EFFECT OF VARIOUS NITROGEN FERTILIZERS ON SOLUBILITY AND

PLANT AVAILABILITY OF PHOSPHORUS IN DUAL N-P BANDS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

OF THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF MANITOBA

DEPARTMENT OF SOIL SCIENCE

WINNIPEG, MANITOBA

August, 1987 ©

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ACKNOWLEDGMENTS

Abstract

Studies were performed to characterize the chemical environment in dual N-P bands for three chemically different soils, an acidic Stockton fsl (pH 5.6), a neutral Stockton fsl (pH 7.2) and an Almasippi fsl (pH 8.5). Treatments consisted of fertilizer bands of urea + MAP, urea + TSP, $(NH_4)_2SO_4$ + MAP, NH_4NO_3 + MAP, NH_4OH + MAP, H_3PO_4-urea + MAP, MAP alone, TSP alone and a control (no fertilizer). Water soluble P, NH_4^+ + NH_3-N, NO_3^- + NO_2^--N, Ca^{2+}, Mg^{2+} and pH were determined at various distances from the application site.

Phosphorus solubility in the acidic Stockton and Almasippi soils were increased above that of MAP alone when urea, NH_4OH or H_3PO_4-urea were added to MAP. Urea or $(NH_4)_2SO_4$ additions to MAP increased P solubility in the neutral Stockton soil. The addition of urea to TSP increased P solubility in both Stockton soils. Phosphorus movement was not consistently increased by any one fertilizer treatment in all soils. Phosphorus movement was, however, generally greater for the Stockton soils than for the Almasippi soil regardless of treatment. High pH and high concentrations of NH_4^+ + NH_3-N were found near the application site for all soils treated with urea, NH_4OH and H_3PO_4-urea.

In subsequent growth chamber studies, initiation of fertilizer P uptake by seedlings and P utilization were measured for wheat, canola and flax grown on a Willowcrest soil and for canola grown on an Almasippi soil. Treatments consisted of dual bands of urea + MAP, $(NH_4)_2SO_4$ + MAP, and NH_4NO_3 + MAP (7.5 cm below and beside the seed) and separate bands of urea and MAP (7.5 cm below and beside the seed)

and urea and MAP (MAP 2.5 cm below and beside the seed and urea 7.5 cm below and beside the seed).

Wheat, canola and flax effectively utilized fertilizer P from the dual bands. Fertilizer P uptake from dual bands was generally equal to or greater than from P placed near the seed-row. In the first experiment, fertilizer P uptake was greater from the $(NH_4)_2SO_4$ + MAP dual band than for P placed near the seed row, particularly for canola and wheat. In addition, fertilizer P uptake at the heading or flowering stage was 12 and 16 percent higher from dual $(NH_4)_2SO_4$ + MAP bands than from P placed near the seed row, for canola and wheat, respectively.

The number of days to the initiation of fertilizer P uptake from dual N-P bands were greater for canola and flax than for wheat. Also days to initiation of fertilizer P uptake were greater for urea + MAP dual bands than for $(NH_4)_2SO_4$ and NH_4NO_3 dual N-P bands. Attempts to detoxify the dual N-P bands by acidifying the fertilizer band (use of H_3PO_4-urea) or by using a slow release N fertilizer (SU) were generally unsuccessful. In contrast, incubation of the urea dual N-P band for a period of 10 d prior to seeding significantly reduced the time period prior to initiation of fertilizer P uptake.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I INTRODUCTION

The placement of fertilizer N and P in a single band is referred to as dual banding. The practice of dual banding, as opposed to the conventional method of placing fertilizer P near the seed at seeding and placement of N away from the seed-row, is of interest for several reasons. Dual banding allows the farmer to apply both N and P fertilizers prior to seeding thereby reducing fertilizer handling at seeding time. Secondly, dual banding has been shown to be more effective in meeting plant requirements for P than broadcast applications, particularly when NH_4^+-N is added with fertilizer P. In many instances, fertilizer P uptake from pre-plant dual N-P bands has been found to be equal to or greater than that from fertilizer P placed in or near the seed row.

Flaten (1987) in 1983 and 1984, conducted experiments to study the reasons why the application of urea-N greatly enhanced P uptake from pre-plant fertilizer bands. Phosphorus solubility in the fertilizer band was found to increase by as much as 50 to 100% when urea was added to monammonium phosphate (MAP). This partly explained why urea-N enhanced P uptake by plants treated with urea + MAP. It was also noted in these studies that uptake of P during the seedling stage from dual N-P bands was low compared to that from N and P applied separately. The low uptake during the seedling stage was attributed to a lack of root growth into the fertilizer band resulting from high concentrations of NH_3 from the urea fertilizer.

The studies conducted during 1983 and 1984, however, included only one soil type and one N fertilizer (urea). Thus, studies were conducted

in 1985 and 1986 using different soil types and different N fertilizers. The studies were conducted to define more clearly the soil and fertilizer band conditions under which N fertilizer enhances P solubility and plant uptake. A secondary objective was to identify reasons for the slow plant uptake of fertilizer P from dual bands during the seedling stage.

II LITERATURE REVIEW

1. Influence of NH_4^+-N on P utilization from dual N-P bands

Since the 1940's research has been conducted to determine the effect of NH_4^+-N on fertilizer P uptake and crop yields. Early findings indicated that the addition of NH_4^+-N to fertilizer P increased fertilizer P uptake above that of fertilizer P and N applied separately (Soper and Rennie 1958; Rennie and Mitchell 1954; Robertson et al. 1954). More recently, Liekam et al. (1983) reported higher yields and fertilizer P utilization from winter wheat treated with dual N-P bands than with separate applications of N and P when fertilizer P was either broadcast or banded in direct contact with the seed. Similarly, Flaten and Racz (1982) found that fertilizer P uptake by wheat was greater from dual N-P bands of urea and MAP than from separate bands when the fertilizer bands were placed more than 2.5 cm from the seed row. Fertilizer P uptake from dual N-P bands was approximately equal to that from separate bands placed close to the seed row (2.5 cm below and beside the seed).

2. Mechanism responsible for the NH_4^+ ion effect

Several different mechanisms have been proposed over the past 40 yr to explain the effect of NH_4^+-N on absorption of fertilizer P by plants. These mechanisms can be categorized as either biological or chemical in nature (Grunes et al. 1958). Biological mechanisms refer to those mechanisms which result in increased P uptake due to changes in

the morphology and/or physiology of the plant. Chemical mechanisms refer to those mechanisms which increase P absorption by altering fertilizer P availability. A list of mechanisms as categorized above is shown in Table 1.

Table 1. Mechanisms responsible for the NH_4^+ ion effect.

I. Chemical Mechanisms

    1. Increased size of the fertilizer P reaction zone

    2. Increased fertilizer P concentrations in the fertilizer band or fertilizer placement zone

II. Biological Mechanisms

    A. Morphological

        1. Increased root contact with fertilizer P

    B. Physiological

        1. Cation/anion balance

        2. Absorption transfer processes

2.1. Chemical Mechanisms

i. Increased size of the fertilizer P reaction zone

Phosphorus is a relatively immobile nutrient, thus plants must proliferate roots into the fertilizer P reaction zone to absorb fertilizer P. Any factor which results in an increase in the size of the fertilizer reaction zone will increase root contact with fertilizer P. Increased root contact would be expected to increase fertilizer P uptake by plants which do not strongly proliferate roots into the

reaction zone or have roots of a relatively low absorptive capacity (Strong and Soper 1974a, 1974b).

Bouldin and Sample (1958) showed that additions of NH_4NO_3 or KNO_3 to concentrated superphosphate (CSP) in two different soils had little effect on the maximum distance of movement of fertilizer P from the application site. However, the amount of fertilizer P which moved into the soil from the application site was increased by the addition of N salts to CSP. The authors suggested that the addition of N salts to CSP reduced the fraction of $Ca(H_2PO_4)_2 \cdot H_2O$ which formed $CaHPO_4$ at the pellet site and thus increased the amount of fertilizer P which moved out from the application site.

Studies by Miller and Vij (1962) showed that additions of $(NH_4)_2SO_4$ to CSP increased the distance of fertilizer P movement at both the 3 and 6 wk sampling periods but had little affect after 8 wk. Since plant absorption of fertilizer P was not increased until the eighth wk it was concluded that distance of fertilizer P movement from the application site had little influence on absorption of fertilizer P.

Blanchard and Caldwell (1966) placed monocalcium phosphate monohydrate (MCP) alone, MCP + NH_4Cl, and MCP + KCl in a soil and then leached the soil with 4 cm of water. After leaching the distribution of P was determined. The distance of fertilizer movement did not differ significantly among the three applications, leading the authors to conclude that fertilizer P movement was not affected by the application of N.

Previous to the above study, Blanchard and Caldwell (1966a) reacted MCP, MCP + NH_4Cl and MCP + KCl with a Nicollet soil for 2 wk.

Soil samples were taken at various distances from the application site and analyzed. Plant growth studies using corn as the test crop were also conducted. Fertilizer P movement was between 3 and 4 cm irrespective of fertilizer treatment. Corn roots grew to within 2, 6, and 8 cm of the placement site for MCP alone, MCP + KCl and MCP + NH_4Cl, respectively. The authors concluded that plant roots do not grow into the initial fertilizer band resulting from free diffusion of MCP and associated salts under static conditions. The distance of movement from freely diffused bands, if increased by the application of a N salt, may not affect P uptake due to the inability of the plant roots to enter the fertilizer reaction zone.

It can be concluded that the addition of fertilizer N to fertilizer P does not generally result in an increase in the maximum distance of P movement. However, addition of fertilizer N to fertilizer P does alter the distribution of fertilizer P such that more P leaves the application site. Thus, increasing the size of the fertilizer P reaction zone does not appear to be the dominant factor responsible for increased P uptake from dual N-P bands. However, potentially beneficial effects of increased P movement or alteration of the P distribution may be masked by the inability of plant roots to enter an area of high nutrient concentration.

ii. Increased fertilizer P concentrations in the fertilizer band or fertilizer placement zone

The amount of fertilizer P absorbed by plants is not only dependent upon the amount of root area in contact with the fertilizer reaction zone but also upon the absorptive capacity of the root. Any

factor which affects the absorption rate per unit root area will influence total P uptake. Increases in solution concentration of P have been shown to increase the P absorption rate per unit root area (Carter and Lathwell 1967). Thus, some researchers have attributed the NH_4^+ ion effect to a N effect on solubility of fertilizer P reaction products.

The effect of KNO_3 and $(NH_4)_2SO_4$ on fertilizer P uptake, distribution and solubility was studied by Bouldin and Sample (1958). Both KNO_3 and $(NH_4)_2SO_4$ increased fertilizer P content in the reaction zone and decreased the amount of P precipitated at the placement site. These results were well correlated with P uptake in growth experiments. The authors concluded that increased uptake of fertilizer P may be the result of an increased solubility of reaction products away from the granule site and a reduction in the amount of P precipitated at the granule site during dissolution of the granule.

In a later study by the same authors, the effect of various salts on the fraction of added P remaining at the granule site and plant response to soil P reaction products remaining outside the granule site were studied. The results indicated that additions of $(NH_4)_2SO_4$ to MCP resulted in the lowest amount of P remaining at the application site. The amount of P remaining at the application site with NH_4NO_3, NH_4CL, KNO_3 and K_2SO_4 was slightly greater than for $(NH_4)_2SO_4$, but still lower than for MCP alone. Phosphorus uptake by sorghum in response to soil-P reaction products produced outside the granule site, as compared to MCP alone was only higher for $(NH_4)_2SO_4$ + MCP. This treatment also resulted in 20% more P external to the granule site. Reaction products produced by salts other than $(NH_4)_2SO_4$ were thought to have a lower solubility than those produced by MCP. The authors concluded that

uptake of P by plants was influenced by both quantity of P transported into solution and composition of the solution leaving the granule site (Bouldin and Sample 1960).

Starostka and Hill (1954) studied the effect of various N salts on the solubility of dicalcium phosphate (DCP) in solution. The presence of $(NH_4)_2SO_4$ increased DCP solubility substantially, while NH_4NO_3 only increased solubility slightly and $Ca(NO_3)_2$ decreased solubility in solution. These findings corresponded well to alfalfa growth studies; the salts which enhanced solubility resulted in greater crop responses.

The increased solubility of P in the P reaction zone with additions of N fertilizer has been attributed by some authors to alteration in pH within the fertilizer band. A lowering of pH generally increases P solubility. pH of the fertilizer band could be decreased by the acidity of the salt per se. or due to oxidation of the NH_4^+ ion to NO_3^-.

Rennie and Mitchell (1954) showed that the availability of triple superphosphate (TSP) was increased by additions of NH_4NO_3. The authors attributed this increase to a reduction in pH around the TSP reaction zone, which reduced the rate of fertilizer P fixation and prolonged plant availability of fertilizer P. Similar findings were reported by Grunes et al (1958), who found fertilizer P uptake from TSP to be increased by the addition of $(NH_4)_2SO_4$. The increase was associated with decreased soil pH in the P reaction zone. However, the above findings were refuted by several studies. Olson et al. (1956) performed a study in which CSP and various N and non-N salts were combined to determine their effect on fertilizer P availability in soil. They found no distinct differences due to the addition of a N

salt and there appeared to be no benefit of acidifying substances on fertilizer P uptake. Any effect of modifying soil pH on prolonging fertilizer P solubility was thought to have been offset by a release of Ca^{2+} from the soil which would react with P to form relatively insoluble precipitates.

The effect of increased acidity on uptake of fertilizer P was also studied by Rennie and Soper (1958). In their study, $KHSO_4$ was mixed with MAP in an amount equivalent to the acidity produced from an application of $(NH_4)_2SO_4$. The pH in the vicinity of both $KHSO_4$ + MAP and $(NH_4)_2SO_4$ + MAP bands was reduced, however uptake of fertilizer P was only increased by the $(NH_4)_2SO_4$ treatment. The $KHSO_4$ + MAP treatment actually resulted in a reduction in P uptake. The authors attributed this to a rapid drop in pH caused by the acid salt. Similar results were obtained in other studies leading the authors to conclude that increased acidity in the fertilizer band was not the factor responsible for increased uptake of fertilizer P.

Ammonium nitrate, KCl or urea applied at rates of 22.4 kg ha^{-1} and 67.2 kg ha^{-1} with MCP or MAP were found to decrease solution P concentrations in simulated fertilizer bands (Isensee and Walsh 1970,1972). Reduction in P concentration caused by NH_4NO_3 and KCl was attributed to increased concentration of Ca^{2+} and Mg^{2+}, resulting in increased formation of Ca and Mg-phosphates. A drastic decrease in P solubility caused by addition of urea was initially attributed to an increase in pH enhancing the formation of Ca-phosphates. A decrease in P concentration at the later periods of incubation was attributed to a reduction in pH caused by nitrification of NH_4^+. Decreased pH was

thought to favor the formation of aluminum and iron-phosphates of low solubility.

The effect of high pH N salts on P availability as noted by Isensee and Walsh (1970, 1972) was contrary to that described by Hanson and Westfall (1985). Hanson and Westfall found applications of NH_4OH plus ammonium polyphosphate (APP) when applied with or without nitrapyrin increased $NaHCO_3$ extractable P in three out of four soils tested. The authors suggested that increased solubility of P was the result of a higher injection zone pH caused by the application of NH_4OH to APP. Three mechanisms for the increase in extractable P in the reaction zone were postulated by the authors. First, the high pH caused by NH_4OH can result in the formation of the more soluble Ca-phosphate reaction products as opposed to less soluble aluminum or iron-phosphates which are usually formed at lower pH values. Secondly, decreases in pH caused by nitrification may increases the solubility of dicalcium phosphate dihydrate and dicalcium phosphate reaction products. Finally, reduction in pH resulting from nitrification of NH_4^+ may allow soluble reaction products to persist for a longer period of time.

Miller and Vij (1962) measured water soluble P in solution surrounding the application site of CSP and $(NH_4)_2SO_4$ treatments. Uptake of P was increased by additions of $(NH_4)_2SO_4$ to CSP whereas the solubility of P in the reaction zone was decreased by $(NH_4)_2SO_4$. The authors concluded that any influence of N on water-solubility of fertilizer P was not responsible for enhanced P uptake by $(NH_4)_2SO_4$.

Increased availability of fertilizer P resulting from additions of various fertilizer salts may be explained by the "snow-plow" effect.

This effect as defined by Barry et al. (1983), occurs when a soil with a relatively low cation exchange capacity has adsorbed ions on the exchange desorbed by an incoming solution of a high concentration. Desorption is the result of competition for exchange sites between species, with the more abundant species occupying the most sites and desorbed ions entering the solution. Desorbed ions are pushed ahead by the incoming solution front similar to a snow plow (Barry et al. 1983). This effect is thought to occur in fertilizer bands with the saturated fertilizer solution moving from the application site supplying the solution of high concentration. Under field conditions displacement of cations on the exchange and movement of these ions out of the reaction zone is thought to occur for at least short distances (Starr and Parlange 1979).

A numerical investigation of the "snow plow" effect by Cho (1985) indicated that concentration distributions of both displacing and displaced ions within a soil column are dependent upon the selectivity coefficient of the ion exchange reaction, the exchange capacity of the soil and the concentration of the displacing ions. As the selectivity coefficient or affinity for adsorption became greater for the displacing ions, removal of ions on the exchange was nearly complete and penetration of the displacing ion was limited. The concentration of displaced ions in front of displacing ions was very high and sharply defined. As the selectivity coefficient was reduced, penetration by displacing ions increased due to inefficient removal of ions on the exchange and concentration of the displaced ions in front of the displacing ions was very low. Variation in the soil cation exchange capacity was found to alter ion desorption. Soils with a large cation

exchange capacity favor desorption of divalent cations over monovalent. The reverse was found to be true of lower cation exchange capacities.

Variation in ion concentration and distribution as described by the "snow plow" effect may help to explain the effect of N on P solubility and uptake. However, much more research must be done on this phenomenon to determine its true merit.

It can be concluded from the above studies that increased plant availability of fertilizer P may be related to a N effect on reaction zone pH and its effect on the type and solubility of reactions products initially formed. Support for the hypothesis that N fertilizer placed in intimate contact with P fertilizer increases the solubility of fertilizer P in the reaction zone appears to be well documented. Several authors have correlated increases in P solubility to increases in plant uptake of P. This indicates that increased P solubility in fertilizer bands with added N is at least partly responsible for enhanced uptake of P by plants when both N and P fertilizers are placed in the same band. However, much more research must be carried out to denote the specific reactions which result in increased fertilizer P solubility and the conditions under which enhanced solubility in the reaction zone occur.

2.2. Biological Mechanisms

i. Morphological

a. Increased root contact with the fertilizer band

Increased root surface contact with fertilizer P due to applications of fertilizer N has been suggested as a possible explanation for enhanced fertilizer P uptake when NH_4^+-N is placed with

fertilizer P. Grunes et al (1958) found additions of $(NH_4)_2SO_4$ with CSP increased the proportion of barley roots in the fertilizer band. The authors suggested that an increased proportion of roots in the fertilizer band could explain increases in the percentage of total P absorbed from dual N-P bands. These finding were supported in studies conducted by Miller and Ohlrogge (1958), who found additions of $(NH_4)_2SO_4$ to CSP to result in a 100% increase in the wt of P per plant. The authors indicated increased development of root mass in the dual band area as the most important mechanism responsible for the increased P uptake. Miller and Vij (1962) also noted that the addition of $(NH_4)_2SO_4$ to CSP resulted in a 100% increase in oven dry weight of roots in the N-P reaction zone and fertilizer P content of sugar beet tops harvested 8 and 10 wk after planting. Multiple regression analysis indicated that increased root weight in the fertilizer band accounted for 87% of the variability in fertilizer P content of plants harvested 8 wk after planting.

Blanchard and Caldwell (1966) equilibrated fertilizer pellets of MCP, MCP + NH_4Cl and MCP + KCl in a Dakota loamy sand soil for 2 wk. Pots were then leached with variable amounts of water and planted to corn. Corn tops were harvested after 2 wk of growth, weighed and analyzed for P uptake. In pots leached with 4 cm of water, P uptake from MCP + NH_4Cl was three fold greater than MCP alone or MCP + KCl. However, increased root growth occurred in both the MCP + NH_4CL and MCP + KCl treatments. The authors concluded that increased uptake was not related to increased root production in the fertilizer reaction zone and that increased root production may only be an effect of increased P

uptake or P uptake may not be related to the quantity of roots if P diffusion to roots is not limiting P uptake.

In three experiments carried out by Miller (1965) absorption of P was increased by the addition of $(NH_4)_2SO_4$ to CSP. However, only in the first experiment was there a corresponding increase in the development of a single lateral root which was allowed to grow into the dual N-P band. It was concluded that increased root growth was not a prerequisite to increased absorption of P from dual N-P bands.

The quality of root growth induced by N and P was also investigated by Duncan and Ohlrogge (1958). In their study a single corn root was allowed to grow into N and P bands placed singly or in combination. Roots developing in dual N-P bands were finer and more silky in appearance. Also, the number of roots in the dual N-P band was greater than in separate N-P bands. In a subsequent study, the authors indicated that rapid first order root growth into fertilizer bands of low salt concentration resulted in meristem death. However, smaller secondary roots were not affected by the band possibly due to their slower rate of growth, permitting adjustment to salt concentrations in the band. Similarly third, fourth, fifth and sixth order roots were observed in the dual band area. These results indicated that a possible mechanism for increased P uptake with NH_4^+-N may be the alteration in the quality and quantity of roots found in dual N-P reaction areas (Duncan and Ohlrogge 1959). These results, however, were not supported by the work of Miller and Vij (1962), who reported no apparent change in the degree of branching or fineness of sugar beet roots exposed to a dual band of $(NH_4)_2SO_4$ and CSP.

In general, several researchers have noted increased root proliferation with addition of NH_4^+-N to fertilizer P. However, Blanchard and Caldwell (1966) demonstrated that increased root proliferation did not necessarily increase fertilizer P uptake. Furthermore, Miller (1965) did not observe increased root proliferation with the addition of NH_4^+-N although P uptake was increased. Thus increases in P uptake from these bands may have been due to increases in either number of roots or improved root quality in the N-P reaction zone.

ii. Physiological

a. Cation/anion balance

During ion uptake plants must maintain electroneutrality. Thus, a cation/anion balance is maintained by the plant. Changes to the plant and soil surrounding the roots resulting from maintenance of this balance will be reviewed in this section, with emphasis on those factors effecting P availability and plant uptake of P.

Riley and Barber (1969) observed that an accumulation of HCO_3^- and a pH increase in the rhizosphere were closely associated with an increased supply of NO_3^- to plant roots. The authors attributed this to an increased uptake of anions resulting in a release of HCO_3^- by the plant to maintain electrical neutrality. Similarly, increased NH_4^+ uptake has been found to cause a decrease in rhizosphere pH. This was attributed to an increased uptake of cations resulting in excretion of H^+ by plant roots to maintain electroneutrality (Miller et al. 1970; Riley and Barber 1971; Smiley 1974). The reduction in pH resulting

from extrusion of H^+ ions was thought to play a major role in increasing P availability and uptake.

Riley and Barber (1971) applied NH_4^+-N or NO_3^--N to soybeans grown on four different soils. Rhizocylinder pH was decreased by additions of NH_4^+-N, while additions of NO_3^--N increased rhizocylinder pH. Ammonium fertilized soybeans absorbed more P and contained a higher concentration of P than NO_3^- fertilized soybeans. Increased P absorption was closely correlated with decreases in rhizosphere pH but not with bulk soil pH. Increases in pH caused by the addition of NO_3^- resulted in a lower amount of P uptake. The authors concluded that increased availability of P was mainly due to the effect of N on the rhizosphere pH.

Soon and Miller (1977) grew corn seedlings on three soils with pH values of 7.1, 5.5 and 4.3, fertilized with MCP and either $(NH_4)_2SO_4$, $Ca(NO_3)_2$ or $CaCl_2$. The rhyizocylinder (roots plus adhering soil) and bulk soil were analyzed for pH and phosphate after 11 d of growth. Rhizocylinder pH was reduced by the addition of NH_4^+-N in all soils while additions of NO_3^--N increased rhizocylinder pH in all but one soil. Reduced rhizocylinder pH was associated with increased rhizocylinder P concentration and increased P uptake. The authors noted that P absorption was 50% greater in the presence of NH_4^+-N and 30% greater in the presence of NO_3^--N than could be explained on the basis of rhizocylinder P concentration alone. Differences in P absorption between NO_3^- and NH_4^+ treatments were attributed to changes in the $H_2PO_4^-$ concentration in the rhizosphere associated with pH changes induced by ion absorption. Changes in $H_2PO_4^-$ concentration were thought to be partly due to changes in total P concentration and partly to

changes in the proportion of total P in the $H_2PO_4^-$ form. The additional uptake was attributed to enhanced physiological capacity of roots to absorb P and increased root development.

Miller et al. (1970), showed an accumulation of Ca and P on the surface of corn roots grown in the presence of MCP alone. No accumulations were found when $(NH_4)_2SO_4$ was mixed with MCP. Root interface pH was reduced by additions of $(NH_4)_2SO_4$ while the $H_2PO_4^-$/HPO_4^{-2} ratio was increased. These results lead the authors to suggest that an increase in the amount of $H_2PO_4^-$ increased P absorption and reduced the tendency for precipitation of P as $CaHPO_4 \cdot 2H_2O$.

Increasing P in the $H_2PO_4^-$ form has been associated with increased P absorption due to a greater absorption rate for $H_2PO_4^-$ as compared to that of HPO_4^{2-} (Hagen and Hopkins 1955). The effect would be expected to be greatest on alkaline soils where HPO_4^{2-} is the dominant ionic form present. However, in soils of a lower pH the majority of the P would already be in the $H_2PO_4^-$ form; thus the $H_2PO_4^-$/HPO_4^{2-} hypothesis does not fully explain increased P uptake from soils of low pH (Blair et al. 1971).

It would appear that alteration of rhizosphere pH in response to a cation/anion balance does play a role in explaining the NH_4^+ ion effect. However, it does not completely explain the increases in uptake as noted by Soon and Miller (1977).

b. Absorption-transfer processes

Cole et al. (1963), found the rate of P uptake per unit dry weight of root and the rate of P translocation to plant shoots were increased by pretreatment of corn roots with N. The rate of uptake was highly

correlated with total N in plant roots. However, the presence of NO_3^- and NH_4^+ in the test solution during the 2 h uptake period did not have an effect on P uptake. From these results the authors suggested that stimulation of P uptake rates may be related to higher levels of N intermediates whose syntheses have processes in common with those of P uptake. The above result also countered the possibility of special companion effects of ions on the entry of phosphate ions into the root.

A similar study by Thien and McFee (1971) supported the finding of Cole et al. (1963). Ammonium and NO_3^- pretreated corn plants transferred to treatment solutions containing labelled P alone or with NH_4^+ or NO_3^- were monitored for uptake and translocation of labelled P. Nitrogen pretreatment of corn plants significantly increased P absorption and translocation rates to different degrees. However, the presence of NO_3^- or NH_4^+ in treatment solutions did not affect uptake or translocation in plants not pretreated with N. Thien and McFee suggested the existence of a N requiring metabolite influencing the efficiency of P absorption and translocation. The authors also argued against the presence of a companion effect of N and P in movement into root cells.

In a growth chamber experiment conducted by Miller (1965), a single seminal root from a corn seedling was grown in a soil pot containing various fertilizer treatments, while the remaining root system was allowed to grow in sand. Fertilizer treatments consisted of $(NH_4)_2SO_4$ plus CSP, P alone, N alone and a check. The sand and remaining root system were treated with a nutrient solution consisting of NH_4NO_3 at concentrations of 0.022, 0.112 and 0.224 g L^{-1}. Addition of $(NH_4)_2SO_4$ to CSP increased P uptake over five times that of P alone

when the lowest N level was supplied to the sand medium. At higher N levels P uptake was reduced but still greater than P uptake from P alone. The N content of corn tops and roots in the sand medium increased with increasing levels of N applied to the sand medium. Given the decrease in P uptake as N content of corn tops and roots in the sand medium increased, the author suggested that it was unlikely that increased P absorption could be due to an increased N content in the root. These finding are contrary to that which would be expected from the theory suggested by Cole et al. (1963).

White (1973) hypothesized that the rate of influx of orthophosphate into root cortical cells was regulated by the turn-over rate of the inorganic phosphate pool in the cytoplasm, and by the rate of transport of inorganic phosphate to the shoot. He suggested that additions of high amounts of N to plants that were supplied adequate P, would accelerate the turn-over rate and thus accelerate the rate of orthophosphate influx. The effect of N was attributed to an increased demand for P caused by increased shoot growth and a corresponding increase in P transport from the root to the shoot.

Due to the complex nature of the absorption-transfer processes, direct evidence for the effect of N on P absorption and transfer is difficult to obtain. There is, however, some evidence to indicate that N does affect the absorption and transfer of P within the plant. The extent of the effect is difficult to determine due to the complexity of the process.

III METHODS AND MATERIALS

1. Chemical Studies: The effect of various N fertilizers on pH, Ca^{2+}, Mg^{2+}, $NH_4^+ + NH_3$, $NO_3^- + NO_2^-$ and P concentration in dual N-P bands

1.1 Soils investigated

Three soils varying mainly in pH and carbonate content were selected for chemical studies: an Almasippi fine sandy loam (pH=8.5, alkaline, carbonated), a Stockton fine sandy loam (pH=7.2, neutral, noncarbonated) and a Stockton fine sandy loam soil (pH=5.6, acidic, noncarbonated) (Table 2.). Prior to use each soil was air dried, sieved through a 1-mm sieve and stored in 20-L polyethylene containers.

1.2. Column preparation

Soil columns consisted of 20 acrylic rings, 0.5 cm in height with an internal diameter of 5.08 cm. Nineteen rings were fitted using standard electrician tape to form a cylinder 9.5 cm in length, which was then taped onto a column platform. The column platform consisted of the 20th ring glued to a 6.35 cm by 6.35 cm acrylic plate. The platform plate was perforated by 15, 3 mm holes to allow adequate air exchange and covered with 150-mm polyethylene spectramesh to hold the soil in place. A protective collar 3 cm in length with an internal diameter of 5.08 cm was placed on top of the column.

Each soil was uniformly moistened to field capacity (Table 2.) by mixing deionized water and 325 g of air dry soil in a polyethylene bag. After mixing, soils were uniformly packed into soil columns to achieve

Table 2. Chemical and physical characteristics of the Almasippi, and neutral and acidic Stockton soils.

Soil characteristics	Soil Series		
	Almasippi (alkaline)	Stockton (neutral)	Stockton (acidic)
Chemical			
$NaHCO_3$ Ext. P (μg g^{-1})	13	14	15
NO_3-N (μg g^{-1})	15	4	3
Inorganic Carbon (%$CaCO_3$)	7.6	0.2	0.1
Organic Matter (%)	5.5	3.3	2.8
NH_4-Ac Extractable:			
Ca^{2+} (mmol kg^{-1})	198.1	63.9	29.4
Mg^{2+} (mmol kg^{-1})	68.3	10.7	5.8
K^+ (mmol kg^{-1})	2.2	8.4	9.4
Na^+ (mmol kg^{-1})	2.4	2.4	2.0
pH (soil-water)	8.5	7.2	5.6
Physical			
Sand (%)	68	62	75
Clay (%)	18	14	10
Silt (%)	14	24	15
Field Capacity (%)	21	19	17
Bulk Density (g cc^{-1}) after packing	1.17	1.22	1.27
Particle Density (g cc^{-1})	2.45	2.48	2.53
Air Filled Porosity (%) after packing	28.3	27.8	27.8

bulk densities of 1.27, 1.22 and 1.17 g cc^{-1} for the Almasippi, neutral

Stockton and acidic Stockton soils, respectively. Air filled porosity,

at the above bulk densities for the soils was about 28%.

1.3. Treatments

Soil treatments were as given in Table 3. Phosphorus and N

fertilizers were evenly applied to column surfaces at a rate of 0.0576

mg P and 0.230 mg N per column. Application rates were calculated to

reflect fertilizer band concentrations normally occurring under field

condition and were equivalent to a fertilizer band width of 2.5 cm, a

band spacing of 36 cm and a field application rate of 20 kg ha^{-1} P and

80 kg ha^{-1} N (N from MAP was not included in N rate).

Immediately after fertilizer application a protective collar was

fastened to each column with standard electrician tape. Columns were

then covered with parafilm which was punctured six times to allow for

adequate air exchange.

1.4. Column incubation

Columns were incubated for 4 wk near 100% relative humidity and at

a temperature of 20 + 1 C. Environmental conditions were maintained by

placement of the soil columns into incubation containers which were

kept in a controlled environmental room. Incubation containers

consisted of a polyethylene container 60 cm long, 40 cm wide and 30 cm

deep with a lid of similar dimensions and composition. A 2.5-cm thick

sheet of polyurethane foam was placed in the bottom of each container

and saturated with deionized water. A 1.5-cm thick polyethylene grid

was then placed on the surface of the saturated foam sheet to prevent

Table 3. Fertilizer treatments used in chemical studies.

Treatment #	N fertilizer	P fertilizer
1.	Urea	MAP
2.	$(NH_4)_2SO_4$	MAP
3.	NH_4NO_3	MAP
4.	NH4OH	MAP
5.	H_3PO_4-urea	MAP
6.	none	MAP
7.	Urea	TSP
8.	none	TSP
9.	none (control)	none (control)

moisture absorption by soil columns and to ensure adequate air movement to the soil column base. Columns were placed on the polyethylene grid and container lids fitted to reduce evaporative losses. Lids were lifted daily to allow adequate air supply to columns. Water in the incubation containers was changed every 2 wk to reduce microbial growth. All treatments were replicated twice and were placed in a completely randomized design.

1.5. Sectioning and extraction procedures

Columns were sectioned into 0.5-cm sections by cutting the tape between sections using a stainless steel knife. A 6.0-g sample of soil was taken from each ring and placed into a 250-ml Erlenmeyer flask. The remaining soil was placed in a 60-ml polycarbonate jar for gravimetric moisture determination. One hundred ml of deionized water were added to each 6.0-g sample and shaken vigorously for 30 min. Sample solutions were transferred to 250-ml polycarbonate centrifuge bottles and centrifuged at 6,000 RPM for 10 min. Fifteen and 20 ml of supernatant were transferred to a 15-ml polystyrene tube and a 25-ml polyethylene vial, respectively. Solution in each container was then acidified with 2 drops of concentrated sulfuric acid and capped for storage. Acid was added to maintain ion solubility and to flocculate organic matter dispersed in alkaline conditions. An additional 10 ml of supernatant were transferred to a 15-ml polystyrene tube and immediately analyzed for pH.

1.6. Soil analysis

i. Analysis of soil-water extracts

a. Phosphorus determination

Water extractable P was determined by the acid-molybdate procedure as described by Murphy and Riley (1962).

b. Nitrate + Nitrite-N determination

Water extractable $NO_3^- + NO_2^-$-N was determined on a Technicon Auto Analyzer system using a modification of the automated calorimetric procedure (Kamphake et al 1967).

c. Ammonium + ammonia-N determination

Ammonium + ammonia-N was determined on 20-ml soil extracts using a Fisher model 801A pH/mV meter equipped with a Orion Ammonia Electrode model 95-10. The 20 ml extract was made up to a volume of 50 ml using distilled water. One-half ml of 10 mol l^{-1} NaOH was added to the 50 ml solution and thoroughly mixed using a magnetic stirrer. The ammonia electrode was inserted into the diluted extract solution and allowed to equilibrate for approximately 30 s after which a reading was taken. Readings from the diluted extract solution were compared with readings from solutions of known ammonium concentration and solution concentration calculated.

d. Calcium ion and Mg^{2+} determination

Calcium ion and Mg^{2+} concentrations in solution were determined using a Perkin-Elmer 560 Atomic Absorption Spectrophotometer. Lanthanum was used in the diluent to combine with interfering anions.

e. pH determination

Solution pH was determined in 10 ml extracts using a Fisher, Pencil Combination Electrode model E-5M and a Fisher model 801 pH/mV meter.

f. Moisture content determination

Soil samples were weighed and oven dried at 110 C for 2 d. Oven dry weights were then taken and gravimetric moisture contents calculated.

ii. Soil characterization

a. Phosphorus determination

Phosphorus was extracted using $NaHCO_3$ as described by Olsen et al. (1954). Phosphorus in solution was determined by the acid-molybdate procedure as described by Murphy and Riley (1962).

b. Nitrate-N determination

Nitrate-N concentration was determined by the modified phenoldisulphonic acid method (Harper 1924).

c. Inorganic carbon determination

A 1.0-g sample of soil was reacted with 50 ml of 0.1 M HCl for 10 min. The CO_2 evolved was collected using an ascarite absorbtion tube. Inorganic carbon content was calculated from the weight change in the ascarite absorption tube.

d. Organic matter determination

Organic matter content of soil samples was determined by the Walkley-Black method as described by Allison (1965).

e. Calcium ion, Mg^{2+}, Na^+ and K^+ in NH_4OAc extract determination

Calcium ion, Mg^{2+}, Na^+ and K^+ concentrations were determined on a IL-257 Atomic Absorption Spectrometer. Lanthanum was used in the diluent to combine with interfering anions in the Ca^{2+} and Mg^{2+} determination, while lithium chloride was used for similar reasons in the Na^+ and K^+ determination.

f. Particle size determination

Particle size was determine using the standard pipette method as described by Kilmer and Alexander (1949).

g. Field capacity determination

Field capacity moisture content was determined by placing a known quantity of soil in polyethylene cylinders and wetting the soil surface to one-third the depth of the soil. The soil and water were allowed to equilibrate for 5 d after which a sample of moist soil was taken from the center of the cylinder. Samples were weighed and oven dried at 110 C for 2 d. Oven dry weights were then taken and field capacity moisture contents calculated.

h. Particle density determination

The particle density of the soils was determined using a modification of the method described by Blake (1965).

i. Bulk density calculation (after packing soil columns)

Bulk densities were calculated by dividing the volume of oven dry soil present in the soil column by the oven dry weight of soil occupying that volume.

j. Air filled porosity calculation (after packing soil columns)

The air filled porosity of each soil was calculated after packing each soil to its appropriate bulk density. The air filled porosity was calculated using equation 1. as described below.

Equation 1. $N = [((1-BD/PD) \times 100\%)-O$

Where: N = Air filled porosity

BD = Bulk density

PD = Particle density

O = Volumetric water content (O = BD X Gravimetric water content (w%))

2. Plant growth studies: Plant uptake of P from dual N-P bands as affected by various N fertilizers

2.1. Growth study one

i. Soil investigated

A Willowcrest fine sandy loam soil (pH=7.0, noncarbonated) similar in chemical and physical characteristics to the neutral Stockton soil used in the chemical studies was selected (Table 4.). The soil was air dried and sieved through a 2-mm sieve prior to use.

Table 4. Chemical and physical characteristics of the Willowcrest and Almasippi soils.

	Soil Series	
Soil characteristics	Willowcrest	Almasippi
Chemical		
$NaHCO_3$ Ext. P (μg g^{-1})	10	3
NO_3-N (μg g^{-1})	3	11
Inorganic Carbon (%$CaCO_3$)	0.2	4.1
Organic Matter (%)	3.7	2.7
NH_4-Ac Extractable:		
Ca^{2+} (mmol kg^{-1})	103.0	98.8
Mg^{2+} (mmol kg^{-1})	23.5	75.9
K^+ (mmol kg^{-1})	2.8	1.5
Na^+ (mmol kg^{-1})	1.4	6.0
pH (soil-water)	7.0	8.4
Conductivity (S m^{-1})	0.013	0.045
Physical		
Field Capacity (%)	25	22
Texture	Fine Sandy Loam	Fine Sandy Loam

ii. Growth chamber conditions and procedures

Canola (<u>Brassica napus</u> var. Westar), wheat (<u>Triticum aestivum</u> var. Columbus), and flax (<u>Linum usitatissimum</u> var. McGregor) were grown in 15 kg of soil placed in polyethylene containers 33 cm long, 22 cm wide and 23 cm deep. These crops were selected as they are widely grown in Western Canada and have different abilities to utilize fertilizer P from fertilizer bands (Strong and Soper 1974a). A day length of 16 h and day-night temperatures of 22 and 18 C were maintained in a Conviron Model PGW 36 and a Foster Model GR 36 environmental growth chamber. Mean light intensities ranged between 565 and 520 micro-Einstein m^{-1} s^{-1} at the top of the crop canopy.

All treatments were replicated three times and pots were arranged in a completely randomized block design within the growth chamber. Canola, flax and wheat were seeded to a depth of 2.0 cm in each soil container. Two wk after seeding, wheat, canola and flax were thinned to six, seven and eight plants per container, respectively. A gravimetric moisture content of 22% was maintained for the first 24 d of growth, after which a gravimetric water content of 26% was maintained. Distilled water was added when gravimetric moisture content decreased to about 19.5%.

^{32}P intensity during the seedling stage was monitored daily using a hand held Geiger-Mueller survey meter. ^{32}P intensity was determined by reading the average intensity observed as the survey meter was moved across the plant surfaces.

iii. Fertilizer treatments

Potassium and S as K_2SO_4 were added to all pots at a rate of 200 kg ha^{-1} K and 42 kg ha^{-1} S to ensure adequate K and S for optimal plant growth. The K_2SO_4 was dissolved in deionized water and then well mixed with the soil as follows: the soil was spread thinly in a polyethylene container and the dissolved K_2SO_4 sprayed onto the soil surface with continual mixing.

Fertilizer treatments and placements studied were as shown in Table 5. All fertilizers were dissolved in deionized water and applied to the soil in 10 ml volumes using an Oxford 10-ml pipet. MAP was labeled with ^{32}P (74 MBq) as H_3PO_4 in 0.02N HCl, such that each MAP treatment received 1.48×10^6 Bq ^{32}P. All applications were made to moistened soil and placed in bands of 20 cm length. The seed row was approximately 20 cm long and located in the middle of the soil container 2 cm below the soil surface (Figure 1.). Fertilizer bands were either 2.5 cm below and beside the seed row or 7.5 cm below and beside the seed row. In treatments where N and P was placed separately, N and P bands were placed on opposite sided of the seed row (Figure 1.). Application rates were calculated to reflect fertilizer band concentrations normally occurring under field condition and were equivalent to a field application rate of 20 kg ha^{-1} P and 70 kg ha^{-1} N with a band spacing of 36 cm (N from MAP was not included in the above calculation).

Table 5. Fertilizer and placement treatments for growth chamber experiment one.

Treatment	Fertilizers		Band Placement
	N	P	
1.	Urea	MAP	Separate: N- 7.5 cm below and beside the seed P- 7.5 cm below and beside the seed
2.	Urea	MAP	Separate: N- 7.5 cm below and beside the seed P- 2.5 cm below and beside the seed
3.	NH_4NO_3	MAP	Dual: N+P 7.5 cm below and beside the seed
4.	$(NH_4)_2SO_4$	MAP	Dual: N+P 7.5 cm below and beside the seed
5.	Urea	MAP	Dual: N+P 7.5 cm below and beside the seed
6.	Urea	none	--- N 7.5 cm below and beside the seed

Figure 1.   Fertilizer and seed placement.

iv. Harvest procedures

Wheat and flax were harvested 60 d after seeding while canola was harvested 52 d after seeding. Wheat was harvested at the heading stage, while canola and flax were harvested at the flowering stage. Total above ground plant material was harvested and placed in pre-weighed paper bags. Samples were dried for 3 d at 60 C in a forced air oven, weighed and ground through a 2-mm sieve using a Thomas-Wiley Laboratory Mill model 4.

v. Plant analysis

a. Nitric-perchloric acid digest of plant material

Five ml of HNO_3 and 2.5 ml of $HClO_4$ were added to 1.0 g of plant sample and allowed to equilibrate in digestion tubes for approximately 1 h. Samples were digested until the sample solution was pale yellow using a Digestion System 40, 1006 Heating Unit, heated to approximately 240 C. Digested sample solutions were transferred to 25-ml volumetrics, brought to volume and allowed to settle overnight. An aliquot of approximately 12 ml was transferred to a 15-ml polystyrene tube and stored for ^{31}P and ^{32}P analysis.

b. ^{32}P determination

^{32}P radiation was analyzed by Liquid Scintillation Counting using Beckman Ready Solv CP cocktail and a Beckman model 7500 counter.

c. ^{31}P determination

Concentration of ^{31}P in solution was determined by the acid-molybdate procedure as described by Murphy and Riley (1962).

2.2. Growth study two

Methods and materials followed for the second growth chamber experiment were similar to those for the first experiment. An Almasippi fine sandy loam soil (pH=8.4, carbonated) was selected for this study (Table 4.). Soils were pre-treated with 10 μg g^{-1} Zn as ZnCl, 5 μg g^{-1} Cu as CuSO$_4$ and K and S as described in the previous experiment.

Treatments and fertilizer placements were as shown in Table 6. All treatments were applied as previously discussed, however treatment number 8, the urea + MAP dual band was incubated for a period of 10 d prior to seeding. MAP and H$_3$PO$_4$ were labelled with ^{32}P as H$_3$PO$_4$ in 0.02 N HCl such that each treatment with MAP received 1.33 X 10^6 B$_q$ $_3{}^2$P and each treatment with H$_3$PO$_4$ received 1.22 X 10^6 Bq ^{32}P. Canola (<u>Brassica</u> <u>napus</u> var. Westar) was the only crop grown in this study.

A gravimetric moisture content of 18% was maintained for the first 29 d of growth, after which a gravimetric water content of 22% was maintained. Distilled water was added when gravimetric moisture content decreased to about 15.5%. Forty d after seeding additional N in the form of calcium nitrate was added to each pot at a rate of 35 kg ha^{-1}.

Plants were harvested as described in experiment one, 52 d after seeding. Due to differential growth among treatments only a portion of the plants were at the flowering stage when harvested. Plant growth stage was determined using the revised growth stage key proposed by Harper and Berkenkamp (1975).

Table 6. Fertilizer and placement treatments for growth chamber
          experiment two.

| Treat # | Fertilizers | | Band Placement |
	N	P	
1.	Urea	MAP	Separate: N- 7.5 cm below and beside the seed P- 7.5 cm below and beside the seed
2.	Urea	MAP	Separate: N- 7.5 cm below and beside the seed P- 2.5 cm below and beside the seed
3.	NH_4NO_3	MAP	Dual: N+P 7.5 cm below and beside the seed
4.	$(NH_4)_2SO_4$	MAP	Dual: N+P 7.5 cm below and beside the seed
5.	Urea	MAP	Dual: N+P 7.5 cm below and beside the seed
6.	Urea	none	--- N 7.5 cm below and beside the seed
7.	Urea	H_3PO_4	Dual N+P 7.5 cm below and beside the seed
8.	Urea *	MAP	Dual N+P 7.5 cm below and beside the seed
9.	SU	MAP	Dual N+P 7.5 cm below and beside the seed

* Incubated 10 d prior to seeding.

IV RESULTS AND DISCUSSION

1. Chemical Studies: The effect of various N fertilizers on pH, Ca^{++}, Mg^{++}, $NH_4^+ + NH_3$, $NO_3^- + NO_2^-$ and P concentration in dual N-P bands

1.1. pH distribution

After 4 wk of incubation the pH of the soils in columns without added P or N remained relatively constant at approximately 5.8, 7.1 and 8.8 for the acidic Stockton, neutral Stockton and alkaline Almasippi soils, respectively (Appendix A.).

Soil pH immediately adjacent to the fertilizer band, was above that of the untreated soil when MAP or TSP was added to the acidic Stockton soil (Figure 2.). Soil pH decreased to that of the control (pH=5.8) at about 1.25 and 0.75 cm from the fertilizer band for MAP and TSP, respectively. The increase in pH, of about 0.5 to 1.0 pH units immediately adjacent to the fertilizer band was most likely due to the formation of bicarbonate salts with the cations (NH_4^+ and Ca^{++}) of the P salts added.

The pH distribution curves for the urea + MAP, H_3PO_4-urea + MAP and urea + TSP treatments were similar. These treatments increased soil pH from 5.8 (control) to about 8.5 within 2.75 to 3.25 cm of the fertilizer band. Soil pH near the fertilizer band was also increased above that with MAP or TSP alone when urea or H_3PO_4-urea were added. The large increase in pH was attributed to the hydrolysis of urea and the subsequent formation of NH_4^+ and HCO_3^-. These results are consistent with results obtained by Overrein and Moe (1967) who found
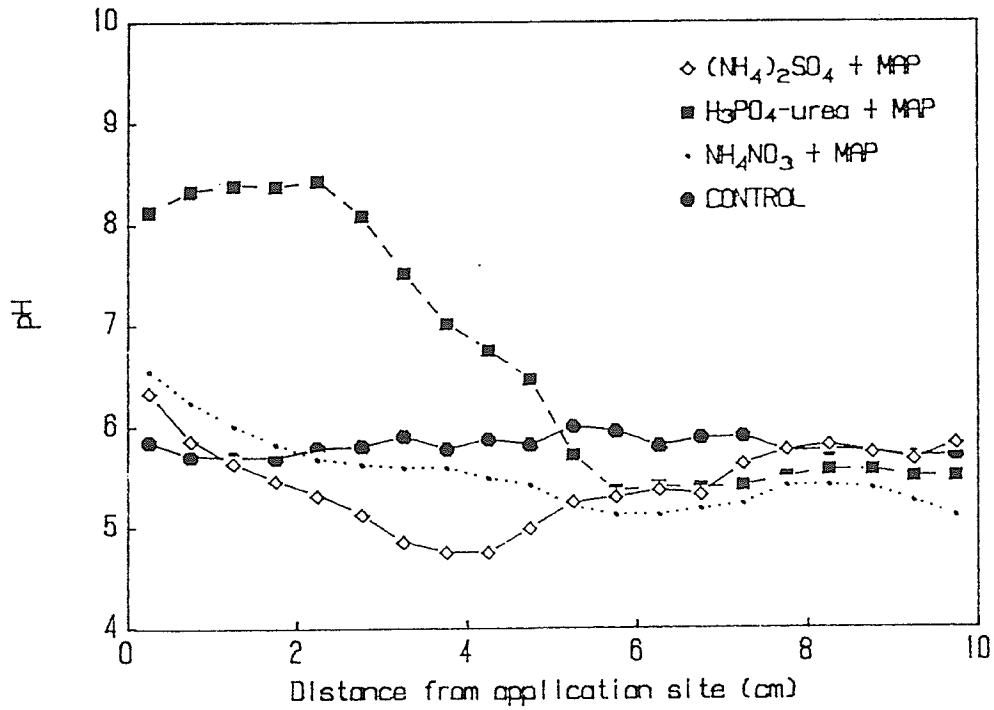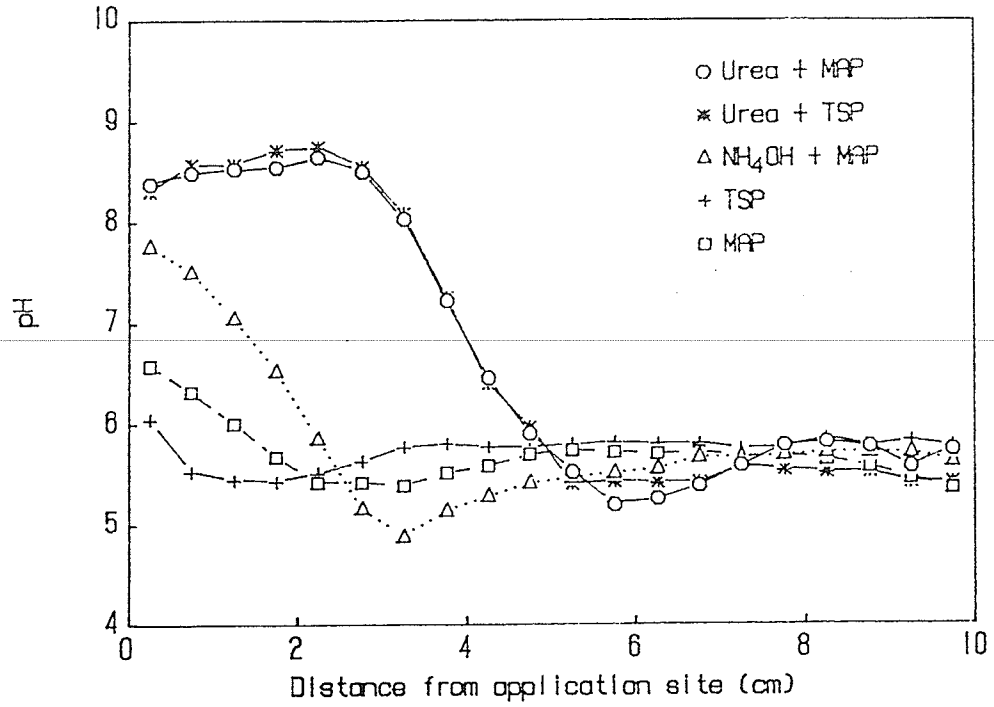
Figure 2. Effect of various N fertilizers on soil pH in dual N-P bands after 4 wk of incubation - acidic Stockton soil.

surface applications of urea (896 kg ha^{-1}) to increase reaction zone pH from approximately 6.5 to 8.8 within 3 d of application. A pH of approximately 8.5 was maintained throughout the 4 wk incubation period in their experiment. Soil pH at about 5.25 cm from the application site decreased below that of the control for the urea + MAP, H_3PO_4-urea + MAP and urea + TSP treatments. The decrease in pH below that of the control was most likely due to the oxidation of NH_4^+. Similar findings were observed by Isensee and Walsh (1970).

The addition of NH_4OH to MAP resulted in pH changes similar to those noted for urea + MAP. However, the magnitude of the pH increase and the distance from the fertilizer band to which pH was increased were less than that for the urea + MAP treatment. The lower pH may have been the result of a higher rate of NH_4^+ volatilization from NH_4OH than from urea. During volatilization, pH would decrease due to the release of H^+ as NH_4^+ was converted to $NH_{3(aq)}$ (Stevenson 1982).

The pH distribution resulting from the NH_4NO_3 + MAP and $(NH_4)_2SO_4$ + MAP treatments did not differ greatly from that of MAP alone. However, the pH was slightly lower than that of MAP near the middle of the soil column. This was probably the result of NH_4^+ oxidation.

In the neutral Stockton soil (Figure 3.) additions of MAP or TSP decreased soil pH below that of the control within about 2.25 and 3.75 cm from the fertilizer band for TSP and MAP, respectively. The reduction in pH was greater for the MAP treatment than for the TSP treatment. These results are contrary to the results obtained for the acidic Stockton soil, in which an increase in pH was observed near the fertilizer band. However, it was noted that the pH of the soil within 1.0 to 2.0 cm of the band varied from about 5.5 to 6.5 for both soils
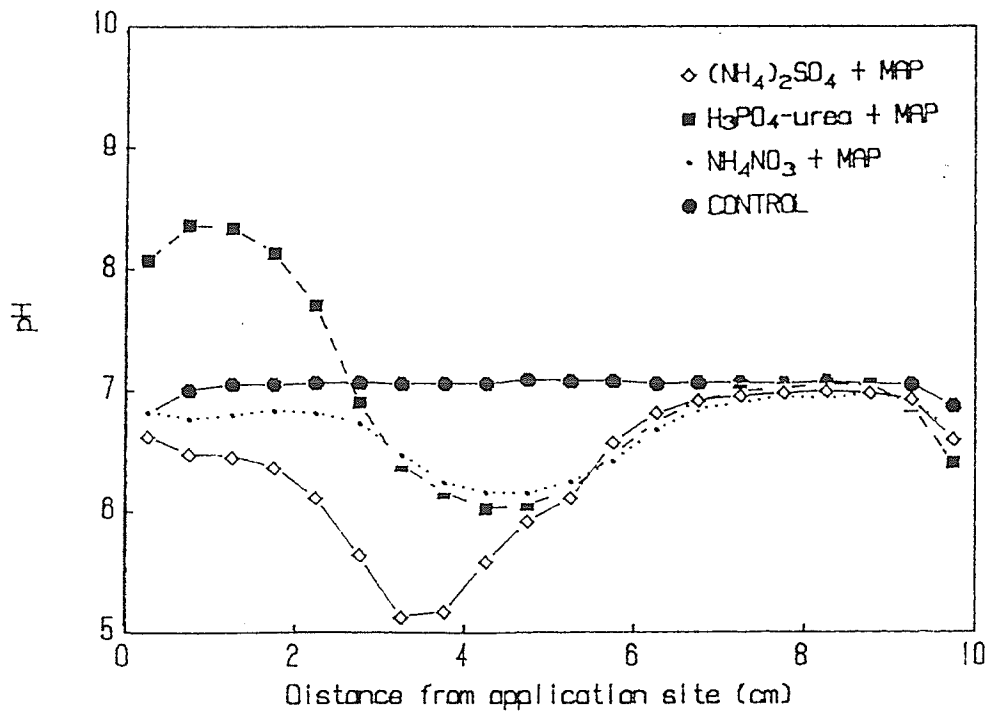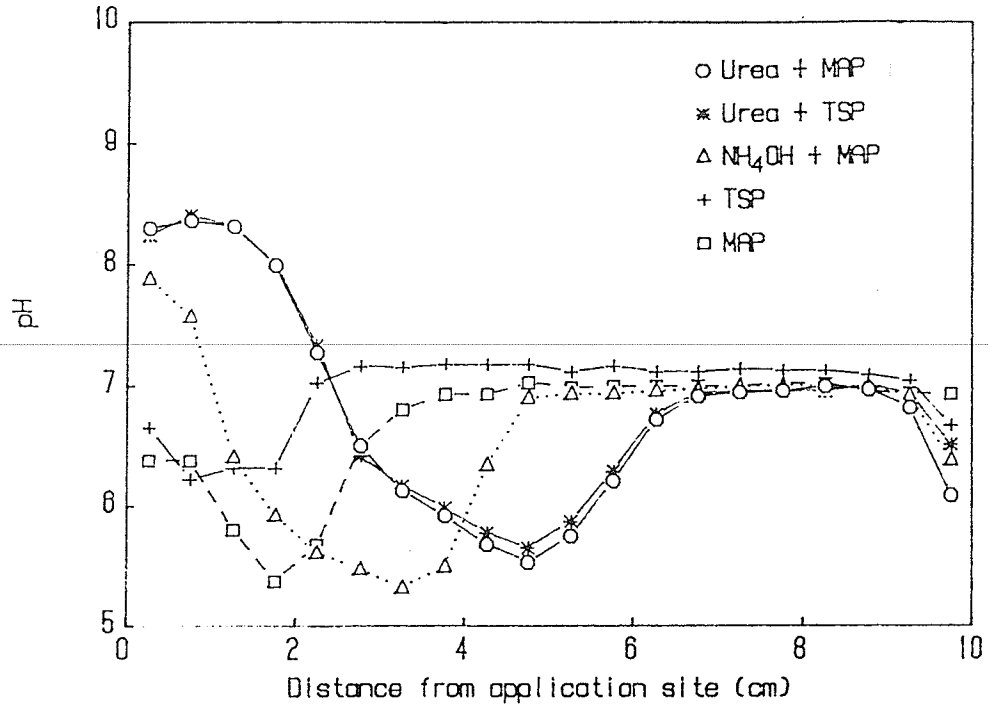
Figure 3. Effect of various N fertilizers on soil pH in dual N-P bands after 4 wk of incubation - neutral Stockton soil.

when treated with MAP or TSP. pH values of 5.5 to 6.5 are consistent with pH values in systems dominated by the $H_2PO_4^-$ ion. The dissolution of MAP results in saturation of the soil adjacent to the fertilizer band with $H_2PO_4^-$ ions. The incongruent dissolution of TSP results in the formation of $CaHPO_4 \cdot 2H_2O$ and H_3PO_4. H_3PO_4 quickly dissociates to form $H_2PO_4^-$. The pH of the acidic Stockton soil was not greatly altered since its initial pH was about 5.8. In contrast the pH of the neutral Stockton soil decreased from 6.4 to about 5.4 with MAP and from 6.7 to about 6.2 for TSP. Thus the pH near the fertilizer band for both soils was controlled by the P applied.

Urea + MAP, H_3PO_4-urea + MAP and urea + TSP treatments increased soil pH near the application site above that of the control and above that with MAP or TSP. However, the distance to which soil pH was increased was less in the neutral Stockton soil than in the acidic Stockton soil. In the urea treatments soil pH decreased below that of the control at about 2.75 cm from the fertilizer band, then continued to decrease to a pH of approximately 5.5 at about 4.75 cm from the fertilizer band. Soil pH with the H_3PO_4-urea treatment decreased below that of the control at about 3.25 cm from the fertilizer band then continued to decrease to a pH of 6.0 at about 4.25 cm from the fertilizer band. The decrease in pH was most likely a result of nitrification.

The distribution of pH with the NH_4OH + MAP treatment followed a trend similar to that discussed for the acidic Stockton soil. Soil pH near the fertilizer band was slightly greater with the NH_4NO_3 + MAP treatment than with MAP alone. At about 3.25 to 7.25 cm from the fertilizer band the soil pH was less with NH_4NO_3 + MAP than with MAP

alone. This decrease in pH was attributed to nitrification. Soil pH
with the $(NH_4)_2SO_4$ + MAP treatment followed a pattern similar to that
of NH_4NO_3 + MAP treatment. Soil pH for the $(NH_4)_2SO_4$ + MAP treatment
was much less than that of MAP alone from about 2.75 to 6.25 cm from
the fertilizer band. The lower pH was attributed to oxidation of NH_4^+.

The shape of the pH distribution curve for MAP and TSP treatments
on the Almasippi soil (Figure 4.) differed markedly from those obtained
for the other two soils. Soil pH immediately adjacent to the fertilizer
band decreased to about 7.5 when TSP or MAP was added. Soil pH
increased to a pH of approximately 8.7 at 3.25 and 1.75 cm from the
fertilizer band with MAP and TSP, respectively.

The shape of the pH distribution curves with urea + MAP, urea +
TSP, H_3PO_4-urea + MAP and NH_4OH + MAP treatments were similar to those
observed for the neutral Stockton soil. Soil pH with the $(NH_4)_2SO_4$ dual
N-P band also behaved similarly to that discussed for the neutral
Stockton soil except that the pH increased slightly for the first three
sections then decreased as previously discussed for the neutral
Stockton soil.

The pH values encountered in these studies were similar to those
observed by other researchers (Overrein and Moe 1967; Isensee and Walsh
1970) studying soil pH's near the fertilizer band. In general, the soil
pH near the fertilizer band was increased by the addition of alkaline N
carriers such as urea, NH_4OH and H_3PO_4-urea. Despite the acidic nature
of H_3PO_4-urea, soil pH was similar to that of urea after 4 wk of
incubation. This indicates that the urea present in H_3PO_4-urea
dominated the reaction zone pH. Acidic N carriers ($(NH_4)_2SO_4$ and
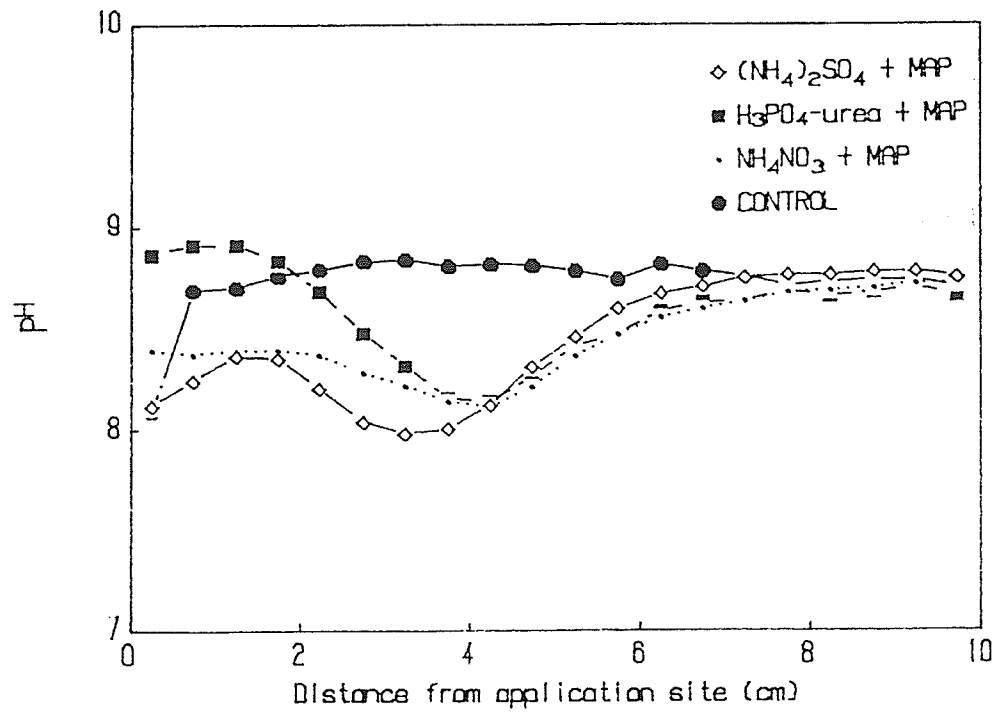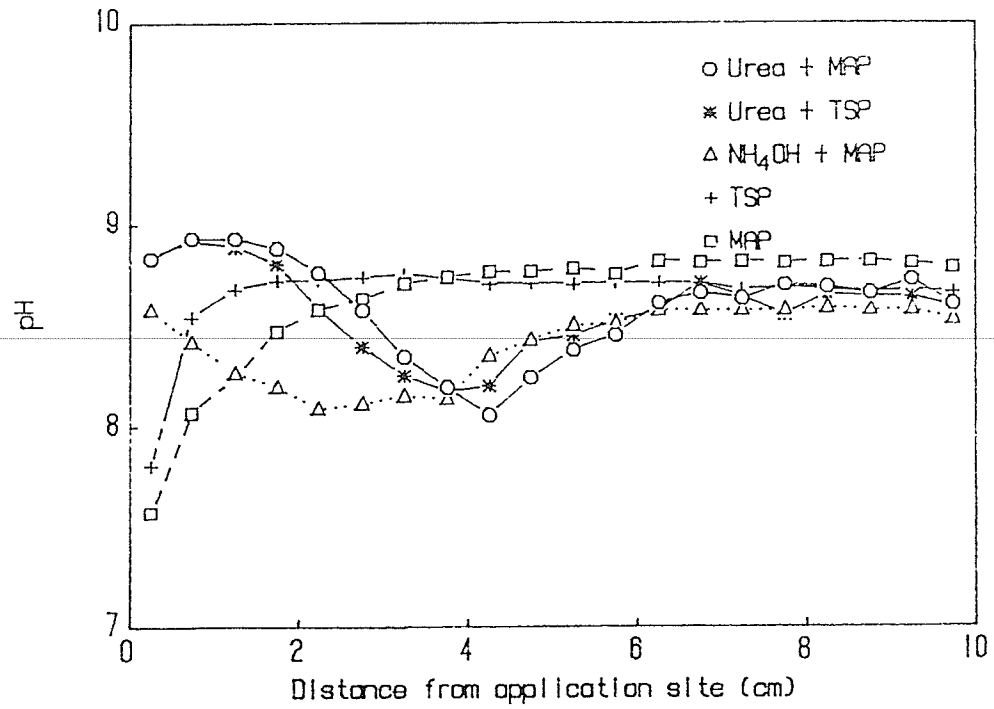
Figure 4. Effect of various N fertilizers on soil pH in dual N-P bands
after 4 wk of incubation - Almasippi soil.

NH$_4$NO$_3$) resulted in soil pH's similar to that of the control and slightly less than the control near the fertilizer band.

1.2. Ammonium + ammonia-N distribution

The NH$_4^+$ + NH$_3$-N concentrations in the untreated soils and soils treated with TSP alone were negligible (Figure 5.).

The distribution of NH$_4^+$ + NH$_3$-N was generally similar among treatments and soils. However, both the highest concentration of NH$_4^+$ + NH$_3$-N found in the soil and distance of NH$_4^+$ + NH$_3$-N movement from the application site varied with N fertilizer and with soil type.

The highest concentration of NH$_4^+$ + NH$_3$-N in the acidic Stockton soil (Figure 5.) was found at about 0.25 cm from the fertilizer band for all treatments except for (NH$_4$)$_2$SO$_4$ + MAP and H$_3$PO$_4$-urea + MAP, in which the highest NH$_4^+$ + NH$_3$-N concentration occurred at about 0.75 cm from the fertilizer band. The highest NH$_4^+$ + NH$_3$-N concentration was greatest with the (NH$_4$)$_2$SO$_4$ + MAP treatment (approximately 2400 μg g^{-1}). All other N treatments resulted in a similar maximum NH$_4^+$ + NH$_3$-N concentration (approximately 1000 μg g^{-1}). The NH$_4^+$ + NH$_3$-N concentration with MAP alone was relatively low and did not exceed a concentration of 370 μg g^{-1}. The very high concentration of NH$_4^+$ + NH$_3$-N in the (NH$_4$)$_2$SO$_4$ + MAP treatment was probably due to two factors; 1. reduced nitrification of NH$_4^+$ to NO$_2^-$ or NO$_3^-$ due to a lower reaction zone pH (Pang et al. 1973), and 2. a reduction in NH$_3$ volatilization resulting from the release of H$^+$ as NH$_4^+$ was converted to NH$_3$(aq). Vlek and Stump (1978) found only 38% of N from a (NH$_4$)$_2$SO$_4$ solution to be lost to NH$_3$ volatilization before volatilization ceased due to decreased pH. In contrast, urea hydrolysis results in the production of

Figure 5. Effect of various N fertilizers on $NH_4^+ + NH_3$-N concentration in dual N-P bands after 4 wk of incubation - acidic Stockton.

NH_4^+ and HCO_3^-. This process causes solution pH to rise and supplies the solution with a buffering capacity to support NH_3 volatilization. These findings explain the lower NH_4^+ + NH_3-N concentration when urea-N was added. The lower NH_4^+ + NH_3-N concentration with NH_4NO_3 + MAP as compared to $(NH_4)_2SO_4$ + MAP was due to the smaller quantity of NH_4^+ added with NH_4NO_3 than with $(NH_4)_2SO_4$. All salts were added at equivalent rates based on amount of total N added.

In all treatments, NH_4^+ + NH_3-N concentration decreased with increasing distance from the zone of highest NH_4^+ + NH_3-N concentration, which occurred immediately adjacent to the fertilizer band or within 0.75 cm of the fertilizer band. The rate at which the NH_4^+ + NH_3-N concentration decreased with increasing distance from the fertilizer band was similar for all treatments containing a N fertilizer except with $(NH_4)_2SO_4$ + MAP or NH_4OH + MAP. The rate of decrease for $(NH_4)_2SO_4$ + MAP or NH_4OH + MAP was greater than that of all other treatments. The NH_4^+ + NH_3-N concentration decreased to at least 50 μg g^{-1} at 6.25 to 7.25 cm from the fertilizer band for all treatments except for NH_4OH + MAP, which decreased to a concentration of about 50 μg g^{-1} at 4.75 cm from the fertilizer band.

Results obtained for the neutral Stockton soil (Figure 6.) were similar to those obtained for the acidic Stockton soil. However, the NH_4^+ + NH_3-N concentration near the fertilizer band was slightly greater for the neutral Stockton soil than for the acidic Stockton soil with all treatments. Ammonium + ammonia-N concentration was reduced to less than 50 μg g^{-1} at about 5.25 cm from the fertilizer band for both urea treatments, at 5.75 cm from the fertilizer band for $(NH_4)_2SO_4$ + MAP, NH_4NO_3 + MAP, and H_3PO_4-urea + MAP treatments and at 3.75 cm from

Figure 6. Effect of various N fertilizers on $NH_4^+ + NH_3$-N concentration in dual N-P bands after 4 wk of incubation - neutral Stockton soil.

the fertilizer band for the NH_4OH + MAP treatment. Decreased movement of NH_4^+ + NH_3-N for urea + MAP and NH_4OH + MAP treatments when compared to those of $(NH_4)_2SO_4$ + MAP, NH_4NO_3 + MAP and H_3PO_4-urea + MAP was likely the result of increased nitrification at the outer edge of the NH_4^+ + NH_3-N reaction zone. High concentrations of NO_3^- + NO_2^--N were found at the advancing front of the NH_4^+ + NH_3-N curve with urea and NH_4NO_3 dual N-P bands (section 1.4).

The highest concentration of NH_4^+ + NH_3-N near the fertilizer band and the distance of NH_4^+ + NH_3-N movement varied with treatment to a greater extent for the Almasippi soil (Figure 7.) than for the other two soils studied. The highest concentration of NH_4^+ + NH_3-N found near the fertilizer band decreased in the order: $(NH_4)_2SO_4$ + MAP > urea + MAP > urea + TSP > H_3PO_4-urea + MAP > NH_4NO_3 + MAP > NH_4OH + MAP > MAP = TSP. Ammonium + ammonia-N concentration in the Almasippi soil decreased with distance from the fertilizer band at a greater rate than was observed for the other soils. Ammonium + ammonia-N concentration was reduced to less than 50 μg g^{-1} at about 4.25, 3.75, 4.75, 2.25, 4.25 and 3.75 cm from the fertilizer band for the urea + MAP, $(NH_4)_2SO_4$ + MAP, NH_4NO_3 + MAP , NH_4OH + MAP, H_3PO_4-urea + MAP and urea + TSP treatments, respectively. The rapid decrease in NH_4^+ + NH_3-N concentration was probably due to a higher rate of nitrification occurring in the calcarious soil.

Very high NH_4^+ + NH_3-N concentrations were observed for all N treatments (eg. up to 2800 μg g^{-1}) in all soils. High NH_4^+ + NH_3-N concentrations in combination with a high soil pH will result in high NH_3 concentrations, which can be toxic to plant roots (Colliver and Welch 1970b). Thus, N carriers which increase the soil pH and increase

Figure 7. Effect of various N fertilizers on $NH_4^+ + NH_3$-N concentration in dual N-P bands after 4 wk of incubation - Almasippi soil.

NH_4^+ concentration (urea, H_3PO_4-urea, or NH_4OH) would probably reduce root growth near the fertilizer band. Strong and Soper (1974a) found root proliferation in the fertilizer band to be very important for fertilizer P uptake. Thus, a reduction in root growth would likely result in reduced P uptake by plants.

The high NH_4^+ + NH_3-N concentrations indicate that there would probably be sufficient NH_4^+ to facilitate an NH_4^+ ion effect even after 4 wk of incubation.

1.3. Calcium ion distribution

Both Ca^{2+} and Mg^{2+} concentrations in the soil samples were determined. Magnesium ion concentrations reflected Ca^{2+} concentrations except that the Mg^{2+} concentrations were much less than those of Ca^{2+}. Due to the similarity in the Ca^{2+} and Mg^{2+} distribution, only the distribution of Ca^{2+} was shown and discussed.

Calcium ion concentrations for the controls remained relatively constant throughout the soil column at concentrations of about 50, 100 and 200 $\mu g\ g^{-1}$ for the acidic Stockton, neutral Stockton and alkaline Almasippi soils, respectively.

The distribution of Ca^{2+} in the soil columns varied with treatment and soil type. Calcium ion concentrations in the acidic Stockton soil (Figure 8.) treated with MAP remained constant with distance from the fertilizer band. Calcium ion concentration in the soil treated with TSP was greatest at 0.25 cm from the fertilizer band then decreased rapidly to untreated soil levels with increasing distance from the application site. The high Ca^{2+} concentration near the fertilizer application site was due to the Ca applied with TSP.
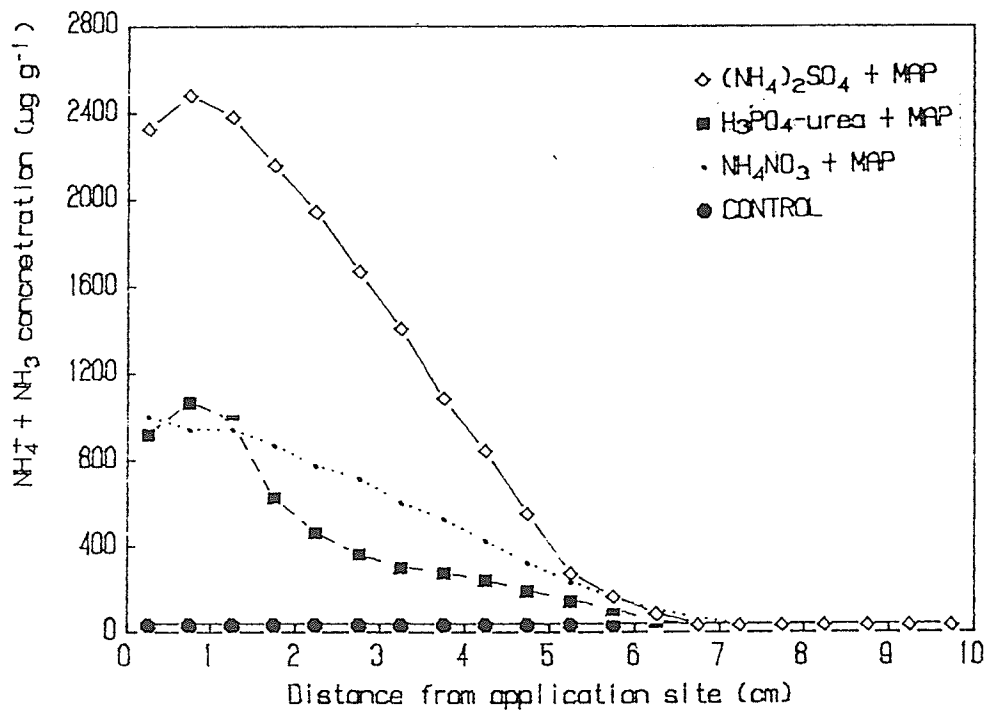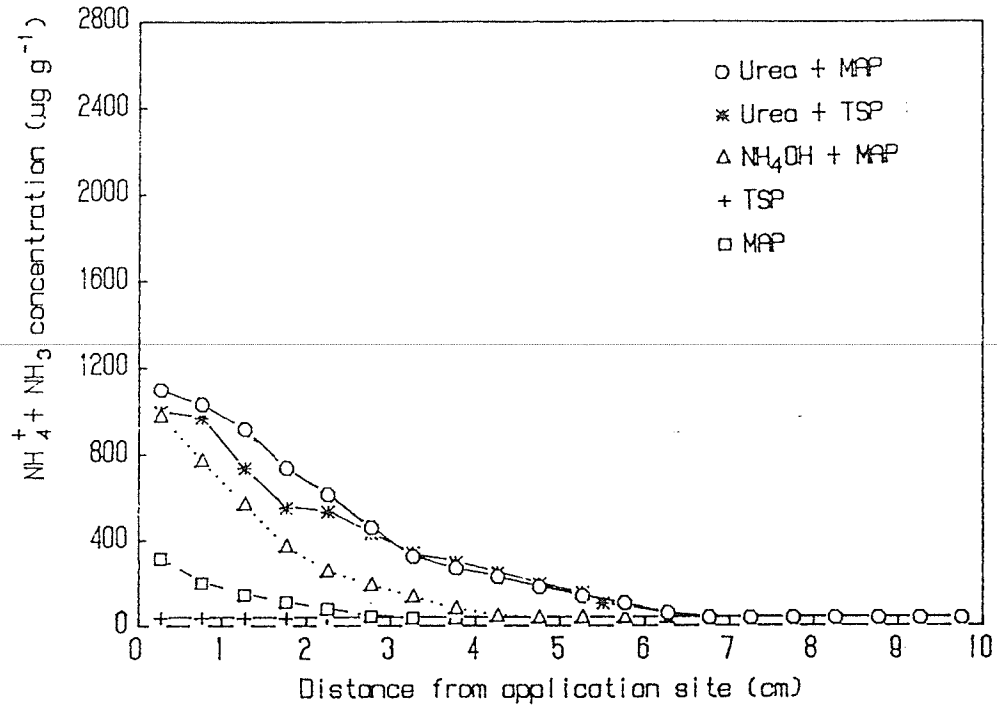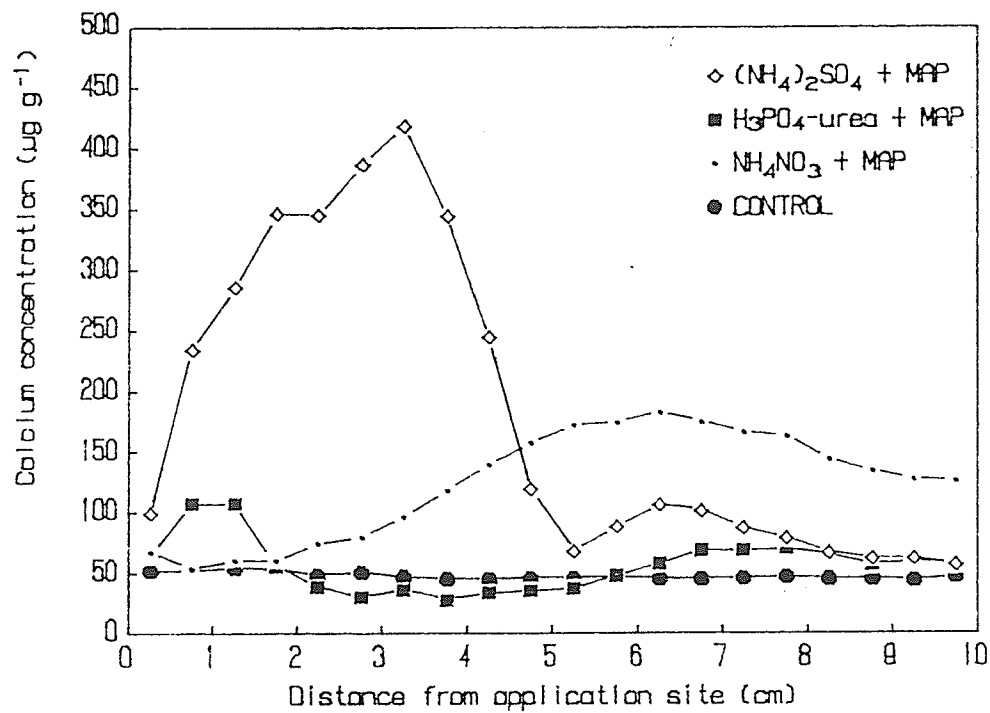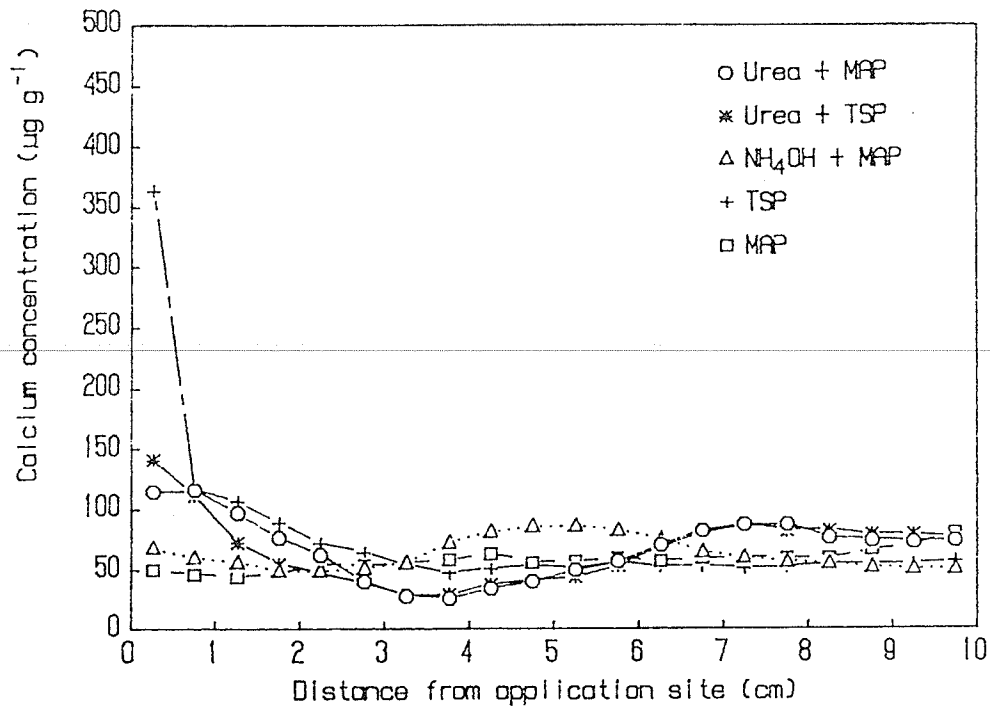
Figure 8. Effect of various N fertilizers on Ca^{2+} concentration in dual N-P bands after 4 wk of incubation - acidic Stockton soil.

The addition of H_3PO_4-urea or urea to MAP increased Ca^{2+} concentration near the application site above that of MAP alone, whereas additions of urea to TSP reduced Ca^{2+} concentration below that of TSP alone. The concentration of Ca^{2+} decreased below that of the MAP with the urea + MAP and H_3PO_4-urea + MAP treatments at 2.75 cm from the fertilizer band. A similar decrease in Ca^{2+} concentration below that of TSP was noted with the urea + TSP treatment. The reasons for the decreases in Ca^{2+} concentration are unknown to the author.

The addition of NH_4OH or NH_4NO_3 to MAP increased Ca^{2+} concentration above that of MAP alone at about 3.75 and 2.25 cm from the fertilizer band, respectively. The magnitude of increase was greater with NH_4NO_3 + MAP than with NH_4OH + MAP. The above increases in Ca^{2+} concentration were attributed to the "snow plow" effect (Cho 1985). Ammonium ions from the fertilizer N moved into the soil and exchanged for Ca^{2+} ions on the soil exchange sites. As the NH_4^+ ions moved further into the soil, they displaced more and more Ca^{2+} such that an accumulation of Ca^{2+} resulted just in front of the advancing NH_4^+ ion front.

The concentration of Ca^{2+} in the soil treated with $(NH_4)_2SO_4$ + MAP increased rapidly from the application site to a distance of 3.25 cm, then decreased rapidly to a distance of 5.25 cm. Calcium ion concentrations at 5.25 to 8.25 cm from the fertilizer band were also higher than with MAP alone. The increase in Ca^{2+} concentration at 5.25 to 8.25 cm from the fertilizer band was probably due to the "snow plow" effect. The large increase in Ca^{2+} concentration near the fertilizer band was probably the result of $(NH_4)_2SO_4$ reacting with $CaCO_3$ to produce $CaSO_4$ (gypsum) (Terman and Hunt 1964). Given the high

solubility of $CaSO_4$ compared to $CaCO_3$, a greater amount of Ca^{2+} would be extracted from the $(NH_4)_2SO_4$ treatment than from other treatments.

Calcium ion concentrations for the neutral Stockton soil (Figure 9.) were similar to that discussed for the acidic Stockton soil for the MAP, TSP, NH_4NO_3 + MAP and $(NH_4)_2SO_4$ + MAP treatments. The Ca^{2+} concentrations resulting from the urea + MAP and H_3PO_4-urea + MAP treatments were similar to that of MAP near the application site, while addition of urea to TSP reduced Ca^{2+} concentration to less than that of TSP alone. Calcium ion concentrations near the center of the soil column with urea + MAP, urea + TSP and H_3PO_4-urea + MAP treatments were greater than that of the TSP or MAP. Increased Ca^{2+} concentrations corresponded to the advancing NH_4^+ front, indicating that the "snow plow" effect may be responsible for the increase in Ca^{2+} concentration. Increased Ca^{2+} concentration also corresponded to decreases in the pH resulting from the oxidation of free NH_4^+. Increased solubility of Ca salts such as $CaCO_3$ due to the lower pH may also have contributed to the enhanced Ca^{2+} concentration.

The concentration of Ca^{2+} for the neutral Stockton soil was much greater than for the acidic Stockton soil. This was most likely due to higher carbonate levels in the neutral Stockton soil than in the acidic Stockton soil.

The treatment effects on Ca^{2+} distribution for the Almasippi soil (Figure 10.) were similar to that of the Stockton soils. However, concentrations of Ca^{2+} were much higher than for the Stockton soils due to the high percentage of $CaCO_3$ in the Almasippi soil. Also, the distribution of Ca^{2+} for the Almasippi soil treated with $(NH_4)_2SO_4$ + MAP was slightly different from that of the other soils in that the
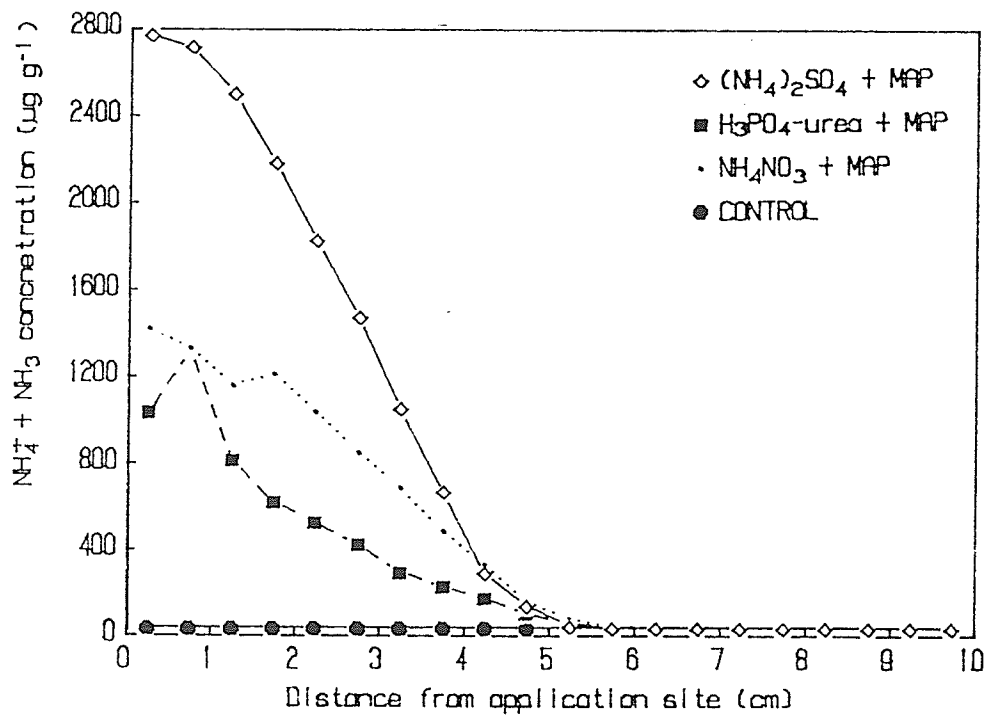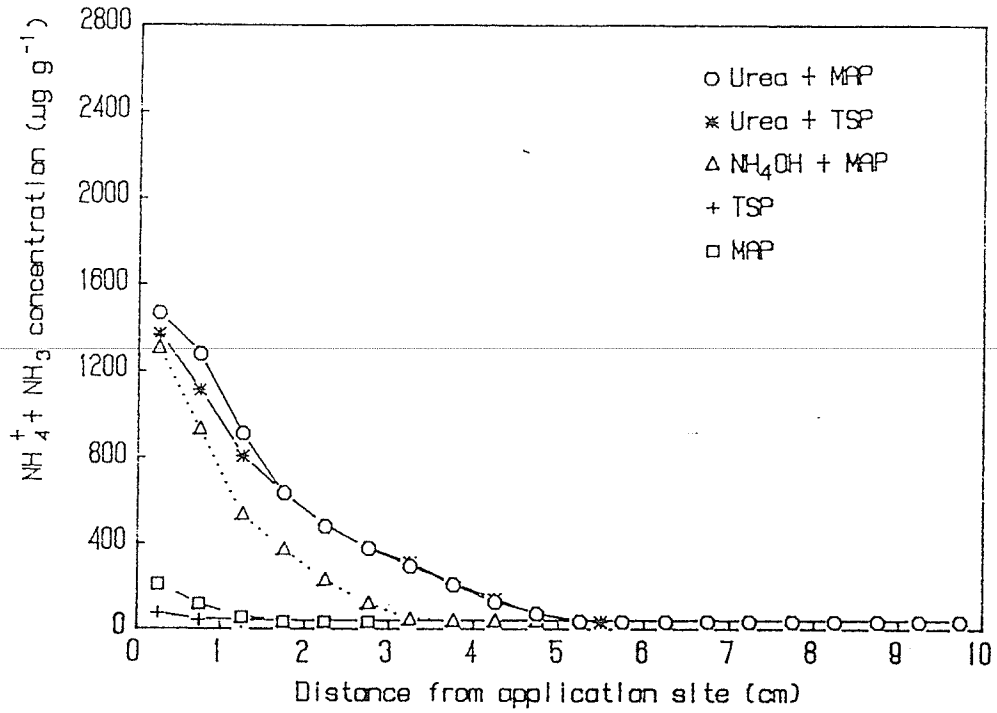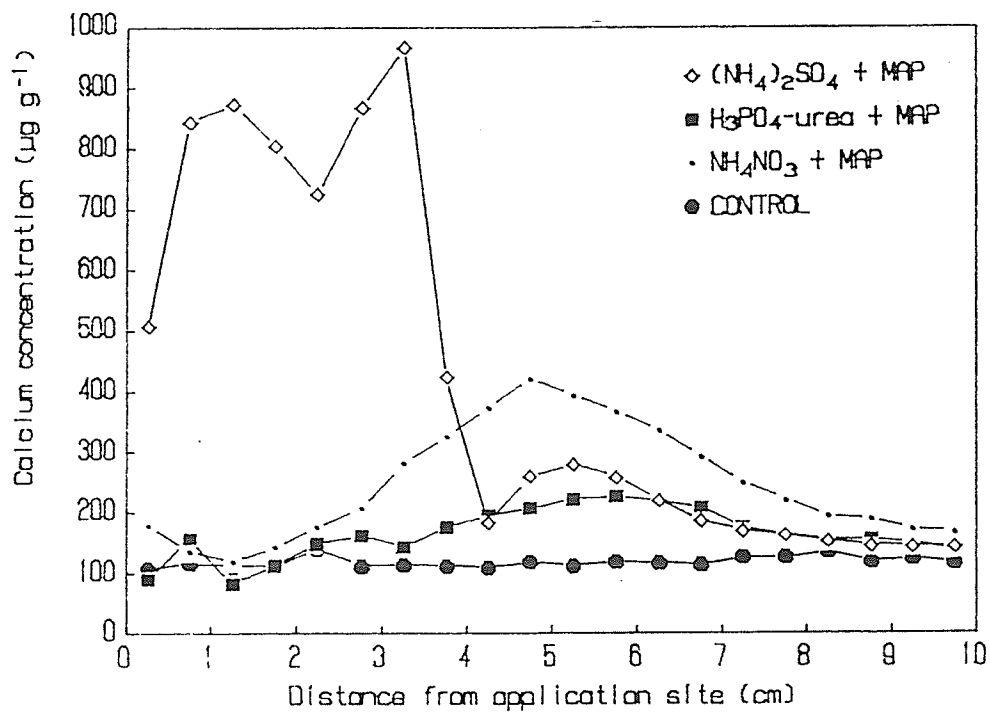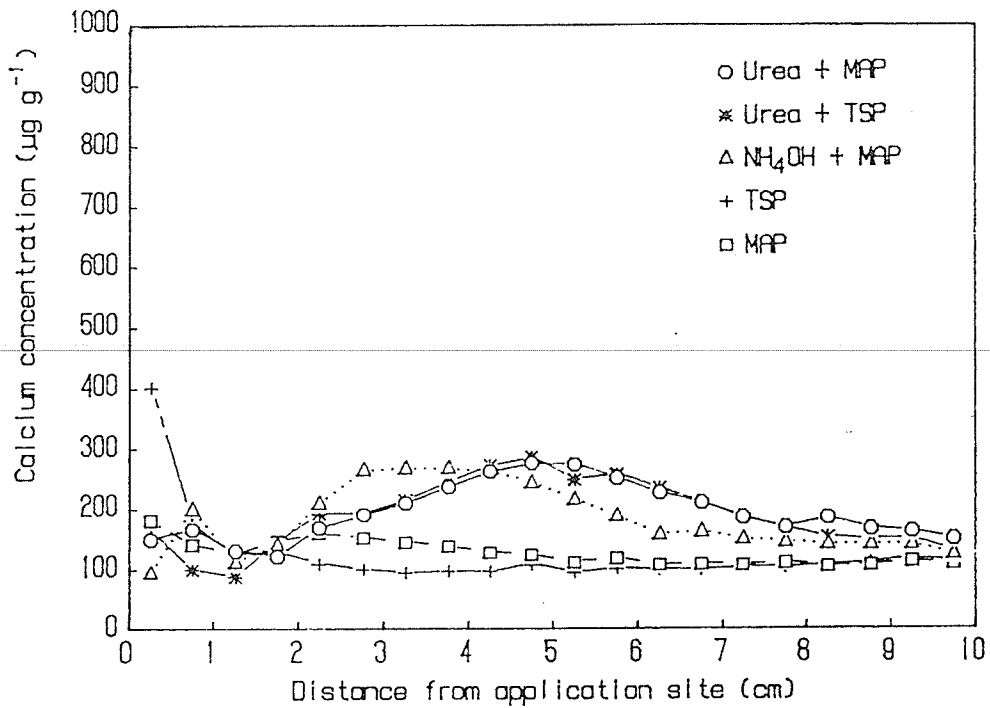
Figure 9. Effect of various N fertilizers on Ca^{2+} concentration in dual N-P bands after 4 wk of incubation - neutral Stockton soil.
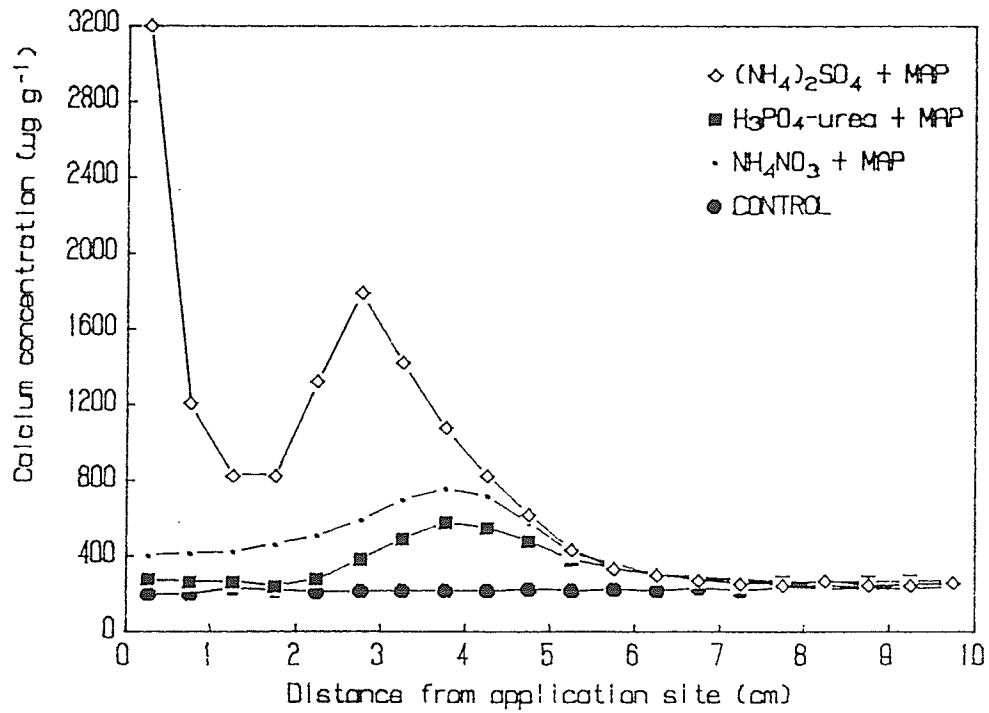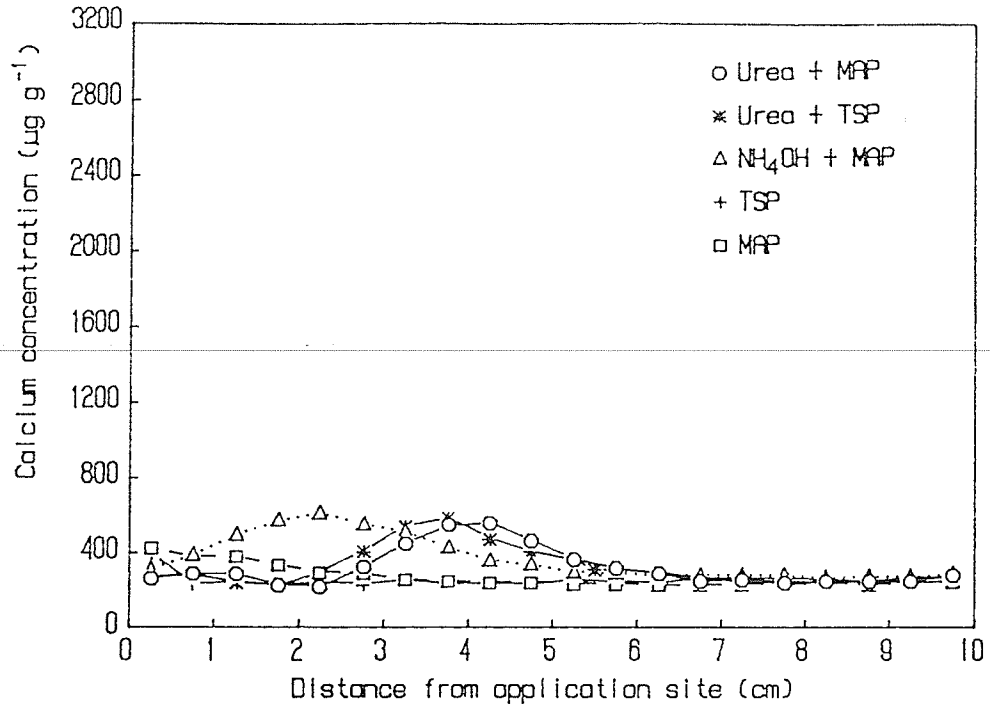
Figure 10. Effect of various N fertilizers on Ca^{2+} concentration in dual N-P bands after 4 wk of incubation - Almasippi soil.

Ca^{2+} concentration immediately adjacent to the fertilizer band was extremely high, then decreased rapidly. Calcium ion concentration increased then decreased for the other two soils. The very high concentration of Ca^{2+} immediately adjacent to the fertilizer band was probably the result of large amounts of Ca^{2+} solubilized by the $(NH_4)_2SO_4$. Since the Almasippi soil contained much higher concentrations of $CaCO_3$ than the other two soils, a larger quantity of Ca^{2+} would be solubilized per unit wt of soil. The large quantity of Ca^{2+} solubilized would be expected to react with sulfate near the fertilizer band resulting in the formation of large amounts of $CaSO_4$ immediately adjacent to the fertilizer band.

There appeared to be a "snow plow" effect for all soils treated with a N fertilizer except for the acidic Stockton soil treated with either urea or H_3PO_4-urea dual N-P bands. However, due to the concomitant decrease in pH (due to nitrification), increased Ca^{2+} concentrations may also be due to increased solubility of Ca precipitates.

Calcium ion concentration near the fertilizer application site should have decreased compared to MAP or TSP alone if the application of the N fertilizer resulted in displacement of soil Ca^{2+} and Mg^{2+} from the site of application ("snow plow" effect). However, large reductions in the Ca^{2+} concentration near the application site were not generally observed. This was probably due to the presence of $CaCO_3$ in the soils. In soils containing $CaCO_3$, the concentration of Ca^{2+} in the soil solution is governed by $CaCO_3$ equilibrium. Thus, as long as $CaCO_3$ is present, a minimum concentration of Ca^{2+} in the soil solution will be

maintained regardless of displacement of Ca^{2+} from the site of application by the N fertilizer.

1.4. Nitrate + nitrite-N distribution

Nitrate + nitrite-N concentrations in the non-treated soils remained relatively constant throughout the soil column at concentrations of about 50 μg g^{-1} for the two Stockton soils and at about 75 μg g^{-1} for the Almasippi soil.

Concentrations of $NO_3^- + NO_2^-$-N for the acidic Stockton soil treated with MAP and TSP were relatively constant throughout the soil column (Figure 11.). However, the $NO_3^- + NO_2^-$-N concentrations for soil treated with MAP were slightly greater than that of soil treated with TSP throughout the soil column. This was due to the nitrification of NH_4^+ applied as MAP.

Nitrate + nitrite-N concentrations at about 1.75 cm from the fertilizer band were higher with urea + MAP, urea + TSP, and H_3PO_4-urea + MAP treatments than for untreated soil or soil treated with P fertilizer alone. A decrease in soil pH concomitant with the higher concentrations of $NO_3^- + NO_2^-$-N indicated that nitrification was responsible for the increase in $NO_3^- + NO_2^-$-N concentrations. Concentrations of $NO_3^- + NO_2^-$-N immediately adjacent to the fertilizer band were not increased above that of MAP despite adequate concentrations of substrate (NH_4^+) for nitrification. The absence of large quantities of $NO_3^- + NO_2^-$-N at the application site was probably a result of reductions in nitrification due to high NH_3 concentrations near the application site. Free NH_3 typically inhibits the oxidation of NO_2^- to NO_3^- by Nitrobacter (Aleem and Alexander 1960). In addition,
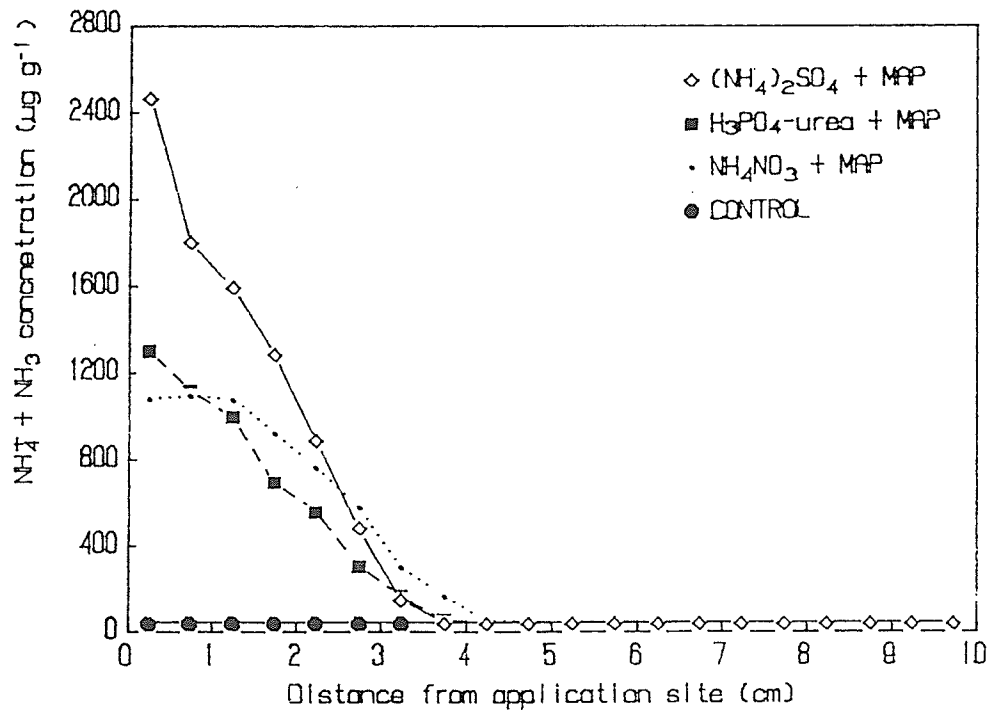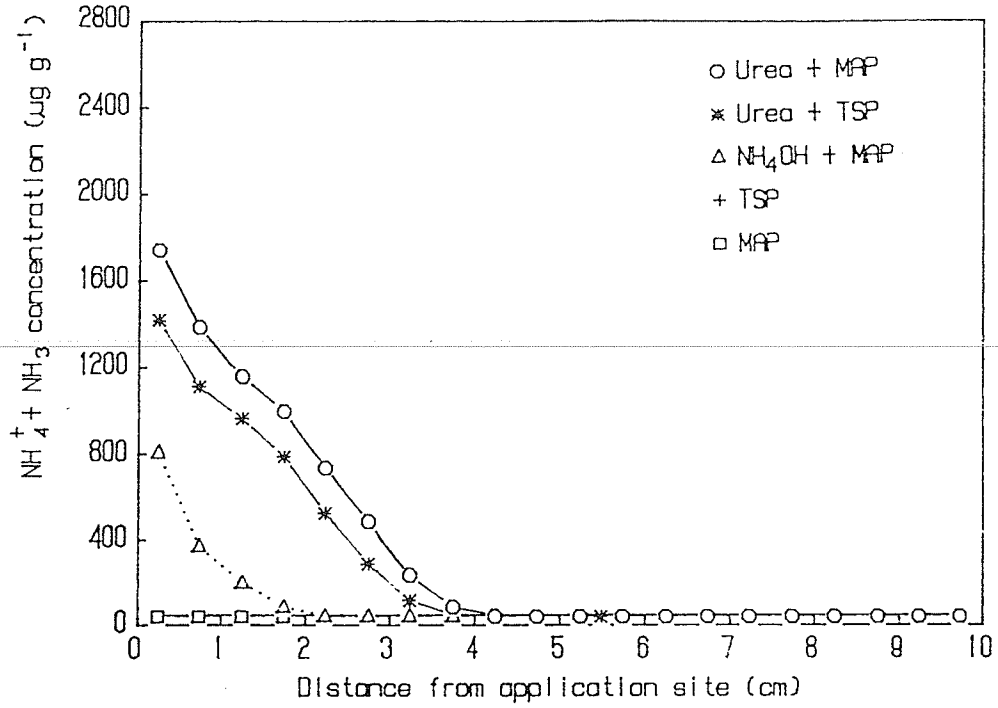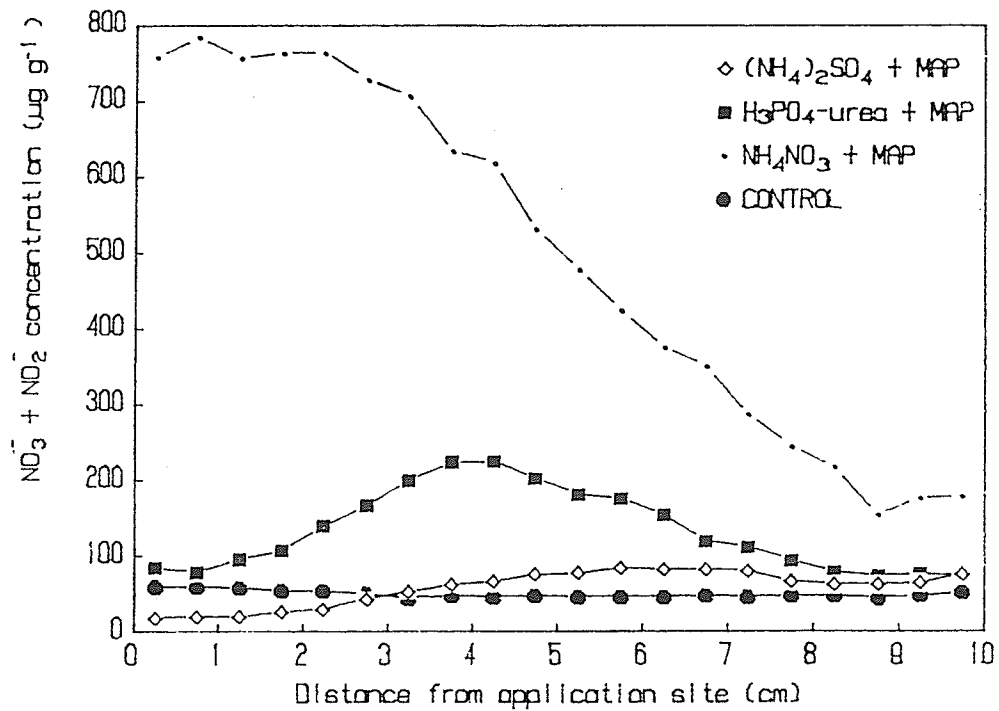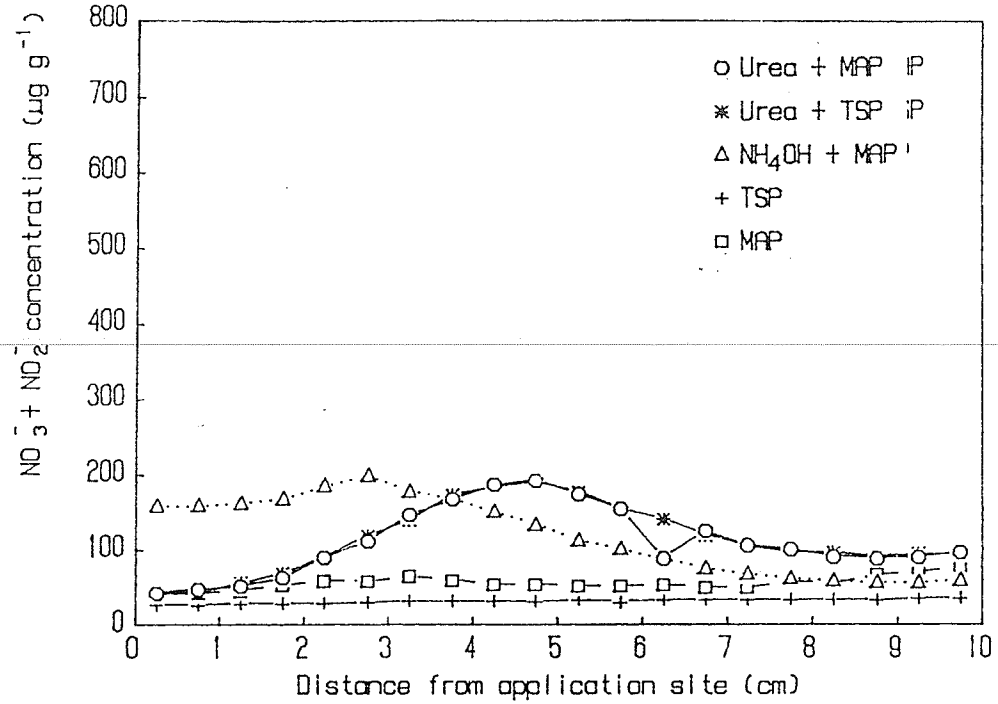
Figure 11. Effect of various N fertilizers on $NO_3^- + NO_2^-$-N concentration in dual N-P bands after 4 wk of incubation - acidic Stockton soil.

high osmotic tensions near the application site, resulting from high nutrient concentrations, may have reduced microbial activity and thus reduced nitrification (Johnson and Guenzi, 1963).

In contrast to the urea or H_3PO_4-urea dual N-P bands, NO_3^- + NO_2^--N concentrations resulting from the NH_4OH + MAP treatment were much greater near the application site than from the MAP treatment. This was probably the result of a more conducive environment for nitrification with the NH_4OH dual N-P band than with the urea or H_3PO_4-urea dual N-P bands. The pH and NH_4^+ concentration near the application site were lower for the NH_4OH dual N-P band than for the urea or H_3PO_4-urea dual N-P bands. The lower pH would tend to reduce NH_3 concentration allowing nitrification to occur near the fertilizer band. Increased NO_3^- + NO_2^--N concentration at about 3 cm from the fertilizer band was attributed to the rapid nitrification of NH_4^+.

The NH_4NO_3 dual N-P band resulted in high NO_3^- + NO_2^--N concentrations near the application site due to the addition of nitrate-N. The concentration of NO_3^- + NO_2^--N decreased rapidly with distance but remained above that of the control treatments at all distances from the fertilizer band. The $(NH_4)_2SO_4$ dual N-P band increased NO_3^- + NO_2^--N concentration slightly above that of MAP alone at about 3.5 cm from the fertilizer band. Near the fertilizer band NO_3^- + NO_2^--N was slightly lower than that of the control.

Nitrate + nitrite-N concentrations for the neutral Stockton soil (Figure 12.) were usually higher than for the acidic Stockton soil. This was due to a greater rate of nitrification in the neutral soil due to a more suitable soil pH for microbial activity. An acidic soil
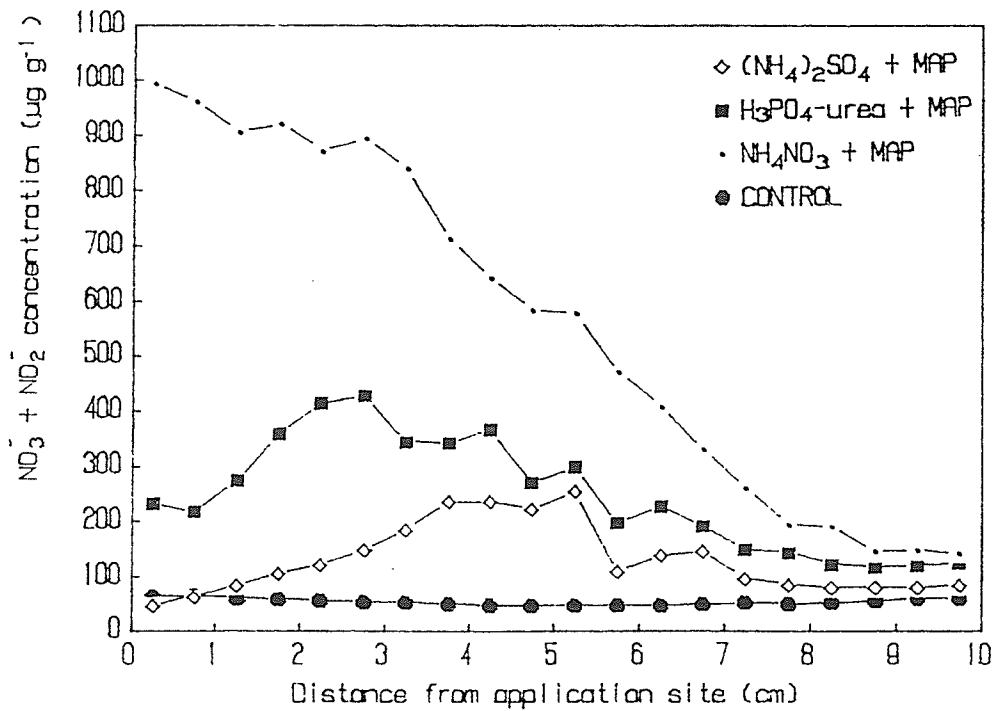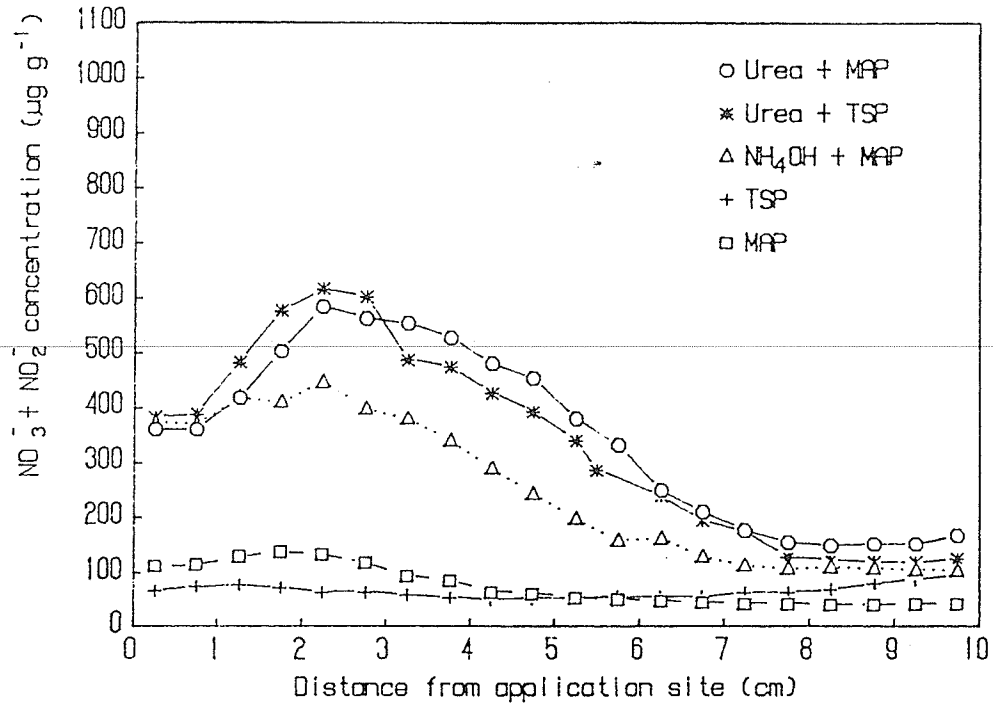
Figure 12. Effect of various N fertilizers on $NO_3^- + NO_2^-$-N concentration in dual N-P bands after 4 wk of incubation - neutral Stockton soil.

environment such as that of the acidic Stockton soil would inhibit microbial activity and reduce the nitrification rate (Alexander 1977).

Nitrate + nitrite-N concentrations in the soil treated with MAP were slightly greater near the application site than in the remainder of the soil column. Whereas $NO_3^- + NO_2^-$-N concentrations with TSP were relatively constant with distance from the fertilizer band and approximated that of the control treatment.

The distribution of $NO_3^- + NO_2^-$-N for the neutral Stockton soil treated with urea + MAP, urea + TSP, and H_3PO_4-urea + MAP was similar to that of the NH_4OH + MAP treatment for the acidic Stockton soil. Increased $NO_3^- + NO_2^-$-N near the fertilizer band probably resulted from diffusion of $NO_3^- + NO_2^-$-N from area of high $NO_3^- + NO_2^-$-N concentrations as well as from nitrification of the NH_4 at the site of application.

Nitrate + nitrite-N concentrations resulting from applications of $(NH_4)_2SO_4$ + MAP or NH_4NO_3 + MAP were similar to those for the acidic Stockton soil. However, $NO_3^- + NO_2^-$-N did not decrease near the application site with the $(NH_4)_2SO_4$ + MAP treatment.

The addition of MAP to the Almasippi soil (Figure 13.) increased $NO_3^- + NO_2^-$-N near the fertilizer band due to nitrification of the NH_4^+ added as MAP. Nitrate + nitrite-N concentrations in soil treated with TSP were similar to that of the untreated soil.

All N treatments except NH_4OH resulted in a reduction in the $NO_3^- + NO_2^-$-N concentrations near the application site when compared to MAP alone. This was attributed to a reduction in nitrification due to high NH_3 concentrations. Nitrate + nitrite-N concentrations increased for all N treatments with increasing distance from the application site.
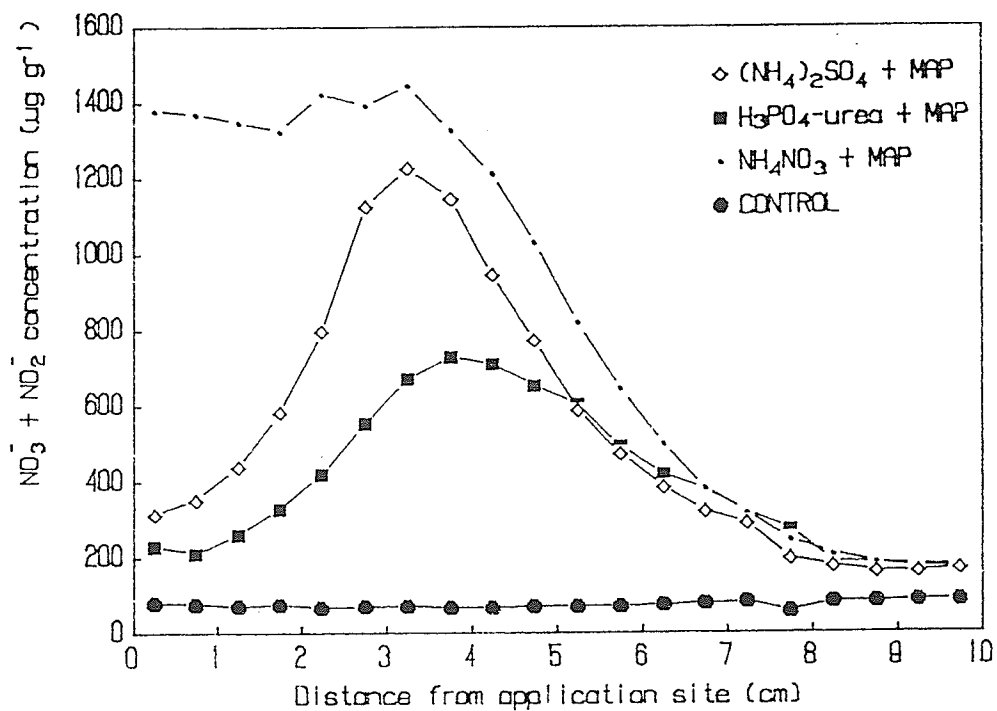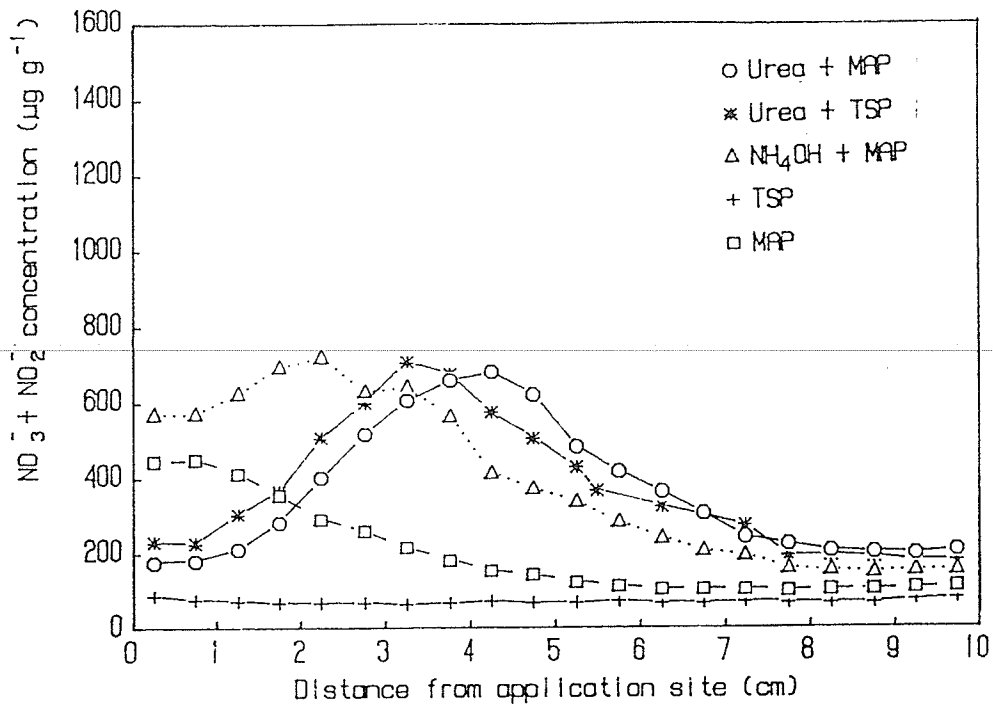
Figure 13. Effect of various N fertilizers on $NO_3^-+NO_2^-$-N concentration in dual N-P bands after 4 wk of incubation - Almasippi soil.

The concentrations of NO_3^- + NO_2^--N for the Almasippi soil were greater than for the other two soils, with all treatments. This was probably due to the generally higher pH of the Almasippi soil resulting in a soil environment conducive to nitrification.

Nitrification was shown to occur with all N treatments for all soils. The extent to which nitrification occurred varied both with N treatment and soil type. Nitrification was greatest for the Almasippi soil probably due to the high pH of this soil. Similarly, nitrification was higher for the neutral Stockton soil than for the acidic Stockton soil.

A high concentration of NH_4^+ in the fertilizer P band is needed to manifest an NH_4^+ ion effect on P uptake by plants (Soper and Rennie 1958). Since nitrification rates were greater in the alkaline than in the neutral or acidic soils, it would be expected that the effect of the N fertilizer on P fertilizer uptake would be less persistent in the alkaline soil. However, it should be noted that large amounts of NH_4^+ + NH_3-N were present for all soils, even after 4 wk of incubation. Thus, if large amounts of N are applied, such as was the case in these studies, sufficient NH_4^+ + NH_3-N would be present to manifest a relatively long term ammonium ion effect despite relatively high nitrification rates.

1.5. Phosphorus

i. Movement of P

Phosphorus concentration usually decreased with distance from the fertilizer band. It was difficult to determine the exact distance to which fertilizer P moved since P concentrations at the periphery of the

reaction zone were only slightly higher than that of the untreated soil. The following criterion was adopted to determine whether or not a particular soil section contained fertilizer P. Fertilizer P was considered to be present in a section if the soil P concentration was at least one standard deviation greater than the average section P concentration in the untreated soil (Appendix A.).

Movement of fertilizer P from dual N-P bands was affected by both soil type and type of N fertilizer applied (Table 7.). Distance of P movement from MAP in the acidic Stockton soil was increased by additions of urea or H_3PO_4-urea, while movement from TSP was increased by the addition of urea. The addition of $(NH_4)_2SO_4$ to MAP had no effect on fertilizer P movement whereas additions of NH_4OH or NH_4NO_3 reduced fertilizer P movement when compared to that of MAP alone.

Distance of fertilizer P movement from MAP in the neutral Stockton soil was increased by the addition of $(NH_4)_2SO_4$ or NH_4OH, with the greatest increase resulting from the addition of $(NH_4)_2SO_4$. Additions of NH_4NO_3 had no influence on fertilizer P movement, while urea or H_3PO_4-urea reduced fertilizer P movement from MAP. Movement of fertilizer P from TSP was decreased by the addition of urea.

For the Almasippi soil, fertilizer P movement from MAP was increased by additions of urea or H_3PO_4-urea, but was not affected by $(NH_4)_2SO_4$, NH_4NO_3 or NH_4OH additions. Movement of fertilizer P from the TSP band was similar to that from MAP and was increased by the addition of urea.

Movement was generally greater for the non-calcareous Stockton soils than for the calcareous Almasippi soil. These results support the findings of Lewis and Racz (1969), who found fertilizer P movement in

Table 7. Fertilizer P movement for the Almasippi, and neutral and
         acidic Stockton soils.

| Treatments | Fertilizer P movement from the application site (cm) | | |
| | Soils | | |
	Almasippi (alkaline)	Stockton (neutral)	Stockton (acidic)
1. Urea + MAP	2.25 a*	1.75 e	4.25 a
2. $(NH_4)_2SO_4$ + MAP	0.75 b	4.75 a	3.25 c
3. NH_4NO_3 + MAP	0.75 b	2.25 cd	2.75 d
4. NH_4OH + MAP	0.75 b	3.75 b	2.75 d
5. H_3PO_4-urea + MAP	2.25 a	1.75 e	3.75 b
6. MAP alone	0.75 b	2.75 c	3.25 c
7. Urea + TSP	2.25 a	1.75 e	4.00 ab
8. TSP alone	0.75 b	2.25 d	2.75 d

* Duncan's Multiple Range Test. Means, within columns, with the same
letter are not significantly different at the 0.05% probability level.

calcareous soils to be less than that in non-calcareous soils. The authors attributed reduced movement to the high soil pH and high Ca^{2+} and Mg^{2+} concentrations in the soil solution of calcareous soils. Large amounts of Ca^{2+} and Mg^{2+} from $CaCO_3$ and dolomite would be expected to result in the precipitation of fertilizer P near the application site thus restricting fertilizer P movement.

The effect of the N fertilizers on P movement was similar for the acidic Stockton and Almasippi soils, with additions of urea or H_3PO_4-urea increasing P movement from MAP and additions of urea increasing P movement from TSP. For the neutral Stockton soil fertilizer P movement from MAP was increased by the addition of $(NH_4)_2SO_4$ or NH_4OH. An increase in the size of the reaction zone as noted for the above treatments would be expected to increase uptake of P by plants which do not strongly proliferate roots into the reaction zone or have roots of a relatively low absorption capacity (Strong and Soper 1974ab).

ii. Solubility of P

Solubility of P as affected by various N fertilizers was expressed for each soil and treatment as total mg of P extracted by water from the entire soil column (Table 8.).

Phosphorus solubility in the acidic Stockton soil was increased above that of MAP alone when urea, NH_4OH or H_3PO_4-urea were added to MAP. Solubility of P from MAP was not affected by the addition of $(NH_4)_2SO_4$ and was decreased by the addition of NH_4NO_3. Phosphorus solubility from TSP was increased by the addition of urea. It would appear that the addition of strongly alkaline N fertilizers such as NH_4OH or urea increased the solubility of P in the acidic Stockton

Table 8. Total water soluble P content of each treatment for the
Almasippi, and neutral and acidic Stockton soils.

| Treatments | Total water soluble P / column (mg) | | |
	Almasippi (alkaline)	Soils Stockton (neutral)	Stockton (acidic)
1. Urea + MAP	8.5a*	29.6a	31.8a
2. $(NH_4)_2SO_4$ + MAP	3.6d	25.7b	20.1de
3. NH_4NO_3 + MAP	3.7d	17.2e	18.0d
4. NH_4OH + MAP	8.5a	21.0cd	30.7a
5. H_3PO_4-urea + MAP	6.7b	23.4bc	28.9b
6. MAP alone	5.7c	19.3dc	20.6d
7. Urea + TSP	5.6c	20.7dc	25.7c
8. TSP alone	8.1a	16.3e	18.6fe
9. none	1.1e	2.2f	2.2g

* Duncan's Multiple Range Test. Means, within columns, with the same
letter are not significantly different at the 0.05% probability level.

soil. This observation was supported by results obtained by Hanson and Westfall (1985), who found additions of strongly alkaline N fertilizers with APP to result in the formation of relatively available Ca-phosphate reaction products, when applied to acidic soils. In contrast, less available iron and aluminum-phosphate reaction products (strengite and variscite) were formed when APP (acidic P fertilizer) was added alone. Thus, the precipitation of Ca-phosphates rather than iron and aluminum-phosphate may partially explain the increase in P solubility observed for the acidic Stockton soil.

The solubility of P from MAP for the neutral Stockton soil was increased by the addition of urea, $(NH_4)_2SO_4$ or H_3PO_4-urea. Phosphorus solubility from MAP was not influenced by NH_4NO_3 or NH_4OH additions. Solubility of P from TSP was increased by the addition of urea. Statistically significant increases in P solubility with urea or $(NH_4)_2SO_4$ additions were probably due to the so called "snow plow" effect described by Cho (1985) and described on page 11 of this manuscript. The "snow plow" effect results in the displacement of Ca^{2+} and Mg^{2+} ions from the soil exchange by the advancing front of NH_4^+ resulting from the addition of NH_4^+ N fertilizers. Displaced Ca^{2+} and Mg^{2+} ions are pushed ahead of the advancing front of NH_4^+ resulting in a depletion of Ca2+ and Mg2+ at the site of application and an accumulation in Ca^{2+} and Mg^{2+} at the advancing front of NH4+. A reduction in Ca^{2+} and Mg^{2+} concentration at the fertilizer P reaction zone would be expected to reduce the precipitation of Ca and Mg-phosphates. The "snow plow" effect was also observed for the NH_4NO_3 application. However, increases in P availability were not observed. This was probably due to increases in Ca^{2+} and Mg^{2+} concentrations near

the fertilizer band resulting from the low pH created by the addition of NH_4NO_3 with MAP.

Increased P solubility resulting from the addition of $(NH_4)_2SO_4$ may be due to increased reaction product solubility. In studies by Bouldin and Sample (1958) additions of $(NH_4)_2SO_4$ to CSP decreased the amount of P precipitated at the placement site and increased fertilizer P content in the reaction zone. However, it is unknown to the author why this effect only appeared for the neutral soil.

The solubility of P for the Almasippi soil was much less than that of the other two soils. The lower solubility of fertilizer P was attributed to the high pH and high Ca^{2+} and Mg^{2+} concentrations in the soil solution of the Almasippi soil. Large amounts of Ca^{2+} and Mg^{2+} from $CaCO_3$ and dolomite would reduce P solubility firstly by precipitation and secondly by reducing solubility through common ion effects.

Solubility of P from MAP was increased with the addition of urea, NH_4OH or H_3PO_4-urea, while additions of $(NH_4)_2SO_4$ or NH_4NO_3 decreased P solubility. Phosphorus solubility from TSP was increased by the addition of urea. Increased P solubility may have been a result of the "snow plow" effect. Decreases in P solubility resulting from the addition of NH_4NO_3 or $(NH_4)_2SO_4$ to MAP were probably related to the dissolution of $CaCO_3$ and dolomite as a result of the low application site pH created upon application of these N carriers. High Ca^{2+} and Mg^{2+} concentrations would be expected to reduce the solubility of fertilizer P due to precipitation of Ca and Mg-phosphates and through common ion effects.

In general, P solubility from MAP or TSP was increased when alkaline N carriers were added. The increase in solubility was attributed to the "snow plow" effect for the neutral and alkaline soils and to changes in the nature of the reaction products as a result of pH changes for the acidic soil. For the acidic soil, alteration of reaction products due to large pH changes may have occurred. Westfall and Hanson (1985) indicated that Ca-phosphates form at a high pH, while aluminum or iron-phosphates form at a lower pH. In our study, the addition of alkaline N carriers increased the reaction zone pH probably leading to the formation of Ca-phosphate reaction products rather than iron or aluminum phosphates. Due to the higher solubility of Ca-phosphates compared to iron or aluminum phosphates, increased P solubility would be expected. For the soils with a higher pH the effect would not be expected since the soil pH would generally be too high for iron or aluminum phosphate formation.

For the neutral and alkaline soils, increased P solubility resulted from the addition of alkaline N fertilizers (increased P solubility due to the addition of H_3PO_4-urea and NH_4OH were statistically nonsignificant on the neutral soil). These increases in P solubility were probably due to reduced Ca^{2+} concentrations near the fertilizer band resulting from the "snow plow" effect. However, large reductions in Ca^{2+} concentration near the application site were not generally observed. This was probably due to the presence of $CaCO_3$ in the soil or the extraction procedure may have resulted in Ca^{2+} concentrations larger than that actually found in the soil solution. This would be expected since a large soil to extractant ratio was used in the extraction procedure. A large soil to extractant ratio would

allow Ca^{2+} from Ca precipitates to come into solution. The vigorous shaking used in the extraction procedure would also expose new soil surfaces to the extracting solution allowing more Ca^{2+} into solution.

Phosphorus solubility from MAP was decreased by the addition of acidic N carriers (NH_4NO_3 or $(NH_4)_2SO_4$) on the alkaline soil. This was probably due to the acidic nature of these N carriers increasing the solubility of $CaCO_3$ and dolomite near the application site. Increased concentrations of Ca^{2+} and Mg^{2+} in the soil solution would enhance the formation of Ca and Mg-phosphates, increase common ion effects and thus decrease P solubility. The addition of acidic N carriers to the neutral and acidic soil generally resulted in P solubilities similar to those of MAP alone, except when $(NH_4)_2SO_4$ was added to MAP on the neutral soil.

Increases in P solubility have been shown to increase the P absorption rate per unit root area (Carter and Lathwell 1967). Thus, it is likely that increased solubility of P as noted for the above N treatments would result in increased absorption of P by a plant.

iii. Phosphorus distribution

The P concentration for the controls remained relatively constant throughout the soil column at concentrations of about 9 μg g^{-1} for the Stockton soils and at about 5 μg g^{-1} for the Almasippi soil.

Phosphorus concentration for the acidic Stockton soil (Figure 14.) generally decreased with increasing distance from the application site with all fertilizer treatments except with H_3PO_4-urea + MAP. With the H_3PO_4-urea + MAP treatment P concentration increased for a short distance then decreased. Although the general shape of the P
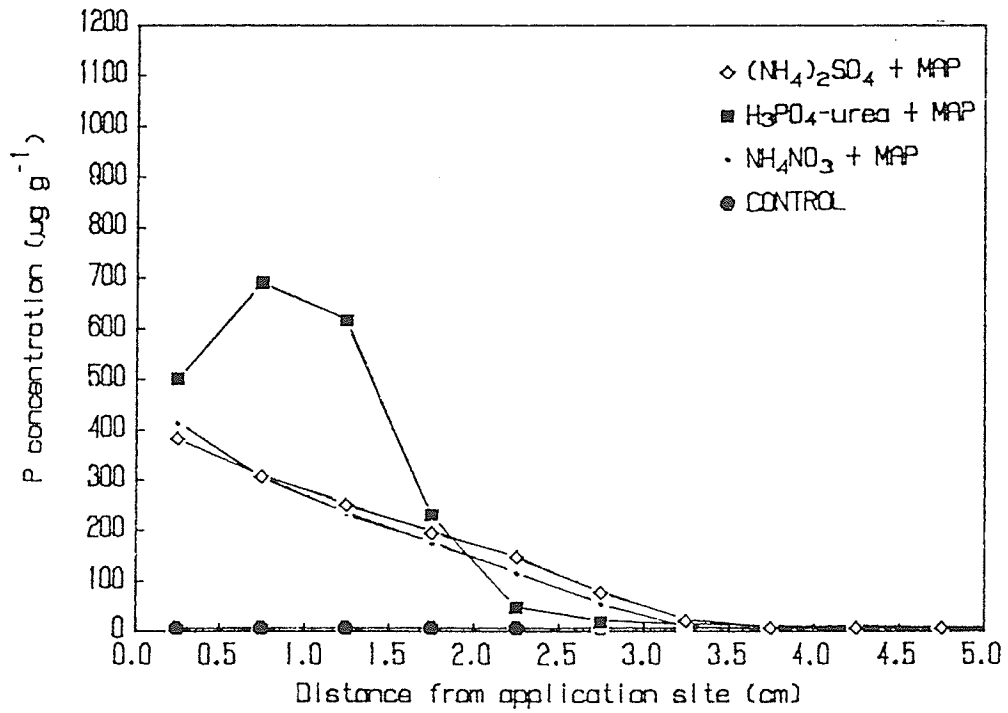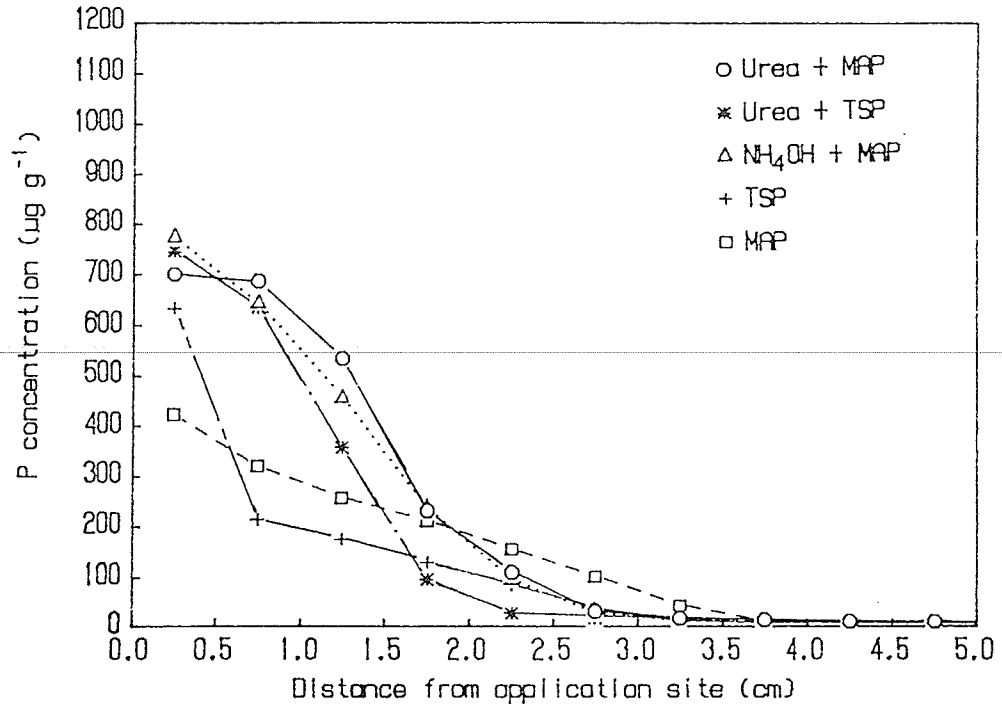
Figure 14. Effect of various N fertilizers on P concentration in dual N-P bands after 4 wk of incubation - acidic Stockton soil.

distribution curves were as described above, differences in the rate at which P concentration decreased with increasing distance from the fertilizer band and differences in the magnitude of P concentration were observed among treatments.

The P concentration near the application site with the H_3PO_4-urea + MAP, urea + MAP, NH_4OH + MAP and urea + TSP treatments was greater than that with either MAP or TSP. Phosphorus concentration generally decreased less rapidly with distance for the MAP and TSP treatments than for the NH_4OH + MAP, H_3PO_4-urea + MAP, urea + MAP and urea + TSP treatments. The rapid decline in P concentration for the dual bands resulted in P concentrations below that of MAP and TSP at about 2.25 and 1.75 cm from the application site, respectively. This indicates that increased P solubility was the result of a greater P concentration near the application site. Increased fertilizer movement as discussed in section 4a. for the H_3PO_4-urea + MAP, urea + MAP and urea + TSP treatments indicates an increase in P solubility at greater distances from the application site. However, these increases were small in comparison to increases in solubility of P immediately adjacent to the fertilizer band. The addition of $(NH_4)_2SO_4$ and NH_4NO_3 to MAP did not result in any apparent changes in P distribution.

The shape of the P distribution curves for the neutral Stockton soil (Figure 15.) were as described for the acidic Stockton soil. The P concentration adjacent to the fertilizer band was similar with the NH_4OH + MAP, H_3PO_4-urea + MAP, NH_4NO_3 + MAP and MAP treatments, while P concentration resulting from the urea + MAP and urea + TSP treatments were greater than that with MAP or TSP alone. Phosphorus concentration decreased with distance from the fertilizer band for all treatments
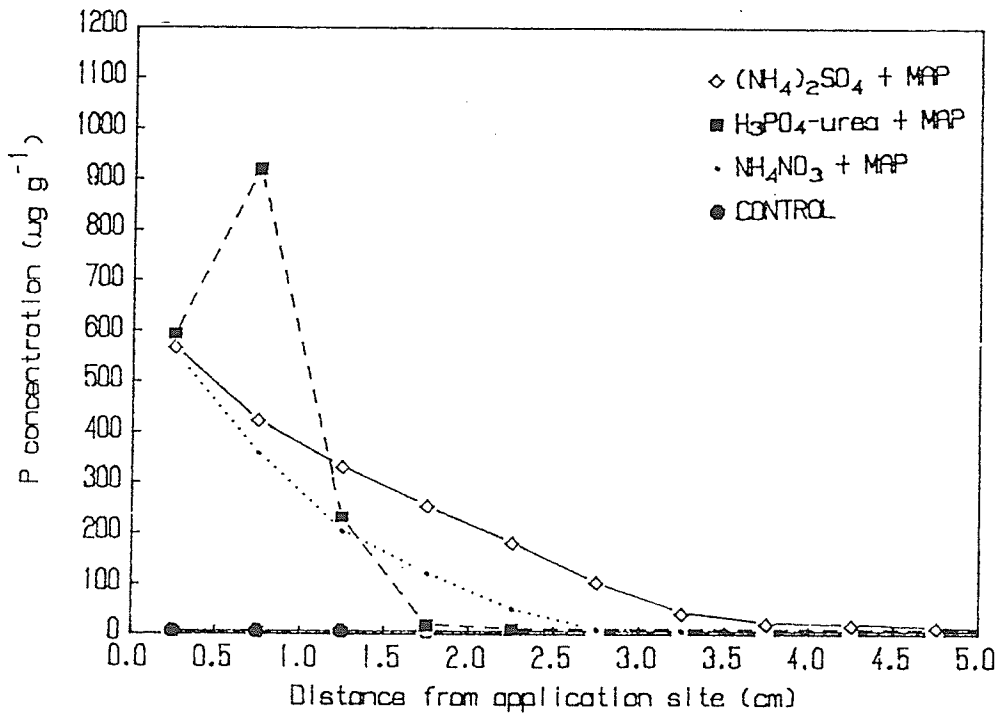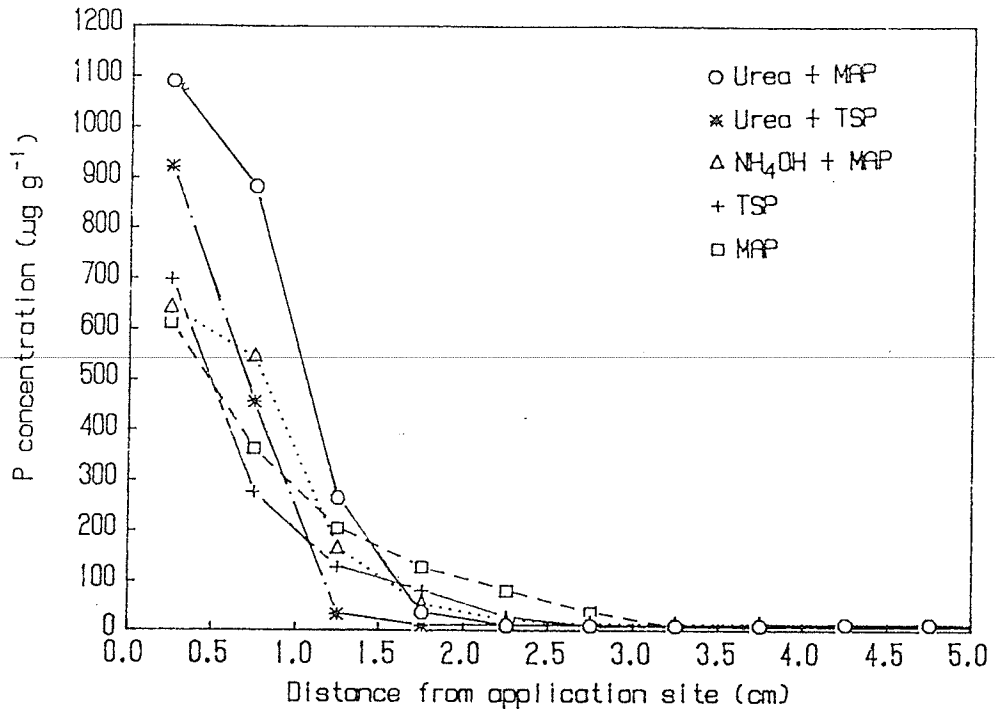
Figure 15. Effect of various N fertilizers on P concentration in dual N-P bands after 4 wk of incubation - neutral Stockton soil.

except the H_3PO_4-urea + MAP treatment. However, the rate of decline in P concentration with increasing distance from the application site was less with the $(NH_4)_2SO_4$ + MAP treatment than with any other treatment. As a result, the P concentration was above that of MAP alone at distance of 0.75 cm to about 4.0 cm from the dual N-P band. All other treatments followed a similar trend to that discussed for the acidic Stockton soil. It would appear that increased P solubility due to the $(NH_4)_2SO_4$ + MAP treatment was the result of increased P solubility in the reaction zone away from the application site. Increased solubility of P resulting from the addition of urea to both MAP and TSP appears to be due to increased solubility of P near the application site.

The P concentration distribution for the Almasippi soil (Figure 16.) was similar to that of the Stockton soils. However, P concentrations near the application site were slightly less and the rate of decrease in P concentration with increasing distance from the fertilizer band was greater than that observed for the other two soils. This was attributed to the high soil pH and carbonate content of the Almasippi soil. High soil pH and high carbonate content have been shown to reduce P solubility in P fertilizer bands (Lewis and Racz 1969).

The P concentration adjacent to the fertilizer band was greater with the urea + MAP and NH_4OH + MAP treatments than with MAP alone. The concentration of P with urea + TSP was less than that with TSP alone. Phosphorus concentration decreased rapidly with increasing distance from the fertilizer band with all treatments. For the NH_4OH + MAP treatment, P concentration decreased to that of the MAP alone at about 0.75 cm for the fertilizer band. For the urea + MAP and urea + TSP treatments, P concentration did not decrease to that of the control
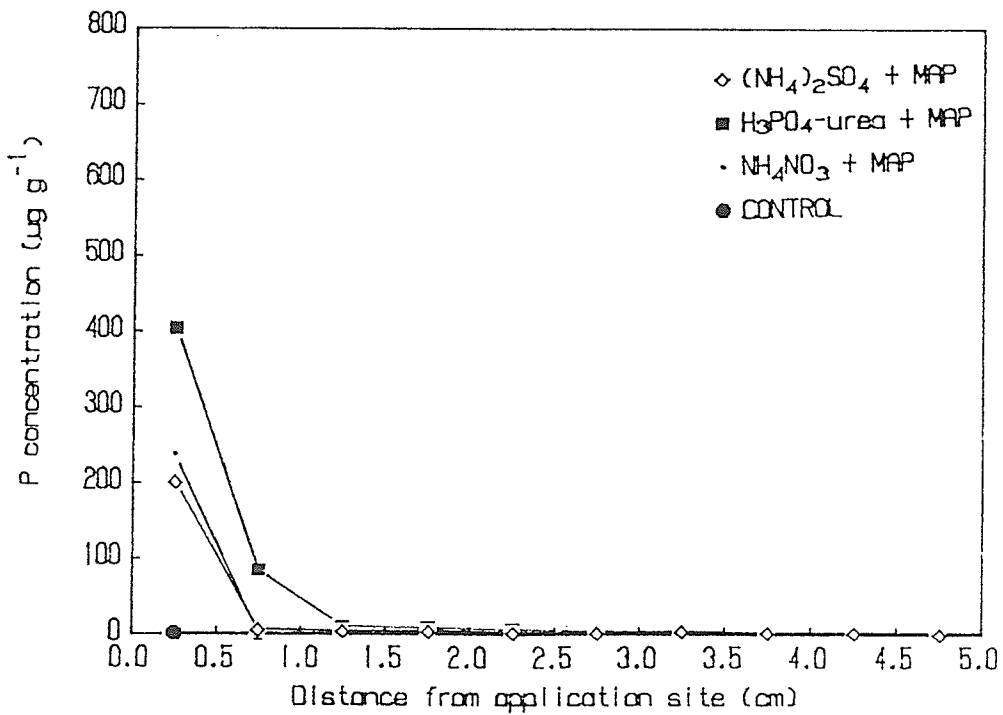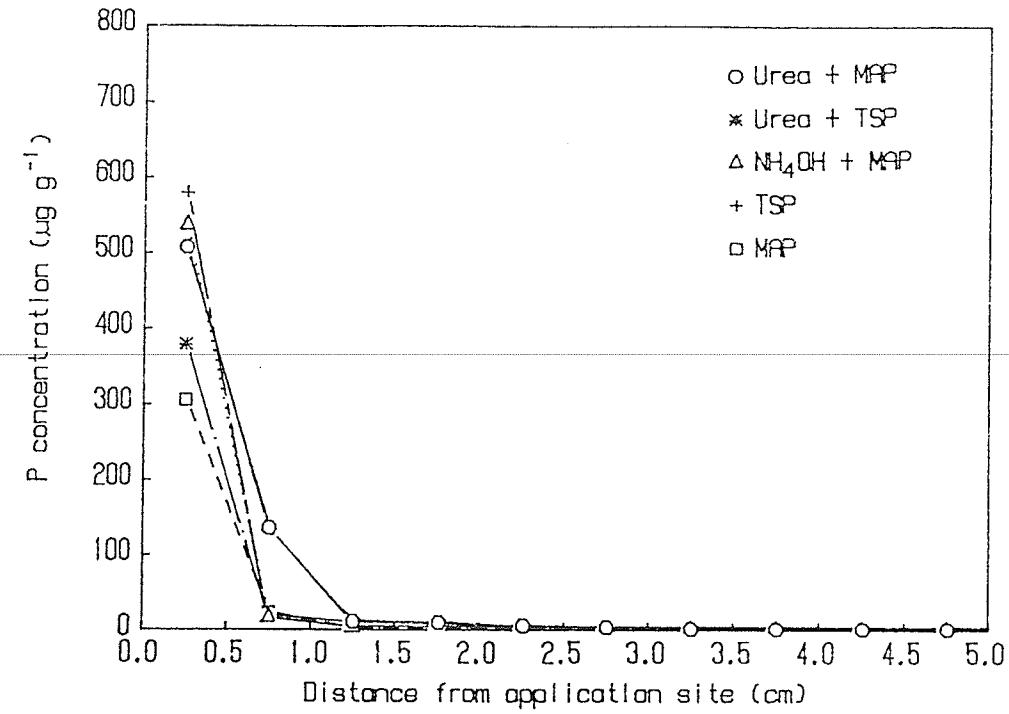
Figure 16. Effect of various N fertilizers on P concentration in dual
N-P bands after 4 wk of incubation - Almasippi soil.

until about 2.25 cm from the application site. The P distribution for H_3PO_4-urea + MAP was similar to that of the urea + MAP treatment. Addition of $(NH_4)_2SO_4$ or NH_4NO_3 to MAP decreased the P concentration at the application site, while the P concentration at about 0.75 cm from the fertilizer band was similar to that of MAP. As a result of the reductions in P concentration near the application site, additions of $(NH_4)_2SO_4$ or NH_4NO_3 to MAP reduced P solubility in the entire reaction zone below that of MAP alone. Increases in P solubility with urea + TSP and urea + MAP were the result of increased solubility of P throughout the reaction zone. Increased P solubility with the addition of NH_4OH to MAP was the result of increased solubility at the application site.

1.6. Summary and implications

Phosphorus movement was generally greater for the Stockton soils than for the Almasippi soil regardless of treatment. Phosphorus movement was not consistently increased by any particular treatment.

Phosphorus solubility from MAP was generally increased by the addition of alkaline N carriers such as urea, H_3PO_4-urea or NH_4OH. Increases in P solubility were probably due to either the "snow plow" effect in the alkaline soils or a change in the nature of reaction products in the acidic soil. Increased P solubility has been found to increase uptake of P per unit root area (Carter and Lathwell 1967). Increases in P solubility away from the application site were generally small compared to those increases in solubility near the application site.

High pH and high concentrations of NH_4^+ + NH_3-N were found near the application site for all soils treated with urea, NH_4OH and H_3PO_4-

urea. High NH_4^+ + NH_3-N concentrations when coupled with high pH have been shown to result in high concentrations of NH_3 which are toxic to plant growth (Colliver and Welch 1970). Reduction in root growth near the application site resulting either directly or indirectly from NH_3 toxicity would be expected. Reduction in root growth in the fertilizer band would decrease fertilizer P uptake. These conditions would be expected to occur when urea, NH_4OH or H_3PO_4-urea are applied with MAP or TSP.

High NH_4^+ + NH_3-N concentrations indicate that NH_4^+ concentrations were sufficient to manifest a long-term NH_4^+ ion effect despite NH_4^+ losses due to volatilization and nitrification during the 4wk incubation period.

2. Plant growth study: Plant uptake of P from dual N-P bands as effected by various N fertilizers

2.1. Experiment one

i. Days to ^{32}P uptake

The interval of time between seeding and initiation of fertilizer P uptake varied with treatment and crop species (Table 9.). Fertilizer P uptake from dual bands commenced at a later date for canola and flax than for wheat. The period of time prior to fertilizer P uptake from P placed close to the seed row was relatively similar for all crop species (6 to 8 d after seeding). However, when the P band was placed separately from the N fertilizer and far from the seed row, days to initiation of fertilizer P uptake was greater for both canola and flax than for wheat. Differences in the rate of root growth to the fertilizer band may be due to differences in root morphology among the species of the plants used. Canola and flax have a tap root system whereas wheat has a fibrous root system.

Days to initiation of fertilizer P uptake by canola and flax increased in the order: urea + MAP separate (MAP 2.5 cm below and beside the seed and urea 7.5 cm below and beside the seed) < $(NH_4)_2SO_4$ + MAP = NH_4NO_3 + MAP = urea + MAP separate (7.5 cm below and beside the seed) < urea + MAP. Fertilizer P uptake by wheat from the urea + MAP dual band commenced at a later date than from all other treatments.

In all crops, days to initiation of fertilizer P uptake from urea + MAP dual bands placed 7.5 cm below and beside the seed were greater than those resulting from urea and MAP placed separately 7.5 cm below and beside the seed. This indicates that the distance between the P

Table 9. Days before uptake of ^{32}P, as measured from the date of
seeding for canola, wheat and flax grown on a Willowcrest
soil.

Treatments		Days before P^{32} uptake		
Fertilizer	Band placement	Canola	Wheat	Flax
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	15.0 b*	9.0 bc	15.3 b
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	5.5 c	8.0 c	8.0 c
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	15.0 b	10.7 b	15.3 b
4. Urea and MAP dual banded	7.5 cm below and beside the seed	22.0 a	14.7 a	22.7 a
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	13.0 b	9.7 bc	15.7 b

* Duncan's Multiple Range Test. Means, within columns, with the same
letter are not significantly different at the 0.05% probability level.

band and the seed row was not completely responsible for the delay in fertilizer P uptake. The additional delay in fertilizer P uptake was probably due to a lack of root growth into the fertilizer band, resulting from high concentrations of NH_3 and/or NO_2^- in the MAP reaction zone. In the chemical studies, high soil pH values and, high concentrations of NH_4^+ + NH_3-N were observed near the urea + MAP dual band. Nitrite-N may also have been present in the reaction zone. In the presence of high concentrations of NH_3, the oxidation of NO_2^- to NO_3^- by Nitrobacter can be retarded resulting in the accumulation of NO_2^- (Aleem and Alexander 1960). High concentrations of NH_3 or NO_2^- have been shown to be toxic to plant growth (Court et al. 1964; Coliver and Welch 1970ab; Goyal and Mulfaker 1984) and would restrict root growth into the fertilizer band.

ii. Final harvest

The stage at which all crops were harvested was relatively uniform among treatments. Canola and flax were harvested at the flowering stage, while wheat was harvested at the heading stage.

Dry matter yield of wheat and flax was not significantly affected by treatment (Table 10.). The lack of yield response to the addition of fertilizer P was unexpected since soil P concentrations, as determined by sodium bicarbonate extraction, did not appear to be adequate to sustain optimal plant growth. Yield of canola was higher with fertilizer P placed near the seed and with the NH_4NO_3 dual N-P band than without added P.

Fertilizer P uptake varied with crop species and was generally greatest for canola and least for flax (Table 11.). Strong and Soper

Table 10. Total dry weight as affected by fertilizer treatment for canola, wheat and flax grown on a Willowcrest soil.

Treatments		Dry weight (grams)		
Fertilizer	Band Placement	Canola	Wheat	Flax
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	46.2 ab*	46.2 a	21.3 a
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	48.7 a	46.3 a	20.0 a
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	48.7 a	41.2 a	19.7 a
4. Urea and MAP dual banded	7.5 cm below and beside the seed	46.8 ab	46.3 a	20.2 a
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	47.2 ab	44.2 a	19.6 a
6. Urea alone	7.5 cm below and beside the seed	40.1 b	40.5 a	19.7 a

* Duncan's Multiple Range Test. Means, within columns, with the same letter are not significantly different at the 0.05% probability level.

Table 11.   Percent fertilizer P utilized by canola, wheat and
            flax grown on a Willowcrest soil.

Treatments		Percent fertilizer P utilized		
Fertilizer	Band Placement	Canola	Wheat	Flax
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	36 c*	27 d	17 c
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	38 c	31 dc	24 ab
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	44 b	37 b	23 b
4. Urea and MAP dual banded	7.5 cm below and beside the seed	30 d	34 bc	22 b
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	50 a	47 a	27 a

* Duncan's Multiple Range Test. Means, within columns, with the same
letter are not significantly different at the 0.05% probability level.

(1974a, 1974b) indicated that root absorption rates and root proliferation into the fertilizer band may influence utilization of fertilizer P. Differences in fertilizer P uptake noted among crop species were probably due to differences in root proliferation into the fertilizer band and rate of P absorption by the various species.

Fertilizer P uptake by canola and wheat from urea and MAP placed separately was similar regardless of distance between the seed row and the MAP fertilizer band. In contrast, fertilizer P uptake by flax from fertilizer P placed near the seed was significantly greater than that from urea and MAP placed separately 7.5 cm below and beside the seed. The differences in response to placement among crop species, was probably the result of the physiological differences in root growth into the fertilizer band and rate of P absorption. Strong and Soper (1970ab) indicated that flax had less root proliferation into a fertilizer reaction zone and absorbed P at a lower rate than either canola or wheat.

Fertilizer P uptake by all crops was greater with the $(NH_4)_2SO_4$ and NH_4NO_3 dual N-P bands than with urea and MAP placed separately 7.5 cm below and beside the seed. Also, it is interesting to note that the NH_4NO_3 and $(NH_4)_2SO_4$ dual N-P bands were more effective in supplying P to canola and wheat plants than MAP placed near the seed. However, with flax, P uptake for the dual N-P bands was similar to that from MAP placed near the seed-row.

The Willowcrest soil used in the above growth experiment was similar to the neutral Stockton soil used in the chemical study. In the chemical studies, the $(NH_4)_2SO_4$ + MAP treatment significantly increased P solubility compared to MAP alone, while the NH_4NO_3 + MAP treatment

did not affect P solubility. Since the NH_4NO_3 + MAP dual band did not increase P solubility but did increase fertilizer P uptake in the growth study, we can conclude that increased solubility of fertilizer P was not responsible for increased fertilizer P uptake from the NH_4NO_3 + MAP dual band. The increase in P uptake with the NH_4NO_3 + MAP dual band was thus due to the effect of the NH_4^+ on plant or biological factors which enhance P uptake. However, fertilizer P uptake from the $(NH_4)_2SO_4$ + MAP dual band was significantly greater than from the NH_4NO_3 + MAP dual band. The increase in fertilizer P uptake with $(NH_4)_2SO_4$ may have been due to the increase in P solubility in the $(NH_4)_2SO_4$ + MAP dual band as well as the effect of NH_4^+ on biological factors which enhance P uptake.

Fertilizer P uptake by canola from urea + MAP dual bands was less than that from all other treatments. This was probably a result of the large delay in fertilizer P uptake from the urea + MAP dual band during the seedling stage. Fertilizer P uptake by wheat and flax from the urea N-P dual band was similar to that from the NH_4NO_3 dual N-P band but less than that from the $(NH_4)_2SO_4$ dual N-P band. Decreased uptake at heading or flowering from the urea N-P dual band was probably a result of NH_3 toxicities which reduced fertilizer P uptake during the seedling stage.

Fertilizer P uptake by wheat and flax was similar from the urea + MAP dual band and the urea and MAP placed separately (placement 7.5 cm below and beside the seed) despite initial delays in fertilizer P uptake from the urea dual N-P band. This indicates that the rate of fertilizer P uptake, after the initial delay in uptake, was much greater from the urea N-P dual band than from urea and MAP banded

separately 7.5 cm below and beside the seed. However, for canola, fertilizer P uptake from the urea + MAP dual band was less than that from urea and MAP banded separately 7.5 cm below and beside the seed. This suggests that the rate of fertilizer P uptake, after the initial delay in uptake from the urea + MAP dual band, was probably lower or similar to that from urea and MAP placed separately 7.5 cm below and beside the seed. The above findings indicate that NH_3 toxicity (resulting in a delay in fertilizer P uptake) had a different effect on the rate of fertilizer P uptake by canola than it did for flax and wheat. Further study into the physiological reasons for the differential rates of fertilizer P uptake are needed to explain these observations.

2.2. Experiment two

i. Days to ^{32}P uptake

Days to initiation of fertilizer P uptake, as measured from the time of seeding, for NH_4NO_3 + MAP, urea + MAP and urea + H_3PO_4 dual bands were greater than that of urea and MAP placed separately 7.5 cm below and beside the seed (Table 12.). The delay in initiation of fertilizer P uptake was probably due to NH_3 toxicities preventing root growth into the fertilizer band or due to high solute concentrations creating an osmotic effect on plant roots. As in experiment one, direct evidence for high concentrations of NH_3 was not obtained in the plant studies. However, in a soil similar to that used in this experiment (Almasippi soil) it was observed that high concentrations of NH_4^+ + NH_3-N and a high soil pH resulted near the urea + MAP dual band. These

Table 12. Days before uptake of ^{32}P, as measured from the date of
seeding for canola grown on an Almasippi soil.

Treatments

Fertilizer	Band Placement	Days before uptake of ^{32}P
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	17.3 d*
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	8.0 e
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	21.7 cb
4. Urea and MAP dual banded	7.5 cm below and beside the seed	26.0 a
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	18.7 cd
6. Urea and H_3PO_4 dual banded	7.5 cm below and beside the seed	24.7 ab
7. SU and MAP dual banded	7.5 cm below and beside the seed	16.3 d
8. Urea and MAP dual banded (Incubated**)	7.5 cm below and beside the seed	19.7 cd

* Duncan's Multiple Range Test. Means with the same letter are not
significantly different at the 0.05% probability level.

**Incubated for a period of 10 d prior to seeding.

conditions have been shown to result in high NH_3 concentrations (Warren 1962).

The delay in fertilizer P uptake with the NH_4NO_3 + MAP dual band was probably not due to NH_3 induced toxicities, since the soil pH was likely low enough to reduce NH_3 concentrations. The delay was more likely attributable to high concentrations of solute near the fertilizer band resulting in an osmotic effect on plant roots. A similar effect was not observed for the $(NH_4)_2SO_4$ + MAP dual band. This was probably due to the precipitation of the SO_4^{2-}, causing a reduction in solute concentration, thus reducing the osmotic effect on plant roots.

Attempts to decrease NH_3 toxicity by acidifying the urea dual band with H_3PO_4, incubation of the urea + MAP dual band, or the use of a slow release form of urea (sulfur coated urea (SU)) were successful for two of the three treatments. The addition of SU to MAP reduced the days to initiation of fertilizer P uptake when compared to that for the urea + MAP dual band. This indicates that NH_3 induced toxicities were decreased by the use of a slow release form of urea. However, it was noted during monitoring for ^{32}P that the activity of ^{32}P in this treatment was less than for other treatments suggesting that the late release of urea may have slowed the rate of fertilizer P uptake by canola. Further studies are needed to confirm this.

Days to initiation of fertilizer P uptake from the urea + MAP dual band which was incubated for 10 d prior to seeding was significantly less than that from the urea + MAP dual band. The decrease was probably due to a reduction in the NH_4^+ concentration due to nitrification.

Acidifying the urea dual band with H_3PO_4 did not significantly decrease days to fertilizer P uptake when compared to that of urea + MAP dual bands. This was probably due to the high buffering capacity of the soil and to the dominance of urea in the reaction zone.

ii. Final harvest

Differences in growth stage were observed among fertilizer treatments (Table 13.). Plants treated with urea + MAP and urea alone were at growth stage 3.3, whereas plants treated with all other treatments were at a growth stage of between 4.1 and 4.3, at the time of harvest. The slower rate of development with the urea + MAP dual band was probably due to P deficiencies during the seedling stage as a result of delays in fertilizer P uptake. The difference in growth stage between plants treated with the urea + MAP dual band (growth stage 3.3) and plants treated with MAP near the seed (growth stage 4.3) was equivalent to 10 growing days (Morrison 1987). The effect of this delay on final yield or days to maturity was not determined. However, the large apparent differences in growth stage 55 d after seedings, warrant further study into the effect of the above treatments on final yield and days to maturity.

Yield of canola was greatly increased by P fertilization (Table 14.). Dry weight yield from all dual bands was lower, although not always statistically lower, than with the N and P placed separately. The urea + MAP dual band incubated for 10 d, the SU + MAP dual band and the NH_4NO_3 + MAP dual band resulted in yields statistically similar to that of urea and MAP placed separately 7.5 cm below and beside the seed. Urea + MAP, urea + H_3PO_4 and $(NH_4)_2SO_4$ + MAP dual bands resulted

Table 13. Representative growth-stages at harvest for canola grown on
an Almasippi soil (Harper and Berkenkamp scale, 1975).

Treatments

Fertilizer	Band Placement	Growth-stage
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	4.2: Many flowers open, lower pods elongating
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	4.3: Lower pods starting to fill
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	4.2: Many flowers opened, lower pods elongating
4. Urea and MAP dual banded	7.5 cm below and beside the seed	3.3: Inflorescence raised above level of rossett
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	4.1: First flower open
6. Urea and H_3PO_4 dual banded	7.5 cm below and beside the seed	4.1: First flower open
7. SU and MAP dual banded	7.5 cm below and beside the seed	4.2: Many flowers opened, lower pods elongating
8. Urea and MAP dual banded (Incubated**)	7.5 cm below and beside the seed	4.1: First flower open
9. Urea alone	7.5 cm below and beside the seed	3.3: Inflorescence raised above level of rossett

**Incubated for a period of 10 d prior to seeding.

Table 14. Total dry weight as affected by fertilizer treatment for
canola grown on an Almasippi soil.

Treatments		
Fertilizer	Band Placement	Dry weight (grams)
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	40.1 ab*
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	46.8 a
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	31.9 bc
4. Urea and MAP dual banded	7.5 cm below and beside the seed	26.8 c
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	27.8 c
6. Urea and H_3PO_4 dual banded	7.5 cm below and beside the seed	26.4 c
7. SU and MAP dual banded	7.5 cm below and beside the seed	33.6 bc
8. Urea and MAP dual banded (Incubated**)	7.5 cm below and beside the seed	37.5 ab
9. Urea alone	7.5 cm below and beside the seed	11.2 d

* Duncan's Multiple Range Test. Means with the same letter are not
significantly different at the 0.05% probability level.

** Incubated for a period of 10 d prior to seeding.

in yields statistically lower than for treatments in which the N and P were placed separately. The lower yield for all but the $(NH_4)_2SO_4$ + MAP dual band was attributed to the large delay in uptake of fertilizer P during the seedling stage. The results generally indicate a need for "starter P" in combination with dual N-P bands on extremely P deficient soils for canola.

Fertilizer P uptake was similar for all treatments and varied from 44 to 51% (Table 15.). However, all treatments were not harvested at the same growth stage. If the plants with a slow growth rate would have been allowed to grow to the stage of growth achieved by plants with a faster growth rate, uptake of fertilizer P may have varied among treatments ie. the fertilizer P uptake from the urea + MAP dual band may have exceeded that of other treatments. Although not statistically significant, it should be noted that P uptake from MAP placed near the seed was less than from most dual bands except for treatments with SU and H_3PO_4.

2.3. Summary and implications

In the previous study (chemical study) the solubility of P in MAP bands was usually increased by the addition of urea or NH_4OH, while the addition of NH_4NO_3 or $(NH_4)_2SO_4$ to MAP generally did not increase P solubility. Plant uptake of fertilizer P did not reflect the changes in P solubility observed in the chemical studies. Fertilizer P uptake by canola, wheat and flax (at the heading or flowering stages) was usually greatest with the MAP + $(NH_4)_2SO_4$ dual band. The generally lower uptake of fertilizer P with urea, than with $(NH_4)_2SO_4$ or NH_4NO_3, was attributed to reduced uptake of fertilizer P from the urea + MAP dual

Table 15. Percent fertilizer P utilized by canola grown on an
Almasippi soil.

	Treatments	
Fertilizer	Band Placement	
1. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-7.5 cm below and beside the seed	50 a*
2. Urea and MAP separately banded	N-7.5 cm below and beside the seed P-2.5 cm below and beside the seed	44 a
3. NH_4NO_3 and MAP dual banded	7.5 cm below and beside the seed	51 a
4. Urea and MAP dual banded	7.5 cm below and beside the seed	50 a
5. $(NH_4)_2SO_4$ and MAP dual banded	7.5 cm below and beside the seed	52 a
6. Urea and H_3PO_4 dual banded	7.5 cm below and beside the seed	44 a
7. SU and MAP dual banded	7.5 cm below and beside the seed	45 a
8. Urea and MAP dual banded (Incubated**)	7.5 cm below and beside the seed	50 a

* Duncan's Multiple Range Test. Means with the same letter are not significantly different at the 0.05% probability level.

** Incubated for a period of 10 d prior to seeding.

bands during the seedling stage. The reduction in fertilizer P uptake during the seedling stage was most likely due to high concentrations of NH_3 in the fertilizer band restricting root growth into the fertilizer band.

Days to initiation of fertilizer P uptake from dual N-P bands were greater for canola and flax than for wheat. Also days to initiation of fertilizer P uptake were greater for urea + MAP dual bands than for $(NH_4)_2SO_4$ and NH_4NO_3 dual N-P bands. This was attributed to NH_3 toxicity reducing root growth into the urea + MAP dual bands. These results imply that starter fertilizer, ie. fertilizer P added with or near the seed to provide P for plant growth during the seedling stage, is more of a requirement for crops such as canola and flax than for wheat. Also, starter P fertilizer is more of a requirement with urea + MAP dual bands than with NH_4NO_3 + MAP and $(NH_4)_2SO_4$ + MAP dual bands.

Attempts to detoxify the dual N-P bands by acidifying the fertilizer band (use of H3PO4-urea) or by using a slow release N fertilizer (SU) were generally unsuccessful. In contrast, incubation of the urea dual N-P band for a period of 10 d prior to seeding significantly reduced the time period prior to initiation of fertilizer P uptake. Thus delays in fertilizer P uptake during the seedling stage can be decreased by application of the dual bands a wk or more prior to seeding.

The delays in fertilizer P uptake, due to NH_3 toxicity affected the rate of fertilizer P uptake by the three crops differently. For flax and wheat the rate of uptake after initiation of fertilizer P uptake was greater for the urea + MAP dual band than for urea and MAP placed separately 7.5 cm below and beside the seed. With canola the

urea + MAP dual bands did not result in a large increase in the rate of fertilizer P uptake as noted for flax and wheat. The above observations indicate that different crop species react differently to NH_3 toxicity, even after root growth into the fertilizer band commences. Detailed studies into the reasons for these differences are needed to explain the results observed in this study.

Finally, it should be noted that all crops, wheat, canola, and flax, effectively utilized fertilizer P from the dual bands. Fertilizer P uptake from dual bands was generally equal to or greater than from P placed near the seed-row. In fact, fertilizer P uptake at the heading or flowering stage was greater from the $(NH_4)_2SO_4$ + MAP dual band than for P placed near the seed row, particularly for canola and wheat. For canola and wheat in experiment one, fertilizer P uptake at the heading or flowering stage was 12 and 16 percent higher from dual $(NH_4)_2SO_4$ + MAP bands than from P placed near the seed row. These results suggest that certain dual bands plus starter P may be a more effective method of placement than placement of all of the P near or in the seed row.

V BIBLIOGRAPHY

Alleem, M. I. H. and M. Alexander. 1960. Nutrition and physiology of Nitrobacter agilis. Appl. Microbiol. 8:80-84.

Alexander, M. 1977. Introduction to Soil Microbiology. 2nd Edition. John Wiley and Sons. New York. pp. 252-254.

Allison, L. E. 1965. Organic Carbon. In Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. pp. 1367-1378. Monograph No. 9 in the series of Agronomy, Amer. Soc. of Agron. Madison, Wisconsin. C. A. Evans, J. L. White, L. E. Ensmigner and F. E. Clark (Eds.).

Barry, D. A., J. L. Starr, J-Y. Parlange, and R. D. Braddock. 1983. Numerical analysis of the snow-plow effect. Soil Sci. Soc. Amer. J. 47:862-868.

Blake, G. R. 1965. Particle Density. In Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling. pp. 371-373. Monograph No. 9 in the series of Agronomy, Amer. Soc. of Agron. Madison, Wisconsin. C. A. Black, D. D. Evans, J. L. White, L. E. Ensminger and F. E. Clark (Ed.).

Blair, G. J., C. P. Mamaril and M. H. Miller. 1971. Influence of nitrogen source on phosphorus uptake by corn from soils differing in pH. Agron. J. 63:235-238.

Blanchard, R. W. and A. C. Caldwell. 1966a. Phosphate-ammonium-moisture relationships in soils: I. Ion concentrations in static fertilizer zones and effects on plants. Soil Sci. Soc. Amer. Proc. 30:39-43.

Blanchard, R. W. and A. C. Caldwell.1966b. Phosphorus-ammonium-moisture relationships in soils: II.Ion concentrations in leached fertilizer zones and effects on plants. Soil Sci. Soc. Amer. Proc. 30:43-48.

Bouldin, D. R. and E. C. Sample. 1958. The effect of associated salts on the availability of concentrated superphosphate. Soil Sci. Soc. Amer. Proc. 24:124-129.

Bouldin, D. R., J. R. Lehr and E. C. Sample. 1960. The effect of associated salts on transformations of monocalcium phosphate monohydrate at the site of application. Soil Sci. Soc. Amer. Proc. 26:464-468.

Carter, O. G. and D. J. Lathwell. 1967. Effects of temperature on orthophosphate absorption by excised corn roots. Plant Physiol. 42:1407-1412.

Cho, C. M. 1985. Ionic transport in soil with ion-exchange reaction. Soil Sci. Soc. Amer. J. 49:1379-1386.

Cole, C. V., D. L. Grunes L. K., L. K. Porter, and S. R. Olsen. 1963. The effect of nitrogen on short-term phosphorus absorption and translocation in corn (Zea Mays). Soil Sci. Soc. Amer. Proc. 27:671-674.

Colliver, G. W. and L. F. Welch. 1970a. Toxicity of preplant anhydrous ammonia to germination and early growth of corn: I. Field studies. Agron. J. 62:341-346.

Colliver, G. W. and L. F. Welch. 1970b. Toxicity of preplant anhydrous ammonia to germination and early growth of corn: II. Laboratory studies. Agron. J. 62:346-348.

Court, M. N., R. C. Stephen and J. S. Waid. 1964. Toxicity as a cause of the inefficiency of urea as a fertilizer. II. Experimental. J. Soil Sci. 15:49-65.

Duncan, W. G. and A. J. Ohlrogge. 1958, Principles of nutrient uptake from fertilizer bands. II. Root development in the band. Agron. J. 50:605-608.

Duncan, W. G. and A. J. Ohlrogge. 1959. Principles of nutrient uptake from fertilizer bands. III. Band volume, concentration and nutrient composition. Agron. J. 51:103-106.

Flaten, D. and G. J. Racz. 1982. The influence of banded urea and placement on monoammonium phosphate by wheat. Pages 154-161 in Proc. 25th Annual Man. Soil Sci. Meetings, Jan. 11-12, 1982.

Goyal, S. S. and R. C. Mulfaker. 1984. In Nitrogen in crop production. Nitrogen toxicity in plants. pp 97-118. ASA Madison, Wisconsin. Hauck, R. D. Ed.-in-Chief.

Grunes, D. L., H. R. Haise and L. O. Fine. 1958. Proportionate uptake of soil and fertilizer phosphorus by plants as affected by nitrogen fertilization: II. Field experiments with sugar beets and potatoes. Soil Sci. Soc. Amer. Proc. 22:49-52.

Hanson, R.L. and D. G. Westfall. 1985. Orthophosphate solubility transformations and availability from dual applied nitrogen and phosphorus. Soil Sci. Soc. Amer. J. 49:1247-1289.

Harper, F. R. and B. Berkenkamp. 1975. Revised growth-stage key for Brassica Campestris and B. Napus. Can. J. Plant Sci. 55:657-658.

Harper, H. J. 1924. The accurate determination of nitrate in soils. Ind. Eng. Chem. 16:180-183.

Isensee, A. R. and L. M. Walsh. 1970. Influence of banded fertilizer on the chemical environment surrounding the band. I. Effect on pH and solution nitrogen. J. Sci. Fd. Agric. 22:105-109.

Isensee, A. R. and L. M. Walsh. 1972. Influence of banded fertilizer on the chemical environment surrounding the band II. Effect on soil-solution cations, cation-anion balance and solution phosphorus. J. Sci. Fd. Agric. 23:509-516.

Johnson, D. D. and W. D. Guenzi. 1963. Influence of salts on ammonium oxidation and carbon dioxide evolution from soil. Soil Sci. Soc. Amer. Proc. 27:663-666.

Kamphake, L. J., S. A. Hannah and J. M. Cohen. 1967. Automated analysis for nitrate by hydrazine reduction. In Water Research, Vol 1, Pergamon Press.

Kilmer, V. J. and L. T. Alexander. 1949. Methods of making mechanical analysis of soils. Soil Sci. 68:15-24.

Leikam, D. F, L. S. Murphy, D. E. Kissel, D. A. Whitney and H. C. Moser.1983. Effects of nitrogen and phosphorus application method and nitrogen source on winter wheat grain yield and leaf tissue phosphorus. Soil Sci. Soc. Amer. J. 47:530-535.

Lewis, E. T. and G. J. Racz. 1969. Phosphorus movement in some calcareous and noncalcareous Manitoba soils. Can. J. Soil Sci. 49:305-311.

Miller, M. H. 1965. Influence of $(NH_4)_2SO_4$ on root growth and P absorption by corn from a fertilizer band. Agron. J. 57:393-396.

Miller, M. H., C. P. Mamaril and G. J. Blair. 1970. Ammonium effects on phosphorus absorption through pH changes and phosphorus precipitation at the soil-root interface. Agron. J. 62:524-527.

Miller, M. H. and A. J. Ohlrogge. 1958. Principles of nutrient uptake from fertilizer bands. I. Effect of placement of nitrogen on the uptake of band-placed phosphorus at different soil phosphorus levels. Agron. J. 50:95-97.

Miller, M. H. and V. N. Vij. 1962. Some chemical and morphological effects of ammonium sulfate in a fertilizer phosphorus band for sugar beets. Can. J. Soil Sci. 42:87-95.

Morrison, M. 1987. Personal communication, Department of Plant Science, University of Manitoba, Winnipeg Manitoba.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Analy. Chem. Acta 27:31-36.

Olsen, R. A., A. F. Dreier, B. W. Lowrey and A. D. Flowerday 1956. Availability of phosphate carriers to small grains and subsequent clover in relation to: I. Nature of soil and method of placement. Agron. J. 48:106-111.

Olson, R. A., A. F. Dreier, B. W. Lowery and A. D. Flowerday. 1956. Availability of phosphate carriers to small grains and subsequent clover in relation to: II. Concurrent soil amendments. Agron. J. 48:111-116.

Olson, R. A. and A. F. Dreier. 1956. Nitrogen, a key factor in fertilizer phosphorus efficiency. Soil Sci. Soc. Amer. Proc. :509-514.

Overrein, L. N. and P. G. Moe. 1967. Factors affecting urea hydrolysis and ammonia volatilization in soil. Soil Sci. Soc. Amer. Proc. 31:57-61.

Pang, P. C., R. A. Hedlin and C. M. Cho. 1973. Transformation and movement of band-applied urea, ammonium sulfate, and ammonium hydroxide during incubation in several Manitoba soils. Can. J. Soil Sci. 53:331-341.

Rennie, D. A. and J. Mitchell. 1954. The effect of nitrogen addition on fertilizer phosphate availability. Can. J. Agric. Sci. 34:353-356.

Rennie, D. A. and R. J. Soper. 1958. The effect of nitrogen additions on fertilizer-phosphorus availability. II J. Soil Sci. 9:155-167.

Riley, D. and S. A. Barber. 1969. Bicarbonate accumulation and pH changes at the soybean (Glycine max (L.) Merr.) root-soil interface. Soil Sci. Soc. Amer. Proc. 33:905-907.

Riley, D. and S. A. Barber. 1971. Effect of ammonium and nitrate fertilization on phosphorus uptake as related to root-induced pH changes at the root-soil interface. Soil Sci. Soc. Amer. Proc. 35:301-306.

Robertson, W. K., P. M. Smith, A. J. Ohlrogge and D. M. Kinch. 1954. Phosphorus utilization by corn as affected by placement, nitrogen and potassium fertilization. Soil Sci. 77:219-226.

Soon, Y. K. and M. H. Miller. 1977. Changes in the rhizosphere due to NH4+ and NO3- fertilization and phosphorus uptake by corn seedlings (Zea mays L.). Soil Sci. Soc. Amer. J. 41:77-80.

Starostka, R. W. and W. L. Hill. 1954. Influence of soluble salts on the solubility of and plant response to dicalcium phosphate. Soil Sci. Soc. Amer. Proc. 18:193-198.

Starr, J. L. and J-Y. Parlange. 1979. Dispersion in soil columns: The snow plow effect. Soil Sci. Soc. Amer. J. 43:448-450.

Strong, W. M. and Soper, R. J. 1974a. Phosphorus utilization by flax, wheat, rape and buckwheat from a band or pellet-like application. I. Reaction zone proliferation. Agron. J. 65:597-601.

Strong, W. M. and Soper, R. J. 1974b. Phosphorus utilization by flax, wheat, rape and buckwheat from a band or pellet-like application II. Influence of reaction zone phosphorus concentration and soil phosphorus supply. Agron. J. 65:601-605.

Terman, G. L. and C. M. Hunt. 1964. Volatilization losses of nitrogen from surface-applied fertilizers, as measured by crop response. Soil Sci. Soc. Amer. Proc. 36:667-672.

Thien, S. J. and W. W. McFee. 1970. Influence of nitrogen on phosphorus absorption and translocation in Zea mays. Soil Sci. Soc. Amer. Proc. 34:87-90.

Vlek, P. L. G. and J. M. Stumpe. 1978. Effects of solution chemistry and environmental conditions on ammonia volatilization losses from aqueous systems. Soil Sci. Soc. Amer. J. 42:416-421.

Warren, K. S. 1962. Ammonia toxicity and pH. Nature 195:47-49.

White, R. E. 1973. Studies on mineral ion absorption. II. The interaction between metabolic activity and the rate of phosphorus uptake. Plant and Soil 38:509-523.

VI APPENDIX

Appendix A

Table 1. Chemical analysis for the neutral Stockton soil treated with
urea + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.30	1089.34	13.37	149	23	356	1474
0.75	8.37	883.38	10.57	165	31	358	1286
1.25	8.32	265.77	3.15	129	23	416	918
1.75	7.99	36.52	0.45	121	24	499	643
2.25	7.27	11.04	0.13	169	33	581	484
2.75	6.50	12.10	0.15	191	39	559	382
3.25	6.13	12.38	0.15	209	43	551	303
3.75	5.93	12.76	0.16	235	51	523	214
4.25	5.69	13.98	0.17	262	55	476	136
4.75	5.54	14.40	0.18	276	58	451	81
5.25	5.76	12.20	0.15	275	58	375	<50
5.75	6.21	9.28	0.12	250	54	328	<50
6.25	6.72	7.70	0.09	226	49	247	<50
6.75	6.91	7.53	0.09	208	44	206	<50
7.25	6.95	7.66	0.10	185	39	171	<50
7.75	6.96	7.89	0.09	169	37	151	<50
8.25	7.00	8.09	0.10	184	36	146	<50
8.75	6.97	8.02	0.10	166	35	147	<50
9.25	6.82	8.96	0.12	162	34	148	<50
9.75	6.09	12.78	0.17	149	30	164	<50

Table 2. Chemical analysis for the neutral Stockton soil treated with
$(NH_4)_2SO_4$ + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.62	567.60	8.27	506	95	46	2778
0.75	6.48	423.27	4.35	844	128	60	2724
1.25	6.45	331.46	4.03	874	139	81	2512
1.75	6.37	255.05	3.15	802	141	103	2189
2.25	6.12	183.02	2.25	722	138	119	1832
2.75	5.65	103.62	1.33	868	156	145	1479
3.25	5.13	44.25	0.54	966	165	183	1059
3.75	5.18	22.97	0.27	423	91	232	676
4.25	5.50	19.43	0.25	183	40	232	296
4.75	5.92	13.38	0.17	259	52	219	150
5.25	6.12	9.80	0.12	280	56	251	51
5.75	6.57	8.06	0.10	257	52	105	<50
6.25	6.82	7.66	0.09	219	45	136	<50
6.75	6.92	8.07	0.10	184	38	142	<50
7.25	6.96	8.42	0.10	167	34	92	<50
7.75	6.98	8.57	0.11	160	33	81	<50
8.25	6.99	8.60	0.11	151	33	76	<50
8.75	6.98	8.70	0.10	144	31	77	<50
9.25	6.94	8.80	0.11	142	31	78	<50
9.75	6.60	10.43	0.13	141	30	83	<50

Table 3. Chemical analysis for the neutral Stockton soil treated with
NH_4NO_3 + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu\lambda\ g^{-1}$
0.25	6.83	558.34	7.11	177	48	993	1431
0.75	6.77	361.02	3.98	133	36	957	1342
1.25	6.80	205.61	2.48	118	32	902	1163
1.75	6.84	121.15	1.43	142	36	916	1217
2.25	6.82	50.76	0.64	175	42	868	1042
2.75	6.73	10.60	0.13	206	48	892	854
3.25	6.47	8.87	0.11	281	61	835	692
3.75	6.24	9.26	0.11	323	72	708	494
4.25	6.15	9.49	0.12	373	81	637	340
4.75	6.15	9.37	0.11	421	89	578	171
5.25	6.25	8.39	0.11	391	84	574	91
5.75	6.42	7.41	0.10	366	80	469	<50
6.25	6.68	7.04	0.09	334	74	405	<50
6.75	6.85	6.87	0.09	290	65	328	<50
7.25	6.90	7.19	0.09	247	56	257	<50
7.75	6.96	7.50	0.09	220	49	191	<50
8.25	6.94	8.02	0.10	193	43	188	<50
8.75	6.98	8.02	0.10	188	41	142	<50
9.25	6.91	8.66	0.11	171	37	145	<50
9.75	6.66	9.78	0.12	165	36	139	<50

Table 4. Chemical analysis for the neutral Stockton soil treated with
NH_4OH + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	7.88	644.26	9.28	95	33	370	1312
0.75	7.57	545.03	7.23	199	50	368	935
1.25	6.41	163.76	1.83	110	22	416	536
1.75	5.92	54.29	0.66	140	30	408	379
2.25	5.61	19.43	0.23	209	44	445	233
2.75	5.48	15.44	0.19	264	57	394	130
3.25	5.32	15.59	0.18	266	59	375	56
3.75	5.51	13.53	0.16	267	59	336	<50
4.25	6.35	9.27	0.11	261	58	287	<50
4.75	6.90	7.39	0.09	242	55	237	<50
5.25	6.93	7.44	0.09	213	49	192	<50
5.75	6.93	7.64	0.10	188	43	153	<50
6.25	6.96	7.82	0.09	156	36	158	<50
6.75	6.97	7.73	0.10	162	38	124	<50
7.25	7.00	8.16	0.12	148	35	109	<50
7.75	7.01	8.38	0.09	144	34	104	<50
8.25	6.99	8.23	0.10	139	33	107	<50
8.75	6.99	8.35	0.09	139	33	103	<50
9.25	6.91	9.27	0.12	139	33	100	<50
9.75	6.38	11.55	0.14	124	27	99	<50

Table 5. Chemical analysis for the neutral Stockton soil treated with
H_3PO_4-urea + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.08	594.59	6.48	88	13	231	1040
0.75	8.36	921.00	11.84	156	29	214	1332
1.25	8.34	230.96	2.84	82	20	271	823
1.75	8.14	20.83	0.26	113	27	356	625
2.25	7.71	11.11	0.13	149	34	414	533
2.75	6.90	11.60	0.14	161	35	425	434
3.25	6.38	11.07	0.15	142	33	342	304
3.75	6.15	11.47	0.15	176	39	338	238
4.25	6.02	12.49	0.15	194	45	365	183
4.75	6.06	11.41	0.14	207	48	267	116
5.25	6.18	10.35	0.12	222	50	295	66
5.75	6.47	8.84	0.11	227	53	192	<50
6.25	6.74	7.93	0.10	217	52	224	<50
6.75	6.91	7.65	0.10	207	49	187	<50
7.25	6.99	7.85	0.10	173	42	146	<50
7.75	7.02	8.04	0.10	162	39	139	<50
8.25	7.05	7.97	0.10	155	38	119	<50
8.75	7.05	8.28	0.11	154	37	113	<50
9.25	6.87	9.29	0.10	148	35	117	<50
9.75	6.41	11.54	0.15	138	33	123	<50

Table 6. Chemical analysis for the neutral Stockton soil treated with
MAP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.62	613.06	7.89	180	63	109	322
0.75	6.38	362.53	4.48	140	45	111	224
1.25	5.80	204.33	2.41	124	40	128	128
1.75	5.38	127.70	1.65	146	48	135	65
2.25	5.69	79.53	0.93	159	41	129	<50
2.75	6.50	36.14	0.42	152	41	114	<50
3.25	6.80	9.62	0.12	144	38	91	<50
3.75	6.93	8.05	0.10	136	42	83	<50
4.25	6.93	8.23	0.10	127	36	62	<50
4.75	7.03	8.39	0.11	123	46	59	<50
5.25	6.98	8.65	0.10	111	39	51	<50
5.75	7.00	8.87	0.11	118	39	47	<50
6.25	6.99	9.06	0.12	107	48	45	<50
6.75	7.00	8.90	0.10	108	36	41	<50
7.25	6.99	8.98	0.11	105	41	39	<50
7.75	7.02	9.10	0.11	111	61	39	<50
8.25	7.02	9.14	0.12	103	51	37	<50
8.75	6.96	9.12	0.11	105	32	38	<50
9.25	6.94	9.19	0.11	112	37	38	<50
9.75	6.94	9.09	0.12	108	42	40	<50

Table 7. Chemical analysis for the neutral Stockton soil treated with
urea + TSP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.25	924.30	12.61	163	23	382	1382
0.75	8.41	456.24	5.48	98	24	386	1119
1.25	8.32	33.46	0.39	87	20	482	816
1.75	8.00	12.68	0.15	144	32	573	641
2.25	7.33	10.80	0.13	192	40	614	494
2.75	6.42	12.58	0.17	192	41	597	383
3.25	6.16	12.67	0.15	215	45	483	316
3.75	5.98	13.09	0.16	245	52	471	224
4.25	5.78	14.10	0.18	272	58	424	147
4.75	5.66	13.83	0.17	287	61	390	78
5.25	5.88	11.95	0.15	248	55	336	<50
5.75	6.30	9.24	0.11	258	56	284	<50
6.25	6.77	7.72	0.10	234	51	234	<50
6.75	6.95	7.47	0.09	210	46	190	<50
7.25	6.96	7.75	0.09	185	41	169	<50
7.75	6.96	8.25	0.10	165	37	126	<50
8.25	6.96	8.19	0.10	152	34	118	<50
8.75	7.01	8.35	0.10	149	34	114	<50
9.25	6.93	8.64	0.10	148	33	113	<50
9.75	6.52	10.49	0.14	130	28	121	<50

Table 8. Chemical analysis for the neutral Stockton soil treated with
TSP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.66	699.94	8.18	402	81	64	87
0.75	6.23	278.30	3.63	176	40	71	52
1.25	6.32	126.85	1.52	122	28	74	<50
1.75	6.32	79.61	0.93	128	29	69	<50
2.25	7.03	29.82	0.37	109	24	62	<50
2.75	7.16	9.42	0.11	99	22	60	<50
3.25	7.15	9.01	0.11	94	21	56	<50
3.75	7.17	8.93	0.10	97	21	50	50
4.25	7.17	9.18	0.11	95	20	48	<50
4.75	7.18	9.09	0.12	108	22	50	<50
4.25	7.11	8.89	0.11	93	20	49	<50
5.75	7.16	9.07	0.12	102	22	53	<50
6.25	7.11	8.94	0.11	98	22	52	<50
6.75	7.12	8.87	0.11	97	22	54	<50
7.25	7.14	9.04	0.11	104	23	60	<50
7.75	7.13	8.91	0.11	104	22	61	<50
8.25	7.13	8.75	0.11	106	22	66	<50
8.75	7.09	8.79	0.11	111	24	77	<50
9.25	7.04	9.08	0.11	117	25	84	<50
9.75	6.67	10.51	0.14	113	24	93	<50

Table 9. Chemical analysis for the neutral Stockton soil (control) - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.80	8.90	0.10	106	23	62	<50
0.75	7.01	8.52	0.11	115	24	64	<50
1.25	7.06	8.48	0.11	110	23	59	<50
1.75	7.05	8.48	0.10	110	23	54	<50
2.25	7.07	8.72	0.10	138	26	52	<50
2.75	7.07	8.83	0.12	109	23	51	<50
3.25	7.06	8.79	0.10	114	24	49	<50
3.75	7.06	8.74	0.11	111	24	48	<50
4.25	7.05	8.97	0.12	108	23	46	<50
4.75	7.09	8.85	0.11	117	25	46	<50
5.25	7.08	9.03	0.12	112	23	46	<50
5.75	7.08	8.94	0.11	117	25	46	<50
6.25	7.06	8.99	0.11	115	25	46	<50
6.75	7.07	8.97	0.11	114	25	47	<50
7.25	7.07	9.05	0.11	125	26	49	<50
7.75	7.06	9.09	0.11	125	24	47	<50
8.25	7.08	9.02	0.11	135	28	49	<50
8.75	7.06	8.80	0.11	118	26	52	<50
9.25	7.05	9.10	0.11	123	26	57	<50
9.75	6.87	9.73	0.12	115	25	59	<50

Table 10. Chemical analysis for the acidic Stockton soil treated with urea + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.38	700.93	8.80	114	13	40	1107
0.75	8.48	686.20	9.86	115	14	46	1036
1.25	8.53	534.17	6.83	96	11	50	920
1.75	8.54	230.69	2.78	75	10	61	737
2.25	8.65	109.15	1.34	62	9	88	618
2.75	8.50	32.33	0.41	40	6	110	463
3.25	8.03	17.92	0.23	28	5	143	329
3.75	7.22	13.61	0.18	25	4	165	276
4.25	6.45	11.92	0.16	34	6	184	232
4.75	5.91	10.50	0.14	39	7	191	191
5.25	5.52	9.70	0.13	49	10	172	150
5.75	5.20	9.61	0.12	57	12	152	113
6.25	5.26	9.20	0.12	69	15	86	67
6.75	5.38	8.67	0.11	81	17	122	<50
7.25	5.58	8.07	0.10	86	19	104	<50
7.75	5.79	7.99	0.10	86	18	98	<50
8.25	5.82	8.06	0.10	76	17	89	<50
8.75	5.77	8.36	0.11	74	16	86	<50
9.25	5.57	8.91	0.11	72	16	89	<50
9.75	5.75	9.36	0.13	74	16	94	<50

Table 11. Chemical analysis for the acidic Stockton soil treated with $(NH_4)_2SO_4$ + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.33	383.78	5.18	100	29	17	2333
0.75	5.86	309.61	4.35	234	46	19	2489
1.25	5.63	251.43	3.48	286	57	20	2388
1.75	5.46	195.96	2.39	346	66	24	2167
2.25	5.31	146.16	1.98	344	70	29	1953
2.75	5.12	77.59	1.02	386	74	41	1676
3.25	4.85	22.44	0.29	418	82	51	1410
3.75	4.75	8.46	0.11	343	75	61	1094
4.25	4.75	8.51	0.12	245	61	66	846
4.75	4.99	8.92	0.11	119	35	74	562
5.25	5.25	9.21	0.12	67	19	78	283
5.75	5.30	8.57	0.11	87	22	83	175
6.25	5.37	8.16	0.11	105	26	81	95
6.75	5.32	7.94	0.10	101	25	80	<50
7.25	5.63	7.88	0.11	86	22	78	<50
7.75	5.77	7.88	0.10	78	19	65	<50
8.25	5.82	8.01	0.10	66	16	62	<50
8.75	5.74	8.22	0.10	61	15	62	<50
9.25	5.67	8.74	0.11	62	15	64	<50
9.75	5.83	9.11	0.12	56	13	75	<50

Table 12. Chemical analysis for the acidic Stockton soil treated with NH_4NO_3 + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.55	415.63	5.42	68	17	756	1012
0.75	6.23	304.63	3.92	53	13	783	950
1.25	6.01	234.67	2.91	60	14	753	947
1.75	5.82	177.10	2.28	60	15	762	878
2.25	5.68	114.33	1.47	75	18	762	781
2.75	5.61	54.60	0.69	80	20	725	722
3.25	5.59	9.35	0.12	97	23	703	605
3.75	5.58	6.74	0.08	118	28	631	529
4.25	5.49	6.80	0.09	139	32	616	429
4.75	5.42	6.84	0.09	158	37	529	331
5.25	5.20	7.09	0.09	172	39	474	239
5.75	5.13	7.13	0.09	175	40	421	165
6.25	5.12	7.36	0.09	183	42	373	114
6.75	5.18	7.32	0.10	174	42	348	72
7.25	5.24	7.19	0.09	166	40	284	<50
7.75	5.42	7.17	0.09	163	36	243	<50
8.25	5.41	7.37	0.10	143	34	216	<50
8.75	5.39	7.70	0.09	134	31	152	<50
9.25	5.26	8.40	0.11	126	29	174	<50
9.75	5.11	9.14	0.12	125	28	177	<50

Table 13. Chemical analysis for the acidic Stockton soil treated with NH$_4$OH + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	NO$_3^-$+NO$_2^-$ $\mu g\ g^{-1}$	NH$_4^+$+NH$_3$ $\mu g\ g^{-1}$
0.25	7.77	774.98	11.08	67	23	156	980
0.75	7.51	644.34	7.48	59	49	156	776
1.25	7.04	456.68	5.63	55	41	159	571
1.75	6.53	236.97	3.49	49	17	165	379
2.25	5.85	96.32	1.06	48	26	182	261
2.75	5.16	28.04	0.35	51	17	196	193
3.25	4.88	11.04	0.14	55	20	174	144
3.75	5.14	10.34	0.14	72	24	165	86
4.25	5.28	9.28	0.12	81	23	148	51
4.75	5.41	8.59	0.11	86	60	130	<50
5.25	5.47	8.40	0.11	85	42	110	<50
5.75	5.51	8.23	0.10	81	27	98	<50
6.25	5.56	8.37	0.12	75	36	85	<50
6.75	5.67	8.50	0.10	64	26	73	<50
7.25	5.68	8.62	0.11	59	23	66	<50
7.75	5.69	8.69	0.13	55	21	59	<50
8.25	5.72	8.94	0.11	54	22	56	<50
8.75	5.71	8.93	0.12	50	31	55	<50
9.25	5.71	9.13	0.12	49	22	55	<50
9.75	5.61	9.11	0.12	50	32	58	<50

Table 14. Chemical analysis for the acidic Stockton soil treated with H$_3$PO$_4$-urea + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	NO$_3^-$+NO$_2^-$ $\mu g\ g^{-1}$	NH$_4^+$+NH$_3$ $\mu g\ g^{-1}$
0.25	8.12	501.09	6.89	64	11	82	929
0.75	8.32	692.29	8.62	107	18	78	1078
1.25	8.39	616.69	7.90	107	15	93	993
1.75	8.37	231.81	2.82	55	12	106	631
2.25	8.43	48.49	0.66	38	7	138	469
2.75	8.08	19.39	0.25	30	6	164	371
3.25	7.52	15.70	0.19	37	8	197	312
3.75	7.01	12.76	0.17	28	6	223	279
4.25	6.75	10.78	0.14	34	7	223	250
4.75	6.46	9.18	0.12	35	8	200	205
5.25	5.71	9.50	0.12	38	8	179	155
5.75	5.36	9.64	0.13	48	10	172	113
6.25	5.40	8.85	0.11	58	13	153	62
6.75	5.38	9.70	0.13	69	16	118	<50
7.25	5.42	8.40	0.11	68	17	110	<50
7.75	5.50	8.28	0.11	69	17	92	<50
8.25	5.57	8.29	0.11	65	16	78	<50
8.75	5.57	8.52	0.12	57	14	72	<50
9.25	5.50	8.80	0.11	58	14	74	<50
9.75	5.50	9.08	0.12	58	13	72	<50

Table 15. Chemical analysis for the acidic Stockton soil treated with
MAP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.58	423.98	5.20	49	11	38	320
0.75	6.32	318.81	3.97	46	9	40	210
1.25	6.01	258.15	3.39	43	8	45	157
1.75	5.67	209.55	2.63	47	9	52	124
2.25	5.42	156.74	2.09	54	11	58	87
2.75	5.42	99.72	1.21	53	13	56	55
3.25	5.39	42.40	0.54	56	13	63	<50
3.75	5.51	11.04	0.14	57	13	58	<50
4.25	5.59	8.84	0.13	62	15	52	<50
4.75	5.70	8.63	0.10	56	14	51	<50
5.25	5.74	8.71	0.11	56	14	50	<50
5.75	5.72	8.73	0.11	59	15	50	<50
6.25	5.70	8.84	0.12	56	15	51	<50
6.75	5.72	8.76	0.12	58	15	49	<50
7.25	5.67	8.91	0.11	61	15	49	<50
7.75	5.69	8.79	0.12	59	14	56	<50
8.25	5.64	8.37	0.11	59	14	55	<50
8.75	5.57	8.96	0.11	66	17	65	<50
9.25	5.45	9.50	0.12	70	17	70	<50
9.75	5.35	9.76	0.13	80	18	74	<50

Table 16. Chemical analysis for the acidic Stockton soil treated with
urea + TSP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.31	746.97	9.45	140	12	38	1003
0.75	8.57	633.71	8.10	110	11	42	976
1.25	8.57	357.69	4.50	72	9	54	742
1.75	8.71	95.68	1.21	54	8	67	561
2.25	8.75	27.73	0.35	46	8	91	540
2.75	8.54	20.65	0.26	38	7	117	437
3.25	8.08	18.24	0.23	28	6	139	343
3.75	7.24	13.46	0.18	29	6	171	300
4.25	6.40	11.75	0.15	37	8	183	252
4.75	5.96	9.97	0.13	41	8	189	202
5.25	5.40	9.64	0.12	43	9	175	163
5.75	5.43	9.80	0.13	53	12	153	117
6.25	5.41	9.01	0.11	69	16	138	67
6.75	5.42	8.39	0.12	79	18	116	<50
7.25	5.58	8.12	0.11	86	20	102	<50
7.75	5.55	8.03	0.10	81	19	94	<50
8.25	5.52	8.15	0.10	81	20	95	<50
8.75	5.51	8.51	0.11	78	18	89	<50
9.25	5.40	9.01	0.12	78	18	92	<50
9.75	5.42	9.52	0.13	76	17	93	<50

Table 17. Chemical analysis for the acidic Stockton soil treated with TSP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	6.05	635.81	9.19	364	64	24	54
0.75	5.53	213.98	2.40	115	27	25	<50
1.25	5.44	176.30	2.23	106	28	27	<50
1.75	5.43	131.22	1.65	88	24	27	<50
2.25	5.51	83.94	1.10	71	18	27	<50
2.75	5.63	37.22	0.44	63	15	29	<50
3.25	5.77	10.31	0.13	53	12	30	<50
3.75	5.80	8.83	0.11	47	11	31	<50
4.25	5.77	8.70	0.11	50	11	31	<50
4.75	5.77	8.70	0.12	53	12	32	<50
5.25	5.80	8.66	0.11	51	12	33	<50
5.75	5.82	7.75	0.11	55	11	28	<50
6.25	5.81	8.81	0.11	52	12	33	<50
6.75	5.81	8.75	0.12	52	11	33	<50
7.25	5.74	8.75	0.11	50	11	33	<50
7.75	5.77	8.72	0.11	51	11	34	<50
8.25	5.86	8.73	0.11	54	13	32	<50
8.75	5.77	8.89	0.12	54	11	33	<50
9.25	5.83	8.86	0.11	54	12	35	<50
9.75	5.77	8.80	0.12	56	11	35	<50

Table 18. Chemical analysis for the acidic Stockton soil (control) - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	5.85	8.13	0.09	51	11	58	<50
0.75	5.70	8.72	0.13	51	11	57	<50
1.25	5.69	8.43	0.11	54	12	55	<50
1.75	5.69	8.44	0.11	53	11	53	<50
2.25	5.79	8.55	0.11	48	10	51	<50
2.75	5.81	8.68	0.11	50	11	49	<50
3.25	5.91	8.64	0.11	47	11	43	<50
3.75	5.77	8.74	0.11	45	11	46	<50
4.25	5.88	8.93	0.11	44	10	44	<50
4.75	5.82	8.87	0.12	45	10	46	<50
5.25	6.01	9.01	0.11	45	10	44	<50
5.75	5.95	8.90	0.12	46	10	44	<50
6.25	5.80	8.79	0.11	45	10	44	<50
6.75	5.89	8.90	0.11	44	10	46	<50
7.25	5.91	8.93	0.12	46	10	45	<50
7.75	5.75	9.02	0.12	47	10	45	<50
8.25	5.76	8.79	0.11	45	10	46	<50
8.75	5.74	8.86	0.12	45	11	42	<50
9.25	5.69	8.93	0.11	44	10	46	<50
9.75	5.72	8.73	0.12	47	11	50	<50

Table 19. Chemical analysis for the Almasippi soil treated with urea + MAP - average of two replicates.

Section cm	pH	P $\mu g \ g^{-1}$	Total P mg	Ca^{2+} $\mu g \ g^{-1}$	Mg^{2+} $\mu g \ g^{-1}$	$NO_3^- + NO_2^-$ $\mu g \ g^{-1}$	$NH_4^+ + NH_3$ $\mu g \ g^{-1}$
0.25	8.83	508.39	5.94	264	88	172	1745
0.75	8.93	136.67	1.45	282	130	176	1387
1.25	8.93	14.31	0.17	281	179	206	1156
1.75	8.88	10.71	0.13	221	210	277	994
2.25	8.76	7.65	0.09	217	257	396	735
2.75	8.57	5.43	0.06	322	319	512	482
3.25	8.34	4.63	0.06	449	363	601	237
3.75	8.19	4.41	0.05	542	376	654	86
4.25	8.05	4.30	0.06	556	377	676	<50
4.75	8.24	3.72	0.04	463	361	614	<50
5.25	8.38	3.51	0.05	363	345	478	<50
5.75	8.45	3.61	0.04	312	335	413	<50
6.25	8.61	3.85	0.05	282	312	358	<50
6.75	8.66	3.92	0.05	249	278	300	<50
7.25	8.63	4.12	0.05	253	274	237	<50
7.75	8.70	4.19	0.05	238	259	217	<50
8.25	8.69	4.38	0.05	249	256	198	<50
8.75	8.66	4.42	0.05	248	253	195	<50
9.25	8.72	4.35	0.05	247	244	192	<50
9.75	8.60	4.31	0.05	274	242	202	<50

Table 20. Chemical analysis for the Almasippi soil treated with $(NH_4)_2SO_4$ + MAP - average of two replicates.

Section cm	pH	P $\mu g \ g^{-1}$	Total P mg	Ca^{2+} $\mu g \ g^{-1}$	Mg^{2+} $\mu g \ g^{-1}$	$NO_3^- + NO_2^-$ $\mu g \ g^{-1}$	$NH_4^+ + NH_3$ $\mu g \ g^{-1}$
0.25	8.12	201.93	2.61	3198	1073	311	2471
0.75	8.24	6.81	0.08	1206	623	350	1802
1.25	8.36	5.37	0.06	824	538	439	1598
1.75	8.35	5.01	0.07	823	621	581	1285
2.25	8.20	4.55	0.05	1324	770	797	888
2.75	8.03	4.68	0.05	1796	845	1124	483
3.25	7.97	4.81	0.05	1422	637	1221	155
3.75	8.00	4.19	0.05	1080	547	1141	<50
4.25	8.12	3.03	0.04	822	532	944	<50
4.75	8.31	2.83	0.03	615	512	768	<50
5.25	8.46	3.26	0.04	433	444	584	<50
5.75	8.60	3.66	0.04	329	370	468	<50
6.25	8.67	3.96	0.05	298	334	381	<50
6.75	8.71	4.18	0.05	269	288	317	<50
7.25	8.75	4.42	0.05	257	266	283	<50
7.75	8.77	4.55	0.05	247	256	194	<50
8.25	8.77	4.75	0.06	268	249	175	<50
8.75	8.78	4.68	0.06	248	243	159	<50
9.25	8.78	4.68	0.06	243	237	159	<50
9.75	8.75	4.68	0.06	263	233	166	<50

Table 21. Chemical analysis for the Almasippi soil treated with
NH$_4$NO$_3$ + MAP - average of two replicates.

Section cm	pH	P μg g^{-1}	Total P mg	Ca^{2+} μg g^{-1}	Mg^{2+} μg g^{-1}	NO$_3^-$+NO$_2^-$ μg g^{-1}	NH$_4^+$+NH$_3$ μg g^{-1}
0.25	8.39	239.61	2.76	397	324	1376	1085
0.75	8.37	6.85	0.08	414	278	1363	1096
1.25	8.39	5.67	0.06	423	319	1342	1076
1.75	8.39	5.14	0.06	459	381	1319	920
2.25	8.36	4.56	0.05	508	432	1421	760
2.75	8.28	4.12	0.05	590	477	1388	579
3.25	8.21	3.90	0.05	702	523	1443	302
3.75	8.13	3.66	0.04	754	536	1321	170
4.25	8.11	3.20	0.04	714	522	1208	60
4.75	8.21	3.23	0.04	570	497	1026	<50
5.25	8.36	3.04	0.03	414	430	817	<50
5.75	8.47	3.31	0.04	353	397	643	<50
6.25	8.56	3.57	0.04	298	334	495	<50
6.75	8.60	3.77	0.04	282	300	378	<50
7.25	8.64	4.03	0.05	268	270	310	<50
7.75	8.68	4.20	0.05	247	247	242	<50
8.25	8.69	4.23	0.05	241	236	204	<50
8.75	8.70	4.40	0.05	234	226	179	<50
9.25	8.72	4.54	0.06	254	228	169	<50
9.75	8.72	4.34	0.05	255	226	164	<50

Table 22. Chemical analysis for the Almasippi soil treated with
NH$_4$OH + MAP - average of two replicates.

Section cm	pH	P μg g^{-1}	Total P mg	Ca^{2+} μg g^{-1}	Mg^{2+} μg g^{-1}	NO$_3^-$+NO$_2^-$ μg g^{-1}	NH$_4^+$+NH$_3$ μg g^{-1}
0.25	8.57	538.08	7.35	307	372	566	805
0.75	8.41	18.48	0.22	384	296	567	367
1.25	8.26	5.49	0.06	490	356	620	202
1.75	8.19	4.83	0.06	568	393	688	90
2.25	8.08	4.58	0.07	606	402	717	<50
2.75	8.11	4.65	0.03	549	397	624	<50
3.25	8.15	4.02	0.05	582	504	769	<50
3.75	4.13	2.21	0.02	221	191	279	<50
4.25	8.35	3.83	0.04	356	352	408	<50
4.75	8.43	4.02	0.05	328	337	366	<50
5.25	8.50	4.06	0.05	296	314	330	<50
5.75	8.51	4.39	0.05	286	296	277	<50
6.25	8.57	4.42	0.05	278	287	234	<50
6.75	8.57	4.59	0.06	277	276	199	<50
7.25	8.57	4.59	0.05	277	263	189	<50
7.75	8.57	4.66	0.06	277	268	154	<50
8.25	8.59	4.73	0.07	265	259	149	<50
8.75	8.57	4.72	0.05	266	260	143	<50
9.25	8.57	4.96	0.06	267	257	149	<50
9.75	8.52	4.56	0.05	288	253	149	<50

Table 23. Chemical analysis for the Almasippi soil treated with H_3PO_4-urea + MAP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.87	404.95	4.57	274	138	225	1304
0.75	8.91	85.61	1.02	265	149	206	1116
1.25	8.91	12.45	0.13	262	197	259	944
1.75	8.83	9.80	0.11	237	247	326	692
2.25	8.68	7.18	0.09	280	304	420	556
2.75	8.47	5.44	0.07	386	341	555	309
3.25	8.31	4.87	0.05	493	362	670	167
3.75	8.15	4.80	0.06	577	390	725	62
4.25	8.13	4.61	0.05	543	377	708	<50
4.75	8.26	3.94	0.05	476	372	651	<50
5.25	8.41	3.83	0.04	378	345	600	<50
5.75	8.47	3.98	0.05	334	334	489	<50
6.25	8.59	4.19	0.05	297	310	415	<50
6.75	8.63	4.33	0.05	279	286	374	<50
7.25	8.64	4.52	0.05	274	268	317	<50
7.75	8.69	4.55	0.06	264	253	268	<50
8.25	8.66	4.57	0.05	264	254	185	<50
8.75	8.68	4.66	0.05	258	246	178	<50
9.25	8.71	4.65	0.06	271	245	173	<50
9.75	8.66	4.59	0.05	273	239	173	<50

Table 24. Chemical analysis for the Almasippi soil treated with MAP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	7.57	307.09	4.61	425	501	444	<50
0.75	8.07	25.70	0.22	377	359	445	<50
1.25	8.24	4.04	0.05	375	343	408	<50
1.75	8.47	3.58	0.05	328	312	350	<50
2.25	8.58	3.81	0.03	289	292	284	<50
2.75	8.63	3.98	0.04	283	288	254	<50
3.25	8.71	4.15	0.05	256	275	213	<50
3.75	8.74	4.12	0.05	246	255	176	<50
4.25	8.77	4.24	0.05	235	238	151	<50
4.75	8.77	4.34	0.05	236	236	137	<50
5.25	8.78	4.41	0.05	231	224	118	<50
5.75	8.75	4.53	0.05	230	223	107	<50
6.25	8.82	4.45	0.06	225	217	100	<50
6.75	8.81	4.55	0.05	219	213	101	<50
7.25	8.82	4.55	0.05	230	216	99	<50
7.75	8.81	4.54	0.05	225	211	95	<50
8.25	8.82	4.69	0.06	239	220	99	<50
8.75	8.82	4.62	0.05	220	216	100	<50
9.25	8.80	4.75	0.06	242	220	104	<50
9.75	8.78	4.68	0.06	245	217	108	50

Table 25. Chemical analysis for the Almasippi soil treated with urea + TSP - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^- + NO_2^-$ $\mu g\ g^{-1}$	$NH_4^+ + NH_3$ $\mu g\ g^{-1}$
0.25	8.84	380.23	4.16	272	122	229	1417
0.75	8.92	20.73	0.27	277	149	224	1110
1.25	8.89	12.01	0.12	242	199	299	965
1.75	8.80	9.48	0.12	223	244	363	790
2.25	8.58	6.71	0.08	293	310	504	522
2.75	8.39	5.35	0.06	411	362	597	290
3.25	8.25	4.89	0.06	539	398	703	124
3.75	8.17	4.83	0.06	586	400	669	<50
4.25	8.20	1.47	0.05	168	121	168	<50
4.75	8.42	3.70	0.05	402	345	499	<50
5.25	8.45	4.04	0.05	352	339	424	<50
5.75	8.52	4.24	0.05	311	320	361	<50
6.25	8.57	4.43	0.06	290	302	318	<50
6.75	8.71	4.34	0.05	261	261	291	<50
7.25	8.64	4.74	0.06	260	263	269	<50
7.75	8.55	4.83	0.05	259	254	187	<50
8.25	8.65	4.90	0.06	256	249	188	<50
8.75	8.64	5.06	0.05	249	245	183	<50
9.25	8.64	5.04	0.06	266	249	173	<50
9.75	8.59	4.86	0.06	271	239	175	<50

Table 26. Chemical analysis for the Almasippi soil treated with TSP alone - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^- + NO_2^-$ $\mu g\ g^{-1}$	$NH_4^+ + NH_3$ $\mu g\ g^{-1}$
0.25	7.80	580.25	6.84	391	419	84	<50
0.75	8.54	17.16	0.20	231	234	73	<50
1.25	8.68	5.12	0.06	235	224	69	<50
1.75	8.72	4.96	0.06	226	218	66	<50
2.25	8.72	4.97	0.07	237	221	65	<50
2.75	8.74	5.00	0.05	232	221	65	<50
3.25	8.75	5.16	0.06	253	227	61	<50
3.75	8.73	5.06	0.06	233	224	65	<50
4.25	8.70	5.04	0.06	230	226	68	<50
4.75	8.71	5.10	0.06	232	227	66	<50
5.25	8.70	5.20	0.06	251	227	65	<50
5.75	8.71	5.23	0.07	247	229	69	<50
6.25	8.71	5.23	0.06	239	229	66	<50
6.75	8.70	5.22	0.06	258	236	66	<50
7.25	8.67	5.22	0.06	244	230	68	<50
7.75	8.69	5.16	0.06	234	235	66	<50
8.25	8.67	5.13	0.07	241	235	66	<50
8.75	8.66	5.27	0.06	245	237	66	<50
9.25	8.67	5.27	0.06	245	239	73	<50
9.75	8.66	5.14	0.07	247	243	77	<50

Table 27. Chemical analysis for the Almasippi soil (control) - average of two replicates.

Section cm	pH	P $\mu g\ g^{-1}$	Total P mg	Ca^{2+} $\mu g\ g^{-1}$	Mg^{2+} $\mu g\ g^{-1}$	$NO_3^-+NO_2^-$ $\mu g\ g^{-1}$	$NH_4^++NH_3$ $\mu g\ g^{-1}$
0.25	8.09	3.89	0.04	202	183	75	<50
0.75	8.69	4.40	0.05	203	184	74	<50
1.25	8.70	4.51	0.05	233	192	69	<50
1.75	8.76	4.40	0.06	214	184	71	<50
2.25	8.79	4.45	0.05	204	181	67	<50
2.75	8.83	4.53	0.05	218	185	68	<50
3.25	8.84	4.60	0.05	217	198	68	<50
3.75	8.80	4.64	0.05	215	189	65	<50
4.25	8.82	4.66	0.06	214	190	66	<50
4.75	8.81	4.74	0.06	226	198	68	<50
5.25	8.78	4.70	0.06	212	192	68	<50
5.75	8.74	4.71	0.05	223	197	69	<50
6.25	8.80	4.74	0.06	219	195	73	<50
6.75	8.78	4.84	0.06	228	199	75	<50
7.25	8.75	4.75	0.06	217	196	82	<50
7.75	8.71	4.84	0.06	239	206	52	<50
8.25	8.73	4.86	0.06	225	210	80	<50
8.75	8.74	4.83	0.06	222	201	80	<50
9.25	8.74	4.77	0.05	232	216	84	<50
9.75	8.70	4.48	0.06	237	217	85	<50