

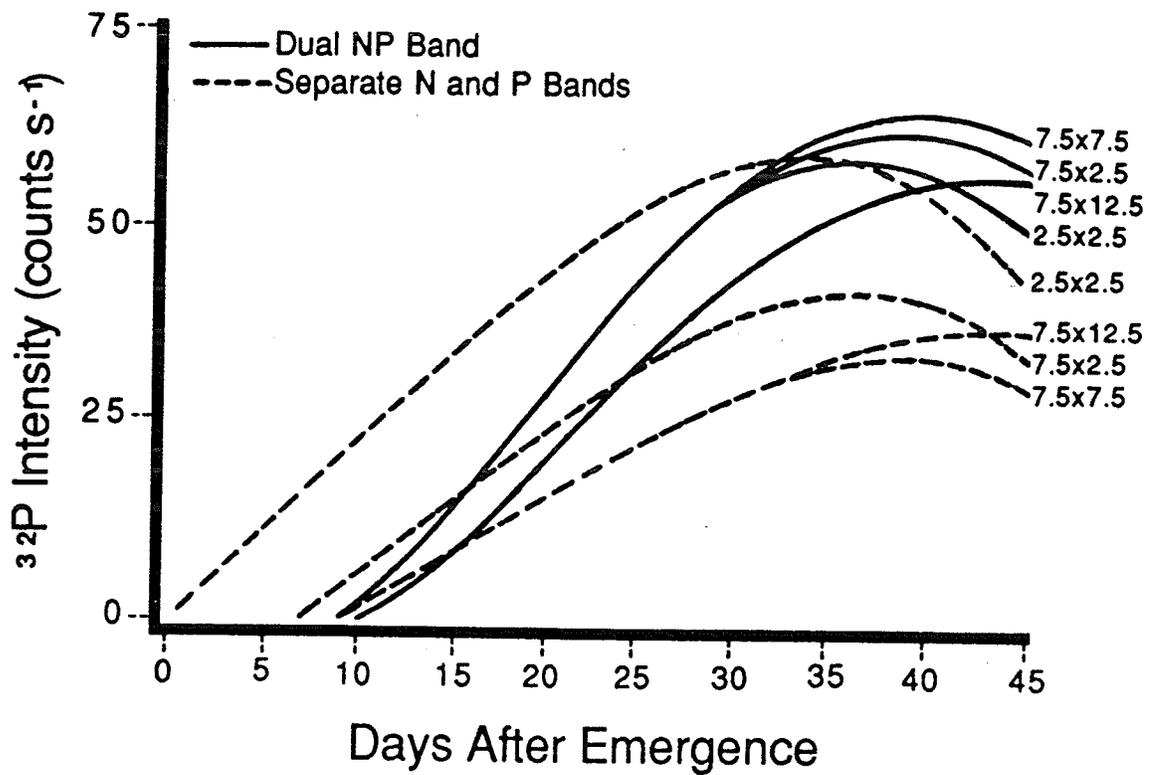


Figure 32. Effect of urea and MAP placement on ^{32}P intensity of wheat. Numbers indicate the position of the MAP band, measured in cm below and beside the seed row.

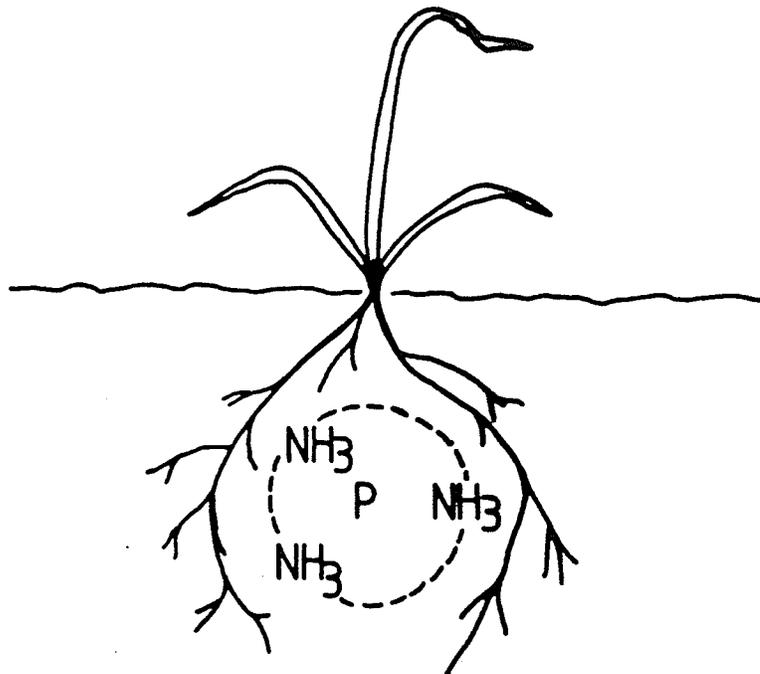


Figure 33. Proposed mechanism by which urea delays root penetration into dual MAP-urea bands.

plus ammonia bands was equal at lateral distances of 0, 10 and 20 cm from the seed row in winter wheat grown for 44 d.

Final harvest.

Dry matter yield, at final harvest, was not increased significantly by P fertilization, despite a visible response to P fertilization at the tillering stage of growth (Table 9). Yield responses to P have been observed using this soil in other field and growth chamber experiments. However, in this study the soil temperatures were considerably higher than those typical for the field and the soil to plant ratio was much higher than those typically used in other growth chamber experiments.

Significant differences in fertilizer P uptake were observed among MAP placement methods. Scintillation counting of digested samples indicated trends similar to those observed by surveying for ^{32}P intensity with the hand held GM meter. This shows that the in vivo monitoring was a reasonably accurate method of assessing fertilizer P uptake at the seedling stage. Uptake of fertilizer P was significantly less when the distance between the seed row and the separate MAP band was increased from 2.5 cm below and beside the seed to 7.5 cm below and 12.5 cm beside the seed. In contrast, the uptake of MAP from the dual bands was relatively similar regardless of distance from the seed row and was not significantly different from the amount taken up from separate MAP bands 2.5 cm below and beside the seed row. It is not known why the presence of urea in MAP bands enhanced the uptake of fertilizer P from dual bands placed further from the seed row. The availability of MAP may have been improved chemically by the urea in a manner similar to that observed in the diffusion studies (section 3.1). The availability of the MAP may also have been improved by

Table 9. Effects of Urea and MAP Placement on Growth and Fertilizer Uptake by Spring Wheat Grown in a Growth Chamber.

Placement of P, Below and Beside Seed	Dry Matter Yield	Fertilizer P Uptake	Total P Uptake	Fertilizer N Uptake	Total N Uptake
cm x cm	g/box	mg/box	mg/box	mg/box	mg/box
<u>Control (N only)</u>					
---	44.8	---	120B ¹	166C	1220
<u>Urea and MAP Banded Separately (Separate Bands)</u>					
2.5 x 2.5	48.4	51.5A	158A	227A	1310
7.5 x 2.5	45.8	40.5B	156A	188AB	1250
7.5 x 7.5	45.0	33.5C	150A	185BC	1230
7.5 x 12.5	49.5	36.7BC	162A	181BC	1330
<u>Urea and MAP Banded Together (Dual Bands)</u>					
2.5 x 2.5	46.5	54.0A	160A	199ABC	1270
7.5 x 2.5	46.0	53.1A	165A	205AB	1250
7.5 x 7.5	46.0	55.8A	154A	205AB	1230
7.5 x 12.5	46.5	52.1A	152A	206AB	1240
Pr>F	0.51	0.0001	0.0007	0.04	0.52

¹ Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test, alpha = .05.

physiological acidification of the rhizosphere during ammonium uptake (Miller et al. 1970) or by increased root proliferation in a zone enriched with both N and P (Duncan and Ohlrogge 1958a; Drew 1975).

Total P uptake was increased as a result of applying fertilizer P, but no significant differences in total P uptake among MAP placements were observed. The substantial differences in fertilizer P uptake among P treatments were counterbalanced by differences in soil P uptake. This observation is similar to that observed in N-P interaction experiments with

corn grown on high P soils (Miller and Ohlrogge 1958). It is likely that the plants, with access to moderate supplies of soil P, were able to regulate their intake of P in accordance with their internal P status (Lefebvre and Glass 1982). It is doubtful, though, whether this sort of compensation would have occurred if the plants had been grown in soils more deficient in available P.

No significant differences in total N uptake were observed. The small differences in fertilizer N uptake that were observed followed a pattern similar to differences in fertilizer P uptake. However, the differences in fertilizer N uptake among treatments were relatively small compared to those for fertilizer P.

Conclusions

Uptake of fertilizer P from separate MAP bands and dual MAP-urea bands was delayed by approximately 7 d when MAP was placed at a distance greater than 2.5 cm below and beside the seed. However, the presence of urea in dual bands also delayed uptake of fertilizer P, probably as a result of ammonia toxicity. Although the evidence of ammonia toxicity is indirect, the literature surveyed indicated ammonia toxicity problems in fertilizer bands is likely to be most pronounced when the fertilizers are banded immediately before seeding and where wide spacings between bands increase the fertilizer concentration in each band. There was no effect of delayed uptake of fertilizer P on dry matter yield in this study. However, no significant yield increase was obtained due to any method of applying P fertilizer. It is not known whether or not delays in P uptake during the seedling stage would significantly reduce yields on soils responsive to P application.

The rate of uptake of fertilizer P and total amount of fertilizer P utilized decreased with increases in distance between the seed row and MAP band when the MAP and urea were banded separately. In contrast, uptake of fertilizer P from dual bands was relatively similar regardless of distance from the seed row and was equivalent to the highest for the separate MAP placements. The reasons for this large enhancement of fertilizer P uptake from dual bands were unclear.

In summary, the ratio of $N:P_2O_5$ for optimum uptake of fertilizer P appears to vary with band placement relative to the seed row. Ratios greater than 1:4 suggested by Miller and Ohlrogge (1977) may offer advantages when MAP is banded at considerable distances from the seed row prior to planting.

3.4 Optimum Urea Concentration Study

In the initial N and P placement study the ratio of N:P₂O₅ for optimum uptake of fertilizer P appeared to vary with the position of the band relative to the seed row. Adding urea to the MAP band greatly enhanced fertilizer P uptake when MAP was banded far from the seed row. However, uptake of fertilizer P was also delayed by the presence of urea in the band, probably as a result of incipient ammonia toxicity delaying penetration of the root into the dual band.

The purpose of the second growth chamber experiment was to examine the influence of different concentrations of urea in the MAP band on uptake of fertilizer P, attempting to achieve the greatest urea-induced enhancement of P uptake with the least amount of urea-induced delay of P uptake.

Similar to the first experiment, large soil containers and a soil moderately low in available P were used in an attempt to represent typical field conditions.

Experimental Procedures

The soil used for this experiment was obtained from the Ap horizon of a Gleyed Rego Black Chernozemic loamy fine sand, Willowcrest series, collected near Graysville, Manitoba, SE 24-7-6 W1 (Table 10). Prior to use, the soil was air-dried, mixed and passed through a 10 mm sieve. A basal application of 200 mg K, 90 mg S, 10 mg Cu and 10 mg Zn/kg soil was applied to the soil. These nutrients were applied as an aerosol of dissolved sulfate salts and thoroughly mixed into the soil.

Large wooden boxes (45x25x28 cm deep) lined with polyethylene bags were used as soil containers. Each box contained 36 kg soil, 23 cm deep.

Table 10. Some Properties of the Soil Used in the Optimum Urea Concentration Growth Chamber Experiment

pH (1:1, soil:water)	7.8
NaHCO ₃ -extractable P	10 mg/kg
NO ₃ -N	5 mg/kg
NH ₄ Ac-extractable K	90 mg/kg
SO ₄ -S	1 mg/kg
Carbonates	none detected
Texture	loamy fine sand
% water, field capacity	23 %

The soil and fertilizer bands were added to the soil in a procedure similar to that in the initial N and P placement study.

Treatments included a control with urea only and eight placements of urea and MAP applied in bands at rates of 0.92 g N/box (80 kg N/ha) and 0.23 g P/box (20kg P/ha). N application was equalized in all treatments to account for N added as MAP. MAP was placed either 2.5 cm below and 2.5 cm beside or 7.5 cm below and 7.5 cm beside the seed row. The proportion of urea applied in the MAP band was either 0, 33, 66 or 100% of the total applied. The remainder of the urea was applied in a band on the opposite side of the seed row at an equal distance. The fertilizer bands were placed across the narrower (25 cm) dimension of the boxes, resulting in a concentration of fertilizer in the bands equivalent to that of bands applied at 45 cm spacings. There were three replicates of each treatment. The MAP and the total complement of urea were each applied in 10 mL of

solution pipetted onto the soil. Where urea and MAP were applied in the same band, the urea solution was applied first, followed by MAP. The urea solution consisted of reagent grade urea dissolved in distilled water. The MAP solution consisted of reagent grade MAP dissolved in distilled water and was labelled with 148 kBq $\text{H}_3^{32}\text{PO}_4/\text{mL}$. The band zone was then covered with the top layer of soil, which was then watered to field capacity.

One d after banding the fertilizer, 15 seeds of spring wheat (Triticum aestivum cv. Neepawa) were planted in a row 2.5 cm below the soil surface, perpendicular to the midpoint of the length of the box. The boxes were arranged in randomized complete blocks on growth benches and rotated weekly. Lighting was from a mixture of incandescent and fluorescent lamps giving an average intensity of $350 \mu\text{Em}^{-2}\text{s}^{-1}$ at the top of the canopy (measured with a Licor LI-185 B Quantum meter and Q4027 Quantum sensor). Daylength was 16 h. Day and night temperatures averaged 25°C and 18°C , respectively.

The plant stand was thinned to 10 plants per box 6 d after emergence. The soil was watered to field capacity once per wk in the initial stages of growth and twice per wk thereafter.

Radioactive P intensity in the plants was monitored in the plants during the first 6 wk of growth using a method similar to that in the initial N and P placement study.

The shoot portion of the plants was harvested 61 d after emergence when the wheat was fully headed. Harvest procedures, sample handling, tissue analyses for total and fertilizer P and statistical analyses were similar to those outlined for the initial N and P placement experiment.

Results and Discussion

MAP Uptake During Growth

In vivo monitoring of ^{32}P intensities revealed trends that were similar to those observed in the initial N and P placement experiment. The enhancement of fertilizer P uptake by adding urea to MAP bands was relatively large when bands were placed far from the seed row, but not when placed close to the seed row. Uptake of fertilizer P commenced at time of emergence where MAP was banded without urea 2.5 cm below and beside the seed row (Figure 34). Urea in the MAP band delayed the uptake of fertilizer P banded near the seed row by 3 or 4 d, considerably less than in the initial experiment. After the initial delay in fertilizer P uptake, rate of uptake of fertilizer P from dual bands was rapid and accumulations became similar to that from separate bands applied near the seed row.

Placing the MAP bands 7.5 cm below and beside the seed row delayed uptake of fertilizer P until approximately 6 to 9 d after emergence. The delay in P uptake increased with amounts of urea placed in the dual band (Figure 35). After 17 d of plant growth, urea in the MAP band enhanced uptake of fertilizer P from the bands placed 7.5 cm below and beside the seed. Placing 47 kg/ha of urea-N in the MAP band 7.5 cm below and beside the seed row appeared to allow optimum uptake of fertilizer P; the delay in fertilizer P uptake was brief and ^{32}P intensities were high. Adding 23 kg/ha of urea-N did not enhance fertilizer P uptake as much as higher rates. After 4 wk of growth the uptake from all dual band placements in which 47 or 70 kg/ha of urea-N was added was at least as great as that from MAP bands placed 2.5 cm below and beside the seed row.

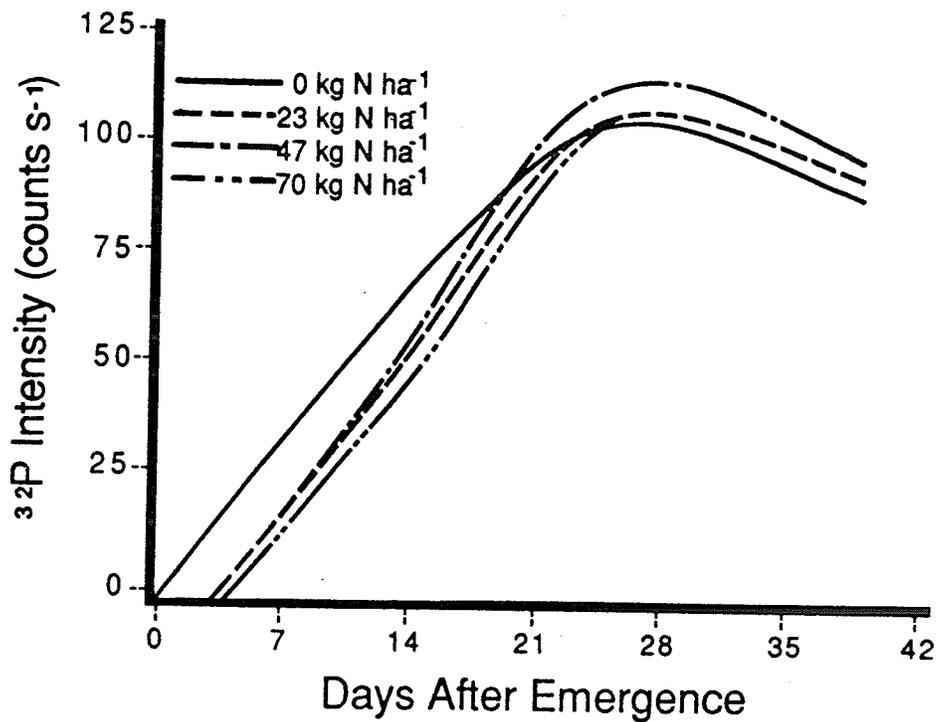


Figure 34. Effect of concentration of urea-N in MAP band on ^{32}P intensity of wheat--P banded 2.5 cm below and beside the seed.

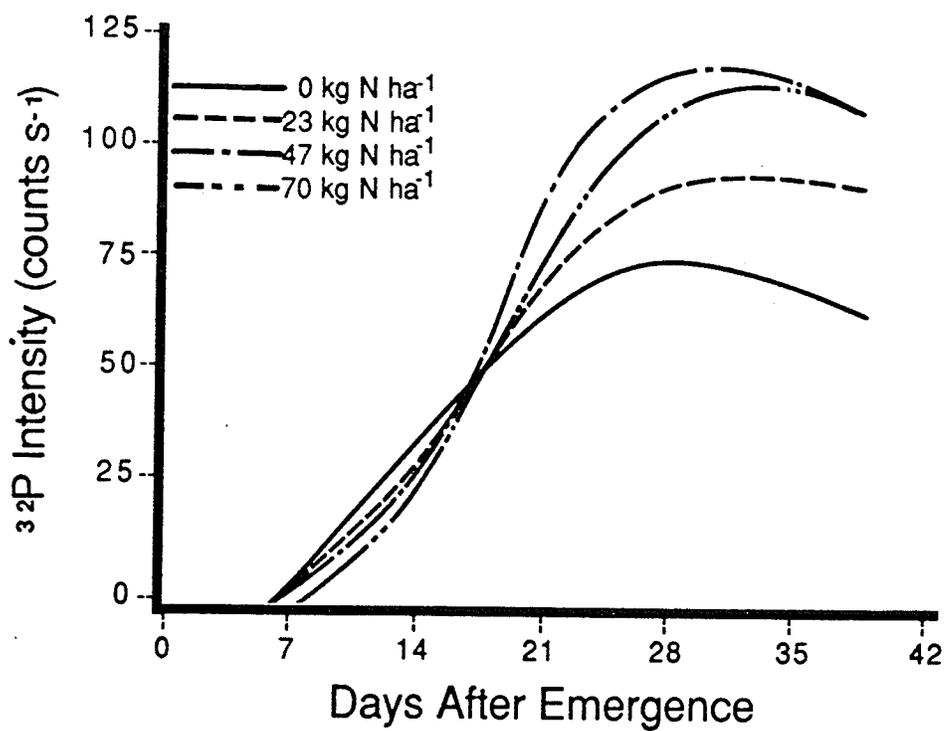


Figure 35. Effect of concentration of urea-N in MAP band on ^{32}P intensity of wheat--P banded 7.5 cm below and beside the seed.

Final Harvest

Dry matter yield, at the fully headed stage, was not increased significantly by adding P fertilizer, despite a visible response to P at the tillering stage (Table 11). Although the soil used in this experiment was different from that used in the initial N and P placement experiment, similar problems were encountered. Crops responded to P fertilization of this soil in the field, but there was a P response only in early stages of growth in the growth chamber using the large soil containers.

Total P uptake was also not increased significantly by adding P fertilizer.

The average efficiency of fertilizer P uptake was 21% of that applied. Fertilizer P uptake was influenced significantly by the concentration of urea in the MAP band and distance of the MAP band from the seed row. Fertilizer P uptake from separate MAP and urea bands was greatest for MAP placed 2.5 cm below and beside the seed, which was significantly greater than that for MAP and urea banded separately, 7.5 cm below and beside the seed row. Urea in the dual bands enhanced uptake of fertilizer P from MAP bands placed 7.5 cm below and beside the seed row but the degree of enhancement varied according to the proportion of urea placed in the band. This interaction between band position and amount of urea in the fertilizer band was statistically significant (F-test value of 0.025 according to ANOVA). MAP uptake was highest from bands that contained 47 kg/ha of urea-N, whether those bands were near or far from the seed row. Although the increase in P uptake from dual bands was not statistically significant when bands were placed 2.5 cm below and beside the seed row,

Table 11. Effects of Urea Concentration in the MAP Band on Growth and P Uptake by Spring Wheat in a Growth Chamber.

Urea-N in the MAP Band	Dry Matter Yield	Fertilizer P Uptake	Total P Uptake
kg/ha	g/box	mg/box	mg/box
<u>Control (N only)</u>			
---	72	0	358
<u>MAP Banded 2.5 cm Below and 2.5 cm Beside the Seed</u>			
0	74	48.3B ¹	387
23	74	47.0B	363
47	77	51.9B	379
70	69	48.4B	344
<u>MAP Banded 7.5 cm Below and 7.5 cm Beside the Seed</u>			
0	76	40.4C	388
23	71	46.1BC	373
47	74	58.8A	373
70	71	50.3B	337
Pr>F	0.77	0.002	0.59

¹ Means followed by the same letter are not significantly different according to LSD comparison, alpha = .05.

the increase was significant when bands were placed 7.5 cm below and beside the seed row. This interaction between N:P ratios and placement may help explain why different optimum N:P ratios have been cited in the literature (Rennie and Soper 1958; Duncan and Ohlrogge 1958b; Miller and Ohlrogge 1977).

The uptake of soil P was sufficient to offset any differences in fertilizer P uptake, resulting in no significant differences in total P uptake among different MAP application methods.

Conclusions

The optimum urea concentration study confirmed several observations made during the initial N and P placement study. Less fertilizer P was taken up from MAP bands as distance between the seed row and fertilizer band increased except for treatments where a substantial amount of urea was placed in the MAP band. The effect of urea on fertilizer P uptake varied with distance between the dual band and the seed row. Although adding urea to the MAP band increased uptake of fertilizer P only slightly when the MAP was banded 2.5 cm below and beside the seed row, it increased fertilizer P uptake substantially when MAP was banded 7.5 cm below and beside the seed row. Urea in dual bands also delayed fertilizer P uptake, especially with 70 kg/ha of urea-N in the dual band. These observations reinforce the concept that the optimum concentration of ammonium-N in a dual band varies with the likelihood of urea toxicity and the position of the band relative to the seed row .

In this and the initial N and P placement experiment the fertilizer bands were applied to a coarse textured soil, immediately prior to planting and at concentrations equivalent to band spacings of 45 cm, conditions which are conducive to ammonia toxicity. Also, the plants were not harvested at maturity in either experiment. Thus, the observations from the first two growth chamber experiments do not have clear implications with respect to the effect of dual banding on yield of grain under typical field conditions.

3.5 Urea Detoxification Study

The previous growth chamber experiments showed that fertilizer P uptake was enhanced when urea was added to MAP bands placed far from the seed, but the quantity of urea required to achieve this enhancement also delayed fertilizer P uptake from MAP bands placed near the seed row. Although the optimum concentration of urea-N in the band in the second growth chamber experiment was 47 kg/ha, the optimum urea concentration under field conditions would vary with soil type, environmental conditions, band spacing and the time between fertilization and planting. These factors make it very difficult to predict the optimum urea concentration in dual bands. Therefore it may be better to reduce the toxicity of the dual band, allowing enhanced MAP uptake without the risk of delay.

Several techniques have been used to detoxify ammoniacal fertilizers. Delaying planting for several wk after applying ammoniacal fertilizer allows diffusion and nitrification to reduce the concentration of free ammonia (Stephen and Waid 1963; Colliver and Welch 1970). However, if nitrite accumulates in the band a second phase of ammoniacal N toxicity develops (Passioura and Wetselaar 1972). A long delay period may also be impractical where fertilizer is applied in the spring, before planting. However, where fertilizer is applied in the fall, the delay period presents few problems.

Coating urea granules with various compounds has been shown to reduce ammonia concentrations in the fertilizer reaction zone. Coating urea with sulfur slows the dissolution and hydrolysis of urea, reducing the release of free ammonia (Matocha 1976) and reducing the toxicity of urea applied at planting with spring wheat (Deibert et al. 1985). Urease inhibitors such

as phenylphosphorodiamidate (PPD) may also reduce urea toxicity by decreasing the rate of ammonia release (Byrnes et al. 1983; Martens and Bremner 1984; Broadbent et al. 1985). Acidic substances such as triple superphosphate, phosphoric acid and sulfuric acid have also been used in attempts to reduce the alkalinity of the fertilizer reaction zone (Terman 1979; Nelson 1982). Buffering agents and carbonate-precipitating, soluble calcium salts have also been added with urea to reduce the alkalinity of the reaction zone (Sander and Barker 1978; Fenn et al. 1982).

Delayed planting and using urea incorporated with PPD urease inhibitor were selected as the two methods of urea detoxification to be evaluated in the third growth chamber experiment. This experiment differed in several ways from the previous two. To evaluate the influence of dual banding on grain yield, the wheat was grown until mature. Also, a midseason harvest was taken during this study because the previous growth chamber studies revealed a temporary, early season response to added P. Also, instead of placing the seed and bands across the narrower dimension of the growth boxes, both were placed along the longer dimension, reducing the equivalent band spacing and decreasing the soil to plant ratio. The soil used in this study was extremely deficient in P, in contrast with previous experiments where the degree of P deficiency was less severe but more typical of Western Canadian field conditions.

Experimental Procedures

The soil used for this experiment was obtained from the Ap horizon of a Gleyed Rego Black Chernozemic very fine sand, Haywood series, collected near Haywood, Manitoba, SE 36-8-6 W (Table 12). Prior to use, the soil was

air dried, mixed and passed through a 10 mm sieve. A basal application of 270 mg K, 13.5 mg Cu and 13.5 mg Zn/kg soil was applied as an aerosol of dissolved sulfate salts and thoroughly mixed into the soil.

Table 12. Some Properties of Soil Used in Urea Toxicity Study

pH (1:1, soil:water)	7.8
NaHCO ₃ -extractable P	3 mg/kg
NO ₃ -N	21 mg/kg
NH ₄ Ac-extractable K	40 mg/kg
SO ₄ -S	>20 mg/kg
carbonates	low
texture	very fine sand
% water, field capacity	20%

Large wooden boxes (45x25x28 cm deep) lined with polyethylene bags were used as soil containers. When filled, each box contained 31 kg soil, 20 cm deep. The sequence of filling the containers with soil and applying the fertilizers was similar to that of the first two growth chamber experiments.

In one series of treatments dual and separate bands of urea and MAP were placed either 2.5 cm below and 2.5 cm beside the seed row or 7.5 cm below and 7.5 cm beside the seed row 1 d prior to planting. Where urea bands and MAP bands were separated, the bands were placed at an equal distance on opposite sides of the seed row. A second series of deep and shallow dual bands was applied 11 d prior to planting and incubated at field capacity and room temperature. A third series of deep and shallow

dual bands was treated with urea that had been incorporated with 1% phenylphosphorodiamidate (PPD). For each of the three series of treatments there was a control with 0.92 g N/box (80 kg N/ha). All P treatments received 0.92 g N/box plus 0.23 g P/box (20 kg P/ha). There were three replicates of each treatment.

Contrary to the previous two growth chamber experiments the seed rows and fertilizer bands were oriented along the longer dimension (45 cm) of the boxes, decreasing the soil to plant ratio and reducing the equivalent band spacing to 25 cm. Also, granular urea was applied to the soil directly instead of as a urea solution. This was necessary because of the low solubility of PPD in water. The PPD-urea was produced by IFDC, Muscle Shoals, Alabama and was in the form of minus 6 plus 14 mesh granules made by compaction. Urea for the other treatments was in the form of commercial prills.

After the urea was applied, MAP was applied by pipette in 10 mL of solution. The MAP solution consisted of reagent grade MAP dissolved in distilled water and was labelled with 222 kBq $\text{H}_3^{32}\text{PO}_4$ /mL. The fertilizer bands were immediately covered with the top layer of soil which was watered to field capacity 1 d prior to planting.

Forty-four seeds of Spring Wheat (Triticum aestivum cv. Neepawa) were planted in a row 2.5 cm below the soil surface 12.5 cm from the longer sides of the box. The boxes were arranged in randomized complete blocks on growth benches and rotated weekly. Lighting was from a mixture of incandescent and fluorescent lamps giving an average intensity of 350 $\mu\text{Em}^{-2}\text{s}^{-1}$ at the top of the canopy (measured with a Licor LI-185B Quantum meter and Q4027 Quantum sensor.) Daylength was 16 h. Day and night

temperatures averaged 25°C and 16°C respectively.

The plant stand was thinned to 20 plants per box, 12 d after emergence. The soil was watered to field capacity once per wk in the initial stages of growth and twice per wk near the end of the experiment. Between flag leaf and flowering, the wheat was fertilized with two additional 55 kg/ha applications of N in the form of calcium nitrate.

The intensity of ^{32}P radiation in the plants was monitored during the first 40 d of growth. The method used was similar to that used in the previous growth chamber studies.

The shoot portion of 5 of the 20 plants was harvested 22 d after emergence. The wheat was in the tillering stage (Feekes 4 to 5). Dry matter yield, fertilizer P uptake and total P uptake data for midseason harvest were multiplied by four to estimate these parameters on a per box basis. The intensities of ^{32}P radiation monitored after the midseason harvest were multiplied by 1.33 to compensate for the harvested plants. Final harvest of the shoot portion was taken at maturity, 96 d after emergence. For both harvests, sample handling, tissue analyses for total and fertilizer P and statistical analyses were similar to those outlined for the previous growth chamber experiments. Final harvest data were not adjusted for the removal of plants at midseason, assuming that the removal of 25% of the young seedlings would have had a minor effect on the final yield from each box.

Results and Discussion

MAP Uptake During Growth

In vivo monitoring of ^{32}P intensities revealed trends similar to those observed in the previous growth chamber experiments (Figures 36 and 37). Uptake of fertilizer P was observed at time of emergence where MAP and urea were placed separately in bands 2.5 cm below and beside the seed row. Uptake of fertilizer P was delayed for approximately 6 d where dual bands were applied 2.5 cm below and beside the seed row at time of planting. Delayed uptake of fertilizer P due to the presence of urea in MAP bands was not observed where dual bands were incubated 11 d before planting. PPD appeared to have only a small, if any, detoxifying effect on the dual bands placed 2.5 cm below and beside the seed row at time of planting. Because PPD is less soluble than urea, perhaps it did not diffuse to the periphery of the dual bands where the incipient toxicity to root growth is likely to have occurred. Adding urea to MAP bands placed near the seed row did not appreciably enhance MAP uptake at any stage of growth.

As in the previous experiments, urea enhanced the uptake of fertilizer P from MAP bands placed 7.5 cm below and 7.5 cm beside the seed row. However the uptake of fertilizer P was delayed 7 to 9 d after time of emergence when MAP was placed 7.5 cm below and beside the seed row. Uptake of fertilizer P was initiated approximately 2 d earlier from MAP bands placed separately from urea or incubated 11 d prior to planting, than from dual bands with or without PPD applied at time of planting. The uptake of fertilizer P from all dual bands applied at time of planting continued to lag behind that from other treatments for approximately 15 to 20 d. After approximately 20 d uptake of fertilizer P from dual bands applied with or

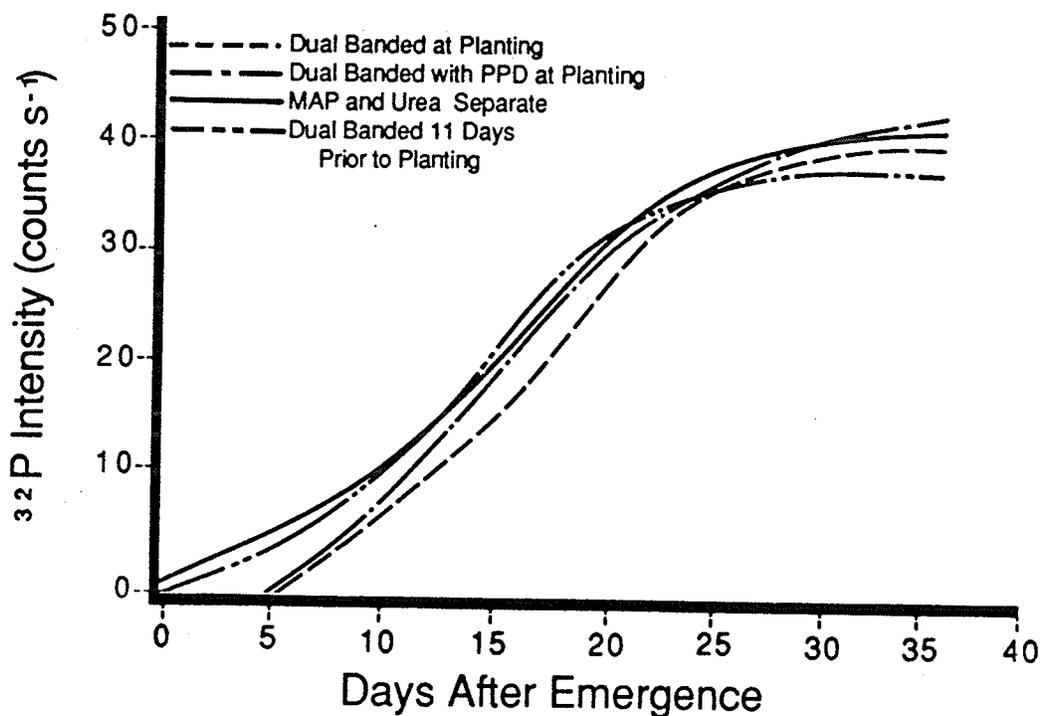


Figure 36. Effect of delayed planting and PPD on ^{32}P intensity of wheat - MAP banded 2.5 cm below and 2.5 cm beside the seed row.

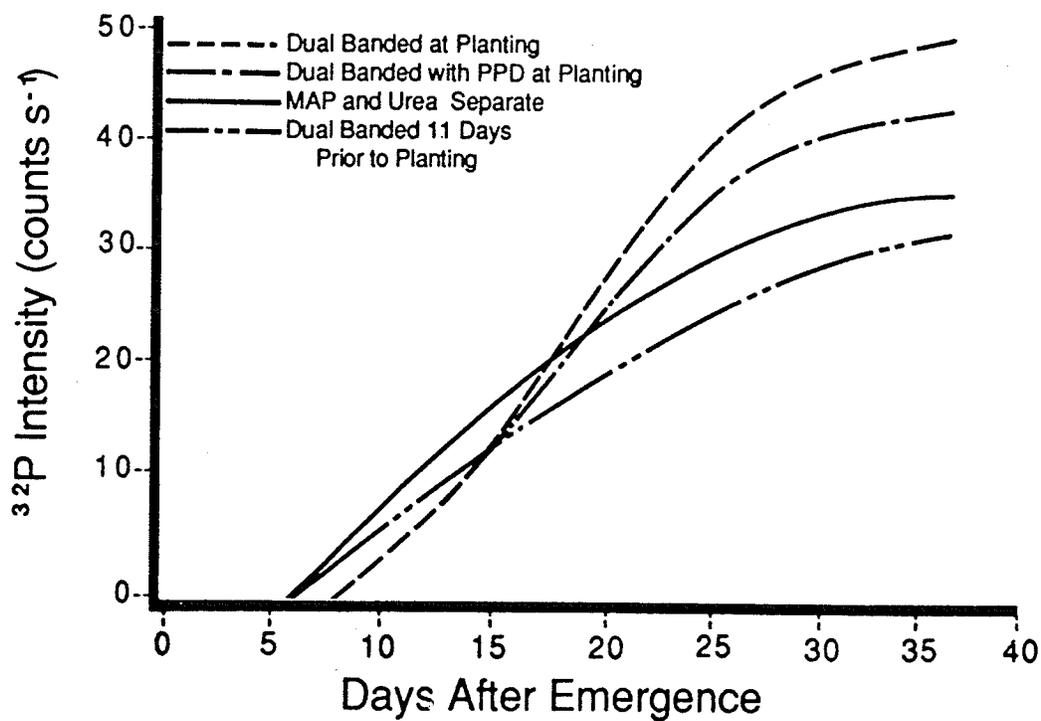


Figure 37. Effect of delayed planting and PPD on ^{32}P intensity of wheat - MAP banded 7.5 cm below and 7.5 cm beside the seed row.

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without PPD at time of planting appeared to be superior to that from dual bands incubated 11 d prior to planting. After 20 d of growth, banding MAP separately from urea at time of planting or with urea 11 d prior to planting resulted in the lowest uptake of fertilizer P from MAP bands placed 7.5 cm below and beside the seed row. Adding PPD to dual bands applied at planting did not appear to enhance uptake of fertilizer P from dual bands placed 7.5 cm below and beside the seed row.

Midseason Harvest

A midseason harvest of 5 of the 20 plants in each box was taken 22 d after emergence, when the plants were beginning to tiller. At this stage there was a very large and statistically significant yield response to fertilizer P especially where MAP was banded near the seed (Table 13). Increases in yield corresponded closely with increases in fertilizer P uptake and increases in total P uptake. However, because of variability among replicates there were no statistically significant differences in fertilizer P uptake. The variability was greatest in the treatments where delayed uptake of fertilizer P had been observed earlier during the in vivo monitoring. Larger subsamples, a later harvest or more replicates may have alleviated some of the variability. In spite of the variability there was a clear trend for the dry matter yield and uptake of fertilizer P to be greater for P bands placed 2.5 cm below and beside the seed than for bands placed 7.5 cm below and beside the seed row.

The midseason harvest data reflect most of the trends observed during in vivo monitoring of ^{32}P intensity for treatments where MAP was placed 2.5 cm below and beside the seed row. The lag in uptake of fertilizer P from

Table 13. Effects of Delayed Planting and PPD on Growth and MAP Uptake by Spring Wheat Harvested at the Tillering Stage.

Treatment	Dry Matter Yield	Fertilizer P Uptake	Total P Uptake
	g/box	mg/box	mg/box
<u>P band 2.5 cm below and beside the seed.</u>			
MAP and Urea separate	6.8AB	17	27BC
Dual banded, delayed planting	8.0A	21	34A
Dual banded with PPD at planting	6.4B	17	28ABC
Dual banded at planting	6.1BC	13	25BCD
<u>P band 7.5 cm below and beside the seed.</u>			
MAP and Urea separate	6.0BC	11	23CDE
Dual banded, delayed planting	4.8CD	8	20DEF
Dual banded with PPD at planting	6.0BC	15	30AB
Dual banded at planting	4.8CD	11	24BCD
<u>Control (N only)</u>			
Urea, delayed planting	3.7D	--	14G
Urea + PPD at planting	4.1D	--	17EFG
Urea at planting	4.3D	--	16FG
Pr>F	0.0001	0.10	0.0001

Note: Means followed by the same letter are not significantly different according to LSD comparison, alpha = 0.05.

dual bands applied at time of planting resulted in low yields and low uptake of fertilizer P at the tillering stage. PPD had a small detoxifying effect on the dual bands. Delayed planting allowed dual bands to detoxify, resulting in yield and fertilizer P uptake greater, although not statistically greater, than that from separate urea and MAP placement.

The midseason harvest data from treatments where MAP was banded 7.5 cm below and beside the seed row were not always consistent with the trends observed during in vivo ^{32}P monitoring. Although dual banding 7.5 cm below and beside the seed row 11 d prior to planting resulted in the lowest fertilizer P uptake, similar to the trend observed in the in vivo monitoring, the ranking of the other treatments was different. According to the harvest data, adding PPD to the urea in dual bands appeared to increase MAP uptake and yield slightly. At 22 d, in vivo monitoring indicated no such increase and perhaps some decrease in uptake of fertilizer P as a result of adding PPD to urea in dual bands. Also, according to the harvest data, separate banding of MAP and urea resulted in dry matter yield and uptake of fertilizer P at least as large as those from dual bands applied without PPD at time of planting. In vivo monitoring at the same stage indicated higher uptake of fertilizer P from dual bands compared to the separate MAP bands.

The differences in estimates of fertilizer P uptake for the different methods of measuring the uptake of fertilizer P are probably due to several factors. First, the fertilizer P uptake data from the midseason harvest were not very accurate, as indicated by the lack of statistically significant differences. The variability between replicates harvested at midseason was largely due to the small number of plants harvested. In vivo

monitoring indicated that the effects of urea toxicity for dual bands and distance between the band and the seed row for treatments where the MAP band was placed 7.5 cm below and beside the seed were inconsistent from one plant to another within a row. ^{32}P intensities measured in vivo were less variable from replicate to replicate because the readings were averaged along the length of the entire seed row. Secondly, the uptake of fertilizer P for treatments where dual bands were applied at time of planting was in a phase of very rapid uptake after initially lagging behind the other treatments. This meant that the ^{32}P intensity curves from various treatments were intersecting at this growth stage.

Total P uptake for all treatments where MAP was banded 2.5 cm below and beside the seed row was significantly greater than for the respective control (N-only) treatments. Also, where MAP was placed 2.5 cm below and beside the seed row, fertilizer P comprised at least half of total P resulting in parallel trends in fertilizer and total P uptake.

Total P uptake for all treatments where MAP was placed 7.5 cm below and beside the seed row was also significantly greater than for the respective control (N-only) treatments. However, increases in total P uptake for dual bands placed 7.5 cm below and beside the seed were usually less than where the dual bands were placed 2.5 cm below and beside the seed row. There was a trend, however, for the total P uptake for dual band treatments applied at time of planting to be greater than for dual bands applied 11 d prior to planting or for separately placed MAP and urea. Fertilizer P accounted for a smaller proportion of total P in the treatments applied 7.5 cm, instead of 2.5 cm, below and beside the seed row. Trends in fertilizer P uptake were parallel to those for total P

uptake in both placements. Comparing equivalent fertilizer treatments at the two band positions, there was one case of a statistically significant difference. Delayed planting after applying the dual bands 7.5 cm below and beside the seed row resulted in significantly less total P uptake compared to the same treatment applied 2.5 cm below and beside the seed row. Otherwise, placement of MAP bands 7.5 cm, instead of 2.5 cm below and beside the seed row did not result in significantly less total P uptake.

Mature Harvest

Differences in yield and P uptake among treatments were smaller at maturity than at the tillering stage (Table 14). Dry matter yield was increased significantly by the addition of MAP fertilizer, regardless of time and method of MAP placement. However, the average dry matter yield increase due to P fertilizer was 17% at maturity compared to 52% at the tillering stage. In contrast to yields measured at the tillering stage there were no significant differences in total dry matter yield at maturity among the different MAP treatments. The yield response to early uptake of P fertilizer observed at the tillering stage was no longer evident. No significant differences in total dry matter yield were observed among the three control (N-only) treatments.

Grain yield was increased significantly by the addition of MAP fertilizer except when dual bands were placed 7.5 cm below and beside the seed row at time of planting. The latter treatment did, however, result in a 13% increase in yield over its respective check and a significant increase in dry matter yield. Part of the reason for the small discrepancy between dry matter yield response and grain yield response is the slightly

Table 14. Effects of Delayed Planting and PPD on Yield and MAP Uptake by Spring Wheat Harvested at Maturity.

Treatment	Dry Matter Yield	Grain Yield	Fertilizer P Uptake	Total P Uptake
	g/box	g/box	mg/box	mg/box
<u>P band 2.5 cm below and beside the seed</u>				
MAP and Urea separate	116A	50A	95A	258A
Dual banded, delayed planting	112A	46ABC	77CD	230B
Dual banded with PPD at planting	118A	50A	87ABC	254A
Dual banded at planting	118A	49A	87ABC	245AB
<u>P band 7.5 cm below and beside the seed</u>				
MAP and Urea separate	120A	48A	71D	234B
Dual banded, delayed planting	112A	47AB	72D	230B
Dual banded with PPD at planting	116A	48A	89AB	256A
Dual banded at planting	112A	45ABCD	83BC	243AB
<u>Control (N only)</u>				
Urea delayed planting	98B	38D	---	150D
Urea+PPD at planting	100B	40BCD	---	175C
Urea at planting	99B	40CD	---	167C
Pr>F	0.0015	0.009	0.002	0.0001

Note: Means followed by the same letter are not significantly different according to LSD comparison, alpha = 0.05.

larger coefficient of variation in the grain yields. Differences among grain yields for various MAP treatments were not statistically significant. No significant differences in grain yield were observed among the three control (N-only) treatments.

The efficiency of fertilizer P uptake averaged 36% of that applied, which was greater than in the previous two growth chamber studies. In the previous experiments plants were harvested at the fully headed but immature stage. In this experiment the plants were harvested at maturity. The change in orientation of the seed row resulted in a higher plant to soil ratio. These factors, combined with the lower concentration of available soil P resulted in a greater utilization of fertilizer P than in the previous growth chamber studies.

Fertilizer P uptake was influenced significantly by method of MAP application. Banding MAP and urea separately but 2.5 cm below and beside the seed row resulted in the greatest uptake. Slightly but not significantly less fertilizer P was taken up from dual bands placed in the same position at time of planting, with or without PPD. However, delayed planting after dual banding 2.5 cm below and beside the seed row resulted in significantly less fertilizer P uptake compared to banding MAP separately in the same position. This observation was contrary to findings noted at the tillering stage when the fertilizer P uptake from dual bands placed 2.5 cm below and beside the seed row 11 d prior to seeding treatment was the greatest of all treatments and was significantly higher than that for the urea and MAP banded separately. One possible reason why the fertilizer P uptake at final harvest was lowest in the delayed seeding treatment is that nitrification in the band may have acidified the reaction

zone, resulting in the dissolution of CaCO_3 and the precipitation of the P with Ca. Other researchers have observed that fertilizer P uptake from P fertilizers is reduced when the P band is acidified (Soper 1955; Olson and Dreier 1956b; Grunes et al. 1958).

For treatments where MAP was banded 7.5 cm below and beside the seed row, delayed planting did not result in greater fertilizer P uptake from dual bands than from MAP bands placed separate from urea. In contrast, fertilizer P uptake from dual bands applied at time of planting, with or without PPD, was significantly greater than from separate MAP and urea bands. So, although delayed planting may have reduced the initial toxicity of dual bands, it also reduced the enhancement of fertilizer P uptake by urea in later growth stages.

The net effect of banding MAP 7.5 instead of 2.5 cm below and beside the seed row on uptake of fertilizer P differed for the various fertilizer treatments. Uptake of fertilizer P was significantly less where MAP applied separately from urea was banded further from the seed row. In contrast, dual banding with or without PPD at time of planting resulted in similar uptake of fertilizer P from MAP bands placed 2.5 cm or 7.5 cm below and beside the seed row. However, uptake of fertilizer P from all dual bands applied at time of planting was slightly lower and in one case significantly lower than that from the separate MAP and urea bands placed 2.5 cm below and beside the seed row. Uptake of fertilizer P from dual bands placed 11 d prior to planting was low and relatively unaffected by distance between the seed row and the MAP band.

Total P uptake was increased significantly by P fertilization, in contrast to the first two growth chamber experiments. Fertilizer P

accounted for an average 34% of total P uptake, a smaller percentage than at the tillering stage. This decline in the proportional contribution of fertilizer P to total P uptake with increasing plant age is consistent with the observations of Spinks and Barber (1947). However, fertilizer P accumulation at maturity was still large enough that the differences in total P uptake paralleled the differences in fertilizer P uptake. Among the control treatments total P uptake was significantly less for delayed planting than for the other treatments.

Generally, final dry matter and grain yields did not correlate well with early season fertilizer P uptake. These findings contrast with those of Bole (1966) who found an excellent correlation between early season fertilizer P uptake and yield. Treatments that resulted in rapid early fertilizer P uptake did not necessarily result in higher final MAP uptake, grain yield or dry matter yield at final harvest. McConnell et al. (1986) and Hamid and Sarwar (1977) also observed that early P uptake was not necessary for maximum yield. In field experiments on Saskatchewan soils, Soper also observed that the ammonium ion enhanced early season fertilizer P uptake but did not effect higher total P uptake at maturity (Soper 1955). In Soper's experiments, total P uptake at maturity from dual bands was lower than from other treatments because of a substantial reduction in the uptake of soil P. One possible reason for the above phenomena may be the ability of plants initially grown at low P status to become more efficient at taking up P in later growth stages (Barber 1947; Boatwright and Viets 1966; Green and Warder 1973). This allows a plant initially starved for P to resume a relative growth rate that is similar to that of plants grown with a continuously high supply of P (Drew and Saker 1978). However, in

the present study, the high efficiency of fertilizer P uptake (36%) points to another possible factor. The rate of P applied was relatively low (20 kg P/ha) for a growth chamber study. Perhaps the plants were so stressed for P that growth was limited more by the amount of MAP added than by method of application. For whatever reasons, the differences between treatment effects at the tillering stage and those at maturity illustrate the significance of timing of harvest on conclusions about P placement.

Conclusions

Adding urea to the MAP band increased uptake of fertilizer P only when the bands were applied at time of planting and only when MAP was placed 7.5 cm below and beside the seed row. Urea in dual bands applied at time of planting delayed uptake of fertilizer P but did not result in significantly less fertilizer uptake, grain yield or total dry matter yield at final harvest. Delayed planting or adding PPD to the urea did not increase total uptake of fertilizer P from dual bands. Although delayed planting allowed early, rapid uptake of P fertilizer it did not enhance fertilizer P uptake from dual bands at later growth stages. In fact, delayed planting resulted in the lowest total fertilizer P uptake from any of the dual bands. The effect of PPD on urea toxicity in dual bands applied at time of planting was minor or nonexistent.

3.6 Field Experiments Using Commercial MAP

Observations from the growth chamber studies indicated that adding urea to a MAP band could delay and/or enhance uptake of fertilizer P. However, it was decided that information about the performance of dual bands under typical field conditions was also needed. Field experiments were conducted in Southern Manitoba in 1981, 1982 and 1983 to evaluate the response of wheat to preplant band applications of urea and MAP together or separately relative to MAP applied in the seed row. The effects of spacing between dual bands and effect of small amounts of "starter" P placed with the seed in addition to preplant banded urea and MAP were also investigated. To be representative of typical soils in Western Canada, the sites chosen contained moderately low but not extremely low concentrations of available P.

Experimental Procedures

Six field sites, (two in each of 1981, 1982 and 1983) on land which had been cropped the previous year, were selected for study (Table 15). All fertilizer treatments were applied in the spring, immediately prior to planting. In 1981, one site near Carman was damaged by excess residues of trifluralin herbicide and was not harvested. Therefore only five site-years of data are presented. The Latin square experimental design consisted of five replicates of five main treatments. The main treatments were a control with 80 kg N/ha and four methods of banding 80 kg N/ha and 15 kg P/ha using commercial grade urea and MAP (see Table 16). Immediately prior to planting, preplant fertilizer bands were placed approximately 10 cm deep using a double disc press drill. Each of these main plots was

Table 15. Description of Field Plot Sites¹

Site	Texture	pH in 1:1 H ₂ O	Organic Matter	Carbonates % CaCO ₃	Nitrate- N mg/kg	NaHCO ₃ - Ext. P mg/kg
Teulon 1981 SW 35-15-1 E1 Polson, Gleyed Rego Black	FS	8.0	4.0	18	8	9
Elm Creek 1982 NE 32-9-5 W1 Kronstal, Gleyed Black	LFS	7.0	2.5	2.5	3	15
Bagot 1982 SW 7-11-9 W1 Almasippi, Gleyed Rego Black	LFS	7.8	2.3	4.3	3	9
Roland 1983 SW 12-4-5 W1 Altona, Gleyed Rego Black	FSL	7.9	3.3	0.4	5	5
Carman 1983 NW 25-5-5 W1 Willowcrest, Gleyed Rego Black	LFS	6.7	2.8	0.6	6	9

¹ Characteristics reported describe the 0 to 15 cm depth of soil except for NO₃-N which describes the 0 to 60 cm depth.

was split and 5 kg of P/ha was added with the seed to one half of each. The rate of N applied as MAP and/or urea was equalized in all subplots. The double disc press disc drill was also used to plant spring wheat at a depth of 5 cm in rows 18 cm apart, perpendicular to the fertilizer bands. The variety of wheat was Neepawa at all sites except at Elm Creek in 1982 where Benito was sown. Spring wheat was also planted in alleys and borders to reduce edge effects. Nutrients other than N and P, where necessary, were broadcast over the entire site and incorporated. Herbicides were applied at recommended rates to control weeds.

Table 16. Description of Main MAP Placements in Dual Banding Field Experiments

Treatment Designation	Description of Treatments
Control	80 kg N/ha, banded at spacings of 36 cm bands.
Seed Row P	80 kg N/ha, banded at spacings of 36 cm bands. 15 kg P/ha, placed in the seed row.
18 cm Dual	80 kg N/ha plus 15 kg P/ha dual banded at spacings of 18 cm.
36 cm Dual	80 kg N/ha plus 15 kg P/ha dual banded at spacings of 36 cm.
36 cm Separate	80 kg N/ha plus 15 kg P/ha banded separately, each at spacings of 36 cm.

Four midseason and one final harvest were taken, each consisting of the shoot portion of two seed rows, 3 m long. Each harvest was taken from separate areas of the same subplot. The four midseason harvests were taken every 2 wk after emergence and the final harvest at maturity. As a result,

the wheat was harvested at approximately the three leaf, tillering, heading, flowering and mature growth stages. Details of the growth stages at various harvest dates and sites are in Appendix H. Samples taken early in the growing season were dried at 70°C, weighed and ground. Samples taken later in the growing season were air dried prior to grinding and yields were adjusted for moisture content to an oven-dry basis. Subsamples were wet ashed using the nitric-perchloric acid digestion described in Appendix D. P concentrations of digests were determined using the ascorbic acid-molybdate blue method described in Appendix E (Murphy and Riley 1962). The main MAP placement treatments and the main plus additional starter P treatments were statistically analysed separately using the ANOVA procedures of the Statistical Analysis System (SAS 1982).

Results and Discussion

The soils of the sites contained low to medium amounts of nitrate-N and sodium bicarbonate-extractable P. Except for Teulon, the sites received adequate precipitation and yielded well. Still, grain yield was not increased significantly by P fertilization except at the Roland site (Table 21) which had the lowest concentration of sodium bicarbonate-extractable P. The yield responses to P at Elm Creek and Carman were small and inconsistent. At Bagot grain yield was not increased at all by P fertilization and at Teulon the yield response to P was very erratic due to inadequate moisture. However, in spite of inconsistent yield responses to P, the field data reveal some important trends, especially in uptake of P during the early portion of the growing season. In general, the application of an additional 5 kg P/ha as starter fertilizer with the seed

increased P uptake and yields slightly, reducing but not eliminating the differences between the main MAP placement methods (Appendix I). The trends observed in the data from the main treatments plus starter P were generally similar but less significant than those from the main MAP placements without additional starter P. Therefore, only the latter data will be discussed in detail.

P Response After 2 Wk of Growth

The wheat at most sites was in the three leaf stage 2 wk after emergence. Dry matter yields were generally higher for MAP placed in the seed row, in 18 cm dual bands or 36 cm separate bands than without P or for MAP placed in 36 cm dual bands (Table 17). At this stage of growth, dry matter yields with P placed in the seed row were similar to those with P placed in 18 cm dual bands or 36 cm separate bands. However, dry matter yields for the latter two treatments were significantly greater than those for the control treatment at two sites, whereas the dry matter yields for seed row P treatments were not significantly greater than those for the control treatment at any of the sites. Application of an additional 5 kg P/ha with the seed, resulted in no significant differences in dry matter yield due to placement at any site (Appendix I, Table 26).

At Elm Creek the yield for the seed row P treatment was significantly lower than that for the control (Table 17). The reason for the early season yield depression from seed row P application at Elm Creek is not known. Tissue samples from seed row treatments did not contain abnormal concentrations of K, Ca, Mg, Zn, Cu, Mn or Fe. The soil at the Elm Creek site did, however, contain higher concentrations of available P compared to

Table 17. Effect of MAP and Urea Placement on P Uptake and Yield of Spring Wheat Harvested 2 Wk after Emergence.¹

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Control	0.074	0.087AB ²	0.082	0.096B	0.092B
Seed Row P	0.097	0.059C	0.087	0.111AB	0.117AB
18 cm Dual	0.078	0.089AB	0.090	0.124A	0.130A
36 cm Dual	0.086	0.074BC	0.085	0.088B	0.089B
36 cm Separate	0.103	0.095A	0.084	0.122A	0.129A
Pr>F ³	0.16	0.01	0.94	0.04	0.03
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Control	0.29D	0.35C	0.28C	0.33B	0.36C
Seed Row P	0.34BC	0.53A	0.41A	0.50A	0.51A
18 cm Dual	0.39A	0.40C	0.34B	0.38B	0.44B
36 cm Dual	0.30CD	0.37C	0.29C	0.36B	0.38C
36 cm Separate	0.36AB	0.46B	0.37AB	0.48A	0.52A
Pr>F	0.002	0.0001	0.0001	0.004	0.0001
<u>Total P Uptake (kg/ha)</u>					
Control	0.22	0.31B	0.23	0.31C	0.34B
Seed Row P	0.33	0.32B	0.35	0.55A	0.58A
18 cm Dual	0.31	0.35AB	0.31	0.44B	0.56A
36 cm Dual	0.26	0.28B	0.24	0.31C	0.33B
36 cm Separate	0.37	0.43A	0.31	0.54A	0.66A
Pr>F	0.077	0.04	0.09	0.0003	0.001

¹ At most sites the wheat was at the three-leaf stage.

² Means followed by the same letter are not significantly different according to the LSD test (alpha = 0.05).

³ Level of significance according to analysis of variance.

the other sites. The concentration of P in the tissue from the seed row treatment at Elm Creek was high but not much different from the Roland and Garman sites and much lower than the 1% toxicity threshold reported by Bhatti and Loneragan (1970). Ridley and Tayakepisuthe (1974) also observed a reduction in yield where low rates of P were applied with the seed on a soil high in available P. However, in their experiment the soil had received a high rate of broadcast P and they suspected that the high rate of P fertilizer had induced a micronutrient deficiency.

Concentration of P in plant tissue was affected significantly by treatment. MAP placed in the seed row or in separate preplant bands resulted in tissue P concentrations significantly greater than those of the control treatment at all sites. In contrast, dual bands applied at 36 cm spacings did not effect significantly higher P concentrations compared to those of the control treatments at any of the sites. Dual banding at 18 cm spacings generally resulted in intermediate concentrations of P in tissue.

Total P uptake data followed the trends noted for yield and P concentrations. P uptake was higher for P applied in the seed row, 18 cm dual bands and 36 cm separate bands than without P or for 36 cm dual bands, except at Elm Creek where P applied in the seed row depressed dry matter yields. The low P uptake from the 36 cm dual bands was likely due to urea toxicity in the dual bands preventing root growth in the dual band and uptake of P fertilizer. Narrower band spacings (18 cm) appeared to help alleviate the problem somewhat. The P uptake from the 36 cm separate preplant MAP bands at this early growth stage was surprisingly excellent. Adding 5 kg P/ha with the seed to each main treatment resulted in no significant differences between main treatments except at Roland (Appendix

I, Table 26). At Roland the addition of starter P to the main treatments increased the total P uptake for all treatments except seed row P. As a result, the P uptake for the seed row P treatment was not significantly higher than that for any preplant banded treatment. However, it is important to note that the data listed are for samples of 3 m of two seed rows planted perpendicular to the bands. There was likely large variation in plant to plant P uptake depending on the proximity of plants to the P band (Maxwell et al. 1984). Thus, the average P uptake was excellent, some plants may have had luxurious amounts of P while others in the same row may have been deficient in P.

P Response After 4 Wk of Growth

Four wk after emergence the wheat at most sites was in the tillering stage. Most of the data obtained for this stage of growth reflect the trends observed at the three leaf stage. Significant differences between main treatments were observed at four of the five sites (Table 18). Dry matter yields were generally higher for MAP placed in the seed row, in 18 cm dual bands or in 36 cm separate bands than without P or for 36 cm dual bands. Yield for P placed in the seed row was similar to yields for P placed in 18 cm dual or 36 cm separate preplant bands, except at the Roland site where the yield for 36 cm separate bands was significantly less than for P placed in the seedrow. The concentration of available P in the soil at Roland was less than that of the other sites. These data, therefore, corroborate the theory that placement of P in the seed row is of greatest value where the concentration of available soil P is low (Peterson et al. 1981). Dry matter yields for the 36 cm dual band treatment were not

Table 18. Effect of MAP and Urea Placement on P Uptake and Yield of Spring Wheat Harvested 4 Wks after Emergence.¹

Treatment	Teulon	Elm Creek	Bagot	Roland	Garman
<u>Dry Matter Yield (Mg/ha)</u>					
Control	0.382B ²	0.94B	0.603	0.544C	0.606B
Seed Row P	0.553A	0.88B	0.751	0.863A	0.869A
18 cm Dual	0.563A	1.13A	0.699	0.751AB	0.828A
36 cm Dual	0.483AB	0.88B	0.615	0.520C	0.572B
36 cm Separate	0.567A	1.02AB	0.682	0.704B	0.791A
Pr>F ³	0.04	0.03	0.29	0.002	0.005
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Control	0.24B	0.28C	0.28BC	0.37C	0.29C
Seed Row P	0.26B	0.34A	0.33A	0.43B	0.36B
18 cm Dual	0.31A	0.34A	0.31AB	0.55A	0.39AB
36 cm Dual	0.31A	0.30BC	0.26C	0.51A	0.38AB
36 cm Separate	0.26AB	0.31B	0.30ABC	0.44B	0.40A
Pr>F	0.03	0.0004	0.035	0.0001	0.0001
<u>Total P Uptake (kg/ha)</u>					
Control	0.95C	2.65B	1.69BC	2.02D	1.75B
Seed Row P	1.42B	3.01B	2.45A	3.64AB	3.16A
18 cm Dual	1.75A	3.82A	2.16AB	4.13A	3.19A
36 cm Dual	1.50AB	2.61B	1.57C	2.62CD	2.20B
36 cm Separate	1.51AB	3.14B	1.97ABC	3.09BC	3.15A
Pr>F	0.002	0.004	0.03	0.0002	0.002

¹ At most sites the wheat was at the tillering stage.

² Means followed by the same letter are not significantly different according to the LSD test ($\alpha = 0.05$).

³ Level of significance according to analysis of variance.

significantly greater than those without P at any site. Adding 5 kg P/ha with the seed to the main treatments did not result in any significant differences between treatments in dry matter yields (Appendix I, Table 27).

Differences in concentrations of P in plant tissues were not as consistently related to yield differences as those for the first harvest. Main treatments that resulted in large increases in dry matter yields did not necessarily result in higher tissue P concentrations, likely as a result of biological dilution.

Total P uptake data followed trends noted for the first harvest. Significant differences between main treatments were observed at all sites. However, the differences among main placements were less significant than those observed at the first harvest. Placing P in the seed row, 18 cm dual bands and 36 cm separate bands effected greater uptake of P than without P or for 36 cm dual bands. At all sites except Teulon, dual banding at 36 cm spacings did not result in significantly greater uptake of P compared to the control. At all sites except Bagot, placing P in 18 cm dual bands resulted in the highest total P uptake, possibly because of the positive influence of ammonium from the urea in the dual band (Soper 1955) and less urea toxicity in the 18 cm versus 36 cm dual bands. Application of an additional 5 kg P/ha with the seed to all main placements did not result in significant differences between methods of placement except at Carman (Appendix I, Table 27). Split placement of MAP in 36 cm dual bands with 5 kg P/ha as "starter" resulted in the lowest P uptake of all treatments receiving 20 kg P/ha. However, placing all the MAP in the seed row did not result in significantly higher P uptake than for any treatment where MAP was split between the seed row and preplant bands.

P Response After 6 Wk of Growth

Six wk after emergence the wheat at most sites was in the heading stage. Dry matter yield at this growth stage was not increased significantly by P fertilization except at Teulon (Table 19). The yields for the control and 36 cm dual bands continued to be lower than for other treatments, but that trend was less obvious than it was earlier in the growing season. The yields for P placed in the seed row were very similar to those for P placed in 18 cm dual bands and 36 cm separate bands.

At the Elm Creek site, the yield for P in the seed row equalled that of the control. Previous harvests indicated lower yields for P in the seed row than for the control. Thus the plants had apparently recovered from the negative effect of P in the seed row.

Concentrations of P in plant tissue for dual bands tended to be at least as high if not higher than those for the separate and seed row P treatments. The high tissue P concentration for the 36 cm dual band treatment was due in part to reduced biological dilution of fertilizer P because of less growth.

No differences in total P uptake were observed among the placement methods. Total P uptake for P placed in 36 cm dual bands had increased considerably since the previous harvest. After 6 wk, the P uptake for the 36 cm dual bands was equivalent to the other MAP treatments and significantly higher than the control in three of five sites. Thus, the pattern of P uptake for 36 cm dual bands was similar to observations from the growth chamber experiments. The toxic effect of urea in 36 cm dual bands had likely dissipated, allowing rapid uptake of MAP.

Table 19. Effect of MAP and Urea Placement on P Uptake and Yield of Spring Wheat Harvested 6 Wk after Emergence.¹

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Control	1.63C ²	3.34	2.01	2.16	2.48
Seed Row P	2.05AB	3.52	2.46	2.70	2.88
18 cm Dual	2.08A	3.66	2.61	2.71	3.18
36 cm Dual	1.67BC	3.58	2.25	2.39	2.48
36 cm Separate	2.30A	3.34	2.36	2.66	2.88
Pr>F	0.011	0.33	0.063	0.19	0.051
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Control	0.23	0.23	0.20C	0.29B	0.30D
Seed Row P	0.23	0.25	0.23B	0.32AB	0.34C
18 cm Dual	0.24	0.23	0.23AB	0.35A	0.36B
36 cm Dual	0.25	0.22	0.26A	0.34A	0.40A
36 cm Separate	0.22	0.23	0.21BC	0.29B	0.35BC
Pr>F	0.31	0.055	0.009	0.016	0.0001
<u>Total P Uptake (kg/ha)</u>					
Control	3.76B	7.68	4.01B	6.19B	7.4B
Seed Row P	4.71A	8.77	5.60A	8.41A	9.8A
18 cm Dual	4.90A	8.48	5.97A	9.45A	11.5A
36 cm Dual	4.14AB	7.80	5.73A	8.05A	9.9A
36 cm Separate	4.97A	7.71	5.05AB	7.74AB	10.0A
Pr>F	0.04	0.08	0.01	0.02	0.003

¹ At most sites the wheat was at the heading stage.

² Means followed by the same letter are not significantly different according to the LSD test (alpha = 0.05).

³ Level of significance according to analysis of variance.

P Response After 8 Wk of Growth

Wheat at most sites was in the flowering stage 8 wk after emergence. Dry matter yields were increased significantly as a result of P fertilization at most sites, but there was no clear trend for one method of P placement to yield more than others (Table 20).

Concentrations of P in plant tissue did not show any consistent patterns among treatments at the various sites. The P concentration in the plant tissue for the control was often similar to that for treatments where P fertilizer had been applied.

As a result of the inconsistent differences in dry matter yield and tissue P concentration, only one site showed significant differences in total P uptake. Total P uptake was increased significantly by P fertilization at only the Roland site, where the concentration of available P in soil was less than at other sites. At Roland the uptake of P was greatest for the 18 cm dual band treatment. Although total P uptake for the 36 cm dual band treatment was significantly greater than the control it was the lowest of all the P treatments. In general, however, the method of MAP placement had little influence on total P uptake. The small influence of MAP application and placement on total P uptake at the flowering stage contrasts with the large differences observed earlier in the growing season. Toxicity of the dual bands and proximity of the bands relative to the seed row had likely become less important factors influencing the plants access to fertilizer P and the plants were also more capable of taking up soil P.

Table 20. Effect of MAP and Urea Placement on P Uptake and Yield of Spring Wheat Harvested 8 Wk after Emergence.¹

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Control	2.30B ²	5.28B	5.47D	4.28B	4.94
Seed Row P	2.70AB	5.75A	5.72CD	5.89A	5.73
18 cm Dual	3.28A	5.84A	6.18A	5.71A	5.50
36 cm Dual	3.01AB	5.41B	5.79BC	5.42A	5.19
36 cm Separate	3.43A	5.86A	6.01AB	6.07A	5.54
Pr>F ³	0.046	0.004	0.001	0.005	0.57
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Control	0.15	0.22BC	0.17	0.16C	0.18
Seed Row P	0.17	0.21BC	0.17	0.18B	0.18
18 cm Dual	0.15	0.21BC	0.17	0.22A	0.19
36 cm Dual	0.17	0.25A	0.17	0.18B	0.19
36 cm Separate	0.15	0.23AB	0.16	0.17BC	0.20
Pr>F	0.22	0.02	0.93	0.0001	0.27
<u>Total P Uptake (kg/ha)</u>					
Control	3.49	11.5	9.5	6.7C	8.7
Seed Row P	4.50	12.2	9.9	10.5B	10.1
18 cm Dual	4.87	12.3	10.2	12.4A	10.3
36 cm Dual	5.02	13.4	9.7	9.5B	10.0
36 cm Separate	5.01	13.7	9.8	10.1B	11.3
Pr>F	0.072	0.062	0.90	0.0001	0.34

¹ At most sites the wheat was at the flowering stage.

² Means followed by the same letter are not significantly different according to the LSD test (alpha = .05).

³ Level of significance according to analysis of variance.

P Response at Maturity

Grain yield was increased significantly as a result of P fertilization at only the Roland site (Table 21). At Teulon, Elm Creek and Carman, the responses to P fertilization were small but insignificant and at Bagot there was no yield response to P. At Roland, only the seed row P, 18 cm dual band and 36 cm separate band treatments resulted in grain yields that were significantly greater than those without P. Although the yield for 36 cm dual bands was not significantly greater than the yield without P, there were no significant differences among the methods of MAP placement. At Teulon and Elm Creek the yield for the 36 cm dual band treatment was also the lowest of the MAP treatments. At Carman the yields for all placements of MAP were very similar, except where 5 kg P/ha was added with the seed to all main treatments (Appendix I, Table 30). Where 20 kg P/ha was split between the seed row and preplant bands, the grain yield for 18 cm dual bands was significantly less than for other treatments. Adding 5 kg P/ha with the seed to the main treatments at Roland resulted in no significant differences between treatments.

Applying MAP in 36 cm dual bands resulted in lower final grain yields than for MAP placed in 18 cm dual bands, 36 cm separate bands or placed in the seed row at all sites except Carman (Table 21). At Roland, where there was a significant grain yield response to P, trends in grain yield appeared to be similar to those of early season P uptake. This trend has been observed by other researchers in Western Canada. Total P uptake at the tillering stage has been cited as an excellent indicator of grain yield response when comparing different placements of similar fertilizers in the field (Bole 1966). This contrasts with the lack of correlation between

Table 21. Effect of MAP and Urea Placement on P Uptake and Yield of Spring Wheat Harvested at Maturity

Treatment	Teulon	Elm Creek	Bagot	Roland	Garman
<u>Grain Yield (Mg/ha)</u>					
P Check	1.33	2.75	2.88	2.45B ¹	2.59
Seed Row P	1.55	3.00	2.84	3.01A	2.80
18 cm Dual	1.54	3.05	2.80	2.83A	2.72
36 cm Dual	1.14	2.80	2.73	2.69AB	2.80
36 cm Separate	1.42	3.07	2.93	2.88A	2.85
Pr>F ²	0.44	0.20	0.67	0.047	0.12
CV ³	27	8.6	7.8	8.8	5.5
<u>P Concentration in Grain (%P, dry weight basis)</u>					
P Check	0.26	0.48A	0.35	0.39B	0.40
Seed Row P	0.30	0.51A	0.43	0.41AB	0.41
18 cm Dual	0.30	0.52A	0.37	0.44A	0.46
36 cm Dual	0.30	0.40B	0.40	0.41AB	0.43
36 cm Separate	0.29	0.41B	0.42	0.43A	0.43
Pr>F	0.52	0.0001	0.059	0.021	0.10
<u>Total P Uptake in Grain (kg/ha)</u>					
P Check	3.48	13.3B	10.0	9.6B	10.5B
Seed Row P	4.64	15.2A	12.2	12.4A	11.6AB
18 cm Dual	4.59	15.9A	10.5	12.3A	12.4A
36 cm Dual	3.49	11.2C	11.0	11.0AB	12.0A
36 cm Separate	3.88	12.6BC	12.3	12.3A	12.4A
Pr>F	0.22	0.0001	0.11	0.004	0.03

¹ Means followed by the same letter are not significantly different according to the LSD test (alpha = .05).

² Level of significance according to analysis of variance.

³ Coefficient of variation between replicates, in %.

early season uptake and yield observed in the urea detoxification experiment in the growth chamber. Soper (1955) found that early season P uptake did not correlate very well with final P uptake or grain yield during field experiments in Saskatchewan with different chemical combinations of fertilizers. Part of the inconsistencies in the field data and literature may be due to excessive or "luxurious" P uptake by seedlings early in the growing season. P, in excess of plant requirements would be stored as inorganic P (Bielecki 1973), contributing little to plant growth and perhaps inhibiting P uptake allosterically later in the season (Lefebvre and Glass 1982).

The trend for yields to be higher for 18 cm versus 36 cm bands was not always consistent, but is similar to the results reported by Maxwell et al. (1984) in Kansas, who concluded that dual band spacing should be less than 20 cm for winter wheat. Data from the present study support a similar recommendation for spring wheat. Wider band spacings may cause uneven growth and are also more likely to contain high concentrations of ammonia preventing early root proliferation in the dual band. The subsequent delay in MAP uptake is likely more important to a spring versus a winter wheat, because of spring wheat's shorter growing season. The relatively coarse textured and alkaline soils of the test sites plus the application of dual bands immediately prior to seeding contributed to the toxic effect of urea in the dual bands. The toxic effect would likely be less severe in soils with a higher clay content or lower pH and where dual bands were applied several wk prior to seeding.

Concentrations of P in the grain showed no consistent pattern but were generally increased by P fertilization.

Significant differences in total P uptake were observed for the main treatments at three of the five sites. Total P uptake in the grain showed the same pattern as grain yield. However, the differences in P uptake among treatments were more significant than differences in grain yield. Greater uptake of P early in the season tended to result in greater accumulation of P at maturity, although this tendency was not always consistent for reasons outlined earlier. Adding 5 kg P/ha with the seed to all main treatments resulted in no significant differences between methods of placements except at Carman (Appendix I, Table 30). At Carman total P uptake was highest for 20 kg P/ha split between the seed row and 36 cm dual bands. However, none of the treatments with preplant MAP plus 5 kg P/ha resulted in total P uptake significantly greater than that for 20 kg P/ha in the seed row.

Conclusions

Grain yields and early season P uptakes were greater for P placed in the seed row, 18 cm dual bands or 36 cm separate bands than in 36 cm dual bands. Preplant banded P did not result in significantly higher grain yields compared to seed row P at any site. Nor did seed row P effect a consistent "popup" effect compared to the best of the preplant banded P treatments.

Although placing P in the seed row did not significantly increase grain yields compared to placing P in 18 cm dual or 36 cm separate bands at four of the five sites, it did result in a small advantage at Roland, the site with the lowest concentration of available P in soil. Adding 5 kg P/ha as starter to the preplant band treatments at Roland eliminated this

advantage (Appendix I). Therefore there appears to be a need to place at least a small amount of P in the seed row on soils which have very low concentrations of available P especially if preplant bands are widely spaced. This observation concurs with those of Peterson et al. (1981) and Maxwell et al. (1984) from experiments in Nebraska and Kansas.

3.7 Radiotracer Field Experiment

Field studies in Kansas showed that dual bands applied at 46 cm spacing result in uneven growth of wheat (Leikam et al. 1983). Subsequent field studies showed that grain yields of winter wheat were not influenced consistently by spacing of dual bands of ammonia plus ammonium polyphosphate (Maxwell et al. 1984). However, growth and early season P uptake were more uniform from bands at closer spacings. In a subsequent greenhouse study, Maxwell and co-workers (1984) found that P uptake from the dual bands was delayed until between 11 and 22 d after planting. After 44 d, P uptake from dual bands placed up to 20 cm away from the seed row did not decline significantly with increasing distance from the seed row except when other plants shielded the P from access by the more distant wheat plants.

As a result of these findings from Kansas and those from the previous growth chamber experiments a radiotracer experiment was conducted in the field. The objectives of the radiotracer field experiment were to monitor more closely the onset of fertilizer P uptake under field conditions and to determine how individual wheat plants in rows competed for preplant banded P. MAP labelled with ^{32}P was used in a small plot trial adjacent to the commercial MAP field site at Roland during 1983. The radiotracer plot and the commercial MAP plot were planted at the same time and received a similar rate of urea and MAP application. However, in the radiotracer plot the MAP and urea were dissolved and injected in small amounts at a consistent depth and at close spacings in a straight line to simulate fertilizer bands.

Experimental Procedures

The radiotracer plot was adjacent to the commercial MAP plot near Roland, Manitoba in 1983 (Table 16). The fertilizer treatments were applied in rows at 18 cm spacing and at a depth of 5 cm after planting spring wheat (cv. Neepawa). Treatments were designed to duplicate the effect of banding urea and MAP together or separately perpendicular or parallel to the seed row. The fertilizers, in solution form, were injected into the soil using a syringe type of pipettor with a 15 cm cannula which had a closed end and a side port. A series of 2 mL injections, 5 cm apart and 10 cm below the soil surface, formed a simulated band 5 cm below the seed depth. Reagent grade urea and ^{32}P -labelled MAP were applied at rates of 80 kg N/ha and 20 kg P/ha except for the control which received urea and "carrier-free" ^{32}P (the solution referred to as "carrier-free" contained 1 mg/L ^{31}P for greater safety and to reduce adsorption losses during handling). The radioactive solutions contained 123 kBq $\text{H}_3^{32}\text{PO}_4$ per mL. Unfortunately, only one replicate of each treatment was possible due to a shortage of time, equipment and amount of ^{32}P which could be safely handled with available equipment.

Banding Perpendicular to the Seed Row

Radioactive solutions for the three treatments were injected in sets of bands perpendicular to the direction of the seed rows. Spacing between labelled bands within each set was 36 cm. Each series of radioactive bands was separated from the other treatments by at least 1 m and by fertilizer bands of a similar but nonradioactive treatment. The treatments included:

- "carrier-free" ^{32}P with urea banded between ^{32}P bands (Control)
- labelled MAP with urea placed in the same band (36 cm Dual)
- labelled MAP and urea banded separately (36 cm Separate)

Harvests were taken from separate portions of the treatment areas at 2 and 6 wk after emergence and at maturity. Samples were obtained at 6 cm increments, at distances up to 36 cm away from the fertilizer band. Each sample was from four rows of plants. In addition, the wheat plants were monitored weekly using a handheld Geiger-Mueller survey meter.

Banding Parallel to the Seed Row

Radioactive solutions were injected in six single band treatments adjacent and parallel to every sixth seed row. Similar but non-radioactive bands were placed 36 cm to either side at the radioactive treatments. The treatments included:

- "carrier-free" ^{32}P banded below a seed row and urea banded separately
(Control, Below)
- "carrier-free" ^{32}P banded 6 cm beside a seed row and urea banded
separately (Control, Beside)
- labelled MAP banded below a seed row and urea banded separately
(Separate, Below)
- labelled MAP banded 6 cm beside a seed row and urea banded
separately (Separate, Beside)
- labelled MAP and urea banded together below a seed row (Dual, Below)
- labelled MAP and urea banded together 6 cm beside a seed row (Dual,
Beside)

Harvests were taken from separate portions of each treatment area at 2 and 6 wk after emergence and at maturity. Each sample consisted of 1 m of each of the four rows of wheat nearest the labelled fertilizer band. In addition, the wheat plants were monitored weekly, using a handheld Geiger-Mueller survey meter.

Samples from both sets of experiments were dried at 70°C, weighed and ground. Subsamples were wet ashed using the nitric-perchloric acid digest procedure described in Appendix D. Total P concentrations were determined using the ascorbic-acid molybdate blue method described in Appendix E. Fertilizer P contents of digests were determined directly by the Cerenkov counting method using a Beckman 7500 liquid scintillation counter (see Appendix F).

Results and Discussion

Banding Perpendicular to the Seed Row

The yield and P uptake data from the radiotracer plot were similar to those from the adjacent, replicated plot where commercial, unlabelled MAP was applied (Table 22). So, although the radiotracer data were from only a single replicate the data obtained were consistent with observations made from the other field data. Uptake of fertilizer P from the 36 cm dual bands was delayed until the tillering stage whereas uptake from the 36 cm separate bands was observed at emergence. The delay was longer than that observed in the growth chamber experiments perhaps because of the lower soil moisture content and cooler temperatures in the field soil which would retard nitrification or dissipation of ammonia. Although dual and separate treatments resulted in similar total P uptake at maturity, the uptake of

Table 22. Effect of Labelled MAP Banded Perpendicular to the Seed Row on P Uptake and Yield of Spring Wheat at Roland.

Treatment	Dry Matter Yield	Total P Uptake	Fertilizer P Uptake
	Mg/ha	kg/ha	kg/ha
<u>Three Leaf Stage Harvest</u>			
Control	0.10 (0.10) ¹	0.35 (0.31)	---
36 cm Dual	0.13 (0.09)	0.43 (0.31)	0.01
36 cm Separate	0.11 (0.12)	0.63 (0.54)	0.37
<u>Heading Stage Harvest</u>			
Control	2.3 (2.2)	5.9 (6.2)	---
36 cm Dual	2.3 (2.4)	7.9 (8.1)	3.3
36 cm Separate	2.7 (2.7)	7.9 (7.7)	3.7
<u>Mature Harvest, Grain Only</u>			
Control	2.5 (2.5)	10 (10)	---
36 cm Dual	2.6 (2.7)	12 (11)	4.0
36 cm Separate	2.8 (2.9)	13 (12)	5.1

¹ Figures in brackets are means of replicated treatments in the adjacent plot where commercial, unlabelled MAP was applied.

fertilizer P from the dual bands was less than that from separate bands. This contrasted with the growth chamber experiments where uptake of fertilizer P from dual bands was at least as great as that from separate bands of N and P. Grain yield of the 36 cm dual band treatment was intermediate between the control and the 36 cm separate band treatment, the same as in the neighbouring commercial MAP experiment.

Fertilizer P uptake data of individual 6 cm row length samples showed few consistent trends, especially with the dual band treatment (Figure 38). Part of the inconsistency in the fertilizer P uptake data was due to variations in the yield of the very short lengths of row. However the skewed bias in uptake pattern also indicate possible problems with the placement of labelled MAP solution during injection. In spite of these inconsistencies, the data show that the wheat took up significant amounts of fertilizer P from as far as 21 cm from the fertilizer band, although uptake tended to decline as the distance between the plants and the fertilizer band increased. The uneven pattern of fertilizer P uptake resembles the data reported by Cabrera et al. (1986) with dual banded N and P on winter wheat in Kansas. Adding urea to MAP bands appeared to depress uptake of fertilizer P by plants close to the bands but enhanced uptake of fertilizer P by plants further from the bands. The uptake pattern of "carrier-free" ^{32}P (not shown) appeared to be similar to that from separate MAP bands with a rapid decline in uptake of ^{32}P as the distance between the plant and the zone of ^{32}P application increased.

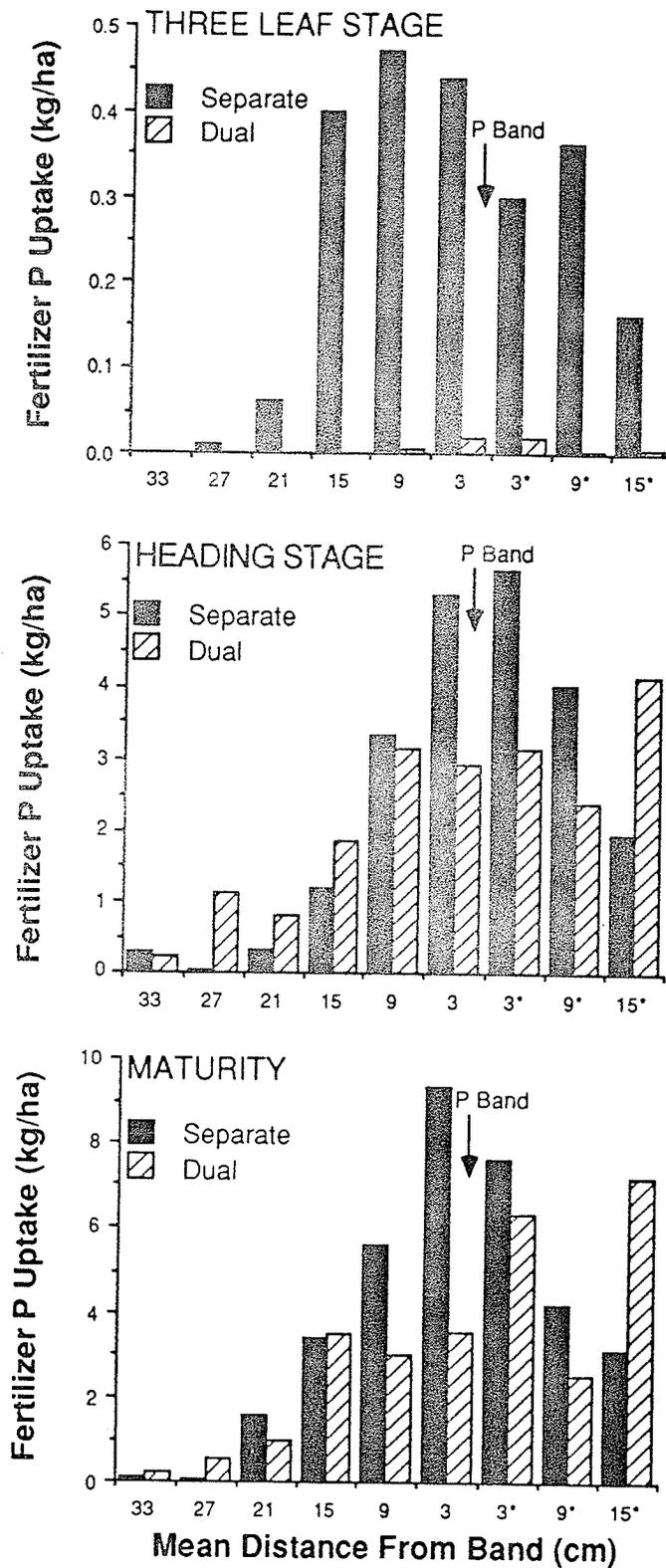


Figure 38. Fertilizer P uptake by wheat as a function of distance from MAP bands placed perpendicular to the seed row. Asterisks (*) indicate samples obtained between a pair of bands of labelled MAP.

Banding Parallel to the Seed Row

Banding labelled MAP parallel to the seed row resulted in yield and total P uptake data that were similar to those of the adjacent area where bands were perpendicular to the seed row (Table 23). Fertilizer P uptake, however, from bands placed parallel to the seed row appeared to be slightly greater than that from bands placed perpendicular to the seed row. Placing the MAP bands either below every second seed row or between the rows resulted in similar P uptake and yield. Once again, dual banding at 36 cm spacing delayed uptake of fertilizer P compared to separate urea and MAP placement.

The fertilizer P uptake data from individual row samples indicate that the plants in the row nearest the separate MAP band took up most of the fertilizer P (Figure 39). Plants in rows further from the separate MAP band took up less fertilizer P than those nearest the band but the amount of fertilizer P taken up by adjacent rows was more than the negligible amounts reported for MAP placed directly into the seed row (Mitchell 1957). At the three leaf stage, preferential uptake of fertilizer P from separate MAP bands for row number 3 was greater with MAP placed directly below row number three than with MAP placed 6 cm to the side. However, at heading and mature harvests, the pattern of fertilizer P uptake from separate MAP bands was similar for MAP placed either below or beside row number 3. The uptake pattern of "carrier-free" ^{32}P (not shown) was similar to that from separate MAP bands.

Uptake of fertilizer P from dual bands, once initiated, appeared to be more uniform, row to row, than that from separate MAP bands. The reasons for the more uniform distribution of fertilizer P uptake from dual bands

were not determined. However, the uniformity came as a result of two factors. Plants in rows near the MAP band took up less fertilizer P when MAP was dual banded than when MAP was banded separately from urea. Also, plants in rows further from the MAP band appeared to take up more fertilizer P when urea was added to the MAP band. The addition of urea to MAP bands increased fertilizer P uptake by plants located far from the band during the growth chamber experiments previously discussed, but there had been no reduction in fertilizer P uptake by plants located near the band such as that observed in the field. In the growth chamber experiments, however, there was no competition from adjacent plant rows. In the field radiotracer experiment, the presence of toxic concentrations of urea in the dual bands early in the season may have prevented the nearest plant rows from exploiting the fertilizer band until the roots from adjacent plant rows were extensive enough to exploit the same band. The presence of high concentrations of nitrogen in the dual band may also have encouraged root proliferation in the band by the roots of plants from adjacent rows.

Table 23. Effect of Labelled MAP Banded Parallel and Below or Beside the Seed Row on P Uptake and Yield of Spring Wheat at Roland.

Treatment	Dry Matter Yield	Total P Uptake	Fertilizer P Uptake
	Mg/ha	kg/ha	kg/ha
<u>Three Leaf Stage Harvest</u>			
Control, Below	0.08	0.27	---
Control, Beside	0.08	0.26	---
36 cm Dual, Below	0.10	0.31	0.008
36 cm Dual, Beside	0.04	0.13	0.004
36 cm Separate, Below	0.11	0.60	0.53
36 cm Separate, Beside	0.12	0.79	0.57
<u>Heading Stage Harvest</u>			
Control, Below	2.7	6.9	---
Control, Beside	2.2	5.8	---
36 cm Dual, Below	2.3	8.3	3.6
36 cm Dual, Beside	2.4	8.7	4.6
36 cm Separate, Below	2.8	7.9	4.5
36 cm Separate, Beside	2.9	7.9	4.6
<u>Mature Harvest, Grain Only</u>			
Control, Below	2.6	11	---
Control, Beside	2.4	10	---
36 cm Dual, Below	2.9	14	5.3
36 cm Dual, Beside	2.5	12	5.0
36 cm Separate, Below	3.0	13	5.5
36 cm Separate, Beside	2.9	13	5.5

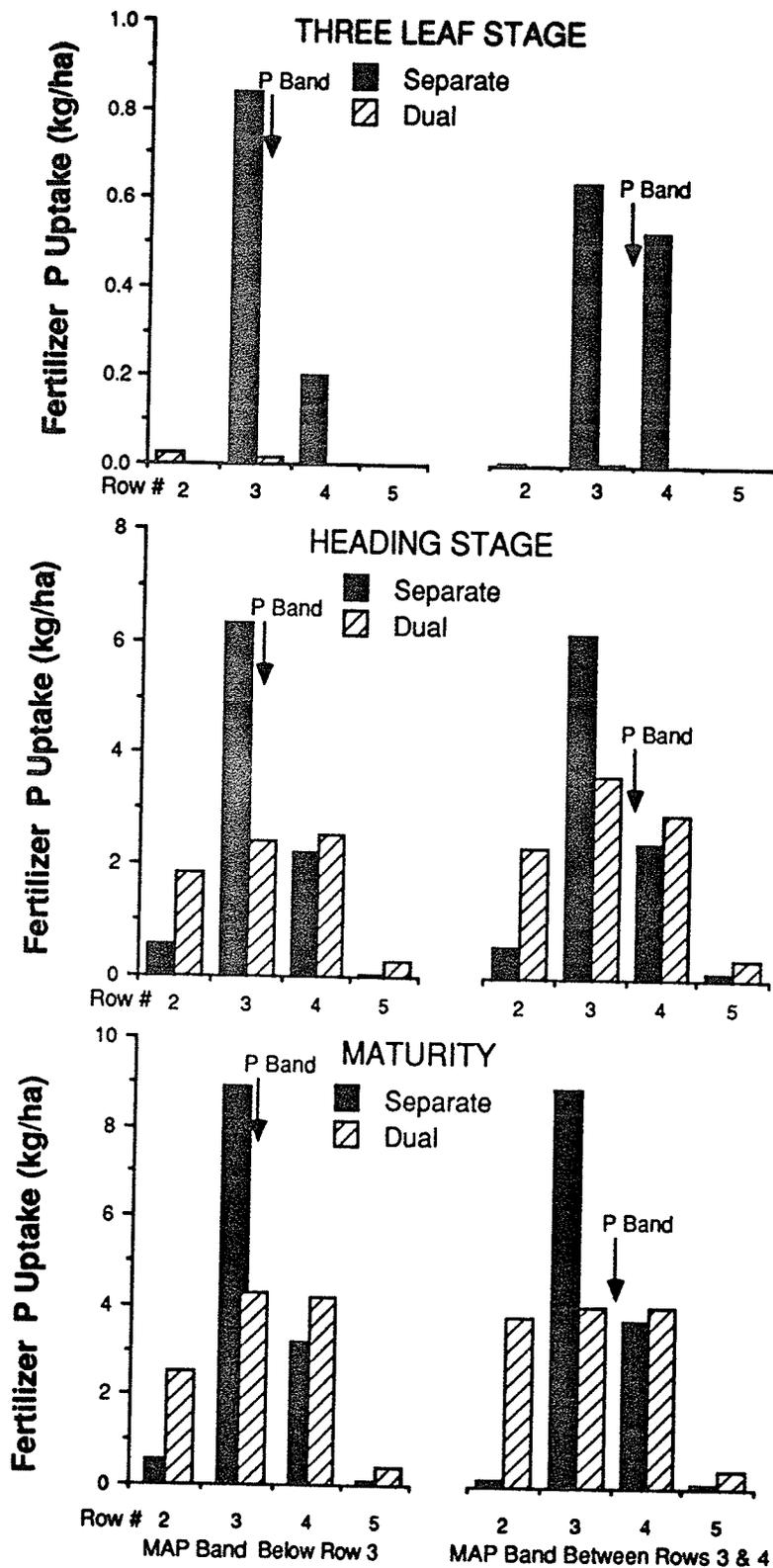


Figure 39. Fertilizer P uptake by wheat as a function of distance from a band of labelled MAP placed parallel to and either below seed row #3 or beside and below seed row #3.

Conclusions

The radiotracer data, although from only a single replicate of each treatment, was consistent with observations made from the growth chamber experiments using ^{32}P and from other field experiments using commercial MAP. Urea banded with MAP in widely spaced bands initially retarded uptake of fertilizer P, but later in the growing season, enhanced uptake of fertilizer P by plants which were not close to the MAP band. The yield data from the replicated field experiment adjacent to the radiotracer field experiment indicated that the delayed uptake of fertilizer P from dual bands may reduce the yield response to P (Table 21).

4. SUMMARY AND CONCLUSIONS

Experiments were conducted between 1981 and 1984 to determine the effect of urea on the solubility and plant uptake of banded MAP.

Two types of laboratory studies were performed to investigate the chemical influence of urea and other compounds placed in MAP bands. The diffusion study indicated that the solubility of P in the MAP fertilizer reaction zone was increased when urea or K_2CO_3 was added with MAP. The solubility of P was not increased when KCl or NH_4Cl was added with MAP. The increase in solubility with added urea or K_2CO_3 was likely due to reduced Ca activity and greater anionic competition caused by high pH and high concentrations of HCO_3 in the reaction zone. The diffusion study also showed that there was a region of high pH and high concentration of ammoniacal-N which extended beyond the furthest extent of fertilizer P movement in a dual band of urea and MAP. These conditions were favourable to the generation of free ammonia which is very toxic to roots.

The elution study illustrated the "snowplowing" effect, where high concentrations of added K or NH_4 displaced exchangeable Ca from exchange sites. As in the diffusion study, much more water-extractable Ca was found in columns treated with KCl or NH_4Cl than in columns treated with urea or K_2CO_3 . More P was eluted from columns treated with MAP + urea than from those treated with MAP (only). However, in contrast to the diffusion study, the increase in solubility of P (as measured by the quantity of P eluted) was less for urea than for other cosolutes. The high solubility of P added with NH_4Cl or KCl in the elution study was likely due to the leaching of displaced Ca out of the columns during elution.

Since chemical availability, exclusive of any influence by the plant, is not the sole factor which influences the plant uptake of P from localized placements of P with other fertilizers, plant uptake studies were also conducted. Several growth chamber experiments were conducted using wheat grown in large growth boxes and MAP labelled with ^{32}P . Unfortunately, yield responses to P fertilization were modest to nonexistent in the growth chamber. No significant differences in dry matter or grain yield were observed among various treatments where MAP was applied with or without urea at time of planting. However, in vivo monitoring revealed that the presence of urea in the MAP bands delayed fertilizer P uptake by 3-10 d, likely because of ammonia toxicity in the dual bands. Rapid uptake of fertilizer P from dual bands followed the initial delay period, resulting in relatively similar uptake of fertilizer P at the heading stage, regardless of distance between the band and the seed row. In contrast, uptake of fertilizer P from MAP bands applied separate from urea decreased with increasing distance between the band and seed row.

An optimum urea concentration study was conducted using urea-N applied in the MAP band at rates of either 0, 23, 47 or 70 kg/ha. Higher concentrations of urea-N in the MAP band resulted in more delay of initiation of fertilizer P uptake. However, the higher concentrations of urea in dual bands also resulted in greater enhancement of fertilizer P uptake from bands placed far from the seed row.

In a succeeding experiment, two methods of detoxifying the dual bands were attempted. Delayed planting reduced the toxicity of the dual bands but also resulted in less enhancement of uptake of fertilizer P from bands

placed far from the seed row. PPD, a urease inhibitor, had little effect on detoxification of the dual band or on the beneficial effects of urea in the MAP band.

Field experiments with wheat were conducted in Southern Manitoba in 1981, 1982 and 1983. Sites were selected to represent soils moderately but not severely deficient in P. As a result yield responses to applied P were small or nonexistent, similar to the responses in the growth chamber. Grain yields and early season P uptake were, however, generally greater for P placed in the seed row, 18 cm dual bands or 36 cm separate bands than for P in 36 cm dual bands. Presumably, the toxicity of ammonia from urea in the dual bands delayed the access of the crop to fertilizer P until the tillering stage. Further evidence of this phenomenon was obtained with the use of ^{32}P at the Roland site where the uptake of fertilizer P from 36 cm dual bands began several weeks later than that from MAP bands placed separate from urea and near the seed row. At all sites, preplant banded P resulted in grain yields that were not significantly greater than those for P placed in the seed row. However, at the only site with a significant P response overall, placement of P in the seed row resulted in the highest yield.

In summary, the effects of urea on the utilization of MAP by wheat are both positive and negative. The chemical availability of P was enhanced when urea was added with MAP in short term studies conducted with soil columns. P uptake data gathered from field and growth chamber experiments indicated that although adding urea with MAP increased the uptake of P from MAP bands that were not close to the seed row, the uptake of P from dual bands was also delayed, regardless of proximity of the dual band to the seed row.

The reason for the delayed uptake of fertilizer P from dual bands was likely the presence of free ammonia which prevented root entry into the band during the seedling stage.

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6. APPENDICES

Appendix A

DETAILS OF THE DIFFUSION AND ELUTION

EXPERIMENTAL PROCEDURES

1) Moisture Retention Characteristics of Soil Used in Diffusion and Elution Experiments

Field capacity moisture content of the soil was estimated by two methods. The first was by adding water to soil columns, allowing the soil columns to stand for 5 d at 22°C and then measuring the moisture loss when dried at 100°C for 30 h. Before the soil was moistened, it was sieved (2 mm) and gently packed into acrylic cylinders 20 cm long and 4.5 cm in diameter. The bottom of the cylinders was covered with plastic mesh and the top of the soil column was covered with parafilm punctured with a small hole. The water front penetrated approximately 3/4 of the length of the soil column and only the wetted soil was removed for moisture content determination. The top third, middle third and bottom third of the moist soil averaged 29, 23 and 15%, respectively over three replicates. The lack of uniform water content made calculation of the field capacity less than precise but it was estimated at approximately 23%.

In a second study two soil samples were moistened, then systematically dehydrated using a pressure-membrane apparatus. The moisture retention data are presented in Table 24. The moisture retention curve was plotted and the water content at 33 kPa was estimated by interpolation.

Preliminary experiments indicated large differences between the

behavior of P in aerobic and anaerobic soil columns. Khalid et al. (1977) also observed that aeration had a large effect on the availability of soil and fertilizer P. Therefore a slightly undersaturated water content of .24 kg water/kg soil was chosen for both the diffusion and elution experiments.

Table 24. Moisture Retention Characteristics of the Soil Used in the Diffusion and Elution Experiments.

Soil Water Potential	Water Content, Weight Basis
kPa	%
10	34.8
27	30.1
67	21.6
133	6.8
1521	2.5

2) Soil Column Handling and Extraction - Diffusion Experiment

The acrylic rings for the soil column were constructed on a lathe to ensure uniformity and a smooth seal between rings. Rings were taped together with plastic "electrician's" tape and using a Nalgene bottle as a form. The water and soil were mixed thoroughly in plastic bag prior to being added to the column because of the nonuniformity of infiltration discussed previously. To maintain aerobic conditions openings were made at both ends of the soil columns and the moist soil was packed loosely with a long tined fork. A smooth surface was formed on the top of the soil column by packing an additional amount (10% more) of moist soil 1 cm above the 10 cm height and then slicing the excess off. Columns were reweighed

to ensure variability of less than 1 g among soil columns. All preparation and dismantling of the soil columns was done in a small, airtight preparation room kept fully humidified using a household humidifier filled with warm water. The MAP and other salts were stored in a dessicator to avoid weighing errors due to differences in hydration. For those treatments receiving MAP and another salt, MAP was added first to ensure even distribution of P. All salts were weighed onto parafilm to reduce sticking due to static electricity problems. Salts were scattered evenly onto the surface of the soil columns using a stainless steel spatula. After taping the protective acrylic collar to the top of the soil columns, the soil columns were covered with parafilm. The parafilm was punctured with 4-1 mm holes and the soil columns were placed in an incubator.

The incubator was a 60x40x30 cm deep polyethylene tub with a lid that fit tightly against a weatherseal. A plastic grate was used for a floor, supported above wet polyurethane foam to assure high humidity. The lid of the box was opened daily to allow air exchange.

During the dismantling of the soil columns, the rings and putty knife were carefully cleaned between discs of soil to avoid cross contamination of samples. It was desirable to maintain a uniform extraction sample mass of approximately 8.3 g of moist soil to allow for a uniform soil to solution ratio of 1:20 during extraction. Complete recovery of soil in the soil columns was attempted at all stages. Samples for extraction were weighed into tared weigh boats and washed into extraction flasks with 135 mL distilled water. After shaking the flasks vigorously on an Eberbach reciprocating shaker, the contents were allowed to settle briefly before decanting the solution into 250 mL centrifuge bottles. Samples were

centrifuged at 6000 rpm for 10 min then decanted into 2-16x100 mm culture tubes. To prepare the bottles for acid extraction, excess supernatant was discarded, except for a remainder of approximately 4 mL which was accounted for in the subsequent acid extract calculations. One of the subsamples of water extract was analysed immediately for pH; the other subsample was acidified with 0.05 ml conc. H_2SO_4 , stoppered and stored for chemical analysis. The acid was added to maintain the solubility of Ca, Mg and P and to flocculate organic matter dispersed by the alkaline salts. The small volume of acid added was considered insignificant (less than 0.5%) and not accounted for in subsequent calculations.

During the acid extraction 135 mL of 0.5M H_2SO_4 was added into the centrifuge bottles which were then shaken and emptied into the original Erlenmeyer flasks. The flasks were covered with vented stoppers during the acid and water extractions to allow carbon dioxide to escape. After 30 min of vigorous shaking the extracts were filtered using Whatman #42 filter paper and the filtrate was stored in stoppered 16x100 mm culture tubes for analysis.

Unfortunately there were several problems with the water and acid extraction techniques described. Other researchers have used soil to water ratios of approximately 1:20 (Strong and Racz 1969; Khasawneh et al. 1974; Blanchar and Caldwell 1966a). However, if one assumes an average soil to water ratio in the soil column of 4:1, the 80-fold dilution of soil solution during extraction may not result in an accurate representation of the fertilizer reaction zone. Secondly, during the acid extraction the acid dissolved compounds that were otherwise, sparingly soluble in water. This released cations from precipitates and partially neutralized the acid

in the process. The latter problem was minor as illustrated by the fact that the total amount of Ca and Mg extracted was similar for most treatments. But to facilitate more reliable and complete extraction of exchangeable cations it may have been prudent to perform sequential acidic extractions sequentially using an acidified NaCl solution.

3) Soil Column Preparation and Handling - Elution Experiment

There were two large problems to overcome while conducting the elution experiment: maintaining an aerobic soil column during incubation and maintaining adequate water flow through the soil columns.

Preliminary experiments indicated that soil columns, 10 cm long and fully saturated with water (approximately 0.3 kg/kg) were anaerobic. This was verified both by analysis of the atmosphere with a mass spectrometer and by the lack of nitrate and nitrite in the eluate. The chemical characteristics and elution profiles of anaerobic soil columns were much different from aerobic soil columns. Yet it was desirable to incubate at a high water content to allow saturated flow during elution. As previously discussed, adding less than 0.3 kg water/kg soil to the top of soil columns resulted in very uneven distribution of water in the soil column, the top being saturated and the bottom barely moist. Prewetting the soil prior to packing was deemed unacceptable due to the inability to establish uniform packing and structure. Therefore, it was decided that suction be applied to water saturated soil columns to draw down the moisture content. The moisture content of soil columns treated this way was fairly uniform.

Similarly it was decided to apply suction to the soil column during elution to maintain that lower water content. The hydraulic conductivity

of the heavily salted soil columns, especially those with alkaline treatments, was often low, probably due to dispersion of the soil particles. As a result, the extraction apparatus between the Masterflex pump and the soil column had to be well maintained and air-tight.

4) Automated Nitrate Plus Nitrite Determination of Water Extracts

Total nitrate plus nitrite-N was determined using a procedure similar to that of Kamphake et al. (1967). Water extracts were diluted with 0.5 M sodium bicarbonate buffered to a pH of 8.5 before being placed into the receiving tray of a Technicon Auto Analyser system. Nitrate was reduced to nitrite with copper and hydrazine in alkaline solution at 53°C. The nitrite was then reacted with sulfanilamide under acid conditions to yield a diazonium salt. The diazonium salt was then treated with N-1-naphthylethylenediamine, forming a colored azo compound. Absorbance of the solution was measured at 520 nm.

5) Automated Phosphorus Determination of Water and Sodium Bicarbonate Extracts

Phosphorus concentrations were determined on a second portion of the sample stream used in the automated nitrate plus nitrite determination. As with the manual method, this was adapted from Murphy and Riley (1962) using ascorbic acid as a reductant for the phosphomolybdate complex. However, the automated method includes a substitution of concentrated hydrochloric acid for sulfuric acid and absorption measurement at 815 nm instead of 885 nm. Water and sodium bicarbonate extracts were diluted with sodium bicarbonate solution buffered at pH 8.5.

Reagents for Auto Analyzer -

Combined Nitrate plus Nitrite Determination

Color Reagent - 400 mL phosphoric acid (H_3PO_4), 40.0 g sulfanilamide and 2.0 g of N-1 Naphthylethylene Diamine Dihydrochloride was added into approximately 3 L of water, diluted to 4 L. 2 mL Brij was added.

Hydrazine Sulfate Stock Solution - 54.0 g Hydrazine Sulfate was dissolved into 1800 mL of water, diluted to 2000 mL.

Hydrazine Sulfate Working Solution - 90 mL stock solution diluted to 4 L using distilled water.

Copper Stock Solution - 2.5 g Anhydrous Cupric Sulfate dissolved in 1000 mL distilled water.

Copper Working Solution - 25 mL copper stock solution diluted to 4 L with distilled water.

Sodium Hydroxide Stock Solution - 120.0 g NaOH dissolved in 1 L distilled water, then cooled and diluted to 2 L.

Sodium Hydroxide Working Solution - 100 mL Sodium Hydroxide stock solution diluted to 1 L.

-Phosphorus Determination

Solution A - 8.0 g Ammonium Molybdate dissolved in 3000 mL distilled water. 400 mL of concentrated HCl added slowly with stirring.

Solution B - 0.4 g of L-Ascorbic Acid added to each 100 mL of Solution A.

6) Ammonium Determination by a Modified Nessler Method

Ammonium-N in water extracts was determined using the Nessler method, modified from Jackson (1958). Twenty mL of distilled water was added to a 50 mL Erlenmeyer flask. Then 0.5 mL of sodium tartrate solution and 1.25 mL of acidified sodium chloride solution was added along with 0.2 to 1.0 mL of extract. Water was added to make 23.75 mL total volume. Then 1.25 mL of the Nessler reagent was added with rapid mixing. After 25 min the absorbance of the solution was read at 410 nm. Each batch included standards prepared from a refrigerated, concentrated standard.

Ammonium-N determination by this method was subject to many interferences including pH. Consequently, ammonium determinations in acid extracts were unreliable, varying with dilution factor. Results of the water extracts were quite reliable, though. Contamination of samples with free amines from deionizer columns and contaminated chloroform used to preserve the ammonium standard solution also presented problems. Shelf life of the Nessler's reagent was only several wk even with careful sealing in an amber colored bottle.

Reagents:

Sodium tartrate - A 10% sodium tartrate solution was prepared by dissolving

100 g $\text{Na}_2\text{C}_4\text{H}_4\text{O}_6 \cdot 2\text{H}_2\text{O}$ in distilled water making a final solution of 1 L.

Acidified Sodium chloride - A 10% sodium chloride solution was prepared by dissolving 100 g NaCl in distilled water making a final solution of 1 L.

The solution was then acidified to pH 2.5 with concentrated HCl.

Nessler Reagent - This reagent is very toxic and corrosive and must be handled carefully. First, 45.5 g of mercuric iodide and 35.0 g of KI was dissolved in a few mL of water. The 112 g of KOH was added and the volume brought to about 800 mL. (Note: It is important to use fresh KOH, not KOH that has been exposed to CO_2 resulting in contamination with K_2CO_3 .) After the solution was mixed and cooled, it was diluted with water to a total volume of 1 L. After being allowed to stand a few days the clear supernatant liquid was decanted into an amber colored bottle and sealed.

Appendix B
COLUMN EXTRACTION DATA FROM
DIFFUSION EXPERIMENT

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - CONTROL TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.52	3.18	35.8	5.9	444	49.8	41	328
0.75	8.48	3.07	34.5	7.6	545	57.6	44	345
1.25	8.55	3.26	34.5	11.5	427	42.1	40	341
1.75	8.55	3.60	36.0	4.0	586	56.0	42	346
2.25	8.56	3.53	35.3	5.8	331	43.1	41	353
2.75	8.57	3.53	37.3	5.8	351	43.2	39	339
3.25	8.62	3.86	38.6	9.6	431	42.5	38	334
3.75	8.61	3.90	39.0	3.9	451	50.7	39	337
4.25	8.63	4.21	42.1	6.0	528	58.2	40	330
4.75	8.58	3.82	43.9	9.5	575	59.2	38	338
5.25	8.60	4.08	44.9	14.3	506	65.4	42	332
5.75	8.64	3.79	43.6	11.3	333	47.4	39	347
6.25	8.62	4.08	40.8	11.6	568	64.2	38	350
6.75	8.62	3.87	38.7	11.6	273	38.7	38	353
7.25	8.63	3.79	37.9	7.5	353	47.4	41	343
7.75	8.68	3.89	38.9	7.7	414	44.7	36	334
8.25	8.68	3.89	36.9	13.6	566	60.3	38	332
8.75	8.65	4.13	31.4	9.8	318	45.2	39	339
9.25	8.65	3.81	28.6	17.1	370	57.2	40	343
9.75	8.65	4.34	29.6	13.8	375	39.5	41	345

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	3002	552	115	331	3447	602	157
0.75	2949	571	115	348	3495	629	159
1.25	2928	551	113	344	3356	593	153
1.75	2949	595	118	349	3536	651	160
2.25	3059	564	113	356	3391	607	155
2.75	2962	544	116	343	3314	587	155
3.25	2914	576	114	338	3345	618	153
3.75	2922	581	117	341	3373	632	156
4.25	2919	576	120	334	3447	635	160
4.75	2717	548	116	342	3292	608	155
5.25	2867	524	116	336	3374	589	159
5.75	3016	525	114	351	3350	573	153
6.25	2948	539	121	354	3516	603	159
6.75	2847	537	122	357	3120	576	161
7.25	2900	545	119	347	3253	593	161
7.75	2871	519	117	338	3285	564	154
8.25	2868	539	121	336	3435	599	160
8.75	2885	504	114	344	3204	549	153
9.25	2915	528	110	347	3286	585	150
9.75	2877	507	122	349	3252	546	164

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - CONTROL TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.53	4.02	13.0	18.1	418	275	50	333
0.75	8.51	3.80	11.4	17.1	315	117	45	334
1.25	8.55	3.40	11.6	14.3	215	93	57	330
1.75	8.54	3.77	11.6	16.1	242	93	37	333
2.25	8.54	4.18	14.2	15.2	329	85	64	325
2.75	8.53	3.84	18.2	9.6	226	74	38	341
3.25	8.54	3.87	21.4	10.2	232	57	38	348
3.75	8.55	4.07	22.4	12.2	393	177	44	343
4.25	8.52	4.15	25.9	8.3	296	126	43	343
4.75	8.56	3.97	26.8	5.9	447	248	43	350
5.25	8.51	4.05	28.8	8.5	429	279	46	351
5.75	8.53	3.98	29.3	8.3	352	257	46	347
6.25	8.53	4.07	32.1	8.5	446	283	51	346
6.75	8.54	3.97	31.4	8.3	305	131	52	342
7.25	8.55	3.86	33.3	6.4	251	70	42	356
7.75	8.53	4.52	32.9	6.1	288	80	34	345
8.25	8.55	4.26	34.1	6.4	219	49	42	349
8.75	8.56	3.97	35.3	8.8	313	110	48	349
9.25	8.55	4.24	33.9	6.3	281	95	38	349
9.75	8.54	4.30	33.9	11.3	418	212	43	351

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	-----mg/kg soil-----	----- Total (Water plus Acid) Extractable -----		
	Ca	Mg	K		P	Ca	Mg
0.25	1724	501	110	337	2143	776	160
0.75	1734	489	106	338	2050	607	151
1.25	1682	486	116	333	1897	579	173
1.75	1731	486	108	336	1974	579	145
2.25	1666	479	105	329	1995	565	170
2.75	1798	486	115	345	2024	560	153
3.25	1865	515	118	352	2098	572	157
3.75	1767	508	109	347	2160	686	154
4.25	1809	500	116	348	2106	627	159
4.75	1788	508	111	354	2236	757	155
5.25	1909	510	115	355	2338	790	162
5.75	1829	486	110	351	2181	744	156
6.25	1874	484	122	350	2321	767	173
6.75	1876	493	119	346	2182	625	171
7.25	1870	493	111	359	2122	564	154
7.75	1847	497	115	349	2135	577	150
8.25	1900	545	113	353	2120	594	155
8.75	1876	501	109	353	2190	611	158
9.25	1877	483	110	353	2159	579	148
9.75	1875	599	108	356	2294	812	151

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - MAP (ONLY) TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	7.14	665.3	5.9	412	193	104	71	1146
0.75	7.22	485.5	9.3	355	204	126	63	885
1.25	7.31	406.0	11.5	304	132	80	63	740
1.75	7.41	292.6	19.5	228	193	94	62	603
2.25	7.45	190.3	26.9	182	163	84	61	465
2.75	7.46	103.1	39.9	128	273	138	58	377
3.25	7.61	42.8	48.7	60	194	91	52	359
3.75	7.88	7.3	45.4	17	174	87	45	345
4.25	8.10	3.9	42.9	33	167	57	53	327
4.75	8.05	4.0	38.8	19	135	38	40	331
5.25	8.10	4.0	41.4	11	131	55	48	337
5.75	8.06	4.1	39.7	9	208	172	51	333
6.25	8.10	4.2	39.4	11	196	121	47	330
6.75	8.17	4.1	39.5	12	191	81	45	344
7.25	8.17	3.9	37.9	11	191	81	43	345
7.75	8.16	3.9	37.1	15	191	99	46	329
8.25	8.15	4.2	39.1	14	248	76	56	332
8.75	8.17	4.6	40.1	18	206	82	50	330
9.25	8.20	3.7	40.0	16	223	78	40	317
9.75	8.20	5.1	38.6	15	167	64	74	339

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----						
	Ca	Mg	K	P	Ca	Mg	K
0.25	2012	470	78	1811	2205	575	150
0.75	1554	398	72	1371	1759	524	136
1.25	1477	385	73	1146	1610	466	136
1.75	1606	380	76	895	1799	474	138
2.25	1299	401	81	655	1462	485	142
2.75	1345	389	80	480	1618	528	139
3.25	1627	420	100	402	1822	512	153
3.75	1629	399	107	352	1804	486	153
4.25	1485	405	107	331	1653	463	161
4.75	1585	412	110	335	1721	451	151
5.25	1704	409	103	341	1835	465	152
5.75	1460	401	104	337	1669	574	156
6.25	1608	366	104	334	1804	487	152
6.75	1695	425	116	348	1886	506	162
7.25	1536	398	105	349	1727	480	149
7.75	1636	393	103	333	1827	493	150
8.25	1340	400	101	336	1589	477	157
8.75	1437	410	105	334	1644	492	156
9.25	1509	356	96	321	1732	434	137
9.75	1330	483	104	344	1498	548	178

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - MAP (ONLY) TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.97	693.9	11.2	398	332	223	67	1172
0.75	7.10	488.6	14.0	324	189	92	64	883
1.25	7.20	396.7	17.5	283	377	183	62	678
1.75	7.24	284.6	25.6	203	320	166	58	556
2.25	7.35	171.7	37.9	121	253	61	51	443
2.75	7.50	88.7	48.7	82	342	168	58	402
3.25	7.85	37.1	51.7	21	279	181	44	346
3.75	8.50	5.7	47.4	8	280	94	57	336
4.25	8.65	4.3	39.5	6	272	81	48	323
4.75	8.65	4.8	40.0	10	310	126	46	350
5.25	8.60	4.2	36.7	6	412	350	46	344
5.75	8.60	4.2	37.1	11	304	163	44	343
6.25	8.62	4.1	37.9	3	291	111	45	341
6.75	8.65	4.2	37.1	10	345	131	44	340
7.25	8.65	4.2	36.8	9	269	75	42	345
7.75	8.67	4.0	35.1	6	323	94	36	338
8.25	8.67	4.7	35.5	8	310	116	34	343
8.75	8.65	4.3	35.7	10	251	73	34	343
9.25	8.63	4.2	35.4	5	182	44	37	337
9.75	8.65	4.6	36.4	10	432	239	52	343

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----						
	Ca	Mg	K	P	Ca	Mg	K
0.25	2119	463	81	1865	2452	687	148
0.75	2013	972	86	1372	2202	1065	151
1.25	1851	471	76	1075	2228	655	139
1.75	1865	751	84	840	2186	918	143
2.25	1781	477	84	614	2034	539	136
2.75	1799	449	91	491	2141	618	150
3.25	1673	445	99	384	1952	626	144
3.75	1782	469	111	341	2062	564	169
4.25	1775	465	107	327	2047	546	155
4.75	1893	814	109	355	2204	940	156
5.25	1850	472	109	348	2262	823	156
5.75	1938	484	103	347	2243	647	148
6.25	1907	475	117	345	2199	587	163
6.75	1894	465	105	344	2240	597	150
7.25	1869	482	106	349	2138	558	149
7.75	1830	611	108	342	2153	705	144
8.25	1863	477	105	348	2173	593	139
8.75	1937	484	108	348	2189	558	143
9.25	1781	469	106	342	1963	514	143
9.75	1999	701	108	347	2431	940	160

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - UREA+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.93	790.5	5.5	1957	217	170	88	938
0.75	8.97	712.6	4.9	1993	175	120	86	838
1.25	9.02	586.2	5.0	1904	198	178	97	824
1.75	9.06	388.1	5.3	1701	125	134	89	550
2.25	9.07	39.4	4.8	1478	99	77	73	332
2.75	9.03	12.2	7.0	1335	156	170	74	313
3.25	9.02	9.4	11.3	1046	51	35	71	330
3.75	9.00	8.6	15.1	810	52	44	80	331
4.25	8.87	6.7	27.5	502	100	130	65	323
4.75	8.56	5.3	42.9	223	101	55	62	322
5.25	8.34	4.4	50.8	128	91	30	54	339
5.75	8.18	3.7	54.0	95	156	44	50	325
6.25	8.02	3.9	51.3	41	260	138	47	322
6.75	8.02	3.6	43.6	19	248	127	40	329
7.25	8.05	3.7	42.1	21	147	43	43	347
7.75	7.47	4.1	35.3	22	174	57	52	343
8.25	8.07	4.1	36.2	20	190	68	66	330
8.75	8.05	4.0	34.9	23	182	57	72	335
9.25	8.06	3.6	38.4	21	184	92	38	328
9.75	8.02	4.4	41.7	30	258	158	94	329

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	Total (Water plus Acid) Extractable P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	1662	421	65	1729	1879	591	154
0.75	1573	404	62	1551	1749	525	149
1.25	1741	493	70	1410	1940	672	167
1.75	1480	428	74	938	1605	562	163
2.25	1630	407	77	372	1729	485	151
2.75	1613	375	78	326	1770	546	152
3.25	1799	413	83	340	1850	449	155
3.75	1601	727	99	340	1653	771	180
4.25	1795	895	105	330	1895	1026	170
4.75	1466	405	90	327	1567	460	153
5.25	1698	432	107	343	1789	463	162
5.75	1554	441	105	329	1711	486	156
6.25	1714	410	112	326	1975	548	159
6.75	1667	409	114	332	1915	537	155
7.25	1623	437	119	351	1771	480	163
7.75	1844	423	116	347	2019	480	169
8.25	1596	414	113	334	1787	482	179
8.75	1669	445	117	339	1852	502	189
9.25	1672	789	121	332	1856	881	160
9.75	1722	405	108	333	1981	563	203

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - UREA+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.85	933.2	2.5	2309	189	55	88	1032
0.75	8.90	799.1	1.8	2139	196	77	75	945
1.25	8.92	695.7	1.9	1947	145	63	79	850
1.75	8.90	510.2	3.1	1881	186	62	75	706
2.25	8.96	115.2	4.3	1602	89	38	68	395
2.75	8.95	16.3	7.3	1431	102	52	64	344
3.25	8.94	10.4	10.4	1267	150	75	64	351
3.75	8.91	8.7	14.5	895	109	67	78	345
4.25	8.85	7.2	23.8	682	91	60	62	339
4.75	8.69	6.5	37.6	391	133	63	55	347
5.25	8.44	5.1	49.1	261	200	120	55	355
5.75	8.40	3.7	53.4	112	258	101	43	347
6.25	8.50	4.0	48.9	46	229	53	51	348
6.75	8.60	3.4	40.8	11	235	75	49	363
7.25	8.60	3.9	36.5	10	233	56	43	347
7.75	8.58	3.9	35.4	7	226	59	37	344
8.25	8.57	3.7	34.6	9	249	67	33	346
8.75	8.60	3.6	34.0	12	250	79	40	335
9.25	8.59	3.8	33.6	10	325	116	44	360
9.75	8.60	4.1	34.0	14	232	65	39	349

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	2324	1320	78	1965	2513	1376	166
0.75	2196	1058	73	1744	2393	1135	149
1.25	2177	1002	65	1545	2323	1066	145
1.75	2285	1219	71	1217	2472	1282	146
2.25	1991	882	77	510	2080	921	145
2.75	2284	1120	84	361	2387	1173	149
3.25	2217	785	82	361	2368	860	147
3.75	2416	991	80	354	2526	1058	159
4.25	2388	1129	87	346	2479	1189	150
4.75	2182	1113	85	354	2315	1176	141
5.25	2142	944	99	360	2343	1065	154
5.75	2001	991	112	351	2260	1093	155
6.25	1949	758	113	352	2178	812	164
6.75	1986	752	113	366	2221	828	163
7.25	1940	810	112	351	2174	866	156
7.75	1916	740	116	348	2142	799	153
8.25	1955	894	113	350	2204	962	146
8.75	1882	775	106	339	2132	854	147
9.25	1866	703	108	364	2192	820	152
9.75	1989	867	113	354	2222	933	152

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.86	702.5	5.2	2705	325	190	81	1283
0.75	7.02	540.7	5.2	2661	394	247	86	971
1.25	7.13	377.0	5.6	2413	262	122	79	739
1.75	7.32	260.3	6.7	2234	374	246	77	570
2.25	7.54	158.6	9.6	1993	386	199	81	413
2.75	7.73	56.4	12.3	1626	264	106	80	368
3.25	7.93	7.0	16.4	1291	321	84	80	351
3.75	8.00	3.3	26.2	1030	371	119	79	332
4.25	8.02	3.6	35.4	766	346	74	91	331
4.75	8.01	2.9	45.8	548	462	188	86	324
5.25	8.04	3.1	57.9	401	493	158	85	342
5.75	8.10	3.1	61.5	275	574	201	84	341
6.25	8.20	3.1	60.7	174	372	96	74	347
6.75	8.45	3.2	56.0	90	317	116	73	338
7.25	8.60	3.3	46.4	44	269	102	55	325
7.75	8.70	3.7	38.9	35	243	101	54	332
8.25	8.76	3.8	33.2	34	285	191	44	325
8.75	8.75	4.1	32.7	26	178	82	41	329
9.25	8.80	3.8	32.2	18	173	73	38	332
9.75	8.84	4.3	31.8	30	173	101	45	330

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	-----mg/kg soil-----	----- Total (Water plus Acid) Extractable -----		
	Ca	Mg	K		P	Ca	Mg
0.25	1648	117	42	1985	1973	308	124
0.75	1747	334	45	1511	2142	581	131
1.25	1426	349	42	1117	1688	472	121
1.75	1514	364	45	830	1889	611	123
2.25	1275	555	49	572	1662	755	130
2.75	1283	375	58	424	1548	482	139
3.25	1502	404	65	358	1823	489	145
3.75	1473	359	58	335	1844	478	137
4.25	1449	379	70	335	1796	454	161
4.75	1466	566	74	327	1929	755	166
5.25	1647	789	80	345	2140	948	166
5.75	1546	394	84	345	2121	595	168
6.25	1430	751	92	350	1802	848	167
6.75	1519	436	107	341	1836	552	180
7.25	1577	418	105	328	1846	520	161
7.75	1671	420	106	336	1914	521	161
8.25	1520	410	104	328	1806	601	148
8.75	1435	420	106	333	1613	502	148
9.25	1743	424	107	335	1916	498	145
9.75	1703	666	114	334	1876	768	160

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.80	709.0	2.2	2700	414	153	74	1336
0.75	6.92	586.5	1.9	2643	376	162	71	1055
1.25	7.07	380.7	1.9	2365	303	90	74	758
1.75	7.26	275.8	1.8	2199	298	78	70	588
2.25	7.51	155.9	2.7	1875	289	107	70	444
2.75	7.68	53.6	4.7	1684	343	97	78	379
3.25	7.86	6.8	10.0	1468	429	117	92	336
3.75	7.94	3.5	14.1	1197	421	113	79	334
4.25	7.96	3.8	20.3	842	478	152	81	333
4.75	7.98	3.5	28.8	606	507	136	86	339
5.25	8.02	3.5	36.4	419	488	152	75	325
5.75	8.11	3.4	43.3	342	702	162	71	339
6.25	8.21	3.7	47.2	190	413	77	62	343
6.75	8.35	3.5	42.6	92	390	94	53	331
7.25	8.53	3.7	36.5	27	369	91	43	343
7.75	8.60	4.2	28.1	15	342	92	42	347
8.25	8.62	3.6	22.7	14	240	61	32	333
8.75	8.60	3.6	18.0	27	331	126	39	351
9.25	8.60	3.7	16.6	22	287	109	38	344
9.75	8.64	4.1	16.6	21	271	101	39	350

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	2177	963	55	2045	2591	1116	130
0.75	1905	813	49	1641	2281	975	120
1.25	1734	749	47	1139	2038	839	122
1.75	1695	874	49	864	1993	952	120
2.25	1611	875	51	600	1901	983	121
2.75	1607	711	54	432	1950	809	133
3.25	1615	702	57	343	2045	819	150
3.75	1702	683	61	338	2124	797	141
4.25	1706	521	64	337	2185	674	146
4.75	1786	875	73	343	2294	1011	160
5.25	1805	973	79	328	2294	1126	154
5.75	1957	845	87	342	2660	1008	158
6.25	2048	967	99	347	2461	1045	162
6.75	1957	1126	107	334	2348	1220	160
7.25	1976	1155	119	347	2346	1247	162
7.75	2088	909	119	351	2430	1002	161
8.25	1924	716	107	337	2165	778	140
8.75	1889	778	110	355	2221	905	150
9.25	1955	839	107	348	2242	948	146
9.75	2024	834	109	354	2296	936	148

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - KCl+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.94	758.3	3.4	375	378	571	6108	1403
0.75	6.99	619.9	2.7	304	328	225	5959	1060
1.25	7.23	403.8	2.8	268	237	86	5526	745
1.75	7.49	241.1	4.4	248	281	143	4823	566
2.25	7.91	128.3	8.0	245	327	188	5102	415
2.75	8.16	33.1	16.0	187	279	94	3742	367
3.25	8.33	3.4	22.5	170	388	143	3053	333
3.75	8.41	3.3	31.1	149	373	99	2430	342
4.25	8.42	2.8	43.4	127	434	143	1836	336
4.75	8.45	2.8	51.3	98	408	106	1417	342
5.25	8.57	2.9	56.4	64	599	134	954	332
5.75	8.63	2.7	55.9	21	420	158	613	334
6.25	8.82	3.1	52.5	13	378	122	356	330
6.75	8.84	3.2	43.9	8	360	145	163	345
7.25	8.83	3.5	39.6	7	523	216	99	334
7.75	8.85	3.8	34.8	6	401	158	63	334
8.25	8.85	4.0	33.4	11	358	172	71	334
8.75	8.85	3.9	34.4	5	238	114	137	330
9.25	8.90	4.3	34.2	8	263	105	103	343
9.75	8.88	4.9	34.6	7	279	225	98	341

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	1592	327	1220	2162	1970	898	7329
0.75	1665	354	1280	1680	1993	579	7240
1.25	1448	369	1268	1149	1686	456	6794
1.75	1331	386	1134	807	1613	530	5958
2.25	1177	354	1010	544	1504	543	6112
2.75	1325	356	976	400	1605	451	4718
3.25	1240	695	853	337	1628	839	3906
3.75	1413	670	724	345	1787	770	3154
4.25	1361	417	584	339	1796	560	2420
4.75	1413	407	476	345	1821	513	1893
5.25	1428	393	391	335	2028	527	1345
5.75	1426	400	284	336	1846	558	897
6.25	1551	394	217	333	1929	516	574
6.75	1531	433	157	348	1891	579	321
7.25	1410	409	113	337	1933	625	212
7.75	1543	428	106	338	1944	586	170
8.25	1538	428	103	338	1897	600	175
8.75	1518	760	103	333	1756	874	241
9.25	1668	1209	107	347	1931	1315	211
9.75	2041	1144	116	346	2321	1369	215

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - KCl+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.82	752.6	7.0	396	501	180	6758	1394
0.75	7.02	567.8	6.8	381	519	188	6864	952
1.25	7.20	354.8	8.6	351	372	140	5989	666
1.75	7.53	216.9	10.0	237	258	74	5232	507
2.25	7.90	111.4	12.7	220	273	74	4651	415
2.75	8.19	22.6	20.4	208	272	72	3901	363
3.25	8.32	4.2	30.0	193	328	77	3052	336
3.75	8.32	3.3	41.2	181	375	78	2374	335
4.25	8.34	3.1	52.4	134	377	79	1722	339
4.75	8.42	3.3	60.3	93	387	80	1126	346
5.25	8.45	3.1	62.3	62	438	106	748	338
5.75	8.50	3.4	56.6	39	378	82	441	338
6.25	8.61	3.1	52.3	19	404	102	203	338
6.75	8.65	3.3	42.7	12	365	98	100	345
7.25	8.63	3.5	41.2	12	253	57	53	332
7.75	8.70	3.9	30.8	16	228	49	37	334
8.25	8.70	4.2	33.8	14	192	50	46	384
8.75	8.70	3.7	32.5	11	167	42	39	340
9.25	8.70	4.0	32.0	16	162	46	44	340
9.75	8.68	4.2	28.9	17	165	47	45	341

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----						
	Ca	Mg	K	P	Ca	Mg	K
0.25	2049	811	1253	2146	2550	991	8011
0.75	1792	436	1133	1519	2311	625	7998
1.25	1710	594	1084	1021	2082	734	7074
1.75	1600	474	1062	724	1859	549	6295
2.25	1669	537	948	526	1943	611	5599
2.75	1773	955	852	386	2045	1027	4753
3.25	1742	705	738	340	2071	783	3790
3.75	1655	531	602	339	2031	609	2976
4.25	1768	638	529	343	2145	718	2252
4.75	1803	867	420	349	2191	947	1546
5.25	1823	680	329	341	2261	787	1078
5.75	1842	506	224	341	2220	588	666
6.25	1932	585	181	342	2337	688	384
6.75	1952	512	128	349	2318	610	228
7.25	1952	524	106	336	2206	582	160
7.75	1908	998	106	338	2136	1047	143
8.25	1893	538	103	389	2086	588	149
8.75	1903	830	100	344	2071	873	139
9.25	1978	1269	103	344	2140	1315	148
9.75	1965	1002	104	346	2130	1049	149

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	9.92	891.1	0.0	208	174	119	7251	687
0.75	9.80	801.2	0.8	170	113	69	6484	545
1.25	9.73	694.5	1.8	161	110	37	5856	493
1.75	9.70	562.3	5.2	235	151	189	5075	477
2.25	9.70	385.6	9.7	218	120	153	3797	449
2.75	9.63	140.6	20.9	190	90	81	2658	400
3.25	9.58	50.0	38.4	153	91	97	1745	357
3.75	9.35	12.5	56.3	129	96	133	983	339
4.25	8.93	4.5	54.3	77	119	134	398	275
4.75	8.75	5.3	93.9	61	218	114	265	414
5.25	8.80	4.2	66.2	13	267	230	116	353
5.75	8.80	4.3	56.6	8	263	169	108	331
6.25	8.85	4.3	43.7	8	216	177	87	344
6.75	8.85	4.0	39.8	4	212	155	143	338
7.25	8.84	3.7	37.5	5	212	139	75	334
7.75	8.84	3.5	36.6	8	209	97	68	331
8.25	8.87	4.2	34.8	8	230	135	84	337
8.75	8.82	3.6	34.6	6	211	126	51	342
9.25	8.88	4.2	33.9	4	191	57	63	336
9.75	8.90	4.2	32.8	8	224	142	63	353

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	1498	816	2124	1578	1672	936	9375
0.75	1870	460	1967	1346	1984	529	8452
1.25	1639	425	1934	1188	1749	463	7791
1.75	1673	516	1860	1040	1825	706	6936
2.25	1724	438	1722	835	1845	592	5520
2.75	1690	432	1540	541	1780	514	4198
3.25	1802	435	1202	407	1894	533	2948
3.75	1598	434	770	351	1694	568	1754
4.25	1145	344	322	280	1265	479	721
4.75	1944	861	265	419	2163	976	530
5.25	1423	440	141	357	1690	670	258
5.75	1500	418	108	335	1763	588	217
6.25	1477	429	107	348	1693	606	195
6.75	1425	431	103	342	1672	586	246
7.25	1460	415	102	338	1672	554	177
7.75	1575	610	103	335	1785	707	171
8.25	1376	826	104	341	1607	962	188
8.75	1553	611	101	345	1765	737	153
9.25	1566	914	111	340	1757	971	175
9.75	1616	710	116	358	1841	852	179

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 1 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	9.93	916.9	2.3	193	265	232	7277	670
0.75	9.85	810.2	1.9	150	100	42	6748	539
1.25	9.80	731.5	1.8	219	165	96	6609	511
1.75	9.75	573.4	4.6	178	133	64	5567	477
2.25	9.70	421.3	6.3	176	93	48	4483	460
2.75	9.52	252.0	11.7	166	117	56	3067	396
3.25	9.32	73.8	28.4	151	102	81	1969	366
3.75	8.75	14.5	46.7	145	149	110	1123	355
4.25	8.60	6.1	62.6	82	102	121	476	339
4.75	8.61	5.2	70.8	49	318	141	262	338
5.25	8.71	5.2	62.9	17	242	110	86	342
5.75	8.60	4.3	50.8	16	292	107	41	328
6.25	8.60	5.0	40.2	16	225	72	38	348
6.75	8.60	3.9	37.4	15	275	100	33	350
7.25	8.71	4.3	35.3	9	183	66	30	350
7.75	8.74	4.8	35.7	15	282	218	30	345
8.25	8.75	5.5	35.1	11	263	135	35	343
8.75	8.75	4.4	35.0	16	194	58	32	341
9.25	8.75	4.4	35.7	12	241	96	30	337
9.75	8.80	6.2	35.1	15	326	135	37	345

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----						
	Ca	Mg	K	P	Ca	Mg	K
0.25	1906	1380	2164	1587	2172	1612	9442
0.75	1854	983	2250	1349	1954	1026	8999
1.25	1904	1031	2233	1243	2069	1127	8842
1.75	1860	838	1995	1051	1994	903	7563
2.25	1924	782	1907	881	2018	831	6390
2.75	1883	766	1651	648	2000	823	4719
3.25	1965	543	1333	440	2067	624	3303
3.75	1987	1465	834	369	2137	1576	1957
4.25	1703	792	430	345	1806	913	906
4.75	1703	506	221	343	2021	647	484
5.25	1881	612	138	348	2124	722	224
5.75	1828	1182	118	333	2121	1290	159
6.25	1885	617	112	353	2111	690	151
6.75	1947	791	116	354	2223	891	150
7.25	1956	740	107	354	2140	806	137
7.75	1914	556	110	350	2196	774	141
8.25	1832	516	107	348	2095	651	142
8.75	1939	599	108	346	2133	657	140
9.25	1814	590	102	342	2055	687	132
9.75	2191	1186	128	352	2517	1322	165

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - CONTROL TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.65	4.0	63	32	951	104	38	339
0.75	8.70	3.9	56	45	398	65	37	342
1.25	8.70	3.7	56	50	589	91	31	336
1.75	8.70	4.0	56	54	429	73	36	349
2.25	8.70	4.1	54	56	468	73	34	330
2.75	8.70	4.3	58	43	460	77	31	337
3.25	8.73	4.3	58	41	405	68	37	344
3.75	8.74	3.7	53	28	450	90	30	348
4.25	8.74	3.8	56	32	317	63	32	328
4.75	8.72	4.6	58	56	481	83	33	338
5.25	8.72	3.8	56	50	496	231	32	351
5.75	8.70	3.8	57	50	525	69	30	330
6.25	8.73	3.8	55	44	376	66	31	336
6.75	8.72	4.0	56	52	396	67	34	353
7.25	8.70	3.9	60	39	464	73	34	344
7.75	8.72	3.8	58	58	319	114	29	348
8.25	8.70	4.3	60	36	332	62	30	341
8.75	8.72	3.9	60	62	352	64	30	342
9.25	8.72	3.7	61	38	412	92	30	340
9.75	8.72	4.7	59	66	433	199	30	460

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	2950	571	103	343	3902	675	141
0.75	2757	520	97	346	3156	586	135
1.25	2793	536	97	340	3382	627	129
1.75	3253	793	99	353	3682	866	136
2.25	2932	600	101	334	3401	674	136
2.75	2935	557	104	342	3395	634	135
3.25	3195	660	105	348	3601	729	143
3.75	2889	542	100	352	3340	633	130
4.25	2881	626	99	332	3199	689	132
4.75	3262	795	102	342	3744	879	136
5.25	2903	489	108	355	3400	721	140
5.75	3035	651	92	334	3560	720	122
6.25	2784	473	96	340	3161	540	127
6.75	3045	730	103	357	3442	797	138
7.25	2767	484	96	348	3232	557	130
7.75	2899	518	99	352	3219	633	128
8.25	2898	553	96	346	3230	615	126
8.75	3013	831	96	346	3365	895	126
9.25	2758	653	88	344	3170	745	118
9.75	2890	530	62	465	3323	729	93

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - CONTROL TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.60	4.2	50	6	430	46	40	338
0.75	8.65	4.0	55	13	449	55	42	328
1.25	8.76	4.1	53	9	350	49	41	342
1.75	8.75	4.4	54	22	467	56	38	333
2.25	8.76	4.4	54	14	523	59	40	347
2.75	8.75	4.3	57	10	567	67	47	335
3.25	8.73	4.5	57	14	488	57	43	338
3.75	8.76	4.3	59	9	499	55	39	348
4.25	8.75	4.4	61	14	414	55	38	338
4.75	8.74	4.0	60	18	596	66	52	340
5.25	8.74	4.1	62	16	692	66	45	342
5.75	8.75	4.1	59	17	585	67	47	336
6.25	8.73	4.2	63	21	364	50	42	327
6.75	8.77	4.2	60	18	435	54	42	346
7.25	8.75	4.5	59	22	354	53	45	343
7.75	8.78	4.3	56	14	394	50	39	345
8.25	8.78	4.4	58	26	474	54	38	334
8.75	8.77	4.2	59	21	388	61	38	336
9.25	8.73	4.2	64	17	520	56	38	337
9.75	8.72	4.4	62	20	467	58	40	343

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----		
	-----mg/kg soil-----					
	P	Ca	Mg	K		
0.25	342	3320	546	150		
0.75	332	3243	587	151		
1.25	346	3218	595	151		
1.75	338	3295	573	149		
2.25	352	3378	560	148		
2.75	339	3461	592	157		
3.25	343	3435	567	155		
3.75	352	3442	600	155		
4.25	342	3301	557	146		
4.75	344	3842	663	164		
5.25	346	3541	578	164		
5.75	340	3376	578	165		
6.25	331	3206	547	155		
6.75	350	3364	595	158		
7.25	347	3246	560	156		
7.75	350	3455	628	152		
8.25	339	3018	489	149		
8.75	340	3068	534	150		
9.25	341	3154	516	148		
9.75	348	3210	616	153		

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - MAP (ONLY) TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.75	412.0	160	236	664	130	51	1282
0.75	6.85	270.1	172	209	495	161	46	977
1.25	7.00	226.9	159	196	639	125	45	838
1.75	7.05	170.6	169	145	709	122	42	723
2.25	6.55	106.9	177	106	469	98	41	503
2.75	6.45	79.4	166	90	509	232	39	460
3.25	6.60	65.7	149	87	372	77	39	428
3.75	6.99	53.5	140	62	564	188	45	428
4.25	7.04	49.9	129	49	437	133	43	418
4.75	8.25	36.3	123	54	465	74	41	387
5.25	8.60	17.8	116	50	434	74	40	357
5.75	8.62	7.1	112	57	407	65	39	346
6.25	8.65	4.3	104	61	441	76	35	344
6.75	8.65	4.7	93	58	638	93	37	346
7.25	8.65	4.2	87	46	531	69	34	353
7.75	8.65	4.0	86	44	401	66	34	344
8.25	8.70	4.0	81	58	518	73	34	359
8.75	8.70	4.0	85	51	320	59	32	361
9.25	8.70	4.0	90	46	377	64	34	338
9.75	8.70	3.5	89	57	532	89	35	334

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	3189	479	92	1694	3853	609	144
0.75	3120	526	80	1247	3616	688	126
1.25	3055	519	86	1065	3704	644	131
1.75	2799	490	88	894	3509	613	126
2.25	2384	515	85	610	2853	613	131
2.75	3243	380	83	539	3752	612	122
3.25	3230	428	89	494	3603	506	128
3.75	2495	484	100	482	3060	672	146
4.25	2731	487	99	468	3168	620	142
4.75	2723	480	103	423	3189	555	144
5.25	2830	554	103	375	3264	628	143
5.75	2972	537	95	353	3380	602	134
6.25	2887	525	100	349	3329	602	135
6.75	2847	532	93	351	3485	625	130
7.25	2901	517	92	357	3433	587	127
7.75	2898	534	98	348	3299	600	132
8.25	2935	520	93	363	3453	594	127
8.75	2858	548	107	365	3179	607	139
9.25	2777	514	89	342	3154	578	123
9.75	2853	525	83	338	3386	614	119

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - MAP (ONLY) TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	6.90	387.8	181	229	891	145	61	1258
0.75	6.95	265.1	207	186	542	115	54	968
1.25	7.02	211.6	198	171	633	106	73	798
1.75	7.00	159.7	190	138	325	88	50	692
2.25	6.60	103.2	186	107	355	81	99	498
2.75	6.52	80.9	180	60	446	81	76	463
3.25	6.67	70.5	177	48	333	71	57	430
3.75	7.10	56.2	166	54	417	74	56	424
4.25	7.97	49.8	147	55	533	76	53	409
4.75	8.37	35.7	141	42	436	84	48	376
5.25	8.56	22.9	136	37	477	73	50	376
5.75	8.65	8.5	118	40	340	59	46	332
6.25	8.60	3.6	116	38	366	62	44	331
6.75	8.70	3.7	111	61	411	61	41	345
7.25	8.70	3.9	102	51	409	57	41	357
7.75	8.72	4.1	101	43	333	92	43	343
8.25	8.70	3.8	98	55	377	81	49	334
8.75	8.70	3.8	95	48	404	59	35	324
9.25	8.70	3.7	93	46	530	68	48	333
9.75	8.70	3.8	96	40	554	76	36	333

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	3335	532	89	1646	4227	677	150
0.75	3093	538	85	1233	3635	654	139
1.25	2974	546	84	1010	3608	653	158
1.75	2721	514	85	852	3047	603	135
2.25	2290	478	82	602	2645	559	182
2.75	2119	428	91	544	2566	509	167
3.25	2271	475	98	500	2605	547	155
3.75	2572	514	103	480	2989	588	160
4.25	2781	544	113	459	3314	621	167
4.75	2819	528	111	411	3256	612	160
5.25	2670	517	119	399	3148	591	170
5.75	2818	555	112	340	3158	615	158
6.25	2901	556	112	334	3268	618	156
6.75	2888	532	107	349	3299	594	149
7.25	2866	548	106	361	3276	606	145
7.75	2854	527	102	347	3188	620	148
8.25	2826	522	99	337	3203	604	141
8.75	2843	521	105	328	3247	580	154
9.25	2898	554	105	337	3429	622	154
9.75	2826	537	100	337	3380	613	136

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - UREA+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.45	623.5	200	967	414	81	81	899
0.75	8.55	553.8	198	959	438	75	77	806
1.25	8.60	470.8	192	833	228	73	80	716
1.75	8.60	257.9	223	760	291	68	69	561
2.25	8.62	230.0	267	682	383	97	65	472
2.75	8.48	171.7	321	528	356	93	69	417
3.25	8.24	30.3	395	387	432	77	59	389
3.75	7.60	13.7	434	301	460	79	56	365
4.25	7.42	8.3	453	252	367	79	55	351
4.75	7.43	5.3	460	261	595	110	51	338
5.25	7.50	4.9	467	309	511	116	51	339
5.75	7.59	5.5	471	314	657	137	48	344
6.25	7.62	5.5	474	154	556	136	48	333
6.75	7.67	5.3	454	93	464	127	49	353
7.25	7.90	4.8	435	70	564	127	55	336
7.75	8.30	3.8	406	61	542	114	55	338
8.25	8.50	2.8	380	62	523	107	53	338
8.75	8.62	3.0	354	102	596	112	57	341
9.25	8.66	3.2	349	38	604	107	54	341
9.75	8.70	3.2	351	92	664	144	56	328

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	-----mg/kg soil-----	----- Total (Water plus Acid) Extractable -----		
	Ca	Mg	K		Ca	Mg	K
0.25	3126	630	81	1523	3540	711	163
0.75	3013	554	79	1360	3452	630	156
1.25	2837	519	70	1187	3066	593	150
1.75	3030	582	73	819	3322	650	142
2.25	3376	651	61	702	3759	748	127
2.75	3696	583	60	589	4052	677	129
3.25	3471	483	55	420	3903	561	114
3.75	2592	455	54	379	3052	534	110
4.25	2384	468	49	360	2752	548	105
4.75	2404	460	57	344	2999	570	108
5.25	2294	509	62	344	2806	626	114
5.75	2237	429	60	349	2895	566	108
6.25	2101	373	61	338	2657	509	110
6.75	2115	347	68	358	2580	475	117
7.25	2124	367	79	341	2688	494	134
7.75	1399	271	88	341	1942	386	144
8.25	1584	309	99	341	2107	416	153
8.75	1691	313	91	344	2287	425	148
9.25	1689	309	94	344	2293	416	148
9.75	1711	328	93	331	2376	473	149

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - UREA+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	8.52	563.0	194	790	575	59	104	986
0.75	8.58	490.7	188	817	575	152	48	901
1.25	8.57	481.4	212	798	547	59	90	885
1.75	8.60	366.7	220	776	390	145	57	648
2.25	8.70	178.5	219	703	433	128	61	468
2.75	8.63	155.1	231	629	361	69	54	454
3.25	8.50	70.9	275	501	556	70	60	404
3.75	8.34	19.9	322	389	416	61	34	384
4.25	8.00	10.2	372	317	529	70	39	371
4.75	7.75	6.9	413	280	537	89	46	351
5.25	7.45	4.8	440	260	714	111	35	344
5.75	7.35	5.1	463	314	763	120	36	340
6.25	7.15	4.9	446	215	547	114	33	345
6.75	7.16	4.7	462	139	529	120	32	336
7.25	7.10	4.9	447	78	593	128	35	347
7.75	7.50	3.9	434	62	632	124	31	365
8.25	8.22	3.3	380	31	785	140	31	359
8.75	8.61	3.9	377	33	593	155	39	335
9.25	8.70	2.4	367	40	715	114	40	344
9.75	8.73	2.5	364	43	510	123	33	334

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	2912	482	81	1549	3487	542	185
0.75	3009	517	77	1392	3585	669	126
1.25	2949	495	78	1367	3496	555	169
1.75	2728	503	77	1015	3119	649	134
2.25	2881	532	74	646	3315	661	136
2.75	3211	594	70	609	3572	664	124
3.25	3604	544	73	475	4160	614	133
3.75	3639	511	68	404	4056	572	102
4.25	2832	462	71	381	3362	533	110
4.75	2686	458	67	358	3224	547	114
5.25	2234	379	141	349	2948	490	177
5.75	2205	374	64	345	2968	495	100
6.25	2148	395	158	350	2696	509	191
6.75	2147	350	172	340	2676	470	204
7.25	2114	341	78	352	2708	469	113
7.75	2257	379	88	369	2890	503	119
8.25	2467	424	99	362	3252	565	130
8.75	2823	465	107	339	3416	620	147
9.25	2881	522	101	347	3596	636	142
9.75	2797	468	155	337	3307	591	189

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	7.10	388.7	121	1134	689	147	67	1468
0.75	7.16	284.5	117	1147	552	94	67	1071
1.25	7.30	218.4	118	1097	678	110	68	880
1.75	7.40	165.9	114	1004	585	107	60	736
2.25	7.55	113.4	124	984	563	112	63	550
2.75	7.57	80.9	135	913	543	95	63	470
3.25	7.60	55.5	163	884	473	96	65	415
3.75	7.58	35.3	179	853	556	108	67	404
4.25	7.40	21.0	200	795	525	114	70	371
4.75	7.37	9.4	226	740	608	129	74	354
5.25	7.36	4.3	245	682	747	160	76	344
5.75	7.23	3.3	281	598	840	184	76	342
6.25	7.14	3.3	302	556	889	194	77	343
6.75	7.15	3.6	308	469	847	197	80	335
7.25	7.19	3.2	327	448	1035	219	84	333
7.75	7.08	3.3	333	364	1039	217	86	329
8.25	7.29	3.3	356	363	1219	239	94	354
8.75	7.40	3.2	368	324	1095	221	98	350
9.25	7.50	3.3	384	421	1188	230	104	335
9.75	7.67	3.6	370	406	1187	238	108	345

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	-----mg/kg soil-----	----- Total (Water plus Acid) Extractable -----		
	Ca	Mg	K		Ca	Mg	K
0.25	2943	449	39	1856	3632	597	106
0.75	2651	407	37	1356	3204	501	104
1.25	2531	381	40	1099	3210	491	109
1.75	2385	409	30	902	2970	517	90
2.25	2262	403	34	663	2826	516	98
2.75	2524	468	37	551	3067	563	100
3.25	2490	455	55	470	2964	552	120
3.75	2491	449	41	439	3048	557	109
4.25	2247	449	41	392	2773	564	111
4.75	2232	442	33	363	2841	572	108
5.25	2439	845	42	348	3187	1006	118
5.75	2102	338	68	345	2942	523	145
6.25	2015	280	45	346	2905	475	123
6.75	1985	284	43	339	2833	481	123
7.25	2100	303	45	336	3135	523	129
7.75	2161	340	47	333	3201	558	133
8.25	2299	353	56	357	3519	593	151
8.75	2435	387	57	353	3530	609	155
9.25	2342	436	57	338	3531	667	161
9.75	2606	460	64	349	3793	698	173

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	7.10	358.7	128	1159	587	108	79	1393
0.75	7.16	254.7	133	1186	374	93	74	986
1.25	7.30	199.8	125	1130	568	99	72	805
1.75	7.45	156.8	119	1026	524	97	79	742
2.25	7.46	109.3	129	996	500	97	71	521
2.75	7.60	87.1	137	940	612	94	75	518
3.25	7.62	51.6	150	890	648	110	70	406
3.75	7.55	29.5	167	827	548	99	75	423
4.25	7.40	14.8	184	768	820	125	75	340
4.75	7.33	4.9	210	689	657	125	78	377
5.25	7.30	3.7	256	653	821	157	80	338
5.75	7.22	4.0	274	570	822	166	95	363
6.25	7.10	3.1	291	507	905	174	91	340
6.75	7.10	3.8	303	430	868	181	94	340
7.25	7.10	4.3	318	374	880	187	92	332
7.75	7.18	3.3	343	343	995	206	99	330
8.25	7.27	3.2	355	416	1027	205	109	355
8.75	7.40	2.9	368	358	1084	213	100	332
9.25	7.43	3.0	385	333	1157	221	111	351
9.75	7.50	2.9	357	344	1194	214	113	320

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----			P	Ca	Mg	K
0.25	3340	521	56	1752	3927	629	135
0.75	2865	427	46	1241	3239	520	120
1.25	2726	435	53	1005	3294	535	125
1.75	2671	427	48	898	3195	525	128
2.25	2549	448	84	631	3049	545	155
2.75	2427	414	81	605	3039	509	156
3.25	2371	429	55	458	3019	539	125
3.75	2364	427	49	453	2912	527	124
4.25	2183	425	114	355	3004	550	189
4.75	2123	400	68	382	2781	526	146
5.25	2267	400	68	342	3088	558	149
5.75	2086	321	64	367	2908	488	159
6.25	2094	321	113	343	2999	495	204
6.75	2033	285	57	344	2901	467	152
7.25	2091	312	60	336	2971	499	153
7.75	2157	337	147	333	3153	543	247
8.25	2207	349	65	358	3234	554	175
8.75	2303	376	77	335	3387	590	177
9.25	2468	410	145	354	3626	632	257
9.75	2432	405	81	323	3627	619	194

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - KCl+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	7.05	454.7	122	179	554	114	2813	1649
0.75	7.17	356.5	121	181	782	129	2794	1154
1.25	7.30	224.5	119	172	592	150	2686	807
1.75	7.60	163.7	129	148	687	121	2595	631
2.25	7.77	84.4	135	124	543	103	2535	479
2.75	7.80	52.7	144	102	789	155	2405	430
3.25	7.30	36.5	150	83	658	199	2322	403
3.75	7.23	25.5	153	69	690	130	2205	360
4.25	7.40	15.8	150	50	705	226	2065	348
4.75	7.60	7.8	156	42	647	130	1969	345
5.25	7.70	4.5	160	34	751	147	1971	346
5.75	8.30	3.6	145	38	552	116	1696	339
6.25	8.55	3.5	131	41	706	116	1618	341
6.75	8.62	3.2	128	34	629	109	1449	330
7.25	8.65	3.1	125	35	626	107	1315	345
7.75	8.71	3.5	112	49	840	137	1220	344
8.25	8.66	2.8	90	37	764	122	1120	334
8.75	8.66	3.7	113	41	979	137	1079	335
9.25	8.67	3.6	109	48	983	266	1017	346
9.75	8.66	3.0	119	43	925	146	991	340

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	3423	453	871	2104	3977	568	3684
0.75	3012	432	826	1510	3795	601	3621
1.25	2842	450	819	1032	3435	626	3505
1.75	2757	505	793	794	3445	632	3388
2.25	2505	483	719	564	3049	586	3255
2.75	2671	477	729	482	3461	671	3009
3.25	2391	472	686	439	3049	841	2847
3.75	2229	710	641	386	2919	570	2662
4.25	2001	344	597	364	2707	499	2565
4.75	2214	368	595	353	2861	502	2543
5.25	2175	354	572	350	2927	532	2243
5.75	2398	415	547	342	2951	608	2156
6.25	2667	491	537	345	3373	593	1973
6.75	2688	483	524	334	3317	554	1800
7.25	2743	446	485	348	3369	618	1651
7.75	2774	481	431	348	3614	601	1556
8.25	2762	479	436	336	3527	577	1484
8.75	2699	440	404	339	3678	732	1369
9.25	2764	466	351	350	3748	628	1369
9.75	2810	482	377	343	3736		

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - KCl+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	7.01	470.0	113	191	902	159	2927	1603
0.75	7.12	390.7	115	188	921	125	2975	1228
1.25	7.30	250.2	119	150	534	176	2859	769
1.75	7.48	143.1	115	149	630	115	2733	601
2.25	7.75	97.1	118	122	611	124	2618	481
2.75	7.71	64.5	124	100	662	100	2533	432
3.25	7.28	43.4	133	74	752	186	2357	397
3.75	7.10	31.8	150	58	525	158	2446	380
4.25	7.15	19.6	143	56	588	115	2230	341
4.75	7.20	9.6	148	44	626	116	2170	345
5.25	7.75	4.3	143	65	773	133	2004	318
5.75	8.20	4.5	134	41	850	138	1900	331
6.25	8.40	3.4	131	36	590	112	1730	329
6.75	8.60	3.8	123	36	664	114	1602	336
7.25	8.68	3.0	119	43	916	135	1563	314
7.75	8.65	4.0	115	42	694	115	1348	317
8.25	8.65	2.6	115	34	686	120	1316	335
8.75	8.65	2.4	117	30	751	194	1266	325
9.25	8.63	3.6	113	32	899	216	1164	353
9.75	8.70	3.2	106	28	661	112	1149	340

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----				P	Ca	Mg
0.25	3212	507	972	2073	4114	667	3899
0.75	3119	600	827	1619	4040	726	3803
1.25	2845	526	821	1019	3380	702	3681
1.75	2814	504	791	744	3444	620	3524
2.25	2592	564	717	578	3204	689	3335
2.75	2587	526	695	496	3250	627	3228
3.25	2364	500	689	440	3116	686	3046
3.75	2193	552	632	412	2718	711	3078
4.25	2069	539	581	361	2657	654	2812
4.75	2070	534	563	354	2697	650	2733
5.25	2084	544	508	322	2858	677	2512
5.75	2184	505	494	335	3034	644	2395
6.25	2577	536	534	333	3168	649	2265
6.75	2644	505	491	340	3308	620	2094
7.25	2637	503	476	318	3553	639	2039
7.75	2612	498	407	321	3307	613	1755
8.25	2685	509	423	338	3372	630	1739
8.75	2627	495	378	327	3379	689	1644
9.25	2637	513	386	357	3537	730	1550
9.75	2721	474	389	343	3382	587	1539

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 1

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	9.90	494.4	65	85	405	83	3409	609
0.75	9.86	428.4	83	63	244	51	3288	534
1.25	9.80	400.4	95	74	299	49	3164	497
1.75	9.74	376.3	96	64	236	52	3028	482
2.25	9.73	336.9	96	45	343	64	2832	476
2.75	9.73	270.3	93	29	222	49	2474	473
3.25	9.71	303.4	94	27	179	48	2338	518
3.75	9.68	286.0	94	32	325	49	2083	537
4.25	9.65	188.1	96	19	376	61	1752	431
4.75	9.56	66.7	97	20	305	42	1350	379
5.25	9.50	16.1	101	20	181	42	1048	333
5.75	9.30	7.3	106	11	264	42	803	340
6.25	9.13	6.6	112	33	229	71	663	339
6.75	8.99	5.6	104	31	363	94	537	337
7.25	8.85	5.0	107	50	440	58	417	345
7.75	8.76	4.4	110	20	360	58	321	343
8.25	8.73	4.0	120	38	322	107	234	333
8.75	8.70	3.6	115	18	351	62	170	334
9.25	8.70	3.5	114	33	358	61	128	344
9.75	8.70	3.6	90	34	468	76	114	350

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	P	Total (Water plus Acid) Extractable		
	-----mg/kg soil-----				Ca	Mg	K
0.25	2880	506	1654	1104	3286	589	5063
0.75	2761	477	1783	962	3006	528	5072
1.25	2908	473	1807	897	3208	522	4971
1.75	2948	502	1749	859	3184	555	4777
2.25	2927	528	1662	813	3271	592	4494
2.75	3225	512	1639	743	3447	562	4114
3.25	3486	562	1529	821	3665	610	3868
3.75	3402	505	1399	823	3728	554	3483
4.25	3207	474	1224	619	3583	536	2976
4.75	3257	480	1149	445	3563	523	2500
5.25	2702	460	922	349	2883	503	1970
5.75	2869	528	831	347	3133	571	1635
6.25	2730	497	619	346	2959	569	1283
6.75	2657	449	457	343	3021	543	994
7.25	2898	580	363	350	3339	639	780
7.75	2826	453	274	348	3186	512	596
8.25	2834	470	218	337	3157	578	452
8.75	2865	471	180	338	3217	533	351
9.25	2905	467	151	348	3263	528	279
9.75	2953	533	138	353	3422	609	252

DIFFUSION EXPERIMENT - EXTRACTION DATA FOR SECTIONS OF SOIL COLUMNS INCUBATED FOR 5 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 2

Distance From Application Site (cm)	pH of Extracts	Water Extractable P	Water Extractable (NO ₃ +NO ₂)-N	Water Extractable NH ₄ -N	Water Extractable Ca	Water Extractable Mg	Water Extractable K	Acid Extractable P
		-----mg/kg of soil-----						
0.25	9.86	502.7	94	83	410	54	3372	627
0.75	9.80	418.9	95	79	548	56	3219	526
1.25	9.75	391.0	98	106	256	82	3100	456
1.75	9.72	377.2	99	56	426	66	3088	530
2.25	9.71	342.7	102	86	308	144	2849	457
2.75	9.70	271.9	100	34	217	44	2638	460
3.25	9.69	280.1	102	32	370	61	2430	496
3.75	9.68	267.0	100	46	468	56	2187	482
4.25	9.66	213.3	100	28	416	65	1977	475
4.75	9.55	95.7	101	23	198	38	1502	383
5.25	9.48	19.8	105	41	513	52	1100	336
5.75	9.21	9.8	116	25	228	36	819	338
6.25	9.02	6.8	120	88	378	244	685	317
6.75	8.90	5.9	113	39	270	43	527	335
7.25	8.80	5.6	120	62	273	98	419	338
7.75	8.74	3.9	121	41	512	79	310	357
8.25	8.68	4.8	122	42	347	50	209	348
8.75	8.65	5.0	130	52	582	76	136	351
9.25	8.64	4.6	124	44	511	74	116	358
9.75	8.70	4.1	129	48	530	77	93	335

Distance From Application Site (cm)	Acid Extractable Ca	Acid Extractable Mg	Acid Extractable K	----- Total (Water plus Acid) Extractable -----			
	-----mg/kg soil-----				P	Ca	Mg
0.25	2704	408	1790	1130	3115	462	5163
0.75	2838	397	1901	945	3387	453	5121
1.25	2716	404	1732	847	2973	487	4833
1.75	2824	541	1776	907	3250	607	4864
2.25	2706	451	1553	800	3014	596	4403
2.75	2875	496	1892	732	3092	540	4530
3.25	3020	443	1533	776	3391	505	3963
3.75	2894	396	1475	749	3363	452	3662
4.25	3028	357	1287	688	3445	422	3264
4.75	2978	339	1261	479	3176	378	2764
5.25	2852	321	1193	356	3366	374	2293
5.75	2665	337	789	348	2893	374	1608
6.25	2751	446	581	324	3130	690	1267
6.75	2757	510	406	341	3028	554	933
7.25	2760	410	638	344	3033	508	1058
7.75	2848	406	733	361	3361	486	1043
8.25	2811	438	205	352	3159	489	415
8.75	2773	411	196	356	3356	487	333
9.25	2811	410	147	363	3322	484	263
9.75	2670	427	115	339	3201	504	209

Appendix C
COLUMN EXTRACTION DATA FROM
ELUTION EXPERIMENT

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - CONTROL TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca	
-----µg/mL of eluate-----								
1	0.61	8.10	0.0					
2	0.85	8.11	0.0	81	2.6	10	141	33.0
3	1.08	7.96	0.0	130	2.7	12	139	34.1
4	1.29	7.93	0.0	108	2.7	12	114	28.0
5	1.50	8.00	0.0	65	3.4	10	75	18.3
6	1.75	8.00	0.0	24	5.1	11	44	10.7
7	2.00	7.99	0.0	9	3.5	7	33	7.3
8	2.24	7.98	0.0	2	2.6	7	28	6.3
9	2.46	7.94	0.0	1	2.0	7	25	5.6
10	2.63	8.00	0.0	0	2.0	7	24	5.4
11	2.82	7.97	0.0	0	2.0	10	23	5.4
12	3.01	7.99	0.0	0	2.0	6	23	5.2
13	3.17	7.99	0.0	0	3.4	6	20	5.0
14	3.34	8.00	0.0	0	3.0	6	18	4.5
15	3.52	8.00	0.0	0	1.8	5	21	5.0
16	3.68	8.00	0.0	0	2.6	5	20	5.3
17	3.84	8.05	0.0	0	1.8	5	21	4.7
18	4.01		0.0	0	1.9	6	21	4.7
19	4.18	8.03	0.0	0	1.9	6	21	4.8
20	4.35		0.0	0	2.0	7	20	4.6
21	4.51		0.0	0	1.7	6	19	4.5
22	4.67	7.99	0.0	0	2.6	5	21	4.5
23	4.85		0.1	0	3.3	5	20	4.6
24	5.01	8.00	0.1	0	2.6	9	19	4.5
25	5.17		0.1	0	2.5	6	19	4.5
26	5.34	8.00	0.1	1	1.4	7	20	4.6
27	5.50		0.1	1	2.4	5	20	4.3
28	5.66	8.15	0.1	1	1.4	5	19	4.3
29	5.82		0.1	1	1.4	5	19	4.3
30	5.98	8.15	0.1	1	1.3	5	19	4.3
31	6.14		0.2	1	1.7	5	19	4.2
32	6.29	8.15	0.2	1	1.7	8	20	4.3
33	6.44		0.2	1	1.3	5	19	4.3
34	6.60	8.12	0.2	1	1.7	5	19	4.0
35	6.74		0.2	2	1.8	5	20	4.3
36	6.89	8.11	0.2	2	2.3	5	19	4.1
37	7.04		0.2	2	1.4	5	19	4.3
38	7.20	8.08	0.2	2	1.4	5	18	4.0
39	7.35		0.2	2	1.3	4	19	4.2
40	7.49	8.08	0.2	2	1.7	5	20	4.3
41	7.64		0.2	2	1.4	5	19	4.0
42	7.79	8.08	0.2	2	1.3	4	19	4.3
43	7.93		0.2	3	2.2	4	20	4.3
44	8.08	8.08	0.2	3	1.8	4	20	4.3
45	8.23		0.2	3	1.4	5	20	4.5
		8.06	0.2	3	1.7	5	20	4.2

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - CONTROL TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.44	8.15	0.0	110	2.2	8	83	10	0
2	0.66	8.21	0.0	120	2.6	12	134	29	0
3	0.88	8.19	0.0	87	3.0	11	98	22	0
4	1.09	8.25	0.0	43	2.7	9	63	13	0
5	1.29	8.31	0.0	19	2.6	7	44	9	0
6	1.49	8.28	0.0	6	2.8	5	34	7	0
7	1.70	8.26	0.0	2	3.3	6	30	6	0
8	1.92	8.24	0.0	0	3.6	6	28	5	0
9	2.12	8.27	0.2	0	2.8	5	21	5	0
10	2.34	8.27	0.2	0	2.1	5	26	5	0
11	2.55	8.25	0.2	0	1.8	5	21	5	1
12	2.77	8.25	0.3	0	1.8	6	25	5	2
13	3.01	8.25	0.3	0	1.0	6	24	5	3
14	3.22	8.26	0.3	0	1.7	6	25	5	4
15	3.44	8.26	0.3	0	2.6	5	23	4	5
16	3.66	8.25	0.4	0	2.6	5	23	4	6
17	3.86	8.28	0.4	0	1.7	5	23	4	7
18	4.07	8.28	0.4	0	3.9	5	24	4	9
19	4.27	8.28	0.4	0	1.6	6	23	4	10
20	4.47	8.25	0.4	0	5.3	5	23	4	11
21	4.63	8.25	0.4	0	5.8	5	23	4	12
22	4.80	8.26	0.4	0	3.7	5	25	5	13
23	4.98	8.26	0.4	0	1.1	5	23	4	14
24	5.15	8.25	0.4	0	2.0	5	23	4	16
25	5.33	8.25	0.4	0	1.5	6	24	4	17
26	5.50	8.24	0.4	0	3.4	5	23	4	18
27	5.68	8.24	0.4	0	1.2	6	23	4	19
28	5.86	8.22	0.4	0	1.7	5	23	4	20
29	6.03	8.22	0.4	0	0.9	5	22	4	22
30	6.21	8.22	0.4	0	1.8	4	22	4	23
31	6.39	8.22	0.4	0	2.1	5	22	4	24
32	6.57	8.23	0.4	0	2.0	4	21	4	25
33	6.74	8.23	0.4	0	1.2	4	20	4	27
34	6.92	8.24	0.4	0	2.4	4	21	4	28
35	7.09	8.24	0.4	0	0.8	5	22	4	30
36	7.25	8.21	0.5	0	1.0	5	21	4	31
37	7.42	8.21	0.5	0	1.8	5	22	4	32
38	7.60	8.21	0.5	0	0.8	4	22	4	34
39	7.77	8.21	0.5	0	0.9	5	21	4	35
40	7.93	8.21	0.5	0	1.2	7	22	4	37
41	8.11	8.21	0.5	0	0.8	4	21	4	38
42	8.28	8.20	0.5	0	1.2	5	23	4	40
43	8.45	8.20	0.5	0	1.2	4	21	4	42
44	8.62	8.21	0.5	0	2.5	4	19	3	43
45	8.80	8.21	0.5	0	1.4	4	20	4	45
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ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - MAP (ONLY) TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate						Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca	Mg	
-----µg/mL of eluate-----									
1	0.47	7.42	0.0	119	5.4	63	133	29	0
2	0.69	7.47	0.0	160	3.2	18	156	34	0
3	0.93	7.40	0.0	102	2.5	23	108	23	0
4	1.14	7.40	4.0	46	3.9	10	77	15	0
5	1.33	7.43	37.3	24	4.4	10	70	15	11
6	1.55	7.29	61.6	13	2.4	13	68	17	109
7	1.77	7.18	78.5	6	3.1	14	76	18	290
8	1.99	7.11	86.3	3	3.3	9	74	18	527
9	2.21	7.04	92.4	3	1.8	10	73	19	790
10	2.42	7.08	96.0	3	1.2	12	75	18	1062
11	2.64	7.02	91.7	3	1.4	11	71	17	1350
12	2.86	7.09	85.6	3	1.4	8	70	18	1628
13	3.07	7.11	81.9	3	1.8	11	62	15	1880
14	3.30	7.11	78.4	3	2.3	11	63	14	2119
15	3.52	7.12	70.5	3	2.7	10	61	14	2375
16	3.73	7.16	72.6	3	3.0	10	58	13	2588
17	3.94	7.13	70.2	3	1.0	10	58	13	2798
18	4.14	.	67.3	3	1.3	11	58	12	2998
19	4.34	7.12	62.3	4	1.2	12	54	12	3193
20	4.54	.	60.6	4	0.9	12	55	12	3368
21	4.72	7.21	53.6	4	1.9	11	53	11	3543
22	4.88	.	55.5	4	2.6	12	54	11	3686
23	5.08	7.40	53.5	4	1.4	12	51	10	3829
24	5.26	.	51.1	4	1.3	12	52	11	3987
25	5.45	7.28	48.5	4	0.9	11	51	10	4135
26	5.63	.	49.7	4	0.9	11	51	10	4274
27	5.81	7.33	44.7	4	1.0	13	50	10	4419
28	5.99	.	44.4	4	1.0	11	49	10	4545
29	6.17	7.34	42.7	5	1.6	10	48	9	4673
30	6.35	.	42.7	5	2.0	12	48	9	4800
31	6.53	7.30	43.1	6	1.8	12	48	9	4924
32	6.70	.	41.6	6	1.3	12	47	9	5045
33	6.87	7.34	40.6	6	0.6	11	47	9	5160
34	7.05	.	37.4	6	1.4	13	45	9	5271
35	7.22	7.31	37.7	7	4.3	11	49	10	5380
36	7.39	.	37.7	7	1.0	14	45	9	5488
37	7.56	7.30	37.3	8	3.2	13	46	9	5600
38	7.73	.	36.3	8	3.7	11	44	9	5705
39	7.90	7.33	34.9	8	1.0	12	45	9	5807
40	8.06	.	34.9	8	3.2	13	43	8	5909
41	8.22	7.34	33.8	8	0.4	13	45	8	6004
42	8.40	.	32.3	8	0.8	13	44	8	6097
43	8.56	7.30	31.5	8	2.6	14	42	8	6197
44	8.73	.	29.8	8	2.3	13	42	8	6280
45	8.89	7.22	29.3	8	2.1	14	39	7	6367
			28.0	8	1.4	14	42	8	6451

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - MAP (ONLY) TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N µg/mL of eluate	K	Ca		Mg
1	0.29	8.15	0.0	123	2.2	16	306	35	0
2	0.53	8.15	0.0	139	2.5	13	166	33	0
3	0.73	7.95	13.4	101	2.9	12	117	28	38
4	0.93	7.61	33.8	55	3.1	11	91	23	134
5	1.13	7.50	52.7	32	3.3	11	117	21	283
6	1.32	7.43	64.9	18	3.1	9	71	20	467
7	1.52	7.37	72.6	12	3.7	9	120	21	677
8	1.71	7.32	76.0	6	3.1	8	70	19	889
9	1.91	7.28	77.4	4	3.7	10	67	18	1120
10	2.11	7.24	79.5	3	2.5	9	67	19	1348
11	2.30	7.23	80.2	3	2.9	8	64	18	1571
12	2.49	7.22	79.2	3	2.4	8	62	17	1802
13	2.67	7.22	79.4	3	3.1	9	69	17	2016
14	2.85	7.21	76.3	3	2.8	7	64	17	2226
15	3.05	7.23	71.1	3	3.0	8	58	16	2434
16	3.23	7.23	70.2	3	1.8	7	88	16	2634
17	3.42	7.28	64.7	3	2.1	8	56	15	2819
18	3.59		62.8	3	2.0	8	56	15	2991
19	3.77	7.31	59.7	3	1.9	8	55	14	3158
20	3.95		54.0	3	1.7	7	51	13	3311
21	4.13	7.37	52.9	3	2.1	7	52	13	3459
22	4.30		51.3	3	2.8	9	52	13	3605
23	4.48	7.40	47.4	3	2.4	8	49	12	3739
24	4.66		46.7	4	2.4	8	67	13	3878
25	4.84	7.44	47.4	4	2.8	8	47	12	4011
26	5.01		44.9	4	2.1	8	46	11	4136
27	5.16	7.48	41.4	4	3.1	8	58	11	4244
28	5.34		40.1	5	2.5	7	44	11	4363
29	5.51	7.49	39.5	5	2.8	8	47	11	4471
30	5.67		37.8	6	1.8	8	43	10	4579
31	5.85	7.52	37.3	6	2.0	8	44	10	4690
32	6.02		34.9	6	2.1	8	43	11	4792
33	6.19	7.59	34.0	6	3.0	8	52	12	4886
34	6.34		33.0	6	2.0	8	43	11	4973
35	6.53	7.55	30.0	5	2.0	8	42	10	5071
36	6.72		31.6	5	1.7	8	36	10	5170
37	6.89	7.61	30.7	6	3.0	9	39	9	5261
38	7.06		31.2	6	3.5	9	39	9	5348
39	7.23	7.61	28.1	6	2.6	9	38	9	5431
40	7.40		28.2	7	2.5	9	38	9	5513
41	7.60	7.61	26.3	7	2.1	9	38	9	5596
42	7.76		27.0	8	1.7	10	38	8	5672
43	7.93	7.66	27.1	8	2.0	10	43	8	5748
44	8.09		26.0	8	2.1	10	36	8	5818
45	8.27	7.62	23.8	8	3.0	9	42	8	5892

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - UREA+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate						Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N µg/mL of eluate	K	Ca	Mg	
1	0.69	7.79	0.0	169	17	15	231	50	0
2	0.89	8.26	0.0	168	63	14	334	75	0
3	1.11	8.49	0.0	89	67	21	303	70	0
4	1.27	8.48	0.0	37	58	20	241	57	0
5	1.41	8.53	0.0	19	47	21	217	54	0
6	1.51	8.70	0.0	12	83	33	204	51	0
7	1.63	8.60	5.3	7	179	60	154	44	10
8	1.76	8.86	15.6	4	347	75	124	35	47
9	1.93	9.10	17.4	0	469	78	127	33	98
10	2.14	9.23	24.5	0	476	62	79	19	182
11	2.30	9.20	40.4	0	422	56	50	13	298
12	2.46	9.18	52.0	0	384	50	40	10	439
13	2.62	9.16	60.9	0	368	47	31	8	611
14	2.78	9.14	67.8	0	343	43	27	7	801
15	2.96	9.15	76.5	0	331	39	20	5	1040
16	3.12	9.13	81.0	0	317	35	18	4	1271
17	3.31	9.15	82.5	0	311	33	15	3	1537
18	3.48		83.3	0	306	29	14	2	1795
19	3.63	9.14	86.6	0	312	33	15	3	2026
20	3.81		90.0	0	304	29	12	2	2304
21	3.98	9.14	85.6	0	289	30	13	2	2557
22	4.15		87.6	0	292	27	11	2	2824
23	4.31	9.07	85.4	0	269	28	12	2	3064
24	4.48		83.2	0	264	26	11	2	3323
25	4.65	8.96	81.9	0	257	23	11	1	3561
26	4.81		79.3	0	258	23	11	1	3792
27	4.97	8.98	79.4	0	235	23	11	1	4020
28	5.14		78.9	0	235	23	10	1	4254
29	5.30	8.98	70.9	0	223	21	10	1	4464
30	5.47		71.8	0	219	20	10	2	4681
31	5.66	8.98	67.5	0	196	23	10	2	4907
32	5.83		58.5	0	195	18	9	1	5084
33	5.97	8.92	61.5	0	195	18	10	1	5238
34	6.13		60.2	0	192	16	9	1	5416
35	6.30	9.01	53.1	0	188	15	9	1	5578
36	6.47		54.1	0	194	15	9	1	5747
37	6.64	9.01	52.0	0	172	15	9	1	5903
38	6.84		48.8	0	174	14	8	1	6074
39	7.03	9.01	49.2	0	171	13	8	1	6240
40	7.18		51.5	0	162	13	8	1	6372
41	7.32	8.97	43.4	0	156	12	10	1	6480
42	7.51		45.1	0	163	11	8	1	6636
43	7.72	9.05	39.7	0	148	11	8	1	6777
44	7.85		39.9	0	149	11	9	1	6870
45	8.09	9.06	31.3	0	148	10	8	1	6993

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	-----Concentration in Eluate-----						Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca	Mg	
-----µg/mL of eluate-----									
1	0.52	7.22	0.0	130	117	53	1399	267	0
2	0.76	7.10	0.0	120	1000	212	5004	681	0
3	0.97	7.08	0.0	58	2245	433	5278	628	0
4	1.15	7.27	0.0	28	2741	346	2286	340	0
5	1.28	7.16	28.2	14	1508	161	754	113	49
6	1.37	7.16	93.1	11	915	90	165	27	178
7	1.48	7.15	218.2	20	592	62	82	12	568
8	1.58	6.91	293.6	35	449	42	60	8	1091
9	1.68	6.97	301.5	35	372	37	51	6	1643
10	1.79	6.86	275.8	40	304	28	41	4	2186
11	1.90	6.83	221.0	39	263	23	35	4	2653
12	2.05	6.99	186.3	33	244	22	39	5	3215
13	2.19	6.90	163.6	34	210	18	31	4	3665
14	2.33	6.89	150.4	32	188	19	24	2	4075
15	2.47	6.92	135.9	31	179	16	22	2	4453
16	2.63	6.88	125.7	30	166	15	19	1	4841
17	2.78	6.90	114.5	30	150	12	17	1	5171
18	2.91		110.2	25	154	13	17	1	5438
19	3.05	7.05	96.8	24	136	13	14	1	5704
20	3.20		97.8	21	143	12	15	1	5992
21	3.34	7.27	91.4	17	143	11	13	1	6242
22	3.49		85.7	18	136	10	13	1	6494
23	3.63	7.37	85.9	17	131	12	12	1	6730
24	3.84		76.1	20	121	10	11	1	7013
25	3.96	7.67	78.8	10	123	11	11	1	7195
26	4.09		74.8	10	123	7	10	0	7389
27	4.23	7.61	69.8	10	121	14	10	0	7565
28	4.37		68.8	13	116	8	10	1	7761
29	4.55	7.09	63.9	19	103	11	9	0	7971
30	4.69		55.8	12	104	7	8	0	8125
31	4.83	7.87	55.5	6	106	10	8	0	8268
32	4.98		54.9	8	105	6	8	0	8429
33	5.13	7.71	48.0	8	101	8	8	0	8558
34	5.28		47.3	8	105	7	7	0	8692
35	5.42	7.89	49.0	7	99	8	7	0	8827
36	5.56		45.5	10	93	6	8	0	8947
37	5.78	7.16	43.7	16	96	10	11	1	9122
38	5.88		39.7	6	93	7	8	0	9198
39	6.13	7.26	39.4	13	88	7	7	0	9367
40	6.22		36.7	4	94	7	8	0	9429
41	6.39	7.72	35.7	11	86	8	7	0	9538
42	6.55		37.7	12	86	5	7	0	9647
43	6.69	7.50	34.7	13	80	8	7	0	9736
44	6.81		29.0	6	85	6	7	0	9800
45	6.90	7.98	27.6	5	82	10	7	0	9852

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - NH₄CL+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
			µg/mL of eluate						
1	0.4C	7.21	0.0	192	197	70	3028	383	0
2	0.6C	6.89	0.0	103	1720	363	5674	668	0
3	0.81	6.89	0.0	55	2532	348	3919	518	0
4	1.0C	7.00	20.7	30	2155	214	2597	276	54
5	1.25	6.73	113.9	16	1462	123	1450	123	440
6	1.45	7.14	187.1	10	748	55	224	36	925
7	1.63	7.45	239.3	9	501	36	121	16	1511
8	1.8C	7.50	238.8	10	344	25	67	9	2101
9	1.96	7.51	222.1	10	275	28	57	8	2614
10	2.11	7.53	196.9	13	240	23	49	6	3044
11	2.26	7.50	162.9	12	209	22	48	5	3435
12	2.40	7.55	162.5	12	199	26	31	4	3805
13	2.54	7.61	143.2	11	184	19	40	4	4136
14	2.68	7.63	133.4	11	173	19	34	3	4454
15	2.82	7.69	120.4	10	174	22	34	3	4743
16	2.95	7.70	117.4	10	166	22	31	3	5014
17	3.08	7.83	109.0	11	156	20	25	3	5288
18	3.22		105.9	11	150	18	33	3	5557
19	3.37	7.82	97.7	10	147	19	43	2	5831
20	3.51		97.3	10	141	18	22	2	6080
21	3.67	7.88	86.8	10	137	8	21	2	6338
22	3.81		82.0	10	139	8	16	1	6548
23	3.96	7.91	76.8	10	126	10	13	1	6769
24	4.11		70.5	9	120	10	18	1	6967
25	4.26	7.93	67.2	8	118	11	13	1	7162
26	4.40		67.5	8	115	9	24	1	7340
27	4.57	7.97	62.6	8	109	6	21	1	7529
28	4.71		60.3	8	107	8	21	1	7691
29	4.86	7.99	60.7	8	103	8	24	1	7865
30	5.00		55.8	7	99	8	25	1	8006
31	5.15	8.00	52.4	7	96	9	13	1	8158
32	5.30		53.1	7	96	8	8	1	8304
33	5.46	7.97	48.8	7	92	14	6	1	8456
34	5.60		48.2	6	90	9	30	1	8584
35	5.77	8.00	43.7	7	87	8	31	1	8718
36	5.91		44.4	7	87	9	16	1	8833
37	6.06	8.07	40.6	7	84	7	21	1	8947
38	6.20		39.5	7	81	7	21	1	9056
39	6.35	7.99	38.4	7	82	21	27	0	9159
40	6.49		36.9	7	79	17	16	0	9259
41	6.67	8.06	35.0	7	80	7	25	0	9377
42	6.77		34.8	7	75	7	27	0	9444
43	6.93	7.80	31.8	8	77	6	23	1	9541
44	7.11		32.6	9	78	6	15	1	9648
45	7.26	7.90	29.6	6	71	2	1	0	9733

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - KCl+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.53	7.85	0.0	92	14	43	1011	84	0
2	0.80	7.58	0.0	115	128	2999	2821	100	0
3	1.04	7.43	0.0	89	430	6723	2620	102	0
4	1.20	7.58	0.0	63	342	6504	2163	113	0
5	1.34	7.52	4.4	43	185	4430	1620	110	0
6	1.49	6.90	44.1	27	139	2919	944	104	9
7	1.62	6.91	97.5	19	97	1922	461	81	102
8	1.75	7.32	145.3	14	71	1269	192	33	306
9	1.89	7.53	165.2	14	59	962	146	22	607
10	2.02	7.86	177.9	9	47	677	82	9	985
11	2.17	8.04	174.0	12	37	568	72	6	1405
12	2.30	8.03	167.9	12	35	488	62	5	1849
13	2.43	8.02	153.8	12	32	471	64	5	2257
14	2.55	8.11	142.5	12	36	424	54	4	2631
15	2.68	8.12	133.9	12	32	397	53	3	2966
16	2.81	8.15	121.9	12	28	360	49	3	3293
17	2.94	8.11	113.5	12	25	361	51	3	3609
18	3.15		105.1	11	23	327	45	3	3918
19	3.29	8.15	93.2	10	19	310	46	2	4336
20	3.42		87.8	11	18	303	41	2	4587
21	3.53	8.27	78.5	11	17	276	42	1	4810
22	3.64		86.2	11	18	301	45	2	4994
23	3.76	8.25	69.4	11	15	252	38	1	5191
24	4.06		71.9	11	30	280	66	6	5369
25	4.17	8.26	62.3	9	15	243	40	1	5770
26	4.29		61.2	9	13	233	37	1	5908
27	4.54	8.12	55.0	9	16	215	31	1	6053
28	4.68		56.6	8	16	234	35	1	6298
29	4.82	8.22	44.1	8	14	195	30	1	6447
30	4.96		47.8	8	14	205	32	1	6563
31	5.09	8.20	43.0	6	16	191	41	1	6693
32	5.22		42.2	7	13	191	84	1	6804
33	5.36	8.24	40.2	7	13	187	29	1	6908
34	5.50		38.4	7	16	181	32	1	7025
35	5.63	8.22	34.3	7	13	209	41	1	7128
36	5.78		33.1	7	12	175	31	0	7219
37	5.96	8.18	32.1	7	12	167	28	1	7321
38	6.12		24.9	6	9	126	26	0	7434
39	6.25	8.15	28.2	7	7	149	28	0	7513
40	6.37		27.7	6	11	163	30	0	7581
41	6.57	8.08	29.1	6	9	147	32	0	7653
42	6.68		24.9	7	8	149	29	0	7762
43	6.84	8.05	24.8	7	10	148	28	0	7815
44	6.98		24.3	7	12	135	29	0	7896
45	7.12	8.14	20.5	7	20	161	30	0	7965
									8021

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - KCl+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.29	7.59	0.0	190	23	1423	2364	433	0
2	0.49	7.48	0.0	134	152	5284	3058	525	0
3	0.67	7.47	6.8	89	196	5833	2180	368	18
4	0.91	6.71	82.8	49	156	4247	1041	170	299
5	1.12	6.95	134.3	24	95	2241	365	59	690
6	1.32	7.27	171.4	17	59	1263	126	26	1180
7	1.51	7.66	193.7	12	40	845	52	10	1726
8	1.69	7.77	179.7	10	32	624	39	7	2183
9	1.87	7.63	172.3	13	24	530	30	5	2652
10	2.03	7.68	155.5	15	17	459	25	4	3039
11	2.19	7.57	139.6	18	13	419	22	3	3391
12	2.34	7.76	125.6	14	15	399	21	3	3685
13	2.49	7.87	112.7	14	13	383	19	2	3960
14	2.61	7.99	110.7	14	17	360	18	2	4193
15	2.73	8.01	105.0	13	15	344	18	2	4422
16	2.86	8.01	92.0	13	15	334	17	2	4655
17	2.99	8.04	91.6	14	14	315	15	2	4878
18	3.11		89.5	12	14	324	15	1	5091
19	3.34	7.90	85.5	14	13	302	15	2	5447
20	3.49		81.2	12	13	314	13	1	5662
21	3.60	8.14	76.7	10	12	249	13	1	5833
22	3.75		73.4	13	10	261	12	1	6037
23	3.93	8.02	71.0	14	11	263	11	1	6280
24	4.08		66.5	12	13	260	11	1	6466
25	4.21	8.25	65.2	13	9	266	12	1	6634
26	4.35		61.6	13	13	251	10	1	6801
27	4.52	8.22	54.2	13	8	243	10	1	6969
28	4.66		54.0	13	8	248	10	1	7123
29	4.84	8.22	51.9	12	8	249	10	1	7296
30	4.98		50.1	11	7	245	9	1	7424
31	5.15	8.25	46.8	11	7	229	9	1	7579
32	5.31		45.6	11	6	220	11	1	7712
33	5.45	8.28	44.0	11	7	220	9	1	7830
34	5.61		40.0	11	8	213	8	1	7950
35	5.77	8.22	39.0	11	6	215	8	1	8062
36	5.93		37.4	11	5	214	8	1	8173
37	6.09	8.25	37.1	11	6	206	7	1	8287
38	6.25		34.6	10	5	213	8	1	8391
39	6.41	8.21	33.5	10	4	198	7	1	8489
40	6.57		29.7	10	4	199	7	0	8573
41	6.73	8.23	30.7	10	3	181	7	0	8664
42	6.90		29.1	9	4	180	9	1	8754
43	7.06	8.18	28.3	10	3	167	7	1	8835
44	7.22		26.6	9	3	159	6	1	8915
45	7.40	8.16	26.3	9	2	158	6	1	8998

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
			µg/mL of eluate						
1	0.07	8.26	0.0	89	11	16			
2	0.23	8.00	0.0	157	13	14	133	23	0
3	0.40	8.22	0.0	233	11	19	235	47	0
4	0.56	7.99	0.0	181	11	21	368	98	0
5	0.69	7.96	0.0	82	12	33	474	125	0
6	0.86	8.05	0.0	38	18	37	435	136	0
7	0.99	8.22	54.1	15	46	319	340	130	0
8	1.16	8.46	133.0	6	65	685	194	72	139
9	1.32	8.54	136.4	5	69	730	94	24	558
10	1.47	8.63	139.2	2	76	674	82	16	962
11	1.63	8.68	125.4	0	73	637	85	12	1373
12	1.79	8.74	133.3	0	72	637	88	11	1748
13	1.95	8.80	152.6	0	81	554	85	10	2148
14	2.10	8.89	154.3	0	83	524	69	8	2598
15	2.26	8.97	156.9	0	88	459	48	5	3049
16	2.42	9.10	154.6	0	90	444	58	4	3524
17	2.57	9.15	155.0	0	91	394	37	3	3988
18	2.73		141.8	0	90	380	29	3	4433
19	2.87	9.02	136.6	0	74	339	19	2	4869
20	3.03		126.8	0	65	330	17	2	5242
21	3.19	9.10	133.1	0	58	327	15	2	5636
22	3.34		106.6	0	52	311	14	2	6038
23	3.49	9.17	106.0	0	49	280	13	2	6343
24	3.65		95.1	0	49	303	13	1	6653
25	3.79	9.23	88.1	0	48	259	12	1	6949
26	3.95		89.7	0	41	35	11	1	7197
27	4.10	9.26	83.2	0	40	264	11	1	7477
28	4.26		80.1	0	37	244	11	1	7720
29	4.40	9.31	73.9	0	37	213	11	1	7959
30	4.56		74.4	0	38	199	10	1	8173
31	4.71	9.33	69.6	0	37	226	10	1	8399
32	4.86		59.9	0	30	259	11	1	8604
33	5.01	9.37	59.1	0	30	218	10	1	8785
34	5.16		50.7	0	30	201	10	1	8957
35	5.31	9.40	54.9	0	26	194	9	1	9108
36	5.47		51.5	C	22	190	9	1	9269
37	5.61	9.44	48.2	0	23	182	9	1	9430
38	5.77		44.0	C	22	177	9	1	9571
39	5.92	9.50	42.5	C	21	168	8	1	9703
40	6.07		38.9	C	19	170	9	1	9832
41	6.22	9.53	34.5	C	25	166	8	1	9946
42	6.37		34.9	C	25	151	8	1	10051
43	6.52	9.55	33.1	C	23	153	8	1	10153
44	6.67		33.4	C	19	151	8	1	10254
45	6.82	9.58	31.9	C	13	144	8	0	10353
					20	138	7	0	10449

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 1 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate						Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca	Mg	
-----µg/mL of eluate-----									
1	0.38	7.92	0	170	7	14	210	48	0
2	0.55	8.19	0	242	6	18	359	83	0
3	0.73	7.81	0	95	7	17	318	81	0
4	0.89	7.69	0	41	8	17	319	81	0
5	1.04	7.76	0	25	10	18	288	79	0
6	1.15	8.09	0	20	14	52	282	79	0
7	1.22	8.45	12	14	25	422	341	67	15
8	1.31	8.05	98	21	34	914	211	36	191
9	1.47	7.76	146	18	34	1004	160	24	629
10	1.63	7.55	178	20	30	1015	150	18	1149
11	1.82	7.76	194	11	40	961	137	14	1800
12	1.96	8.07	193	5	44	830	116	11	2304
13	2.11	7.97	193	5	46	876	115	10	2814
14	2.27	7.96	172	5	45	770	102	8	3310
15	2.44	7.62	172	13	40	684	94	7	3855
16	2.60	7.69	159	14	43	643	87	6	4295
17	2.81	8.55	144	3	63	536	81	6	4814
18	2.94		142	1	67	617	91	5	5147
19	3.13	9.03	131	0	67	511	73	4	5562
20	3.30		131	0	65	495	69	4	5960
21	3.47	9.14	120	0	62	526	70	3	6298
22	3.61		117	0	60	484	67	3	6583
23	3.82	9.20	112	0	60	434	62	3	6966
24	3.97		103	0	53	486	71	3	7238
25	4.18	8.83	97	0	41	546	62	2	7563
26	4.34		96	0	42	546	62	2	7815
27	4.49	8.70	92	0	33	437	55	2	8058
28	4.67		87	0	38	425	82	2	8313
29	4.90	9.17	86	0	35	360	59	2	8629
30	5.06		80	0	33	465	50	2	8834
31	5.27	9.17	75	0	30	386	66	2	9071
32	5.42		71	0	29	325	52	2	9250
33	5.59	9.08	68	0	26	390	55	2	9433
34	5.82		61	0	27	348	132	2	9648
35	6.02	9.16	59	0	23	326	56	2	9829
36	6.20		53	0	23	344	58	2	9975
37	6.41	9.26	52	0	23	370	60	2	10139
38	6.57		49	0	21	290	58	1	10258
39	6.77	9.31	49	0	19	306	56	1	10407
40	6.93		45	0	19	276	26	1	10514
41	7.16	9.27	38	0	18	296	51	1	10646
42	7.34		39	0	16	336	51	1	10753
43	7.53	9.22	37	0	16	307	60	1	10861
44	7.75		36	0	14	301	53	1	10978
45	7.90	9.16	35	0	14	437	52	1	11060
						281	57	1	

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - CONTROL TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
			µg/mL of eluate						
1	0.17	7.82	0						0
2	0.34	7.71	0	39	2.5	13.8	76	17	0
3	0.51	7.75	0	62	2.5	10.0	85	20	0
4	0.69	7.77	0	91	1.6	10.7	108	23	0
5	0.86	7.68	0	111	1.4	10.9	118	27	0
6	1.02	7.50	0	88	1.7	10.3	96	22	0
7	1.18	7.56	0	46	1.3	8.2	64	15	0
8	1.33	7.70	0	20	1.3	7.6	44	10	0
9	1.47	7.74	0	9	1.1	6.3	35	7	0
10	1.62	7.67	0	4	1.6	5.7	30	6	0
11	1.77	7.79	0	0	1.5	5.7	28	6	0
12	1.91	7.74	0	0	1.3	5.4	27	5	0
13	2.07	7.72	0	0	1.1	7.4	35	8	0
14	2.24	7.54	0	0	1.4	5.8	25	5	0
15	2.39	7.76	0	0	1.4	6.3	27	5	0
16	2.56	7.60	0	0	1.0	5.6	24	5	0
17	2.72	7.58	0	0	1.3	5.2	26	5	0
18	2.88		0	0	0.9	5.9	23	5	0
19	3.04	7.58	0	0	1.3	5.0	23	5	0
20	3.19		0	0	0.8	5.3	23	5	0
21	3.35	7.67	0	0	0.9	4.3	23	4	0
22	3.52		0	0	0.9	5.3	31	7	0
23	3.67	7.76	0	0	1.0	6.8	23	5	0
24	3.82		0	0	1.4	4.8	24	5	0
25	3.99	7.76	0	0	2.4	4.3	22	4	0
26	4.15		0	0	1.3	4.7	22	4	0
27	4.30	8.15	0	0	1.0	5.8	23	4	0
28	4.45		0	0	1.4	5.0	24	5	0
29	4.62	7.77	0	0	1.6	4.8	25	5	0
30	4.76		0	0	0.9	5.2	24	5	0
31	4.91	7.71	0	0	1.3	4.9	23	4	0
32	5.06		0	0	1.0	5.1	23	4	0
33	5.22	7.91	0	0	1.3	4.2	24	5	0
34	5.37		0	0	1.4	4.5	23	4	0
35	5.53	7.85	0	0	2.4	4.8	24	4	0
36	5.69		0	0	2.3	2.9	23	4	0
37	5.86	7.44	0	0	1.5	3.4	23	4	0
38	6.02		0	0	1.0	5.2	22	4	0
39	6.18	7.82	0	0	0.9	4.2	21	4	0
40	6.34		0	0	1.6	4.8	21	4	0
41	6.51	7.81	0	0	1.4	4.5	21	4	0
42	6.67		0	0	1.5	5.0	23	4	0
43	6.82	8.25	0	0	3.7	4.2	23	4	0
44	6.96		0	0	1.3	4.6	22	4	0
45	7.12	7.77	0	0	1.5	4.6	21	4	0
				0	1.3	4.5	21	4	0

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - CONTROL TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.17	7.41	0	101	6.6	20.2	126	29	0
2	0.37	7.67	0	132	4.5	13.2	143	33	0
3	0.55	7.58	0	149	3.8	16.3	154	36	0
4	0.73	7.37	0	128	3.3	12.4	130	30	0
5	0.91	7.47	0	92	7.5	10.7	102	22	0
6	1.09	7.52	0	57	5.2	9.4	71	16	0
7	1.27	7.60	0	29	3.3	7.7	49	10	0
8	1.45	7.64	0	10	7.6	6.1	35	7	0
9	1.63	7.50	0	4	2.1	5.9	29	5	0
10	1.82	7.87	0	0	6.5	6.1	26	5	0
11	2.00	7.64	0	0	4.8	5.6	25	5	0
12	2.17	7.65	0	0	2.4	5.4	24	5	0
13	2.34	7.74	0	0	5.3	5.1	23	4	0
14	2.51	7.60	0	0	5.3	5.1	23	4	0
15	2.68	7.51	0	0	3.1	6.5	30	7	0
16	2.86	7.57	0	0	2.9	5.0	22	4	0
17	3.03	7.63	0	0	3.3	4.8	22	4	0
18	3.21	7.52	0	0	2.0	4.5	21	4	0
19	3.39	7.52	0	0	3.7	4.7	21	4	0
20	3.61	7.52	0	0	3.2	5.1	21	4	0
21	3.79	7.88	0	0	9.3	4.8	20	4	0
22	3.98	7.52	0	0	2.3	5.8	20	4	0
23	4.16	7.73	0	0	3.6	4.8	20	4	0
24	4.35	7.52	0	0	2.9	5.3	21	4	0
25	4.53	7.68	0	0	1.7	5.1	20	4	0
26	4.71	7.52	0	0	3.1	4.0	20	4	0
27	4.90	7.63	0	0	2.8	4.5	20	4	0
28	5.10	7.52	0	0	2.5	4.4	20	4	0
29	5.29	7.62	0	0	4.6	4.0	20	4	0
30	5.47	7.52	0	0	2.5	7.7	19	4	0
31	5.66	7.94	0	0	8.0	4.2	21	4	0
32	5.82	7.52	0	0	1.9	6.3	21	4	0
33	6.01	7.62	0	0	2.6	4.2	19	3	0
34	6.18	7.52	0	0	4.5	3.2	19	3	0
35	6.36	7.70	0	0	5.8	4.3	19	3	0
36	6.55	7.52	0	0	2.9	3.7	19	3	0
37	6.74	7.68	0	0	2.1	4.5	20	3	0
38	6.91	7.52	0	0	2.5	3.5	19	4	0
39	7.08	7.64	0	0	2.4	4.5	20	4	0
40	7.27	7.52	0	0	2.6	4.0	19	3	0
41	7.46	7.40	0	0	1.4	3.1	18	3	0
42	7.65	7.52	0	0	2.9	3.4	20	4	0
43	7.85	7.64	0	0	1.4	3.6	18	3	0
44	8.02	7.52	0	0	1.6	2.9	19	3	0
45	8.21	7.55	0	0	2.8	4.0	18	3	0

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - MAP (ONLY) TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.38	7.49	0.0	190	2.2	15.7	188	44	0
2	0.59	7.50	0.0	347	2.2	18.1	313	72	0
3	0.83	7.46	0.0	408	2.3	19.4	362	79	0
4	1.03	7.62	4.7	311	2.9	15.6	258	64	13
5	1.23	7.20	31.3	167	2.7	10.0	138	35	99
6	1.42	7.10	60.1	87	2.5	11.7	119	33	264
7	1.60	7.15	75.5	46	3.1	9.8	96	25	465
8	1.78	7.15	78.6	24	3.3	9.6	81	21	672
9	1.97	7.13	77.3	12	2.5	8.6	72	19	889
10	2.15	7.22	73.4	7	3.4	8.4	66	17	1092
11	2.32	7.27	68.3	6	3.0	7.9	61	15	1279
12	2.50	7.27	64.7	6	2.6	7.5	59	14	1464
13	2.68	7.28	58.4	6	2.9	7.6	57	13	1627
14	2.85	7.28	55.6	5	3.2	6.7	54	13	1782
15	3.03	7.25	53.7	5	2.6	6.9	52	12	1938
16	3.20	7.29	51.3	5	2.4	7.0	51	12	2084
17	3.37	7.61	51.4	5	1.7	7.0	51	12	2230
18	3.55		48.5	5	1.6	6.7	50	11	2369
19	3.71	7.28	47.4	5	2.4	6.2	47	11	2503
20	3.88		44.6	5	3.2	6.2	47	10	2629
21	4.05	7.23	44.3	5	2.4	6.7	46	10	2758
22	4.22		43.4	5	2.4	6.7	46	10	2880
23	4.37	7.35	40.7	6	1.6	6.5	44	10	2993
24	4.55		39.9	6	1.7	7.1	44	9	3114
25	4.72	7.38	37.5	6	3.0	6.9	43	9	3224
26	4.88		37.7	6	1.6	6.4	43	9	3333
27	5.04	7.35	36.4	6	1.6	7.8	42	9	3437
28	5.20		35.0	6	2.6	6.4	42	9	3538
29	5.37	7.39	33.5	6	2.1	6.4	41	9	3637
30	5.53		33.6	6	1.6	6.4	41	8	3734
31	5.69	7.74	32.1	6	2.6	6.9	49	11	3829
32	5.85		31.0	6	2.7	7.5	41	8	3917
33	6.02	7.43	30.4	6	1.4	6.6	40	8	4011
34	6.18		29.7	6	2.7	7.3	40	8	4095
35	6.34	7.30	29.4	7	2.9	7.2	39	8	4182
36	6.49		28.3	7	1.7	8.3	41	8	4263
37	6.66	7.42	27.7	7	2.2	7.3	39	8	4350
38	6.81		27.2	7	1.6	6.5	39	8	4425
39	7.01	7.30	26.8	7	2.1	9.2	39	8	4521
40	7.26		27.3	7	3.1	10.2	37	7	4633
41	7.41	7.33	26.1	7	2.6	11.0	39	7	4702
42	7.59		26.4	7	4.8	11.3	35	7	4784
43	7.77	7.30	25.3	7	3.3	12.5	34	6	4860
44	7.94		24.0	7	3.2	10.9	33	6	4931
45	8.12	7.33	22.7	7	3.3	9.3	33	6	4999

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - MAP (ONLY) TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	-----Concentration in Eluate-----					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N µg/mL of eluate	K	Ca		Mg
1	0.26	7.34	0.0	253	4.0	17.0	22	53	0
2	0.38	7.45	0.0	354	1.8	18.5	303	73	0
3	0.55	7.43	0.0	476	3.8	18.7	393	83	0
4	0.73	7.52	0.0	421	3.9	17.2	350	78	0
5	0.90	7.28	3.3	336	2.6	15.8	272	68	0
6	1.05	7.16	17.3	233	3.0	14.4	209	55	9
7	1.23	7.16	34.7	150	2.5	13.3	150	40	54
8	1.43	7.20	55.9	88	2.6	10.6	118	31	157
9	1.60	7.17	76.8	44	1.6	8.6	94	26	343
10	1.78	7.22	80.0	25	1.7	8.8	80	21	564
11	1.95	7.22	77.2	16	3.3	9.2	72	19	804
12	2.12	7.23	73.9	16	1.8	8.6	67	17	1021
13	2.31	7.18	69.6	6	1.1	8.1	62	16	1236
14	2.48	7.22	64.2	4	3.0	8.0	59	14	1458
15	2.66	7.32	63.0	4	2.4	7.7	56	14	1647
16	2.83	7.26	57.4	4	3.4	7.4	54	13	1832
17	3.01	7.27	56.2	4	1.6	7.2	52	11	2003
18	3.19		50.5	4	2.5	6.9	52	11	2169
19	3.37	7.36	47.7	4	3.7	6.8	52	11	2322
20	3.54		46.8	4	1.0	6.6	48	11	2468
21	3.71	7.37	46.0	4	5.9	6.4	48	11	2607
22	3.89		45.2	4	3.5	6.9	48	11	2737
23	4.06	7.37	41.5	4	6.9	6.9	48	11	2874
24	4.24		41.5	4	2.0	7.2	45	10	2997
25	4.41	7.38	40.0	4	3.0	7.2	55	11	3119
26	4.59		40.0	4	0.5	6.9	44	10	3239
27	4.77	7.41	38.5	5	2.7	6.6	45	10	3356
28	4.94		36.0	5	5.2	6.6	43	9	3463
29	5.10	7.41	34.8	5	1.8	6.4	43	9	3566
30	5.28		34.1	5	1.6	6.8	41	9	3659
31	5.45	7.26	34.4	5	0.2	6.6	42	9	3765
32	5.63		32.1	5	2.4	7.5	42	9	3859
33	5.80	7.33	33.0	5	4.2	6.6	42	9	3962
34	5.97		30.8	5	0.9	7.2	41	9	4052
35	6.14	7.38	30.7	5	2.6	6.1	41	9	4143
36	6.32		29.3	5	2.6	6.6	40	8	4231
37	6.49	7.29	29.4	5	5.4	6.9	40	8	4318
38	6.67		26.6	5	2.0	6.6	36	7	4398
39	6.84	7.37	25.2	5	1.1	7.1	39	8	4474
40	7.02		25.3	5	1.8	6.9	39	8	4551
41	7.20	7.40	26.6	5	3.0	7.4	39	8	4631
42	7.37		26.4	5	2.1	7.4	38	8	4713
43	7.54	7.40	24.1	5	1.4	7.4	38	8	4784
44	7.72		24.1	5	2.0	7.7	38	8	4855
45	7.90	7.37	23.9	5	2.3	7.7	38	7	4928
			23.8	5	3.3	7.9	37	7	5001

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - UREA+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
			µg/mL of eluate						
1	0.27	7.25	0.0	1489	4	69	1579	273	0
2	0.45	7.32	0.0	1615	5	87	1637	290	0
3	0.66	7.35	0.0	1241	110	89	1234	215	0
4	0.85	7.29	6.7	617	111	63	698	112	19
5	1.03	7.17	23.7	398	107	51	451	70	85
6	1.22	7.21	32.1	269	99	43	248	54	180
7	1.39	7.21	43.8	168	93	37	154	36	298
8	1.58	7.34	48.3	120	100	32	112	26	439
9	1.75	7.20	51.5	101	107	31	95	22	584
10	1.92	7.02	51.5	100	114	29	92	21	728
11	2.07	7.13	52.3	90	119	29	74	18	867
12	2.26	7.17	53.9	81	123	26	68	16	1037
13	2.44	7.16	57.6	77	135	24	57	12	1206
14	2.63	7.14	61.7	61	131	22	51	11	1403
15	2.76	7.21	61.3	61	129	21	49	10	1547
16	2.94	7.10	59.5	54	129	20	49	10	1731
17	3.11	6.95	64.3	57	129	19	42	8	1920
18	3.28		64.1	45	121	17	39	8	2111
19	3.45	7.15	62.5	37	114	17	37	7	2300
20	3.62		64.1	32	128	17	44	8	2491
21	3.79	7.60	62.6	24	120	16	37	8	2679
22	3.95		62.8	20	118	15	32	6	2865
23	4.14	7.73	59.0	17	115	14	28	5	3055
24	4.29		62.9	17	113	14	28	5	3226
25	4.44	7.55	59.4	17	109	14	31	6	3395
26	4.62		56.6	13	102	15	35	6	3574
27	4.83	7.73	55.8	12	106	13	23	4	3780
28	4.99		58.6	13	106	13	20	3	3942
29	5.14	7.41	54.5	17	99	12	22	4	4092
30	5.33		56.1	18	101	13	23	4	4275
31	5.48	7.47	54.1	17	97	12	21	4	4428
32	5.64		51.8	16	95	11	20	4	4570
33	5.82	7.38	52.2	18	94	11	22	4	4741
34	5.98		52.4	16	95	13	22	4	4893
35	6.13	7.59	50.5	13	91	12	21	4	5031
36	6.30		45.7	14	90	10	21	3	5180
37	6.49	7.64	42.9	14	89	9	17	3	5322
38	6.65		44.4	13	91	10	17	3	5450
39	6.81	7.85	42.8	12	89	9	16	2	5577
40	6.96		42.1	12	89	9	16	3	5694
41	7.15	7.70	41.1	12	87	8	15	2	5838
42	7.31		38.0	12	88	8	16	2	5944
43	7.51	7.70	35.8	12	85	8	14	2	6072
44	7.64		39.6	10	86	8	15	2	6167
45	7.80	7.94	35.9	11	85	8	16	2	6275

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - UREA+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate						Cumulative Total of P Eluted (µg)
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca	Mg	
			µg/mL of eluate						
1	0.11	7.49	0.0	1996	2	62	1948	338	0
2	0.25	7.42	0.0	2306	2	67	2218	401	0
3	0.39	7.07	0.0	2494	3	73	2319	462	0
4	0.54	6.86	0.0	2212	14	79	1997	418	0
5	0.70	6.56	0.0	1215	38	75	1237	259	0
6	0.89	6.60	3.2	581	69	57	579	108	0
7	1.04	5.75	24.9	294	66	44	210	43	11
8	1.18	5.34	41.2	200	63	42	152	42	75
9	1.33	5.36	53.2	143	60	37	123	34	185
10	1.51	5.21	69.0	105	57	31	106	27	331
11	1.66	5.35	73.7	77	50	28	87	23	559
12	1.80	5.72	75.4	55	47	26	112	29	760
13	1.96	5.29	79.9	43	39	22	71	18	950
14	2.10	5.37	84.2	38	41	23	63	16	1191
15	2.30	5.21	86.5	31	43	22	59	14	1412
16	2.43	5.38	86.4	31	45	26	49	12	1729
17	2.59	5.18	80.6	26	42	22	47	12	1936
18	2.75		87.5	26	40	21	49	13	2186
19	2.89	5.26	86.1	27	41	20	48	12	2438
20	3.05		81.3	28	46	18	38	10	2673
21	3.23	5.67	79.1	25	45	18	37	9	2917
22	3.40		77.3	25	45	18	36	9	3183
23	3.55	6.11	77.8	24	49	18	34	9	3415
24	3.69		76.1	24	49	17	31	8	3643
25	3.85	6.21	72.8	21	51	16	30	8	3841
26	4.01		64.0	17	58	16	28	8	4050
27	4.15	6.99	65.5	15	64	16	36	8	4242
28	4.28		61.4	12	68	16	30	8	4421
29	4.44	7.29	63.2	8	75	15	25	6	4576
30	4.62		59.8	9	79	13	22	5	4774
31	4.76	7.05	58.9	13	71	13	24	6	4973
32	4.93		57.0	18	67	13	20	5	5133
33	5.08	6.81	55.2	18	66	12	19	4	5307
34	5.22		52.0	17	67	12	21	5	5465
35	5.37	6.69	48.4	22	63	12	19	4	5606
36	5.56		51.3	16	68	11	24	6	5746
37	5.69	6.86	48.7	18	65	11	19	5	5926
38	5.85		46.4	18	63	10	16	3	6050
39	5.99	6.92	43.7	13	64	10	14	3	6192
40	6.16		43.6	14	64	10	14	3	6312
41	6.33	6.89	39.5	14	63	9	13	3	6447
42	6.48		35.0	16	60	8	13	3	6572
43	6.64	6.91	42.7	16	65	9	13	3	6672
44	6.80		38.5	14	65	8	12	2	6799
45	6.95	6.76	38.9	18	60	8	12	2	6916
							12	2	7030

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N µg/mL of eluate	K	Ca		Mg
1	0.14	6.57	0.0	1229	504	215	4762	983	0
2	0.34	6.62	0.0	1176	745	207	4304	952	0
3	0.50	6.59	0.0	970	1236	233	3978	918	0
4	0.67	6.61	0.0	687	1743	250	3438	762	0
5	0.84	6.62	3.3	424	1874	200	2179	453	0
6	0.99	6.21	53.2	231	1302	133	1164	218	9
7	1.10	6.15	120.8	129	809	79	601	106	142
8	1.30	6.20	194.5	57	460	39	184	42	397
9	1.45	6.10	203.7	38	232	21	80	18	1053
10	1.61	6.05	172.4	31	168	15	47	10	1621
11	1.75	5.81	145.7	28	123	11	31	6	2089
12	1.92	5.34	134.1	26	99	10	24	5	2478
13	2.06	5.98	120.7	24	93	8	20	4	2871
14	2.21	5.21	102.3	27	80	7	16	3	3195
15	2.35	5.39	97.3	24	78	7	15	3	3476
16	2.49	5.81	96.1	25	73	7	13	2	3738
17	2.62	5.85	91.0	25	70	8	13	2	3982
18	2.76		89.0	26	70	8	12	2	4210
19	2.90	5.15	90.8	27	69	7	12	2	4464
20	3.06		76.5	26	64	6	11	2	4720
21	3.19	6.11	69.5	25	62	6	10	1	4959
22	3.37		71.1	23	66	6	10	1	5137
23	3.53	6.64	69.7	23	69	7	10	2	5379
24	3.68		67.5	22	66	6	10	1	5600
25	3.83	6.64	67.5	22	66	6	10	1	5792
26	3.97		58.1	24	64	6	11	1	5985
27	4.14	6.82	56.8	22	62	6	9	1	6149
28	4.29		54.8	22	63	6	8	1	6326
29	4.44	6.29	51.0	24	61	6	9	1	6488
30	4.60		50.6	26	59	5	8	1	6637
31	4.74	7.08	52.3	27	54	5	8	1	6789
32	4.88		47.2	19	63	5	8	1	6928
33	5.04	6.89	42.5	20	59	4	8	1	7063
34	5.21		42.0	19	55	4	8	1	7192
35	5.39	7.10	43.8	19	57	4	8	1	7326
36	5.52		40.8	19	60	4	7	1	7477
37	5.70	6.85	36.3	23	53	5	8	1	7577
38	5.86		37.4	22	51	5	8	1	7699
39	6.00	7.23	34.2	20	52	4	7	1	7809
40	6.16		36.0	17	53	4	7	1	7902
41	6.33	6.72	30.4	20	54	5	8	1	8009
42	6.50		31.5	22	50	4	7	1	8103
43	6.66	7.18	29.3	21	52	4	7	1	8203
44	6.84		30.3	18	52	4	7	1	8291
45	7.00	7.21	28.1	19	52	3	7	1	8386
				18	50	3	7	1	8469

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - NH₄Cl+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.09	6.56	0.0	1355	245	164	3847	759	0
2	0.28	6.44	0.0	1437	403	180	4182	901	0
3	0.45	6.63	0.0	1137	778	211	3970	899	0
4	0.62	6.67	0.0	812	1284	227	3586	804	0
5	0.79	6.74	0.0	538	1494	209	2692	565	0
6	0.94	6.58	10.3	320	1338	148	1413	274	0
7	1.08	6.31	62.7	142	710	82	591	106	27
8	1.25	5.33	125.7	82	449	40	180	41	186
9	1.42	5.94	166.6	53	266	25	108	25	558
10	1.62	5.08	160.4	38	168	15	57	12	1058
11	1.80	5.06	144.2	31	116	11	34	7	1624
12	1.99	5.38	118.3	30	94	9	26	5	2087
13	2.13	5.95	105.3	25	89	9	23	5	2464
14	2.30	5.33	98.9	24	80	8	18	3	2724
15	2.48	5.26	92.5	23	74	7	15	2	3018
16	2.64	6.09	85.9	24	75	7	14	2	3305
17	2.84	5.34	79.8	24	73	7	12	2	3541
18	2.99		80.1	26	64	7	12	2	3819
19	3.16	5.29	73.8	24	71	6	11	1	4029
20	3.35		69.2	24	64	6	11	1	4244
21	3.51	5.18	64.6	24	67	5	9	1	4470
22	3.68		62.6	23	53	6	9	1	4656
23	3.85	5.89	55.0	24	56	5	13	2	4845
24	4.05		54.5	24	58	5	8	1	5005
25	4.22	6.32	50.7	21	54	5	8	1	5188
26	4.39		47.3	20	56	5	8	1	5339
27	4.61	6.72	40.7	17	50	5	8	1	5473
28	4.77		41.0	20	56	5	10	2	5621
29	4.94	6.59	40.2	20	57	5	7	1	5733
30	5.10		38.2	20	56	5	8	1	5851
31	5.28	6.89	35.8	19	53	5	8	1	5955
32	5.44		32.8	16	53	4	7	1	6065
33	5.64	7.13	32.5	18	58	5	8	1	6154
34	5.81		33.4	17	46	4	8	1	6262
35	5.99	7.21	31.7	15	50	4	8	1	6361
36	6.17		26.8	16	55	4	7	1	6459
37	6.32	7.24	27.4	16	45	4	7	1	6537
38	6.52		27.1	18	50	4	7	1	6611
39	6.75	7.14	25.5	17	49	4	7	1	6703
40	6.94		21.2	15	42	4	7	1	6795
41	7.14	7.19	23.7	15	42	4	7	1	6860
42	7.29		25.0	16	44	5	7	1	6935
43	7.47	7.23	24.0	17	42	4	6	1	6999
44	7.65		24.2	18	43	4	7	1	7070
45	7.83	7.21	24.0	20	46	4	7	1	7140
									7211

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - KCl+MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N µg/mL of eluate	K	Ca		Mg
1	0.21	7.00	0.0	324	3	3310	2396	441	0
2	0.39	7.16	0.0	407	1	3930	2573	488	0
3	0.60	7.15	0.0	467	1	4671	2714	529	0
4	0.71	7.28	0.0	440	10	5261	2589	502	0
5	0.89	7.19	0.0	334	20	4657	1855	363	0
6	1.06	7.12	0.0	208	24	3451	1098	204	0
7	1.32	6.86	59.9	93	24	1719	389	64	240
8	1.51	7.22	146.6	37	20	869	71	17	680
9	1.71	7.38	156.6	19	11	759	31	7	1158
10	1.90	7.46	144.9	13	9	590	23	5	1597
11	2.09	7.44	133.6	13	5	502	18	4	1994
12	2.24	7.55	120.4	12	6	459	16	3	2283
13	2.39	7.67	115.0	12	4	437	16	4	2569
14	2.56	7.64	105.3	13	4	421	13	2	2869
15	2.73	7.67	93.6	13	5	390	11	2	3131
16	2.91	7.63	90.3	13	3	291	11	2	3406
17	3.07	7.69	85.8	12	2	271	10	2	3643
18	3.23		84.3	12	2	261	9	2	3876
19	3.39	7.63	78.3	10	3	248	9	1	4086
20	3.55		76.1	10	3	243	8	1	4297
21	3.73	7.63	70.8	10	1	228	8	1	4524
22	3.91		76.2	11	6	261	9	2	4766
23	4.07	7.77	65.7	10	1	222	7	1	4944
24	4.27		60.7	10	4	212	6	1	5151
25	4.43	7.78	55.4	10	1	202	6	1	5309
26	4.60		53.9	10	1	194	6	1	5464
27	4.76	7.72	54.2	10	1	194	6	1	5616
28	4.93		51.1	10	4	197	7	1	5764
29	5.09	7.62	49.5	10	2	184	6	1	5910
30	5.26		47.2	10	1	180	7	1	6045
31	5.42	7.65	44.2	10	0	176	6	1	6175
32	5.63		45.0	10	1	173	6	1	6332
33	5.80	7.60	42.5	9	0	164	5	1	6461
34	5.97		40.6	10	0	162	5	1	6576
35	6.11	7.67	36.4	0	0	155	5	1	6666
36	6.30		37.7	9	1	160	5	1	6791
37	6.46	7.73	36.3	8	1	152	5	1	6896
38	6.64		35.8	8	0	149	5	1	7005
39	6.80	7.60	33.6	8	2	141	5	1	7103
40	6.98		33.3	7	2	147	5	2	7203
41	7.14	7.66	28.4	7	1	136	5	0	7283
42	7.30		28.2	7	0	138	5	0	7365
43	7.47	7.68	26.9	6	0	129	4	0	7443
44	7.63		26.7	6	0	130	4	0	7522
45	7.81	7.67	26.3	6	1	124	4	0	7606

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - KCl+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.12	7.22	0.0	342	3	3331	2544	466	0
2	0.31	7.10	0.0	431	1	3516	2554	472	0
3	0.48	7.00	0.0	495	0	4134	2769	524	0
4	0.65	7.02	0.0	506	2	5101	2834	561	0
5	0.83	7.10	0.0	417	13	5169	2175	435	0
6	1.00	6.67	3.3	227	22	3103	936	176	0
7	1.17	6.95	71.0	164	23	1693	385	61	9
8	1.35	7.15	146.9	43	21	1291	90	22	218
9	1.55	7.29	166.3	28	19	904	66	16	672
10	1.75	7.36	157.3	19	12	666	41	9	1228
11	1.94	7.45	131.8	15	7	516	25	6	1733
12	2.13	7.42	116.2	13	6	485	20	4	2147
13	2.32	7.51	108.1	9	8	422	18	4	2509
14	2.51	7.59	98.4	8	8	399	15	3	2848
15	2.69	7.59	90.5	8	6	373	14	3	3146
16	2.88	7.61	87.0	8	10	343	13	2	3419
17	3.06	7.70	83.3	9	9	267	12	2	3692
18	3.25		77.0	9	7	261	11	2	3934
19	3.43	7.69	76.6	10	2	252	11	2	4168
20	3.61		70.6	9	7	241	10	2	4391
21	3.79	7.68	65.4	10	6	229	10	1	4603
22	3.97		60.1	10	7	220	9	1	4798
23	4.14	7.73	58.1	10	2	208	10	2	4977
24	4.31		56.7	10	4	214	10	1	5142
25	4.50	7.72	52.9	9	2	201	9	1	5303
26	4.68		52.7	9	5	180	8	1	5467
27	4.85	7.76	45.8	8	9	186	8	1	5632
28	5.03		45.4	9	3	184	8	1	5764
29	5.20	7.72	42.7	9	4	177	8	1	5899
30	5.39		42.2	9	4	174	8	1	6026
31	5.55	7.74	36.8	8	2	166	9	1	6158
32	5.73		37.0	9	2	162	8	1	6259
33	5.89	7.80	35.1	9	5	162	8	1	6373
34	6.08		34.1	9	3	158	8	1	6473
35	6.25	7.77	32.4	8	4	154	8	1	6582
36	6.44		31.2	9	4	152	9	1	6674
37	6.67	7.70	30.4	9	6	146	7	1	6778
38	6.85		28.2	8	1	137	7	1	6892
39	7.03	7.74	26.8	7	3	133	7	1	6974
40	7.18		26.2	7	1	130	7	1	7052
41	7.35	7.72	25.5	6	2	129	7	1	7121
42	7.53		24.1	6	0	129	7	1	7195
43	7.73	7.63	23.3	6	0	125	7	1	7266
44	7.90		21.4	5	2	122	6	1	7344
45	8.08	7.76	21.1	5	3	120	6	1	7407
									7472

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - K_2CO_3 +MAP TREATMENT, REPLICATE # 1

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (μ g)	
			P	(NO_3+NO_2) -N	NH_4 -N <small>μg/mL of eluate</small>	K	Ca		Mg
1	0.11	7.85	0.0	514	7	399	435	83	0
2	0.27	8.18	0.0	514	5	449	487	81	0
3	0.43	8.34	0.0	560	11	606	541	92	0
4	0.58	7.76	0.0	457	9	765	466	83	0
5	0.71	7.89	0.0	335	16	732	258	68	0
6	0.85	8.42	0.0	278	9	795	215	55	0
7	0.99	8.20	17.3	235	17	899	162	42	0
8	1.13	8.13	54.7	141	16	1040	113	27	44
9	1.28	8.18	84.6	91	14	972	98	19	193
10	1.43	8.19	100.1	57	14	860	91	15	439
11	1.58	8.35	110.5	29	11	776	76	12	737
12	1.73	8.36	104.7	10	9	655	57	9	1055
13	1.86	8.39	103.6	3	4	574	41	6	1361
14	2.00	8.40	98.5	0	6	539	33	5	1632
15	2.15	8.41	97.2	0	9	532	29	5	1914
16	2.30	8.36	92.0	0	9	475	27	4	2207
17	2.46	8.34	84.9	0	6	451	24	4	2482
18	2.60	8.08	80.8	0	6	468	23	4	2741
19	2.76	8.43	89.7	0	10	395	21	3	2974
20	2.91	8.52	90.1	0	11	376	19	3	3255
21	3.06	8.52	72.6	0	17	354	17	2	3515
22	3.22	8.51	66.1	0	15	402	18	2	3741
23	3.37	8.51	67.4	0	12	377	17	2	3946
24	3.52	8.58	63.9	0	17	330	17	2	4139
25	3.68	8.58	57.1	0	15	372	15	2	4332
26	3.83	8.63	54.9	0	13	332	15	2	4505
27	3.98	8.63	52.9	0	11	328	15	2	4666
28	4.13	8.78	52.6	0	12	328	15	2	4830
29	4.29	8.78	51.5	0	11	340	14	2	4980
30	4.44	8.84	48.0	0	9	322	14	2	5140
31	4.60	8.84	46.4	0	8	341	13	2	5284
32	4.76	8.92	46.7	0	7	313	13	2	5426
33	4.91	8.92	45.1	0	5	309	13	1	5566
34	5.07	9.09	44.3	0	4	272	12	1	5703
35	5.23	9.09	42.4	0	6	276	12	1	5833
36	5.37	9.11	40.4	0	3	267	12	1	5963
37	5.53	9.11	38.4	0	5	268	12	1	6079
38	5.69	9.31	38.5	0	3	265	12	1	6197
39	5.87	9.31	37.6	0	3	255	11	1	6315
40	6.03	9.34	37.4	0	4	251	11	1	6441
41	6.19	9.34	34.6	0	3	253	10	1	6552
42	6.36	9.30	34.4	0	2	250	11	1	6656
43	6.51	9.30	28.4	0	1	249	10	1	6762
44	6.68	9.51	31.5	0	2	197	10	1	6843
45	6.85	9.51	31.5	0	2	239	10	1	6943
						234	10	1	7043

ELUTION EXPERIMENT - DATA FOR ELUATE COLLECTED FROM SOIL COLUMNS INCUBATED FOR 5 WK - K₂CO₃+MAP TREATMENT, REPLICATE # 2

Fraction Number (h)	Pore Volumes Eluted	pH of Eluate	Concentration in Eluate					Cumulative Total of P Eluted (µg)	
			P	(NO ₃ +NO ₂)-N	NH ₄ -N	K	Ca		Mg
-----µg/mL of eluate-----									
1	0.22	7.99							
2	0.40	8.23	0.0	413	2	666	397	79	0
3	0.57	8.23	0.0	528	2	444	520	92	0
4	0.73	8.24	0.0	564	8	618	580	98	0
5	0.91	8.34	0.0	411	20	696	465	84	0
6	1.06	8.24	0.0	220	20	610	218	51	0
7	1.17	8.07	7.1	139	19	545	139	30	16
8	1.32	7.97	28.1	106	10	610	100	23	75
9	1.49	7.89	58.1	96	8	675	80	18	226
10	1.67	7.95	78.7	95	12	745	77	16	478
11	1.85	8.04	86.8	65	11	758	63	12	753
12	2.00	8.11	98.1	46	8	689	54	10	1054
13	2.18	8.07	95.3	34	8	615	49	8	1317
14	2.34	8.01	92.3	27	6	554	51	7	1606
15	2.53	7.97	92.4	20	6	525	43	6	1878
16	2.68	8.06	89.3	18	8	552	48	7	2162
17	2.89	8.04	90.0	9	6	490	40	6	2410
18	3.06		89.4	9	5	480	39	5	2732
19	3.24	8.04	95.4	5	7	441	34	5	3009
20	3.43		84.7	3	4	423	28	4	3270
21	3.60	8.04	72.1	3	6	409	22	3	3502
22	3.75		70.1	3	6	361	19	2	3703
23	3.93	8.04	68.6	3	6	395	19	2	3887
24	4.11		79.8	3	7	388	21	3	4128
25	4.28	8.09	74.9	3	6	399	19	3	4366
26	4.45		67.5	3	7	340	18	2	4559
27	4.61	8.11	63.0	3	9	456	17	2	4743
28	4.78		60.8	2	8	356	16	2	4916
29	4.97	8.16	58.7	2	8	336	16	2	5091
30	5.14		54.1	2	9	315	14	2	5260
31	5.31	8.21	50.7	2	7	276	14	2	5411
32	5.48		49.3	2	5	280	14	2	5558
33	5.65	8.22	48.1	2	7	271	13	1	5701
34	5.84		45.7	2	5	260	12	1	5833
35	6.00	8.30	44.6	1	5	261	12	1	5975
36	6.17		44.6	2	4	259	11	1	6102
37	6.34	8.40	42.7	2	4	260	11	1	6229
38	6.52		42.7	2	4	257	12	1	6357
39	6.70	8.46	40.0	2	7	253	11	1	6476
40	6.89		38.3	1	2	256	10	1	6595
41	7.07	8.62	38.1	1	4	248	10	1	6716
42	7.25		33.2	1	3	228	9	1	6817
43	7.41	8.56	29.2	1	2	227	11	1	6905
44	7.59		31.2	2	1	230	9	1	6993
45	7.77	8.71	31.7	1	1	227	9	1	7091
			30.4	1	2	225	11	2	7184

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, CONTROL TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	1.62	2.34	9.55	13.77	23.32
1.5	1.34	2.26	8.19	13.81	22.00
2.5	1.92	2.91	13.65	20.67	34.32
3.5	2.35	3.36	16.38	23.40	39.78
4.5	2.46	3.38	15.01	20.63	35.65
5.5	2.41	3.53	15.01	22.04	37.05
6.5	2.40	4.11	17.74	30.39	48.13
7.5	2.68	3.97	20.47	30.31	50.78
8.5	2.80	4.04	19.11	27.54	46.65
9.5	2.72	3.92	19.11	27.54	46.65
REPLICATE #2					
0.5	1.77	5.44	13.65	41.75	55.40
1.5	2.04	6.25	13.65	41.75	55.40
2.5	2.15	5.97	15.01	41.71	56.72
3.5	2.36	6.58	15.01	41.71	56.72
4.5	2.85	6.20	19.11	41.59	60.70
5.5	2.38	6.05	16.38	41.67	58.05
6.5	2.76	6.01	19.11	41.59	60.70
7.5	2.62	6.15	17.74	41.63	59.37
8.5	2.88	6.75	17.74	41.63	59.37
9.5	3.03	6.61	19.11	41.59	60.70

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, MAP (ONLY) TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	118	166	899.5	1266	2165
1.5	57	64	406.7	451	858
2.5	30	31	195.1	205	400
3.5	33	24	218.4	162	380
4.5	41	25	212.9	134	347
5.5	36	24	238.8	161	400
6.5	35	24	245.7	169	415
7.5	35	23	237.5	156	393
8.5	33	22	223.8	150	374
9.5	31	23	236.1	175	411
REPLICATE #2					
0.5	100	114	709.8	810	1520
1.5	62	77	421.7	521	943
2.5	30	28	189.7	177	366
3.5	34	21	226.5	142	368
4.5	37	21	232.0	133	365
5.5	36	21	242.9	141	384
6.5	33	20	230.6	144	375
7.5	32	18	234.7	133	368
8.5	31	18	219.7	131	351
9.5	29	18	200.6	126	326

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, UREA+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	80	99	468.1	576.3	1044
1.5	106	100	771.2	727.6	1498
2.5	106	54	707.0	358.6	1065
3.5	28	14	177.4	93.1	270
4.5	23	8	158.3	57.1	215
5.5	24	8	167.8	56.9	224
6.5	34	9	247.0	71.4	318
7.5	66	13	484.5	98.2	582
8.5	106	17	716.6	119.5	836
9.5	109	25	724.8	169.8	894
REPLICATE #2					
0.5	71	97	479.1	653.3	1132
1.5	76	60	580.1	455.0	1035
2.5	56	34	412.2	249.2	661
3.5	17	10	110.5	67.0	177
4.5	18	9	111.9	58.5	170
5.5	19	9	121.4	58.2	179
6.5	26	10	169.2	65.2	234
7.5	35	11	230.6	71.9	302
8.5	49	12	338.5	88.4	426
9.5	75	16	536.4	116.3	652

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, NH₄Cl+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----mg/soil section-----		
	REPLICATE #1				
0.5	100.3	122.5	618.3	754.6	1372
1.5	50.0	42.0	365.8	306.8	672
2.5	27.7	14.0	184.2	92.9	277
3.5	16.5	9.5	116.0	66.8	182
4.5	16.9	7.7	116.0	52.8	168
5.5	17.6	6.0	113.2	38.8	152
6.5	17.6	5.6	121.4	38.5	160
7.5	17.8	5.5	122.8	38.5	161
8.5	18.5	6.5	125.5	44.0	169
9.5	17.2	7.2	111.9	47.3	159
	REPLICATE #2				
0.5	61.1	85.6	412.2	578.0	990
1.5	42.5	34.8	271.6	222.4	494
2.5	38.5	24.7	251.1	161.2	412
3.5	30.9	15.5	217.0	108.8	325
4.5	20.3	10.1	143.3	71.6	214
5.5	18.2	8.5	113.2	52.8	166
6.5	19.7	7.7	133.7	52.2	186
7.5	20.6	7.2	133.7	46.6	180
8.5	20.7	7.8	151.5	57.3	208
9.5	20.3	9.5	140.5	66.1	206

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, KCl+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	81.6	90.0	536.4	591.2	1127
1.5	64.2	47.0	372.6	272.8	645
2.5	40.9	24.1	245.7	144.5	390
3.5	21.2	10.3	158.3	76.8	235
4.5	17.7	6.8	111.9	43.0	155
5.5	16.4	6.3	121.4	47.0	168
6.5	17.6	6.2	124.2	44.1	168
7.5	18.7	6.4	136.5	46.5	183
8.5	19.6	6.8	129.6	45.3	175
9.5	21.6	8.0	150.1	56.0	206
REPLICATE #2					
0.5	58.6	78.2	432.7	577.4	1010
1.5	35.0	28.7	219.7	180.4	400
2.5	30.2	20.6	197.9	134.7	332
3.5	28.6	16.0	166.5	93.4	260
4.5	24.5	12.2	154.2	76.9	231
5.5	20.9	9.1	132.4	57.9	190
6.5	17.0	7.0	126.9	52.4	179
7.5	17.7	7.2	121.4	49.8	171
8.5	19.1	7.6	131.0	52.3	183
9.5	19.6	8.0	147.4	60.3	207

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 1 WEEK INCUBATION, K₂CO₃+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	16.8	28.4	118.7	200.2	319
1.5	13.6	17.4	85.9	109.8	195
2.5	15.9	16.5	107.8	112.0	219
3.5	25.9	23.4	162.4	146.9	309
4.5	38.7	26.0	240.2	161.5	401
5.5	45.2	25.6	307.1	173.6	480
6.5	28.1	13.0	185.6	85.8	271
7.5	34.8	14.1	248.4	100.9	349
8.5	51.6	18.1	368.5	129.7	498
9.5	86.9	33.9	629.2	245.7	874
REPLICATE #2					
0.5	13.9	26.9	92.8	179.9	272
1.5	10.6	18.7	72.3	127.1	199
2.5	12.8	15.5	79.1	96.0	175
3.5	17.3	18.0	105.1	109.3	214
4.5	24.1	24.1	163.8	163.8	327
5.5	36.9	24.2	257.9	169.4	427
6.5	24.4	13.6	171.9	96.1	268
7.5	34.9	17.4	238.8	119.4	358
8.5	53.5	21.1	384.9	151.7	536
9.5	86.2	32.3	577.3	216.3	793

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, CONTROL TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	1.37	6.03	9.55	41.87	51.4
1.5	1.70	6.52	10.92	41.83	52.7
2.5	2.17	5.54	13.65	34.72	48.3
3.5	2.57	5.02	17.74	34.60	52.3
4.5	2.82	5.10	19.11	34.56	53.6
5.5	3.56	6.36	23.20	41.47	64.6
6.5	3.22	6.15	23.20	44.28	67.4
7.5	2.96	6.45	19.11	41.59	60.7
8.5	3.03	6.15	20.47	41.55	62.0
9.5	1.51	4.83	10.92	34.80	45.7
REPLICATE #2					
0.5	1.42	8.36	9.55	55.92	65.4
1.5	1.71	7.79	12.28	55.84	68.1
2.5	2.25	7.66	16.38	55.72	72.1
3.5	2.36	8.04	16.38	55.72	72.1
4.5	2.82	8.41	17.74	52.87	70.6
5.5	2.91	8.47	19.11	55.64	74.7
6.5	2.88	7.84	20.47	55.60	76.0
7.5	3.21	8.40	19.11	50.02	69.1
8.5	3.30	7.97	21.84	52.75	74.5
9.5	2.99	7.30	20.47	49.98	70.4

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, MAP (ONLY) TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	90	147	592.4	966	1558
1.5	61	100	404.0	662	1066
2.5	55	66	364.4	430	794
3.5	27	33	182.9	219	402
4.5	20	20	133.7	130	264
5.5	22	15	154.2	107	262
6.5	26	16	185.6	118	303
7.5	28	17	184.2	115	299
8.5	26	16	195.1	126	321
9.5	25	15	170.6	107	278
REPLICATE #2					
0.5	117	215	753.4	1382	2136
1.5	83	117	567.8	798	1366
2.5	35	54	210.2	316	527
3.5	23	36	146.0	228	375
4.5	23	25	178.8	191	370
5.5	27	20	185.6	135	320
6.5	31	20	219.7	139	359
7.5	31	20	227.9	147	375
8.5	30	18	217.0	134	351
9.5	30	20	206.1	134	340

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, UREA+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	59.4	83.4	372.6	522.9	895
1.5	89.7	72.8	544.6	442.0	986
2.5	41.6	28.7	253.8	175.2	429
3.5	25.7	14.4	189.7	106.8	296
4.5	28.1	15.3	185.6	101.3	286
5.5	32.1	10.0	206.1	64.2	270
6.5	38.6	10.7	274.3	76.2	350
7.5	45.2	11.5	326.2	83.1	409
8.5	47.2	12.6	330.3	88.6	419
9.5	61.5	15.7	443.6	113.4	557
REPLICATE #2					
0.5	51.2	61.2	343.9	411.4	755
1.5	81.8	71.7	589.6	516.6	1106
2.5	83.8	49.0	517.3	302.3	819
3.5	29.7	18.1	184.2	112.6	296
4.5	28.9	12.8	178.8	79.0	257
5.5	28.1	9.9	182.9	64.8	247
6.5	25.7	8.6	192.4	64.6	257
7.5	29.0	9.2	202.0	64.3	266
8.5	29.1	8.9	208.8	64.1	272
9.5	26.1	10.6	180.1	73.4	253

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, NH₄Cl+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
	REPLICATE #1				
0.5	66.8	107	465.4	752.0	1217
1.5	44.1	52	281.1	335.9	617
2.5	47.3	40	318.0	271.6	589
3.5	42.2	29	270.2	188.7	459
4.5	23.8	15	163.8	107.6	271
5.5	16.1	9	102.3	61.6	164
6.5	17.4	8	109.2	53.0	162
7.5	17.8	7	132.4	52.3	184
8.5	18.2	7	131.0	52.3	183
9.5	21.1	8	146.0	60.3	206
	REPLICATE #2				
0.5	93.2	116	660.6	823.6	1484
1.5	44.3	50	326.2	369.7	696
2.5	41.6	33	285.2	230.4	515
3.5	29.9	18	195.1	120.7	315
4.5	16.8	11	102.3	67.2	169
5.5	14.8	8	90.0	53.5	143
6.5	16.9	7	114.6	52.8	167
7.5	17.0	8	111.9	52.9	164
8.5	15.3	7	109.2	53.0	162
9.5	15.7	7	109.2	53.0	162

SOIL COLUMN DATA FROM EXTRACTATIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, KCl+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
	REPLICATE #1				
0.5	109	144	731.6	962.0	1693
1.5	66	61	442.2	414.1	856
2.5	44	33	286.6	216.4	503
3.5	35	24	238.8	161.6	400
4.5	26	16	166.5	107.5	274
5.5	18	11	114.6	72.5	187
6.5	15	8	105.1	61.5	166
7.5	15	7	111.9	58.5	170
8.5	17	8	111.9	52.9	164
9.5	15	8	114.6	58.4	173
	REPLICATE #2				
0.5	111	170	741.1	1136	1877
1.5	50	61	348.0	425	773
2.5	42	37	278.4	244	523
3.5	40	27	256.6	175	431
4.5	33	20	219.7	134	353
5.5	20	13	148.7	93	242
6.5	16	9	121.4	72	193
7.5	16	8	111.9	58	170
8.5	17	9	114.6	61	175
9.5	18	8	121.4	58	179

SOIL COLUMN DATA FROM EXTRACTIONS CONDUCTED AFTER ELUTION: 5 WEEK INCUBATION, K₂CO₃+MAP TREATMENT

Distance From Application Site (cm)	Water Extractable P	NaHCO ₃ Extractable P	Water Extractable P	NaHCO ₃ Extractable P	Total Extractable P
	-----mg/kg of soil-----		-----µg/soil section-----		
REPLICATE #1					
0.5	10.5	24	65.5	152.6	218
1.5	11.8	18	76.4	118.5	195
2.5	16.7	23	118.7	165.1	283
3.5	37.4	40	226.5	246.2	472
4.5	87.7	114	586.9	762.5	1349
5.5	96.5	70	618.3	448.3	1066
6.5	37.8	16	273.0	118.4	391
7.5	55.9	17	372.6	115.5	488
8.5	66.8	20	468.1	140.8	609
9.5	81.5	22	618.3	172.9	791
REPLICATE #2					
0.5	16.1	29	121.4	221.2	342
1.5	25.9	31	178.8	219.5	398
2.5	36.2	36	221.1	223.9	445
3.5	43.5	40	281.1	258.7	539
4.5	91.3	104	636.0	726.0	1362
5.5	75.4	40	491.4	266.6	758
6.5	47.0	15	300.3	97.9	398
7.5	60.0	15	420.4	105.7	526
8.5	82.2	17	547.3	116.0	663
9.5	82.1	16	563.7	115.5	679

Appendix D
NITRIC-PERCHLORIC ACID
TISSUE DIGESTION PROCEDURE¹

- 1 g dry plant material placed into digest tube.
- 5 mL concentrated nitric acid added; predigested at room temperature for at least 1 h.
- 2.5 mL concentrated perchloric acid added; digested at boiling point until clear. Tecator Block Digestor Model 40-1006 and Autostep 1012 Controller used with a ramp time of at least 30 min to reach a maximum temperature of 230°C. Sustain 230°C temperature for at least 45 min.
- Either filtered through Whatman #42 filter paper, diluting and washing to 25 mL with distilled, deionized water or diluted to 25 mL, centrifuged and decanted.
- Extract stored in translucent plastic scintillation vials.

¹ For determining low concentrations of micronutrients or low counts of ³²P, the quantities of sample and acid were doubled.

Appendix E

MANUAL METHOD OF ^{31}P DETERMINATION

Adapted from Murphy and Riley (1962)

- Reagent A
- 500 mL distilled water
 - 7.5 g ammonium paramolybdate, $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$
 - 0.14 g antimony potassium tartrate
 - 88 mL concentrated sulfuric acid
 - diluted to 1000 mL, store in dark glass bottle
- Reagent B
- 0.5 g of L-ascorbic acid in 20 mL water
 - prepared immediately prior to use
-
- samples diluted to 0.1 - 0.5 mg P/L; used 10 mL
 - 20 mL Reagent B combined with 80 mL Reagent A
 - 2 mL of AB mixture added to each sample; allowed 5 min for color development
 - absorbance read at 885 nm, using 10 mL water plus 2 mL of AB mixture as zero absorbance standard
 - absorbance converted to ^{31}P concentration using standard curve developed from 0.1 - 0.5 mg P/L standards, subtracting ^{31}P concentration in digest blank. Normally the standard curve was linear with a slope of approximately 0.6 absorbance units for each mg P/L.

Appendix F

 ^{32}P DETERMINATION

Concentrations of radioactive P in tissue digests were determined directly using the Cerenkov counting method adapted by Sheppard (1982). This method does not require the addition of scintillation cocktails, allowing the extract to be used for further analyses. Acceptable counting efficiencies of approximately 40% were achieved using translucent plastic scintillation vials and a Beckman model 7500 liquid scintillation counter.

Samples of a consistent volume were counted for 20-60 min or to 1% error, whichever occurred first. Sample counts were then corrected for background and for decay during the counting session and lastly, for counting efficiency. The counting efficiency of each sample was determined and color quench corrected for by the sample channels ratio (SCR) technique described in detail by Sheppard (1982).

The window setting of 0 to 650 was used to monitor the total spectrum of ^{32}P Cerenkov radiation. The window setting of 0 to 200 was used to monitor color quenching. Greater color quenching and lower counting efficiencies were observed in samples having higher sample channels ratios (0-200 channel count)/(0-650 channel count). A quench curve was developed using standards with varying amounts of yellow food coloring. Counting efficiency, in %, was described by a third-order polynomial equation such as: % efficiency = $78.95 - 114.66(\text{SCR}) - 126.24(\text{SCR})^2 + 216.12(\text{SCR})^3$ Unfortunately the automatic quench correction calculation of the liquid scintillation counter did not use channel counts corrected for background (i.e. the counter did not use the same SCR as that which it printed).

Therefore, quenching error had to be corrected manually in situations where counts were low and background interference was significant.

Appendix G

 ^{14}N , ^{15}N KJELDAHL DIGESTION

- 2 g dry tissue placed into macro-Kjeldahl flask
- HgO-Kelpak added with 25 mL conc. sulfuric acid, boiling chips and digested for 1 h then allowed to cool
- 250 mL cold water added with fresh boiling chips, 25 mL of sodium thiosulfate solution (80 g $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ per L)
- 50 mL 0.100 N sulfuric acid added with 3 drops mixed indicator into 500 mL Erlenmeyer flask and placed in distillation rack
- 50 mL of 50% sodium hydroxide added slowly to Kjeldahl flask; flask connected to distillation apparatus; boiled as long as possible
- distillate back titrated with 0.1 N sodium hydroxide until color changed from red to green and titrant volume recorded for N determination
- 1 drop conc. sulfuric acid added to Erlenmeyer and evaporated to approximately 5 mL for ^{15}N determination

Appendix H

DESCRIPTION OF FIELD PLOT HARVESTS

Table 25. Description of Plant Stages for Field Plot Harvests.

Site	Operation					
	Planting	First Harvest	Second Harvest	Third Harvest	Fourth Harvest	Mature Harvest
Date, Feekes Stage						
Teulon 1981	May 19	June 9, F1	June 25, F4.5	July 9, F10.3	July 23, F11.1	Aug. 18, F11.4
Elm Creek 1982	May 26	June 15, F1	June 30, F5	July 15, F10.3	July 29, F10.5.4	Aug. 23, F11.4
Bagot 1982	May 20	June 10, F1.5	June 23, F4.0	July 7, F10.1	July 23, F10.5.2	Aug. 23, F11.4
Roland 1983	May 17	June 9, F1.5	June 23, F5	July 7, F10.1	July 20, F10.5.4	Aug. 10, F11.4
Carman 1983	May 16	June 9, F1.5	June 23, F5	July 7, F10.5.1	July 20, F10.5.4	Aug. 14, F11.4

Appendix I

EFFECT OF SPLIT PLACEMENT OF MAP
ON P UPTAKE AND YIELD OF FIELD PLOTS.

Table 26. Effect of Split Placement of MAP on P Uptake and Yield of Spring Wheat Harvested 2 Wk After Emergence.

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Seed Row P (5 kg/ha)	0.091	0.080	0.080	0.102	0.126
Seed Row P (20 kg/ha)	0.095	0.059	0.087	0.100	0.120
18 cm Dual + starter ¹	0.094	0.081	0.101	0.138	0.169
36 cm Dual + starter	0.089	0.085	0.092	0.110	0.143
Separate P + starter	0.088	0.077	0.079	0.117	0.110
Pr>F ²	0.99	0.15	0.35	0.36	0.24
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Seed Row P (5 kg/ha)	0.32B ³	0.40B	0.34B	0.39B	0.33B
Seed Row P (20 kg/ha)	0.43A	0.59A	0.39A	0.47A	0.54A
18 cm Dual + starter	0.40A	0.45B	0.36AB	0.40B	0.38B
36 cm Dual + starter	0.37AB	0.43B	0.34B	0.39B	0.37B
Separate P + starter	0.41A	0.55A	0.39A	0.53A	0.52A
Pr>F	0.042	0.0001	0.034	0.001	0.0006
<u>Total P Uptake (kg P/ha)</u>					
Seed Row P (5 kg/ha)	0.29	0.32	0.27	0.39C	0.40
Seed Row P (20 kg/ha)	0.40	0.34	0.34	0.45BC	0.62
18 cm Dual + starter	0.37	0.36	0.36	0.51AB	0.60
36 cm Dual + starter	0.33	0.37	0.31	0.43BC	0.50
Separate P + starter	0.36	0.43	0.31	0.62A	0.56
Pr>F	0.42	0.37	0.41	0.01	0.06

¹ Starter was 5 kg P/ha applied as MAP in the seed row supplementary to the main seedrow and preplant P treatments.

² Level of significance according to analysis of variance.

³ Means followed by the same letter are not significantly different according to the LSD test ($\alpha = 0.05$).

Table 27. Effect of Split Placement of MAP on P Uptake and Yield of Spring Wheat Harvested 4 Wk After Emergence.

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Seed Row P (5 kg/ha)	0.516	0.97	0.650	0.817	0.747
Seed Row P (20 kg/ha)	0.518	0.95	0.665	0.799	0.870
18 cm Dual + starter ¹	0.482	1.04	0.733	0.777	0.975
36 cm Dual + starter	0.479	1.01	0.641	0.732	0.946
Separate P + starter	0.524	1.04	0.683	0.838	0.995
Pr>F ²	0.96	0.79	0.81	0.13	0.29
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Seed Row P (5 kg/ha)	0.28	0.31B ³	0.30	0.40D	0.32B
Seed Row P (20 kg/ha)	0.29	0.35A	0.30	0.49BC	0.44A
18 cm Dual + starter	0.31	0.35A	0.31	0.55A	0.44A
36 cm Dual + starter	0.29	0.31B	0.30	0.54AB	0.37AB
Separate P + starter	0.31	0.32B	0.31	0.43CD	0.44A
Pr>F	0.53	0.004	0.86	0.0007	0.011
<u>Total P Uptake (kg P/ha)</u>					
Seed Row P (5 kg/ha)	1.45	2.95	1.96	3.20	2.37C
Seed Row P (20 kg/ha)	1.49	3.39	2.00	3.88	3.85AB
18 cm Dual + starter	1.47	3.61	2.26	4.28	4.22A
36 cm Dual + starter	1.40	3.16	1.94	3.99	3.39B
Separate P + starter	1.58	3.35	2.10	3.61	4.30A
Pr>F	0.97	0.31	0.70	0.07	0.001

- 1 Starter was 5 kg P/ha applied as MAP in the seed row supplementary to the main seedrow and preplant P treatments.
- 2 Level of significance according to analysis of variance.
- 3 Means followed by the same letter are not significantly different according to the LSD test ($\alpha = 0.05$).

Table 28. Effect of Split Placement of MAP on P Uptake and Yield of Spring Wheat Harvested 6 Wk After Emergence.

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Seed Row P (5 kg/ha)	1.49B ¹	3.69	2.35	2.42C	2.68C
Seed Row P (20 kg/ha)	1.92A	3.44	2.71	3.01A	3.09A
18 cm Dual + starter ²	2.21A	3.81	2.52	2.96A	3.18A
36 cm Dual + starter	2.06A	3.47	2.59	2.54BC	2.79BC
Separate P + starter	2.07A	3.54	2.64	2.90AB	3.03AB
Pr>F ³	0.003	0.42	0.21	0.01	0.006
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Seed Row P (5 kg/ha)	0.26AB	0.23	0.21C	0.29C	0.31C
Seed Row P (20 kg/ha)	0.23C	0.23	0.22BC	0.31BC	0.37AB
18 cm Dual + starter	0.26A	0.22	0.25A	0.34A	0.37AB
36 cm Dual + starter	0.24BC	0.22	0.25AB	0.33AB	0.40A
Separate P + starter	0.23C	0.27	0.25AB	0.31BC	0.36B
Pr>F	0.01	0.094	0.011	0.008	0.008
<u>Total P Uptake (kg P/ha)</u>					
Seed Row P (5 kg/ha)	3.83C	8.33	4.81AB	6.88C	8.3B
Seed Row P (20 kg/ha)	4.35BC	7.82	6.07A	9.27AB	11.3A
18 cm Dual + starter	5.82A	8.39	6.37A	10.15A	11.8A
36 cm Dual + starter	4.89B	7.72	6.43A	8.36BC	11.1A
Separate P + starter	4.72B	9.75	6.63A	9.05AB	10.8A
Pr>F	0.0007	0.42	0.02	0.02	0.001

¹ Means followed by the same letter are not significantly different according to the LSD test ($\alpha = 0.05$).

² Starter was 5 kg P/ha applied as MAP in the seed row supplementary to the main seedrow and preplant P treatments.

³ Level of significance according to analysis of variance.

Table 29. Effect of Split Placement of MAP on P Uptake and Yield of Spring Wheat Harvested 8 Wk After Emergence.

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Dry Matter Yield (Mg/ha)</u>					
Seed Row P (5 kg/ha)	2.80	5.69	5.68	5.75	5.20
Seed Row P (20 kg/ha)	3.45	5.78	6.03	5.61	5.56
18 cm Dual + starter ¹	3.09	5.81	6.12	6.17	6.08
36 cm Dual + starter	2.61	5.73	5.72	6.06	5.11
Separate P + starter	2.89	5.65	6.17	6.11	5.68
Pr>F ²	0.60	0.98	0.42	0.65	0.18
<u>P Concentration in Tissue (%P, dry weight basis)</u>					
Seed Row P (5 kg/ha)	0.17	0.22B ³	0.18	0.17	0.16C
Seed Row P (20 kg/ha)	0.15	0.24B	0.16	0.18	0.17BC
18 cm Dual + starter	0.17	0.23B	0.16	0.21	0.18AB
36 cm Dual + starter	0.18	0.22B	0.17	0.18	0.19A
Separate P + starter	0.15	0.26A	0.18	0.17	0.19AB
Pr>F	0.097	0.006	0.13	0.06	0.013
<u>Total P Uptake (kg P/ha)</u>					
Seed Row P (5 kg/ha)	4.99	12.8	10.1	9.4C	8.3
Seed Row P (20 kg/ha)	5.09	13.6	9.8	9.9BC	9.5
18 cm Dual + starter	5.08	13.3	9.5	12.7A	11.1
36 cm Dual + starter	4.74	12.7	9.8	11.0B	9.8
Separate P + starter	4.27	14.4	10.9	10.2BC	10.6
Pr>F	0.90	0.10	0.26	0.006	0.12

¹ Starter was 5 kg P/ha applied as MAP in the seed row supplementary to the main seedrow and preplant P treatments.

² Level of significance according to analysis of variance.

³ Means followed by the same letter are not significantly different according to the LSD test (alpha = 0.05).

Table 30. Effect of Split Placement of MAP on P Uptake and Yield of Spring Wheat Harvested At Maturity.

Treatment	Teulon	Elm Creek	Bagot	Roland	Carman
<u>Grain Yield (Mg/ha)</u>					
Seed Row P (5 kg/ha)	1.31	3.00	2.63	2.84	2.71AB ¹
Seed Row P (20 kg/ha)	1.82	2.69	2.90	2.91	2.93A
18 cm Dual + starter ²	1.39	2.78	2.95	2.81	2.60B
36 cm Dual + starter	1.59	3.00	2.77	2.91	2.93A
Separate P + starter	1.53	2.81	2.85	2.99	2.86A
Pr>F ³	0.31	0.41	0.40	0.85	0.036
Cv ⁴	25	10.5	9.7	9.7	6.1
<u>P Concentration in Grain (%P, dry weight basis)</u>					
Seed Row P (5 kg/ha)	0.26	0.43AB	0.37B	0.41	0.41
Seed Row P (20 kg/ha)	0.34	0.47A	0.39B	0.42	0.43
18 cm Dual + starter	0.31	0.48A	0.42AB	0.43	0.43
36 cm Dual + starter	0.30	0.40B	0.40B	0.42	0.44
Separate P + starter	0.32	0.39B	0.47A	0.43	0.41
Pr>F	0.16	0.012	0.015	0.54	0.063
<u>Total P Uptake in Grain (kg P/ha)</u>					
Seed Row P (5 kg/ha)	3.45	13.0	9.9	11.6	11.0C
Seed Row P (20 kg/ha)	6.29	12.7	11.3	12.3	12.6AB
18 cm Dual + starter	4.36	13.4	12.4	11.9	11.2BC
36 cm Dual + starter	4.59	12.1	11.4	12.1	13.0A
Separate P + starter	4.81	10.7	13.3	12.8	11.8ABC
Pr>F	0.09	0.16	0.08	0.74	0.04

- ¹ Starter was 5 kg P/ha applied as MAP in the seed row supplementary to the main seedrow and preplant P treatments.
- ² Level of significance according to analysis of variance.
- ³ Means followed by the same letter are not significantly different according to the LSD test ($\alpha = 0.05$).
- ⁴ Coefficient of variance among replicates in %.