EFFECT OF BAND GEOMETRY AND CHEMISTRY ON

FERTILIZER PHOSPHORUS AVAILABILITY

by

DERWYN W. HAMMOND

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
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MASTER OF SCIENCE

Department of Soil Science
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ABSTRACT

Growth chamber experiments were conducted from 1992 to 1994 on a calcareous silty clay loam soil (pH≈7.9) low in levels of available phosphorus. A number of different band geometries were assessed for their effect on the efficiency of P utilization from applied monoammonium phosphate (MAP). Ammonium and magnesium sulfates, urea, and organic amendments (lignosulfonates) were also incorporated into P fertilizer bands to study their effect on uptake of applied P by plants. The MAP was labelled with the radioisotope ^{32}P in order to determine utilization of fertilizer P specifically. Dry matter yields and total P uptake were also measured.

Initial studies with wheat and canola as test crops, involved fertilizer applied in solution or powdered form with band geometries ranging from points of application spaced 5 cm apart to continuous bands 2.5 cm in width. The form of fertilizer applied had no effect on observed trends. The canola was very efficient at utilizing applied P, with no apparent benefit from increased area of application or dual banding with N. However, fertilizer P uptake by wheat increased slightly with area of application. Dual banding the P fertilizer with N or $MgSO_4$ stimulated P uptake by wheat. Ammonium sulfate was most effective in increasing P utilization. Urea initially slowed uptake, but increased P utilization at later stages of plant growth. Incorporating calcium-, hydrogen- and ammonium-saturated forms of lignosulfonate into MAP bands was ineffective in enhancing yield or P uptake by wheat.

Studies were also conducted using very wide band widths, similar to those

encountered in the field when using air seeders utilizing openers designed to give wide spread patterns. Labelled MAP was randomly applied in powdered form to several points within the bands, to simulate granular applications. Ammonium sulphate was dual banded with the MAP granules (placed in direct contact) or randomly scattered within the band. Fertilizer P uptake declined slightly as band width increased from 2.5 to 15 cm, particularly at earlier growth stages. Dual banding with ammonium sulphate improved P fertilizer utilization and yield. Application of the nitrogen fertilizer in direct contact with the MAP (ie. applied to the same points) was more beneficial than scattered randomly within the band, particularly for the widest band width. Subsequent studies on rates of MAP at various band widths showed similar trends at double the rate of P application.

ACKNOWLEDGEMENTS

FOREWORD

This thesis has been written in a manuscript style. While the manuscripts presented

in sections 3, 4 and 5 have not been previously published in the form presented herein,

much of the information gained from the studies discussed has been presented previously

at several workshops. The papers presented at these workshops have been published in

the following proceedings.

Hammond, D.W., Racz, G.J. and Cho, C.M. 1993. Effect of band geometry and chemistry on fertilizer phosphorus availability. Proc. of the 36th Annual Manitoba Society Soil Science Meeting. Winnipeg, Manitoba. January 5 and 6. pp. 136-147.

Hammond, D.W., Racz, G.J. and Cho, C.M. 1994. Effect of band geometry and chemistry on fertilizer phosphorus availability. Proc. of the 37th Annual Manitoba Society Soil Science Meeting. Winnipeg, Manitoba. January 4 and 5. pp. 114-124.

Hammond, D.W., Racz, G.J. and Cho, C.M. 1995. Effect of band geometry and chemistry on fertilizer phosphorus availability. Seed and Fertilizer Placement Workshop Sponsored by Sherritt Fertilizers Ltd. Edmonton, Alberta.

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1. INTRODUCTION

Fertilizer use efficiency or the proportion of fertilizer utilized by the crop in the year of application varies with factors such as soil type (nutrient content), crop type, fertilizer placement and environment. Increases in efficiency of fertilizer use result in greater yield benefit per unit of fertilizer and thus reduce costs of production and use of a finite resource. Early work (Spinks and Barber 1948) indicated that use efficiency of P fertilizers was quite low, and averaged about 22% for wheat. As a result, much research was undertaken with the aim of improving the utilization of applied fertilizer phosphorus. Despite the many studies conducted, a recent review has indicated P fertilizer efficiency is still approximately 20% for prairie crops in the year of application (Doyle and Cowell 1993). Benefits resulting from residual P would increase fertilizer use efficiency somewhat, but clearly there is still considerable opportunity for improvement in P fertilizer use efficiency. Two factors which can have a considerable impact on availability and utilization of added P are the geometry of the fertilizer band and the chemical environment within the band.

Band geometry is a term used to describe both the location of the fertilizer band relative to the seed row and the distribution of the P source within the band. The distance between the applied P band and the seed row affects uptake by the plant in two ways. (1) Increases in the distance between the seed row and the fertilizer band increase the time required for initial contact between the root and the fertilizer, since the plant roots must

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grow to the fertilizer band. The time that P is supplied to plants can be an important factor influencing plant growth (Sutton et al. 1983). (2) Increases in the distance between the seed row and the fertilizer band also reduce the probability of occurance of root-fertilizer contact (Sleight et al. 1984). Root-fertilizer contact is an important factor influencing the utilization of applied P due to the relative immobility of P in the soil (Jungk and Barber 1974; Stryker et al. 1974; Schenk and Barber 1979). Phosphorus movement from the point of application is usually very limited (Lawton and Vomicil 1954; Sharpley 1986).

Distribution of applied P within the fertilizer band can also affect the efficiency of applied P (Sleight et al. 1984; Eghball and Sander 1987; Eghball and Sander 1989; Sander and Eghball 1988). Much of the fertilizer P research has involved the use of granular P fertilizers with granule sizes in excess of 15 mg which results in wide granule spacing within fertilizer bands of low to moderate application rates. Use of conventional liquid application equipment results in similar patterns of wide droplet spacing, and hence uptake of P, due to large droplet sizes (Eghball and Sander 1987). Decreasing granule size can improve P fertilizer uptake in wheat (Sander and Eghball 1988), due to the resulting increase in continuity of the fertilizer zone. This increases the frequency of root-fertilizer contact due to greater surface area of fertilizer P affected soil (Eghball and Sander 1989).

Modifying the chemical environment in the fertilizer band also influences fertilizer use efficiency. Adding salts without a common ion, such as potassium chloride or magnesium sulfate, to phosphate fertilizer can enhance solubility of P reaction products due to ionic strength effects (Starostka and Hill 1954; Bouldin and Sample 1958). Adding nitrogen fertilizer with phosphate fertilizers (dual banding) has been shown to greatly

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enhance solubility of P in the fertilizer band (Starostka and Hill 1954; Bouldin and Sample 1958; Beever 1987; Flaten 1989). Adding ammonium nitrogen also enhances P uptake due to other effects such as enhanced root growth (Miller and Ohlrogge 1958; Miller and Vij 1962; Miller 1965), enhanced root absorptive capacity (Miller 1965; Leonce and Miller 1966; Thien and McFee 1970), and alteration of the root rhizosphere organisms (Asea et al. 1988).

The previously described findings indicated the potential to utilize recent knowledge obtained from studies involving modification of the chemical environment and geometry of the fertilizer band to maximize fertilizer P use efficiency. Studies were therefore conducted utilizing monoammonium phosphate (MAP) labelled with the radioisotope ^{32}P to:

(1) assess the efficiency of fertilizer P when applied as either a solution or powder form in a variety of band geometries.

(2) assess the effect of chemical modifications to the band including various fertilizer sources and organic amendments.

(3) to determine if any particular combination of band geometry and chemical amendments was most effective in improving P fertilizer use efficiency.

2. LITERATURE REVIEW

2.1 Plant Uptake of Phosphorus and Its Function in the Plant

Green plants are unique in their ability to convert radiant energy, through the process of photosynthesis, into chemical energy. A key step in this process is the phosphorylation of adenosine diphosphate (ADP) to adenosine triphosphate (ATP), which is driven by electron flow down the electron transport chain. Phosphate performs its most fundamental role in bio-energetics in the transduction of proton motive force to form ATP (Glass et al. 1980). Phosphorus is essential since ATP is the source of energy for practically all energy requiring biological processes or metabolic reactions. In addition, phosphate is also a structural component of a wide variety of biochemicals including nucleic acids, coenzymes, phosphoproteins, and phospholipids which are an essential part of cell membranes (Glass et al. 1980). Proper P nutrition is of great importance in crops grown for seed production because P content of the seed represents approximately 70 to 80% of the total P in the above ground growth for most crops (Doyle and Cowell 1993).

Despite the central metabolic role of P in the plant, more than half of the total P is present as inorganic phosphate under all but conditions of P deficiency (Bieleski 1976). Inorganic P can accumulate in the vacuole in response to improved P status (Bieleski 1973; Chisholm et al. 1981). This process, known as "luxurious uptake" (Bieleski 1973), is probably an ecological adaptation to survive between pulses of P availability. Wheat and

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other small grains take up P rapidly during early growth stages (Clarke et al. 1990). P is

stored in roots, stems and leaves and translocated to grain at heading. Uptake of soil P by

wheat begins to increase when the plant reaches 2 weeks of age and then becomes

increasingly more important until it dominates by heading, while fertilizer P uptake greatly

exceeds soil P uptake for the first 4 weeks of growth, reaching a maximum rate at 2 - 6

weeks of age (Spinks and Barber 1948). Dion et al. (1949b) suggested that early

availability and uptake of fertilizer P may be important due to early development of flower

primordia at the 4-6 week stage which dictates maximum number of flowers in the spike.

This agrees with Campbell et al. (1993) who found uptake of P to be most critical within 4

- 6 weeks after seeding, as reported in Doyle and Cowell (1993). P uptake later in the

season appears to have less effect on yield (Boatwright and Haas 1961; Sutton et al.

1983).

P is absorbed by plants as primary or secondary orthophosphate ions ($H_2PO_4^-$ and

HPO_4^{2-}) which exist transiently in the soil solution and are replenished from exchangeable

and labile forms of soil P (Barber 1980). $H_2PO_4^-$ is the major form present at pH less than

7.2 while HPO_4^{2-} dominates at soil solution pH greater than 7.2. Removal of these

phosphate ions from the soil solution near the roots disturbs the equilibrium between P in

solution and P present in the soil as solid phases, and phosphate ions from the solid phase

replenish the soil solution (Sheppard and Racz 1980). The factors affecting the rate of

replenishment, and hence uptake of P, include mineralization and immobilization rates, rate

of P transport, adsorption and desorption rates and changes in solubility of P minerals or

precipitated P (Sheppard and Racz 1980). Major mechanisms of movement of solution P

to plant roots include diffusion and mass flow mechanisms (Barber 1980; Sheppard and Racz 1980). Proportion of P supplied by these processes is dependent on size of the root system, degree of vesicular-arbuscular mycorrhizal infection (Kucey and Paul 1980), P and water absorption characteristics of the root, and levels of labile and solution P within the rhizosphere soil (Gould and Bole 1980). Root hair density and phosphatase activity are also important factors affecting P supply to plants (Bole 1973). Plant species can have a significant impact on P uptake levels, particularly through their influence on root adsorptive capacities and ability to proliferate in micro-regions of high P concentration similar to those found near points of fertilizer P application (Strong and Soper 1974a,b; Sheppard and Racz 1980).

The ability of fertilizer P applications to improve yields of wheat by increasing P uptake was clearly established during the late 1920's through the 1940's (Mitchell 1946; Spinks and Barber 1948; Dion et al. 1949a,b). Since that time work with other crops has shown that while they may differ in their efficiency of utilizing applied P, most crops will benefit from fertilizer P when grown under P deficient conditions (Strong and Soper 1974a,b). It is important to note that these increases may not be achieved if other nutrients are not supplied in adequate amounts. P nutrition of crops is often improved by increases in the supply of other nutrients (Sheppard and Racz 1980). Zinc deficiencies resulting from high rates of P application have been noted (Singh et al. 1986; Bailey et al. 1980), and copper has also been shown to decrease with P application (Spratt and Smid 1978). However, when other factors are not limiting it is the form and availibility of the applied P fertilizer and its reaction products in the soil which will be most important in

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determining yield increases. The following discussion summarizes the transformations which can occur following the addition of fertilizer P to the soil.

2.2 Fertilizer Phosphate Dissolution and Retention

2.2.1 Dissolution of Fertilizer Phosphate

Monoammonium phosphate, diammonium phosphate and ammonium polyphosphate fertilizers are commonly used in crop production on the Canadian prairies with granular monoammonium phosphate being the predominant form used (Roberts and Green 1994; Penney 1996). These fertilizer sources are highly water soluble (Engelstad and Terman 1980) and dissolve fairly rapidly even under conditions of low soil moisture (Lawton and Vomicil 1954).

The rapid dissolution occurs because application of fertilizer P to soil results in an osmotic gradient between the soil and fertilizer and thus the movement of water into the P fertilizer zone by vapour or capillary transport. This causes a subsequent movement of the resulting concentrated fertilizer solution from the site of application into the surrounding soil by capillary flow until fixation or dilution causes the gradient to cease (Sample et al. 1980). When the fertilizer P is applied as a solution no dissolution step is required. The amount of outward movement depends on the strength of the osmotic gradient. The chemical environment during dissolution is dominated by the properties of the fertilizer solution which dictates properties such as pH, P concentration and accompanying cation concentration. The soil matrix has little influence on these reactions, and acts mainly as a source of water and a sink for the fertilizer solution (Bouldin et al. 1960). The

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concentrated fertilizer solution leaving the application site displaces exchangeable cations

and dissolves some soil minerals, placing relatively large quantities of reactive cations into

the soil solution. Reactions occur between the P in solution and soil constituents resulting

in precipitation and adsorption, and much of the P is retained in the vicinity of application

(Soper and Racz 1980).

2.2.2 Initial Reaction Products and Their Changes Over Time

Precipitation reactions dominate close to the granule site whereas adsorption

reactions are more important at the outer edge of the soil-fertilizer reaction zone where P

concentrations are lower (Barrow 1980; Soper and Racz 1980). Three zones form as a

result, including a central zone which contains the residue of the P fertilizer, an outer layer

through which P fertilizer solution has passed and dissolved soil minerals resulting in

formation of Ca-, Mg-, Fe-, and Al-P precipitates, and an outer zone of low P

concentration where adsorption of P onto the surface of the soil minerals has occurred

(Barrow 1980). The majority of the phosphorus added is retained as precipitates in most

soils (Soper and Racz 1980).

The nature, amount, and rate of production of these initial reaction products will

depend upon the cations and anions supplied by the soil and fertilizer, as well as other soil

factors (Sample et al. 1980; Soper and Racz 1980). Dicalcium phosphate dihydrate

(DCPD) has been identified as a major and common initial reaction product in western

Canadian soils with pH values between 6.0 and 8.5 for all the major orthophosphate

fertilizers (Hinman et al. 1962; Beaton and Read 1963; Racz and Soper 1967; Bell and

Black 1970; Strong and Racz 1970; Larsen and Widdowson 1970). On soils high in Mg

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content dimagnesium phosphate trihydrate (DMPT) is an initial reaction product of ammonium and potassium phosphate fertilizers (Racz and Soper 1967; Strong and Racz 1970). Strong and Racz (1970) found that on soils with a Ca:Mg ratio of <0.64 several insoluble Mg-P precipitates formed instead of DCPD. In acid soils aluminum and iron oxide and hyrous oxides and alumino-silicate minerals have a dominant role in P retention (Soper and Racz 1980), with dissolution of clay minerals and release of Fe and Al resulting in precipitation of Fe- and Al- phosphates at high P concentrations (Sample et al. 1980).

These initial reaction products will continue to react over time to become more stable, less soluble, compounds. For example, on most calcareous soils DCPD is gradually changed to octacalcium phosphate (OCP) and eventually hydroxyapatite (HA), the dominant stable calcium phosphate mineral in prairie soils (Racz and Soper 1967; Bell and Black 1970; Sadler and Stewart 1975; Sample et al. 1980). Reaction with soluble $CaCO_3$ will form precipitates which can then be adsorbed onto the surface of calcium carbonate minerals (Barrow 1980). This tends to lead to a more rapid conversion to more stable, less soluble, compounds in the presence of $CaCO_3$ (Bell and Black 1970). In acid soils variscite and strengite-like compounds will eventually form (Sample et al. 1980).

2.2.3 Adsorption Reactions Following Fertilizer P Application

As mentioned previously, adsorption reactions represent the dominant form of P retention in the outer zone of lower P concentration formed near the perifery of the fertilizer reaction zone, following fertilizer P application to soil (Barrow 1980; Soper and Racz 1980). On highly calcareous soil, soluble P may become immobilized through adsorption onto the surface of $CaCO_3$ minerals. Retention by soil carbonates is thought to

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occur through adsorption of P by the calcite surface at low concentrations, and a nucleation process of Ca-phosphate crystals and subsequent crystal growth at higher P concentrations (Sample et al. 1980). As a result, availability of applied P can decrease quite rapidly. A study of the availability of applied P in 6 calcareous Lebanese soils showed sodium bicarbonate extractable P decreased markedly with time of soil-P contact, with the most rapid decline in the first 24 hours after which only 40 to 65% of the applied P was extractable (Ryan et al. 1985). Thereafter decline in extractable P was relatively uniform to 200 days.

Al and Fe oxides and hydrous oxides have long been known to play a dominant role in P retention in acid soils (Wild, 1950), but are not as important in neutral to calcareous soils (Soper and Racz 1980). However, Ryan et al. (1985) showed that even in calcareous soils the presence of iron oxides could contribute significantly to adsorption of applied P. Al and Fe oxides can occur as discrete compounds, coatings on soil particles, or as amorphous Al hydroxy compounds between layers of expandable Al silicates (Soper and Racz 1980). Adsorption of applied P by Al and Fe oxides occurs through exchange of phosphate for hydroxyl groups on the surface (specific adsorption) (Wild 1950), or penetration of P into less crystalline regions of the clay surface (Sample et al. 1980). Specific adsorption results in increased cation exchange capacity due to greater negative charge on the soil colloid. Retention by alumino-silicate minerals occurs through specific adsorption with OH groups linked to the gibbsite layer, as exchangeable anions to counter negative charge developed by adsorption of hydroxyl groups or protons of the gibbsite layer at low P concentrations (Wild 1950; Soper and Racz 1980). Studies by Ryan et al.

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(1985) indicate the effect of Fe oxides in the rapid initial P retention phase is through

adsorption/precipitation on amorphous surfaces, while the subsequent gradual decline in

available P with duration of soil-P contact is consistent with progressive crystallization of

Fe-P forms. With time the adsorbed P tends to vacate sorption sites and move to less

accessible regions of soil particles or to form discrete crystals.

2.2.4 Factors Affecting P Retention

Some major soil factors which influence P retention in soils include oxide content,

type and amount of clay, $CaCO_3$ content, pH, cation exchange capacity, temperature,

solution P concentration, and type and amount of organic matter (Doyle and Cowell

1993). Another very important factor which impacts on P retention is the method of

application (Bailey et al. 1980). The roles of oxides, clay minerals and $CaCO_3$ in P

retention have already been discussed in detail.

In alkaline and calcareous soils, increased soil pH results in an increase in the rate

of conversion of initial reaction products to more stable compounds. Bell and Black

(1970) noted greater rate of conversion of DCPD to OCP in soils pH>7.9 than in those

pH>6.9. In acid soils the fixation of P by aluminosilicate minerals is generally inversely

related to pH (ie. Higher pH decreases fixation rates) (Soper and Racz 1980).

Increased soil temperature is directly related to greater rates of P fixation (Beaton

et al. 1965; Sheppard and Racz 1980). The rate of hydrolysis of DCPD to OCP has been

shown to increase substantially at soil temperatures above 20°C (Sheppard and Racz

1980). As a result, P concentration in the soil solution tends to be inversely related to

temperature (Beaton et al. 1965). Differences in rate of change to nonextractable P forms

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are related to manner of fertilization and conditions of incubation (Ryan et al. 1985). The rapid rate in this study resulted from use of solution P rather than granules and optimum moisture with relatively constant temperature.

The concentration of phosphate in the soil solution also affects the fixation rate of P in soil because each successive increase in concentration of solution P results in a smaller increase in amount of P adsorbed, while a linear relationship exists between adsorbed phase and the amount of P fixed into ultra-stable forms (Barrow 1980).

Increased soil organic matter content will increase P adsorption (Rennie and McKercher 1959), a reflection of the association of organic matter with cations capable of fixing solution P, such as Ca, Fe and Al (Wild 1950; Weir and Soper 1963; Dormaar 1972; Soper and Racz 1980). These studies indicated that humus in soil organic matter affected P retention through its association with Ca, Fe and Al ions. Complexation of Ca^{2+} in soil solution could decrease precipitation of Ca-phosphates, while release of Al and Fe by humic acids could result in precipitation of Fe- and Al-phosphates. However, other studies (Grossl and Inskeep 1991) have shown organic acids may decrease P adsorption through complexation of calcium ions or competition with P for adsorption sites. Mnkeni and MacKenzie (1985) found that adsorbed P from applied pyrophosphate was negatively correlated with organic carbon levels in soils (ie. increased soil organic matter decreased pyrophosphate retention but had no effect on applied orthophosphate). This may have been due to the greater ability of the pyrophosphate to solubilize soil organic matter exposing more adsorption sites by removing organic matter coatings on soil minerals. Alfalfa residues and farmyard manure increased pH of these acid soils (pH 3.9 to 6.3) and

hence decreased exchangeable Al. This resulted in decreased adsorption of orthophosphate and pyrophosphate, although the results with pyrophosphate were variable with alfalfa additions.

The form of applied P may also affect the retention of applied P. Orthophosphate (OP) and pyrophosphate (PP) were shown to differ in terms of retention on Quebec soils ranging in pH from 3.9 to 6.3 (Mnkeni and MacKenzie 1985). OP adsorption was positively correlated with Fe and Al (sesquioxides), while PP reached a maximum and then declined at higher Fe and Al contents.

The method of fertilizer P application and the resulting placement of the P in the soil is also an important factor affecting P retention and efficiency (Bailey et al. 1980; Barrow 1980; Engelstad and Terman 1980). Increasing the area of fertilizer P affected soil will increase the surface area for precipitation and adsorption reactions, resulting in more rapid fixation and reduced availability. This is demonstrated by the findings that reducing the area of application for soluble P sources through banding as opposed to broadcasting reduces the rate of P retention and improves efficiency (Bailey et al. 1980; Englestad and Terman 1980).

The previous discussion indicates that performance of P fertilizer cannot be assessed completely on the basis of yield of the first or second crop because some of the intermediate reaction products can persist up to 5 to 10 years depending on rate of initial application, form of fertilizer P, crop removal characteristics, and the soil's pH, carbonate content, and buffering capacity for P (Barrow 1980; Soper and Racz 1980). Under dryland conditions residual P has been shown to increase available P status of the soil and

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induce a crop response (Read et al. 1973; Wagar et al. 1986). Conversion of DCPD and

OCP to hydroxyapatite is slow enough that they can persist in soils for long periods under

normal cropping conditions in western Canada and be available to the plant (Dawley 1965;

Read et al. 1973, 1977; Ridley and Tayakepisuthe 1974; Sadler and Stewart 1975, 1977;

Wagar et al. 1986). Residual P pools may be established from regular applications of small

amounts of P fertilizer over an extended period of time (Spratt and McCurdy 1966), or

through large batch applications of P fertilizer (Rennie and McKercher 1959; Sadler and

Stewart 1975).

While it appears that residual P may contribute to crop uptake over several years, it

would appear that major differences in fertilizer efficiency resulting from changes to band

geometry or chemistry would most likely result from differences in accessibility to the crop

or rate of conversion to residual P. The bulk of these differences will most likely be

evident in the year of application.

2.3 Fertilizer Use Efficiency

2.3.1 Influence of Type of Crop on Fertilizer Use Efficiency

Crops vary considerably in their ability to utilize applied P, and these differences

have probably developed at least partially in response to differences in P requirements.

For instance, canola may contain 0.8 to 1.0% P, more than twice that of wheat (0.35 to

0.45%) (Doyle and Cowell 1993). This translates into substantial differences in total P

utilized by crops. For example, on average, a 1961kg ha^{-1} canola crop will utilize 22.4 kg

ha^{-1} of phosphorus, while a 2690 kg ha^{-1} wheat or a 3228 kg ha^{-1} barley crop will only use

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between 14.2 and 14.6 kg ha^{-1} of P (Thomas 1984).

Canola and wheat differ considerably in terms of their feeding habits with regard to P. While advantageous symbiotic associations often form between wheat and vesicular-arbuscular mycorrhizae (VAM) capable of solubilizing P (Kucey 1987), such associations do not normally occur between canola and these microorganisms (Hirrel et al. 1978). However, the ability of canola plants to acidify the rhizosphere so as to increase availability of inorganic P provides an alternative mechanism for improving P uptake (Grinsted et al. 1982; Hedley et al. 1982; Moorby et al. 1985). It has also been shown that canola recovers a greater proportion of its P during early growth stages, while crops like wheat and flax recover their P more gradually (Racz et al. 1965).

Phosphorus utilization from bands and pellet-like applications of P has been shown to vary considerably for flax, wheat, canola and buckwheat (Strong and Soper 1974a). Canola and buckwheat showed a much greater ability to proliferate roots in the fertilizer reaction zone than wheat and flax and as a result were much more efficient at utilizing applied P. A subsequent study indicated that a greater concentration of available P within the reaction zone relative to the surrounding soil enhanced both the proportion of the root system proliferating within the zone and the apparent rate of absorption of P (Strong and Soper 1974b). Canola and buckwheat appear to be more capable of significant adjustments in root performance when they encounter a fertilizer reaction zone, in terms of both root proliferation and absorptive capacity.

2.3.2 Influence of Band Geometry and Placement on Fertilizer Use Efficiency

Band geometry is a term used to describe the position of applied P fertilizer relative

to the seed, or the distribution of the P fertilizer within the band. Both of the above can have a significant effect on the efficiency of use of fertilizer P.

2.3.2.1 Effect of Placement of Fertilizer P on Fertilizer Use Efficiency. Method of fertilizer P placement is one of the most important factors governing efficiency or recovery of supplemental P in the year of application (Bailey et al. 1980; Barrow 1980; Sheppard and Racz 1980). Soluble P reacts rapidly with soil components and becomes immobile, and thus placement to minimize fixation and maximize access to plant roots is desirable (Engelstad and Terman 1980). Method of placement will affect the area of fertilizer P affected soil, and the distance between the fertilizer and the seed. As discussed previously (Section 2.2.4), increasing the area of affected soil increases P fixation. However, while reducing the area of application may increase solubility, it may also limit contact between the plant roots and fertilizer P, and hence P uptake. Eghball and Sander (1989) found this trend was compounded with increases in the distance between the applied P and the seed, since the increased distance also reduced the probability of the roots contacting the fertilizer, as well as increasing the time required for contact to occur.

Placement of P with the seed often results in more efficient utilization than other methods of placement (Olson and Dreier 1956a; Olson et al. 1956a; Bailey et al. 1980; Peterson et al. 1981; Bailey and Grant 1990; Doyle and Cowell 1993), because it reduces surface contact between soil and fertilizer while placing a readily available source of P in close proximity to the roots of young seedlings. Supplemental P applied in this manner is most beneficial under cool wet soil conditions and can cause more rapid, vigorous emergence (sometimes called "pop-up" effect) for fertilized crops than other placement

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methods (Engelstad and Terman 1980; Zentner et al. 1993), particularly at low soil

temperatures. This is due to the restricted availability of soil P to plants at low soil

temperatures resulting from several factors including reductions in the quantity and

availability of available P sources, restricted mineralization of organic P and restricted root

growth (Sutton 1969; Sheppard and Racz 1980). Starter P applied with the seed will

improve growth under these conditions by permitting earlier crop growth, or accumulation

of P allowing more rapid growth when temperatures rise (Sutton 1969). The effectiveness

of seed-placed P will decline as soil temperature increases due to a combination of

improved availability of soil P and increased toxicity of the seed-placed fertilizer (Sheppard

and Racz 1985). Seed-placed P application can become restrictive and less practical as

farm size and fertilizer rates increase, due to toxicity effects which can occur at higher

rates of fertilizer application, particularly for oilseed crops such as canola and flax (Nyborg

and Hennig 1969; Bailey and Grant 1990).

Alternatives to placement of P with the seed include banding near the seed (eg.

side-banding), pre-plant banding and broadcasting. An important factor affecting the

efficiency of banded P fertilizer will be the distance between the applied P and the seed

row (Bailey et al. 1980). Increasing the distance between the seed and fertilizer band has

often been shown to reduce P uptake and yield (Nyborg and Hennig 1969; Beever 1987;

Eghball and Sander 1989; Flaten 1989). These reductions may be due to a longer delay

prior to contact of roots with the fertilizer and initiation of fertilizer P uptake (Beever

1987; Flaten 1989), as well as reduced probability of root-fertilizer contact occurring

(Eghball and Sander 1989). Eghball and Sander (1989) have shown that the surface area

of fertilizer P affected soil must be increased substantially to retain root-fertilizer band contact when the distance between the fertilizer band and seed row is large. However, it is important to note that banding a few cm below the seed depth has been shown to improve fertilizer P uptake when the surface soil is dry, due to higher moisture at lower depths (Singh 1962; McConnell et al. 1986). This is due to the fact that P from fertilizer stranded in dry soil cannot be absorbed by crops such as wheat (Boatwright et al. 1964).

Broadcast application of highly soluble P sources is less efficient than seed-placed or band application due to rapid immobilization of P by soil constituents (Bailey et al. 1980). In contrast, effectiveness of broadcast application of P sources of very low solubility is greater than when banded (Engelstad and Terman 1980). However, the relative efficiency of broadcasting as compared to banding with the seed can vary. Peterson et al. (1981) found that on soils testing low in available P the ratio of the amount of broadcast compared to seed-placed P required to give an equal yield response was 3:1. The ratio declined to 1:1 on soils with medium levels of available P. Sleight et al. (1984) suggested that the greater efficiency of fertilizer P utilization at early growth stages from banding as compared to broadcasting was a result of placing all of the fertilizer in a position where contact by active roots was likely, rather than from increased availabilty due to reduced area for fixation reactions.

Reducing soil-fertilizer contact (concentrating P fertilizer in a smaller volume of soil (eg. banding) to limit fixation processes reduces root-fertilizer contact. An effective method of application must offer a balance between the benefits of reduced opportunity for fixation, and the benefits of improved probability of root-fertilizer contact with all of the

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fertilizer P applied. Most crops respond well to P banded a short distance below or below and to the side of the seed (Bailey et al. 1980), due to good root to fertilizer contact. However, a small amount of seed-placed P may still be required to maximize yields, depending on the distance between the fertilizer band and seed row and soil temperature and moisture.

2.3.2.2 Effects of Fertilizer P Distribution Within the Band on Availability and Utilization. Fertilizer P placed into the soil moves from the point of application to form a near perfect sphere. The volume of this hydration sphere, and hence the surface area of soil-fertilizer contact, varies depending on a number of factors and affects the utilization of applied P. Eghball and Sander (1989) found that the volume of soil affected by P fertilizer increased quadratically as the application rate increased for injection points of ammonium polyphosphate solution. For granular applications the effect was similar, with size of hydration spheres increasing with granule size (Lawton and Vomicil 1954). The soil's P fixation capacity is also important. Soils with a higher fixation capacity will result in less movement of P away from the point of application, and result in a decrease in root-fertilizer contact. Sleight et al. (1984) found that increasing injection point spacing to 48 mm with ammonium polyphosphate solution increased the fertilizer P uptake and yield of oats. The increase in fertilizer P uptake was attributed to an increase in the area of fertilizer P affected soil resulting from less overlapping of hydration spheres at the wider injection point spacing. These trends were less pronounced in the soils with a lower P fixation capacity, where the increased mobility of the added P would make improved root-fertilizer contact less necessary, providing further support for this explanation.

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Most of the currently used methods of P application in western Canada result in discontinuous P distributions within the fertilizer bands. Size of P fertilizer granules influences utilization of applied P by affecting its distribution in soil, effective surface area and, therefore, the reactivity of P fertilizer with soil (Anghinoni and Barber 1980; Sleight et al. 1984). Sander and Eghball (1988) found that fertilizer P uptake and wheat yield were affected by particle size, but effects of granule size tended to decrease as rate of application increased. The relationship between fertilizer P uptake and granule size was quadratic indicating an optimum particle size, the value of which depended on the application rate and soil type. Sizes smaller than the optimum resulted in too great a surface area for reaction with soil and soil constituents resulting in increased fixation of applied P. Sizes greater than the optimum resulted in discontinuous bands and decreased root-fertilizer contact. The optimum granule sizes for both of these soils were well below the common 20 mg particle size found in commercial farm fertilizer sources.

One might expect the distribution of fertilizer within the band to be much more uniform for liquid than granular fertilizer. Results of trials with ammonium polyphosphate solution (Eghball and Sander 1987) showed that distance between droplets within the band, as delivered from a standard John Blue (John Blue Co., Huntsville, AL) hose pump, was significantly increased by reducing rate of P application from each delivery point and decreasing speed of travel below 4.5 km h^{-1} during application. Rate of application at each delivery point declined with lower rates of P application and narrower delivery point spacing. These results clearly indicated that liquid applications under field conditions would often result in discontinuous bands, particularly at lower rates of application.

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The above mentioned studies support the concept that P fertilizer efficiency from bands close to the seed would be improved by increasing root-fertilizer contact. This could be achieved by root proliferation in a continuous band, as compared to discontinuous bands caused either by large dry fertilizer particles or large droplet sizes from liquid applicators. Eghball and Sander (1987) calculated that in a discontinuous band over 80 root-fertilizer contacts could be required by one corn plant to supply an adequate level of P. They suggested that plant roots may follow a continuous band with one root contact, while discontinuous bands would require at least one contact for each droplet or particle. Since plant roots contact only 1-2 % of the soil volume, this would decrease the probability of exploiting discontinuous bands as effectively as continuous ones.

2.3.3 Influence of Organic Compounds on Fertilizer P Utilization.

Several researchers have isolated microorganisms from the soil, including bacteria and fungi, which have the ability to solubilize P (Kucey 1983; Asea et al. 1988; Leyval and Berthelin 1989; Salih et al. 1989; Illmer and Schinner 1992). In some cases these microorganisms have been utilized as inoculum in order to improve P availability and utilization by field crops (Kucey 1988; Kucey and Leggett 1989). With the wide variety of organisms which have been found to have the ability to solubilize inorganic P, the fact that several mechanisms for this process have been proposed is not surprising. Some researchers have suggested that production of organic acids resulting in acidification of the soil is an important mechanism for P solubilization by microorganisms (Kucey and Leggett 1989; Leyval and Berthelin 1989; Salih et al. 1989). However, while acidification will increase the solubility of insoluble phosphates, the weak or lacking linear correlation

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between pH of the culture media and the level of solubilized P in other studies reported in the literature suggests that one or several other mechanisms must be involved (Kucey 1983; Asea et al. 1988; Ehrlich 1990; Illmer and Schinner 1992). One alternative process for solubilization of P by these organisms is release of H^+ from the cytoplasm to the outer surface (Illmer and Schinner 1992), resulting in solubilization directly at the cell surface and rapid absorption. This could occur in exchange for cation (especially NH_4^+) uptake or with the help of H^+ translocating ATPase in the plasmalemma which uses the energy of ATP hydrolysis (Beever and Burns 1980). Other processes by which organisms may solubilize phosphorus include the production of chelators which can complex the cationic portion of phosphate salts such as calcium phosphates, altering their solubility and forcing their dissolution (Kucey 1983; Ehrlich 1990), or accumulation and precipitation of these cations with organic acids making them unavailable for precipitation reactions with phosphate (Beever and Burns 1980). Ehrlich (1990) also suggested the possibility of formation of hydrogen sulphide which can react with iron phosphate and precipitate iron sulphide, releasing soluble phosphate.

While it is unclear which of the above mechanisms are most important for P solubilization in agricultural soils, it is apparent that the microbial community and the organic compounds produced by it are important in solubilizing inorganic P which may otherwise be unavailable to plants. The previous discussion illustrates some promising potential for improving P utilization in agricultural crops by the addition of microorganisms to agricultural soils. However, it is very difficult to introduce foreign microorganisms into agricultural environments. Development of effective inoculum tends

to be complicated, because it tends to be composed of a mixture of species and strains of P solubilizers isolated from local soils. Taha et al. (1969) found that a USSR strain of B. Megatherium var. phosphaticum was not as effective as local strains, due to differences in soil type and other conditions. Mixed inoculation is generally more effective than single, due to cooperative and synergistic effects (Banik and Dey 1981). The inoculum must also be competitive with strains already present in the soil in order to establish a viable population, as shown by Thomas et al. (1985). These authors found the greatest P solubilization from the fungi with the greatest competitive saprophitic ability.

Due to the difficulties in introducing microorganisms into agricultural soils, some studies have been conducted to study the effect of applications of the organic acids to soil on P availability and utilization. Fox et al. (1990) found that low molecular weight organic acids may participate in ligand exchange reactions, resulting in the release of P from the inner-sphere complex of aluminum oxide surfaces. There was generally, with a few exceptions, a trend of increased release of Al and inorganic P with an increase in the log K_{Al} when organic acids were applied to the soil. Grossl and Inskeep (1991) examined the effect of humic, fulvic, tannic and citric acid on the precipitation of dicalcium phosphate dihydrate (DCPD), a common reaction product of P fertilizer in calcareous soils. Results indicated that all of the organic acids inhibited DCPD formation, citrate being the most effective. The primary mechanism appeared to be adsorption of the organic acid onto the DCPD surfaces, blocking sites for new crystal growth.

Lignosulfonates are organic by-products of the pulp and paper industry produced from the sulfite pulping process. They are soluble lignin derivatives with negatively

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charged sulfonate, hydroxyl, carboxylic, and phenolic groups near the surface, contributing to their high water solubility and potential to participate in a variety of reactions in soil. Recently, several researchers have undertaken studies to determine the effects of application of lignosulfonate to the soil, as a means of disposal. These studies have indicated effects including stimulated microbial respiration (Meier et al. 1993), and increased ammoniacal nitrogen concentrations, due to a combination of decreased ammonia volatilization and inhibition of nitrification or blockage of ammonium fixation sites (Al-Kanani et al. 1994; Meier et al. 1993). Al-Kanani et al. (1994) also found little effect on immobilization of N despite the high C/N ratio of 10:1, indicating either resistance to microbial degradation or that the lignosulfonate may act as a general metabolic inhibitor for a period of time after application. Lignosulfonate, which can chelate a variety of micronutrients, was shown by several researchers to improve plant availability and uptake of micronutrients when used as a carrier (Sajwan and Lindsay 1988; Singh et al. 1986; Raese et al. 1986; Cihacek 1984). Xie et al. (1991) demonstrated that addition of calcium lignosulfonate to soil decreased pH and concentration of phosphorus in solution, probably due to precipitation of calcium phosphates. However, addition of ammonium lignosulfonate resulted in increased solution P concentration, apparently through competition between lignosulfonate and phosphate ions for adsorption sites. A subsequent study by Russell et al. (1991) found that applying mixtures of ammonium lignosulfonate and triple superphosphate improved the uptake of P by corn as compared to treatments receiving only triple superphosphate. Further studies of various addition sequences of ammonium lignosulfonate and diammonium phosphate indicated that

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increasing the rate of application of ammonium lignosulfonate decreased P retention, an indication that competition between lignosulfonate and phosphate ions was a major mechanism of improved P availability (Xie et al. 1993). The authors suggested that preincubation with ammonium lignosulfonate resulted in lignosulfonate adsorption which then blocked phosphate adsorption due to increased surface negative charge and the large size of the lignosulfonate ions which cover a large proportion of the surface. Decreased soil pH did not increase P adsorption indicating that the lignosulfonate addition led to calcium complexation and blockage of P adsorption sites.

2.3.4 Nitrogen Fertilizer Effects on Fertilizer P Utilization.

Recent developments in air seeding technology have prompted more farmers to apply their N and P fertilizer in a common band prior to seeding (often referred to as dual banding). This has the benefit of reducing handling of fertilizer at seeding time, as well as decreasing the risk of seedling damage which may result from higher rates of P application in the seed row (Nyborg and Hennig 1969). Another potential advantage may be the positive interaction between dual banded N and P which has been noted by several authors for a variety of crops (Miller and Ohlrogge 1958; Grunes 1959; Miller and Vij 1962; Miller 1965; Grant et al. 1984; Beever 1987; Flaten 1989). However, research has shown that placing P in a band farther away from the seed row can reduce yield response and P uptake (Nyborg and Hennig 1969; Beever 1987; Flaten 1989), due to the increased distance the roots must grow to reach the fertilizer band. The greater distance may delay initiation of fertilizer P uptake substantially (Beever 1987; Flaten 1989). The efficiency of P fertilizer applied in this manner will reflect all of the above effects.

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Some of the earliest research into the positive impact of N on fertilizer P uptake took place in the early 1940's and 1950's in Saskatchewan where researchers found yield responses of cereal grains to P fertilizer additions were greater for MAP than calcium phosphates (Mitchell 1946; Dion et al. 1949a,b; Mitchell 1957; Rennie and Soper 1958; Beaton and Read 1963). Studies as early as 1939 (Mitchell 1946) comparing MAP, triple superphosphate and ammoniated superphosphate found that MAP was most effective in improving yield, particularly at lower application rates and under cool moist conditions. The use of ^{32}P radioisotope in the late 1940's greatly improved the ability of researchers to differentiate between soil and fertilizer P taken up by plants. Dion et al. (1949), in a review of experiments conducted using radiophosphorus at the University of Saskatchewan, indicated that MAP was superior to monocalcium phosphate (MCP) and dicalcium phosphate (DCP) in terms of uptake due to increased availability. MCP and DCP were less available due to rapid conversion of these sources to less soluble tricalcium phosphates.

These initial findings led to further studies of the effects of applying N and P fertilizers together. Plant uptake of P was found to be enhanced when ammonium was blended or combined with a P source (Rennie and Mitchell 1954; Rennie and Soper 1958). Banding of N with P also made distance of application from the seed row less critical than when P was applied alone (Flaten 1989), apparently due to movement of N out of the band resulting in a larger target for root contact.

The positive effects of N on fertilizer P utilization have been most pronounced for those sources providing N in the form of ammonium. Nitrate carriers have been shown to

increase P uptake only to the extent that they stimulate growth of larger plants, while N

salts containing the ammonium ion can give much greater increases in uptake of P from

MAP, though only when applied in direct contact with the P fertilizer (Rennie and Soper

1958). Nielsen et al. (1967) studied the effect of N-serve (2 chloro-6-(trichloromethyl

pyridine)), a nitrification inhibitor, on P absorption by wheat. While ammonium ions were

not as readily absorbed by the plant as nitrate, the ammonium ions still enhanced P uptake

more than nitrate, indicating that the ammonium ion was influencing the process by which

P was absorbed by the plant. Thomson et al. (1993) also found similar results. This

"ammonium ion effect" can be linked to either chemical or biological mechanisms, or more

likely to a combination of both, for enhancing P uptake. The chemical mechanisms involve

increases in reaction zone size and fertilizer P concentration, while the biological

mechanisms involve increases in root contact with, and proliferation in, the fertilizer band

or zone, cation/anion balance, and absorption transfer processes (Beever 1987).

Under certain conditions negative effects of dual banding of N and P on P

utilization can occur. Application of high rates of N in dual N-P bands can interfere with P

uptake unless bands are allowed to "age" (Flaten 1989). Flaten (1989) observed a

depression in P uptake when urea was added in the band if the band was located close to

the seed row, while enhancement of P uptake occurred if the distance was increased. This

interference was attributed to high concentrations of free ammonia and elevated pH levels

(Flaten 1989). Other research has indicated that nitrite accumulation, which is toxic to

plant roots, is enhanced by high concentrations of ammoniacal N and alkaline pH which

can occur in urea bands (Aleem and Alexander 1960; Court et al. 1964). Beever (1987)

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reported high concentrations of nitrite and ammonia persisted in dual N-P bands for a significant period after application and could result in reduced P uptake at early growth stages. However, this effect varied with soil characteristics. Fan and MacKenzie (1994) found that on acid soils the initial increase in pH from urea hydrolysis increased availability and uptake of P from TSP and MAP by corn at the six to nine leaf stage. This was credited to reduced fixation by Fe and Al at the higher pH.

2.3.4.1 Chemical Mechanisms Influencing the Effects of N on Fertilizer P Utilization. The chemical effects of ammoniacal N on P absorption by plants are related to the altering of the availability of the fertilizer P source. These effects result mainly from changes in the pH and ionic strength within the fertilizer band. A study by Cho and Caldwell (1959) found that iron and aluminum phosphates were abundant in acid soils, calcium phosphates dominated in alkaline soils, and a relatively equal distribution occurred under neutral pH conditions. The availability of P was found to decrease as pH of the soil departed from neutral values.

Urea fertilizer applied to soil undergoes rapid hydrolysis releasing ammonium and hydroxyl ions. This has been shown to increase the pH of the fertilizer reaction zone by as much as one unit initially, but over time oxidation of the ammonium to nitrate reduces the pH below that of the control (Isensee and Walsh 1971). The study also indicated that high and perhaps toxic levels of NO_2-N accumulated near the fertilizer band when urea was applied. This was most likely due to the combination of high salt and NH_4-N concentrations and alkaline conditions which inhibit nitrification (Johnson and Guenzi 1963). This initial increase in pH can reduce the solubility of Ca, Mg and P through

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greater formation of insoluble phosphate compounds, but concentrations should then begin to increase as pH declines due to nitrification (Isensee and Walsh 1972). These results are in agreement with Flaten (1989) who reported that addition of urea to P bands resulted in lower initial fertilizer P uptake, followed by enhanced uptake later in the season sufficient to overcome the initial decline, as compared to N and P applied separately. The decrease in initial uptake was greater when the distance between the dual N-P band and the seed row was reduced.

While NH_4^+-N sources have clearly been shown to affect pH in the fertilizer band and the rhizosphere, it is not clear that this is the major mechanism involved in the ammonium ion effect. Rennie and Soper (1958) found that while dual banding with ammonium sulphate increased fertilizer P uptake, the acid salt potassium sulphate added to give an equivalent reduction in pH had a negative, if any, effect on P utilization. The increased P uptake also occurred early in growth, and not at later stages as would be expected from an acidity effect. The lack of improvement in P uptake from acidification of the band, especially in calcareous soils, has been noted by several authors (Olson and Dreier 1956b; Grunes et al. 1958). They postulated that acidification increased the solubility of calcium, resulting in increased precipitation of the P fertilizer and offsetting the benefits of the increase in P solubility. This increase in Ca solubility was also noted by Isensee and Walsh (1971, 1972).

In addition to pH effects, salt effects on the ionic strength of the soil solution and exchange reactions within the fertilizer reaction zone as a result of dual banding need consideration. This effect was described by Barry et al. (1983) as the "snow-plow effect",

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which occurs when adsorbed ions in a soil with a relatively low cation exchange capacity are desorbed by an incoming solution of high concentration through competition for exchange sites. This is thought to occur under field conditions as the saturated fertilizer solution moves outward from the point of application, pushing the desorbed ions ahead of the solution front, at least for a short distance (Starr and Parlange 1979). A numerical investigation of this effect by Cho (1985) indicated that concentration distributions of the displacing and displaced ions are dependent on the selectivity coefficient of the ion exchange reaction, the exchange capacity of the soil and the concentration of the displacing ions. Soils with a high CEC favour desorption of divalent cations over monovalent.

Variations in ion concentration and distribution resulting from the "snow-plow effect" may help to explain the effect of N on P solubility and uptake (Beever 1987). Grunes (1959) noted that ion effects resulting from increased ionic strength could increase solubility of phosphate. However, this benefit could be offset by increased calcium concentrations which would result in increased Ca-phosphate precipitation, a response which was noted by Isensee and Walsh (1971, 1972). The lack of positive response of P uptake to dual banding with nitrate or potassium fertilizers (Olson et al. 1956b; Grunes et al. 1958; Rennie and Soper 1958; Leonce and Miller 1966) also indicates that any benefit of salt effects would be relatively small.

2.3.4.2 Biological Mechanisms Influencing the Effect of N on Fertilizer P Utilization. The biological effects of ammoniacal N on P uptake by plants include changes in the morphology and/or physiology of the plant which have an impact on P utilization (Beever

1987). One suggested effect of N on P utilization is the increase in both contact of roots with the fertilizer band and root proliferation within the zone of elevated nutrient levels. Grunes (1959) suggested that dual application of N and P increased root growth and area of absorption in the phosphate band. Stimulation of root proliferation by localized supplies of nitrate or ammonium has also been demonstrated by other researchers (Duncan and Ohlrogge 1958; Drew 1975; Drew and Saker 1978), particularly when applied in the same zone with P, and provided concentrations of salt, ammonia or nitrite are below toxic levels. Dual banding with urea was found to provide a larger target for root contact (Flaten and Racz 1985), and after contact root proliferation in the area of high nutrient concentration ensured good P uptake provided N levels were not excessive. Miller and Ohlrogge (1958) concluded that ammonium sulphate placed with the P in a localized band increased the relative feeding power of the corn plant on the band P through the development of a root mass in the area of N and P placement. Improved root proliferation cannot completely explain the ammonium ion effect, however. Duncan and Ohlrogge (1959) noted that the root to shoot ratio remained constant, indicating that in some instances the N can cause a change in root distribution rather than an increase in growth. Root proliferation can also be stimulated by KNO_3 and KCl without affecting P uptake (Duncan and Ohlrogge 1958; Blanchar and Caldwell 1966a,b), and the ammonium ion effect may occur in the absence of increased root proliferation (Miller and Vij 1962; Riley and Barber 1971).

Miller (1965) indicated that increased corn root growth within the band volume, increased top growth or N content, in the presence of ammonium sulphate, were not the

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primary causes of increased P absorption. He suggested that the ammonium sulphate exerted a specific influence on the physiological activity that controls P absorption. Rennie and Soper (1958) suggested that the stimulation of P uptake at early growth stages would be well correlated with the rapid ammonium-nitrogen absorption at early growth stages as reported by Stahl and Shive (1933), and hence the effect of the ammonium ion on P uptake was more to do with its influence on the plants ability to take up P than on its effect on solubility of the applied P. Studies by Cole et al. (1963) and Thien and McFee (1970) in which N pretreatments of corn plants increased P absorption and translocation rates, would also appear to support the possibility that N affects the mechanisms of P uptake. However, the complexity of these processes have made collection of any direct evidence for the influence of N on biological uptake processes very difficult.

One final mechanism by which N may affect P utilization is through its effect on the cation/anion balance within the plant. Changes to the plant and the soil surrounding the roots occur in order for the plant to maintain electroneutrality during ion uptake. Riley and Barber (1969) showed that increasing the supply of nitrate to plant roots resulted in accumulation of HCO_3^- and increased pH in the rhizosphere. Ammonium ion uptake decreased pH in the rhizosphere, most likely through excretion of H^+ in exchange for ammonium ions as suggested by Miller et al. (1970). This change in rhizosphere pH has been found to be more closely correlated with changes in P absorption than changes in pH of the bulk soil (Riley and Barber 1971). Reduced rhizocylinder pH is associated with increased rhizocylinder P concentration and increased P uptake (Soon and Miller 1977). However, P absorption was 50% greater in the presence of NH_4^+-N than could be

explained on the basis of rhizocylinder P concentration alone, in these studies.

In addition to direct effects on P solubility, reduced rhizosphere pH would also shift the equilibrium of $H_2PO_4^-$ and HPO_4^{2-} in favour of formation of $H_2PO_4^-$ (Miller et al. 1970; Riley and Barber 1971). This form ($H_2PO_4^-$) is the plant's physiological preference and is absorbed at a greater rate than HPO_4^{2-} (Hagen and Hopkins 1955). However, this would not fully explain the ammonium ion effects on lower pH soils where $H_2PO_4^-$ would already predominate (Blair et al. 1971). Thomson et al. (1993) indicated that decreases in pH in the bulk soil and the rhizosphere were similar for ammonium sulphate added to potassium phosphate bands, unless a nitrification inhibitor was added.

From the above discussion it is evident that no one mechanism can be used to describe the ammonium ion effect. It would appear that there are a number of mechanisms involved in the influence of ammonium ion on fertilizer P utilization, and that the dominant ones may vary depending on the conditions involved.

2.3.5 Effects of Other Fertilizer Sources on the Utilization of Fertilizer P

Non-phosphatic salts other than N sources can also affect the availability and uptake of fertilizer P sources. Bouldin and Sample (1958) studied the effects of KCl, KNO_3, NH_4Cl, NH_4NO_3 and $(NH_4)_2SO_4$ on water soluble and extractable P levels and P uptake by oat plants from concentrated superphosphate (CSP). All of the salts were effective in improving the availability of the CSP. Of the two potassium sources, KCl was the least effective while KNO_3 was the most effective of the five sources. Other studies with KCl have shown reductions in mobility and solubility of applied potassium phosphate when the two are applied together in a system dominated by exchangeable calcium

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(Akinremi and Cho 1993). This was attributed to displacement of calcium into solution resulting in increased precipitation of calcium phosphates near the point of application. Studies including K_2SO_4 as well as these other salts indicated that potassium sulphate would be more effective than than KCl or KNO_3 in improving P availability due to less precipitation of applied P at the point of application (Bouldin et al. 1960). This appears to result from precipitation of calcium sulphates which would reduce the levels of soluble calcium available for precipitation with phosphate.

In several instances the incorporation of sulphur into bands of P fertilizer has been shown to improve yield and fertilizer P uptake. Mitchell et al. (1952) found increasing the rate of sulphur incorporated into MAP bands or dual bands of dicalcium phosphate and nitrate increased fertilizer P utilization by wheat, due to oxidation of the sulphur resulting in acidification within the fertilizer reaction zone. However, field studies resulted in no effect, due to poor oxidation of S under field conditions as compared to the greenhouse. Morden et al. (1986) found that both ammonium and sodium thiosulphate sources incorporated into MAP bands increased fertilizer P uptake and dry matter yield of barley. The benefits were again attributed to oxidation of the thiosulphate to sulphate resulting in acidification of the fertilizer reaction zone. However, the effectiveness of the thiosulphate under field conditions was not studied.

What is clear from all of the previously mentioned studies is that the effectiveness of any particular neutral salt in improving the availability of an applied P source will be dictated mainly by the chemical effects of the salt on the system. This may explain why the ammonium N sources often perform more effectively in this role, since there is clearly

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evidence that the ammonium N has both chemical and biological influences on fertilizer P uptake.

2.4 Prospects for Improving Efficiency of P Utilization

From the preceding review it is clear that the mechanisms influencing the efficiency of P fertilizers are very complex. In spite of the vast amount of research which has been conducted, fertilizer P efficiency remains quite low. Finding the optimum method of application which balances maximizing access to plant roots while minimizing fixation processes remains a challenge. Further research with regard to band geometry, particularly as it applies to form and distribution of the P fertilizer within the band, may yet yield significant improvements. There may also be opportunities for the introduction of chemical or organic amendments into the band which will help maintain the availability of the P over a longer period of time.

3. THE EFFECT OF BAND GEOMETRY AND CHEMISTRY ON FERTILIZER PHOSPHORUS AVAILABILITY

3.1 Abstract

Growth chamber experiments were undertaken to study the potential for increasing the utilization of applied phosphorus by annual crops, through modification of the area (or volume) of application and/or the chemistry of the fertilizer band. The first study was conducted using a silty clay loam soil, with wheat and canola as test crops. Phosphorus was applied as a solution of monoammonium phosphate (MAP) labelled with ^{32}P, in bands centered 1.25 cm below and beside the seed row. Fertilizer band geometries ranged from three spots placed 5 cm apart to simulate granules, to a 2.5 cm wide continuous band. Several band geometries were duplicated as dual bands of MAP with either ammonium sulphate or urea applied in solution. A second study with wheat was conducted using the fertilizers in fine granular form. Fertilizer bands involved similar band geometries, but some of the larger bands involved relatively large volumes of soil being fertilized (eg. 2.5 x 1.0 x 12.5 cm). Magnesium sulphate was also explored as a chemical amendment to study its effect on MAP efficiency.

With canola, increasing the area of fertilizer application and/or dual banding with N failed to increase utilization of applied P, and appeared to decrease fertilizer P uptake in some cases. However, with wheat both Mg_2SO_4 and $(NH_4)_2SO_4$ dual bands were effective

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in improving MAP efficiency. The greatest utilization of applied phosphorus occurred from the ammonium sulphate and MAP dual bands with the greatest area (or volume) of soil fertilized.

3.2 Introduction

Even in P responsive situations and for the most effective of current fertilizer application methods, uptake of greater than one third of applied phosphorus is exceptional for many crops. As a result, much research has been undertaken with the aim of improving the utilization of applied fertilizer phosphorus. Much of the research has involved the use of granular P fertilizers with granule sizes often in excess of 15 mg, resulting in wide granule spacing within the fertilizer band at low to moderate application rates. The use of conventional liquid application equipment appears to result in little improvement in uptake of applied P compared to granular applications, due to large droplet sizes resulting in wide droplet spacing (Eghball and Sander 1987). Decreasing granule size can improve P fertilizer uptake in wheat (Sander and Eghball 1988), due to the resulting increase in continuity of the fertilizer zone. All of these findings can probably be explained by the increased frequency of root-fertilizer contact caused by increasing the surface area of fertilizer P affected soil, which results in increased uptake of the applied P (Eghball and Sander 1989).

Based on the results mentioned above it was postulated that there might be potential for improvement in utilization of applied P by increasing the area and continuity of the fertilizer band. The purpose of these particular studies was to examine several

methods of fertilizer application which might increase the utilization of P from applied

monoammonium phosphate (MAP) fertilizer. These methods involved varying the area or

band width of fertilizer application. The potential for enhancement of uptake through

chemical modifications of the fertilizer band was also explored. Chemical modifications

included dual banding of the MAP with several other fertilizers.

3.3 Materials and Methods

3.3.1 Effect of band geometry and chemistry on fertilizer P uptake by wheat and canola - P fertilizer applied in solution form.

3.3.1.1 Experimental Setup and Procedures. A growth chamber experiment involving

three replicates of thirteen treatments, arranged in a completely randomized design, with

two test crops, wheat (*Triticum aestivum* var. Katepwa) and canola (*Brassica napus* var.

AC Excel) was conducted.

The soil used in the study (Table 3.1) was taken from the surface 15 to 20 cm of

the profile, passed through a sieve with openings of 1.5 x 3.5 cm to break up any large

clods, and spread out on plastic to air dry. The soil was mixed occasionally to speed this

process.

A 2500 gram portion of soil was placed into 3.5 litre pots. The top 2.5 cm of soil

was removed, the remaining soil was watered to field capacity, and the fertilizer bands

applied to the surface. The treatments are described in detail in Table 3.2 and Figure 3.1.

The fertilizers were applied at rates equivalent to 7.5 kg ha^{-1} of P and 50 kg ha^{-1} of N, and

the MAP was labelled with the radioisotope ^{32}P. The solution for the wheat experiment

was labelled with 37 MBq of ^{32}P as H_3PO_4 in 0.02N HCl, such that it received 2.96 x 10^4

3.1 Some chemical and physical characteristics of the soil used[z].

Characteristics	
Soil Classification	Cumulic Regosol
Soil Association	Riverdale Association
Soil Texture	Silty clay loam
Gravimetric field capacity	32%
$NaHCO_3$ extractable P	4.5 $\mu g\ g^{-1}$
Inorganic Carbon	10.6 g C kg^{-1}
Exchangeable Cations:	
Ca^{++}	4078 $\mu g\ g^{-1}$
Mg^{++}	302 $\mu g\ g^{-1}$
K^{++}	271 $\mu g\ g^{-1}$
Na^{++}	30 $\mu g\ g^{-1}$
pH (soil-water)	7.9
Electrical Conductivity	0.43 dS m^{-1}

[z]Note: Detailed descriptions of the soil analysis procedures are outlined in Appendix II.

Bq mg^{-1} ^{31}P. The solution for the canola experiment was labelled with 74 MBq of ^{32}P as H_3PO_4 in 0.02N HCl, such that it received 5.92 x 10^4 Bq mg^{-1} ^{31}P. The MAP was applied as 0.6 ml of solution with a P concentration of 0.807 M. The ammonium sulphate and urea were applied as 1.2 ml of solution with an N concentration of 5.933 M. All fertilizer applications were made using a micro-pipette, and for bands involving areas of application the solution was spread over the entire area as uniformly as possible. One-half of the soil which had been removed from the pots was then replaced, a row of twelve seeds placed along the center of the pots and the remaining soil replaced. The pots were then watered to field capacity, placed into the growth chamber, and kept near field capacity by watering every 2 to 3 days.

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Table 3.2 Treatments for growth chamber study with solution P fertilizer.

Treatment #	P Fertilizer	N Fertilizer	Fertilizer Application[z]
1	None	Ammonium Sulphate	Narrow continuous band.
2	None	Urea	Narrow continuous band.
3	MAP	Ammonium Sulphate	P applied as three 0.2 ml droplets 5 cm apart in a row; N applied as in treatment 1on opposite side of the seed row.
4	MAP	Ammonium Sulphate	P applied as six 0.1 ml droplets 2.5 cm apart in a row; N applied as described in treatment 3.
5	MAP	Ammonium Sulphate	P applied as a narrow continuous band; N applied as described in treatment 3.
6	MAP	Ammonium Sulphate	P applied as a 1.5 cm wide continuous band; N applied as described in treatment 3.
7	MAP[y]	Ammonium Sulphate	P applied as a 2.5 cm wide continuous band; N applied as described in treatment 3.
8	MAP	Ammonium Sulphate	Dual application: P applied as in treatment 3; N applied to same location as P.
9	MAP	Ammonium Sulphate	Dual application: P applied as in treatment 5; N applied to same location as the P application.
10	MAP[y]	Ammonium Sulphate	Dual application: P applied as in treatment 7; N applied to same location as the P application.
11	MAP	Urea	Dual application: P applied as in treatment 3; N applied to same location as the P application.
12	MAP	Urea	Dual application: P applied as in treatment 5; N applied to same location as the P application.
13	MAP[y]	Urea	Dual application: P applied as in treatment 7; N applied to same location as the P application.

z All of the fertilizer bands were centered 1.25 cm below and 1.25 cm beside the seed row.
y The phosphorus fertilizer solution was diluted 1:1 with distilled water to provide sufficient solution for distribution over the entire surface of the 2.5 cm wide band.
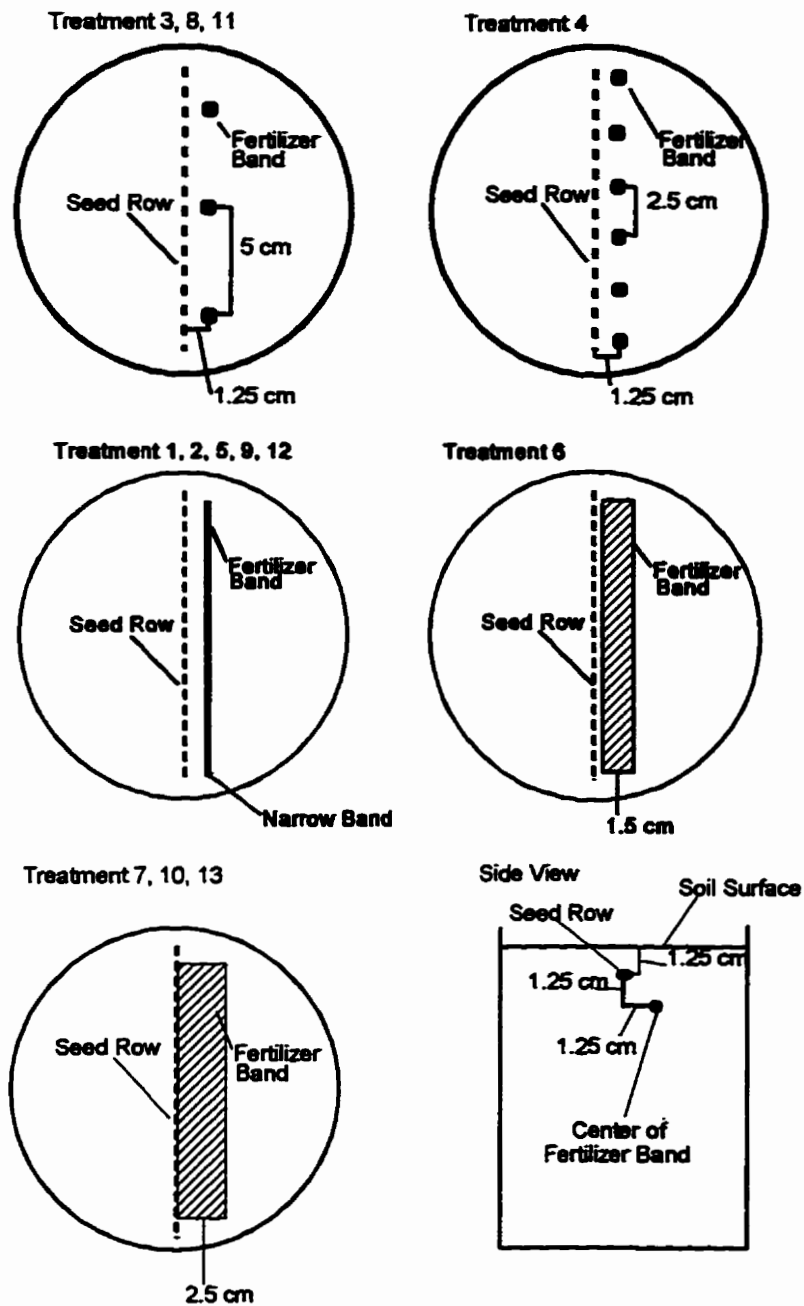
Figure 3.1 Fertilizer band geometries and placement of P fertilizer relative to the seed row.

The growth chambers used included a Foster Model GR 36 and a Conviron Model PGW 36, for the wheat and canola trials, respectively. The daylength maintained throughout the course of the experiment was 16 h. Temperatures were maintained between 23 and 27°C during the day period; night temperatures were 14 to 15°C. The wheat plants were thinned to 9 plants pot^{-1} on the 10th day after emergence, whereas the canola plants were thinned to 5 plants pot^{-1} on the 7th day after emergence. Plants were removed so as to give a uniform distribution along the band. Throughout the course of the growing period the pots were watered to gravimetric field capacity every 2 to 3 days.

From emergence to harvest the plants were monitored for changes in radioactivity resulting from the uptake of P from the ^{32}P labelled MAP using a hand held Geiger-Mueller survey meter. The average intensity, observed as the meter was moved slowly over the plant surfaces, was recorded. Counts were not corrected for radioactive decay.

The above ground plant material was harvested 27 to 28 days after seeding (25 days after emergence), allowed to air dry for 1 day, and then oven-dried at approximately 60°C for 3 days. The mass of the dry plant material was measured, and the samples ground using a Braun (Braun Canada Ltd., 110 Matheson Blvd. W Suite 200, Mississauga, ON, L5R 3T4) AG Type KSM1 coffee grinder. The plant tissue was then digested (nitric-perchloric acid digestion) and analysed for total P content and radioactivity resulting from uptake of ^{32}P (Appendix I). Statistical analyses of the results using ANOVA, means comparison, and correlation procedures were conducted using the Statistical Analysis System (SAS Institute (Canada) Inc., BCE Place, Suite 2220, 181 Bay Street, P.O. Box 819, Toronto, ON, M5J 2T3).

In order to determine the availability of the fertilizer P over a longer time period the pots were reseeded after the first harvest. Soil and roots from the previously harvested plants were left undisturbed. A small glass rod was used to make depressions for the seed in the old seed row, to ensure that the seed was placed at the same depth as for the first crop (1.25 cm). The wheat seeds used were pre-germinated on paper towels moistened with distilled water. The holes were filled with soil after placement of the seeds. The second crop was harvested and analysed as described for the first crop.

3.3.2 Effect of band geometry and chemistry on fertilizer P uptake by wheat - P fertilizer applied in fine granular form

3.3.2.1 Experimental Procedures. The soil and experimental procedures used were the same as for the previous study, with the following exceptions. The fertilizers were applied in a fine granular form and magnesium sulphate was included as a treatment at a rate of 50 kg ha^{-1} of Mg. The ^{32}P labelled MAP was prepared as follows. The 4.64 g of MAP was dissolved and labelled with 37 MBq of ^{32}P as H$_3$PO$_4$ in 0.02 N HCl. The solution was dried in an oven at 35°C until the decrease in mass over a 24 hour period was less than 0.001 g. The dry material was ground in a glass mortar and pestle to a fine granular form. The other fertilizer sources were reagent grade sources in fine granular form. The treatments (Table 3.3 and Figure 3.2) were replicated three times, and wheat (*Triticum aestivum* var. Katepwa) was used as the test crop. For the treatments involving bands in which relatively large volumes of soil were fertilized, the fertilizers were mixed with dry soil prior to application to ensure uniform distribution within the band. The appropriate amount of soil was calculated using the bulk density and volume of the band. A metal

template was made for each of the different band volumes and was used to remove the

appropriate volume of soil from the pre-moistened soil surface. The mixture of fertilizer

and dry soil was placed in the opening in the soil. Soil was replaced to give a depth of

1.25 cm between the seed row and fertilizer band, then the pots were seeded, the

remaining soil replaced, and the pots watered. The plants were thinned to 8 plants pot^{-1} 10

days after emergence and harvested 28 days after seeding. All analysis of the harvested

plants, including statisical analysis of the results, was conducted as described for the

previous study.

Table 3.3 Treatments for growth chamber study with granular P fertilizer.

Treatment #	P Fertilizer	Fertilizer Amendment	Fertilizer Application^z
1	None	Ammonium Sulphate	0.5 x 0.5 x 12.5 cm band
2	None	Magnesium Sulphate	0.5 x 0.5 x 12.5 cm band
3	MAP	Ammonium Sulphate	P applied in a row of 3 spots 5 cm apart; N applied as in treatment #1 but to the opposite side of the seed row.
4	MAP	Ammonium Sulphate	N and P applied together in a row of 3 spots 5 cm apart.
5	MAP	Ammonium Sulphate	N and P applied together in a 0.5 x 0.5 x 12.5 cm band.
6	MAP	Ammonium Sulphate	N and P applied together in a 1.5 x 1.0 x 12.5 cm band.
7	MAP	Ammonium Sulphate	N and P applied together in a 2.5 x 1.0 x 12.5 cm band.
8	MAP	Magnesium Sulphate	P applied as in treatment 3; Mg_2SO_4 and N applied together as oulined for N in treatment 3.
9^y	MAP	Magnesium Sulphate	Mg_2SO_4 and P applied together in a row of 3 spots 5 cm apart.
10^y	MAP	Magnesium Sulphate	Mg_2SO_4 and P applied together in a 0.5 x 0.5 x 12.5cm band.
11^y	MAP	Magnesium Sulphate	Mg_2SO_4 and P applied together in a 1.5 x 1.0 x 12.5cm band.
12^y	MAP	Magnesium Sulphate	Mg_2SO_4 and P applied together in a 2.5 x 1.0 x 12.5cm band.

^{z}The surface of all fertilizer bands were centered 1.25 cm below and 1.25 cm beside the seed row.
^{y}The N source in these treatments was $(NH_4)_2SO_4$ applied in a 0.5 x 0.5 x 12.5 cm band to the opposite side of the seed row.

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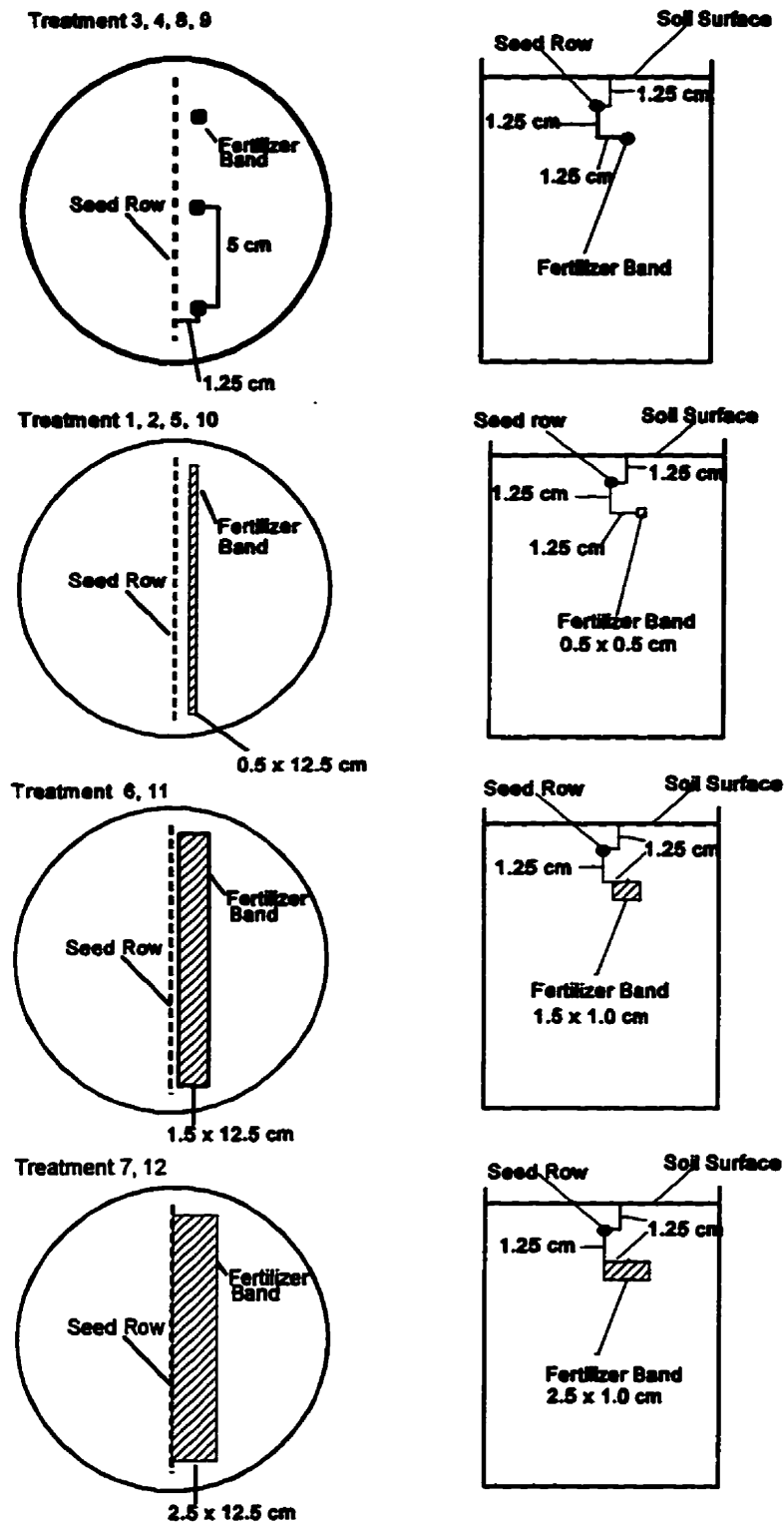
Figure 3.2 Fertilizer band geometries and placement of P fertilizer relative to the seed row.

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3.4 Results and Discussion

3.4.1 Effect of band geometry and chemistry on fertilizer P uptake by wheat and canola - P fertilizer applied in solution form

The increases in radioactivity of the plants, with time after seeding, are shown in figures 3.3 to 3.6. The values plotted represent the averages of the Geiger-Mueller survey meter readings for the three replicates of each treatment, and are not corrected for radioactive decay. Correlation analysis showed a strong correlation between these readings taken just prior to final harvest and decay per minute readings from liquid scintillation counting of the digested plant tissue extracts (Table 3.4), indicating that the measurements made with the Geiger-Mueller survey metre were a good estimate of fertilizer P uptake.

Table 3.4 Correlation analysis of Geiger-Mueller survey meter readings vs. decays per minute measured by liquid scintillation counting.

Test Crop	Pearson Correlation Coefficient	Probability > |R|
Wheat	0.95	0.0001
Canola	0.95	0.0001

Figures 3.3 and 3.5 show the effect of band geometry on fertilizer P uptake patterns for treatments with MAP applied separately from the N source for wheat and canola, respectively. Figures 3.4 and 3.6 indicate the effect of some of these same band geometries with dual bands of MAP with the N sources, for the two crops.

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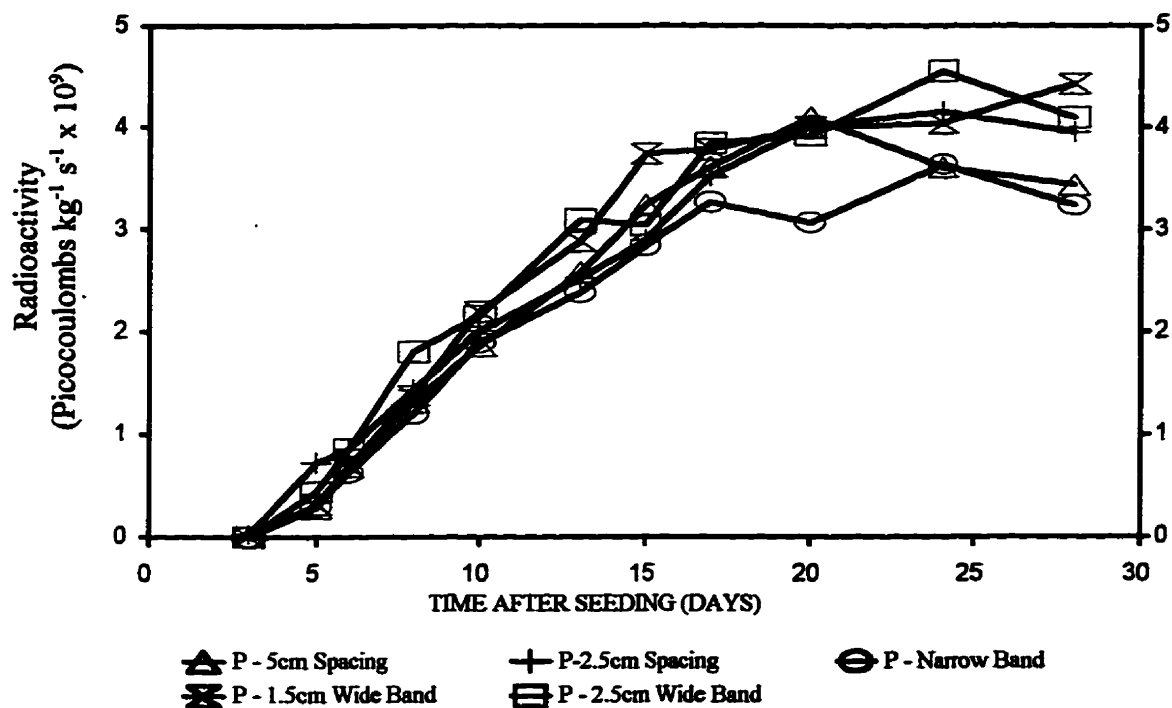
Figure 3.3 Radioactivity of wheat due to P uptake from labelled MAP applied in various band geometries.
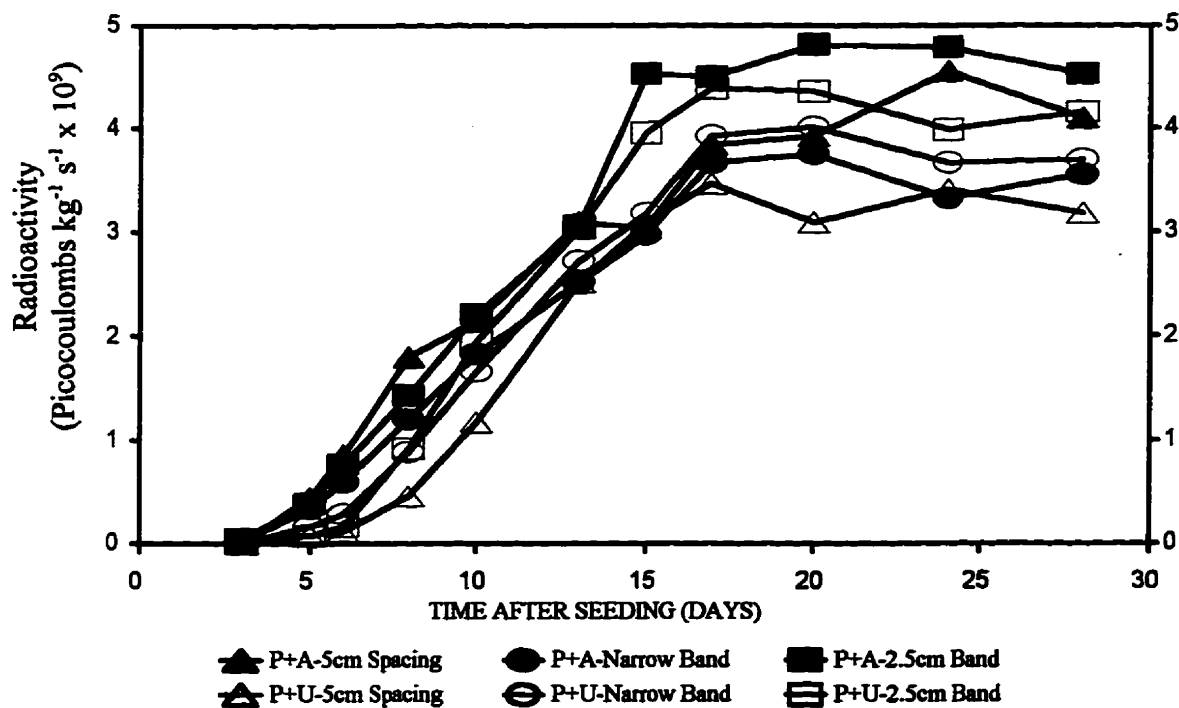
Figure 3.4 Radioactivity of wheat due to P uptake from labelled MAP dual banded with either ammonium sulphate (A) or urea (U) in various band geometries.
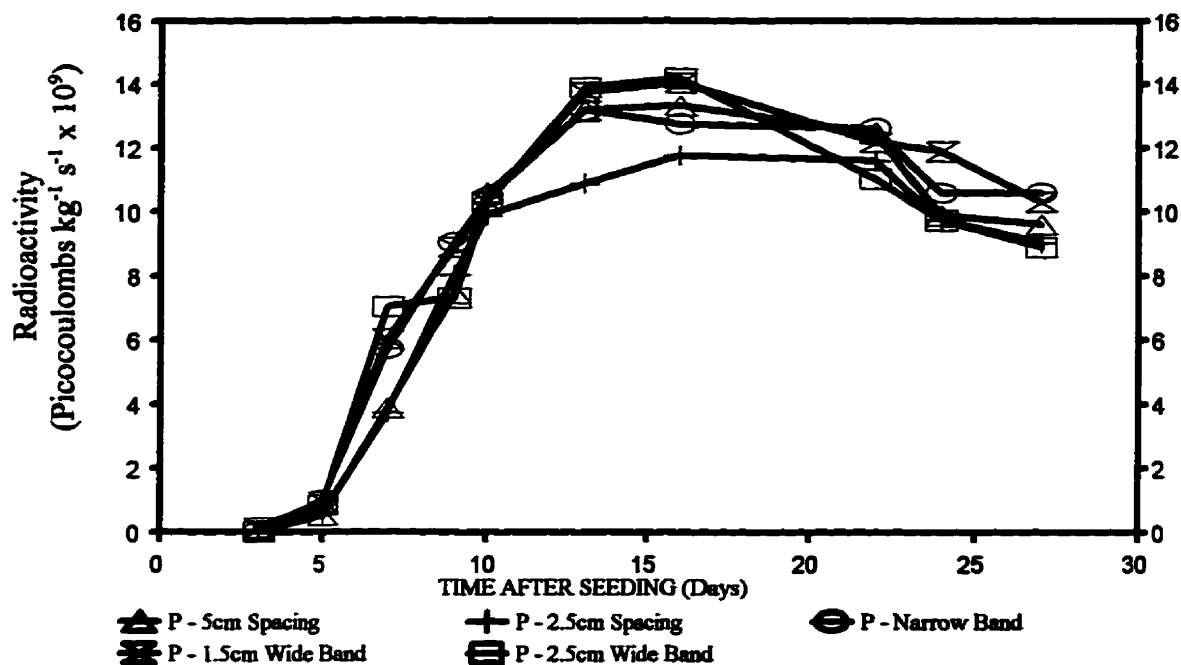
Figure 3.5 Radioactivity of canola due to P uptake from labelled MAP applied in various band geometries.
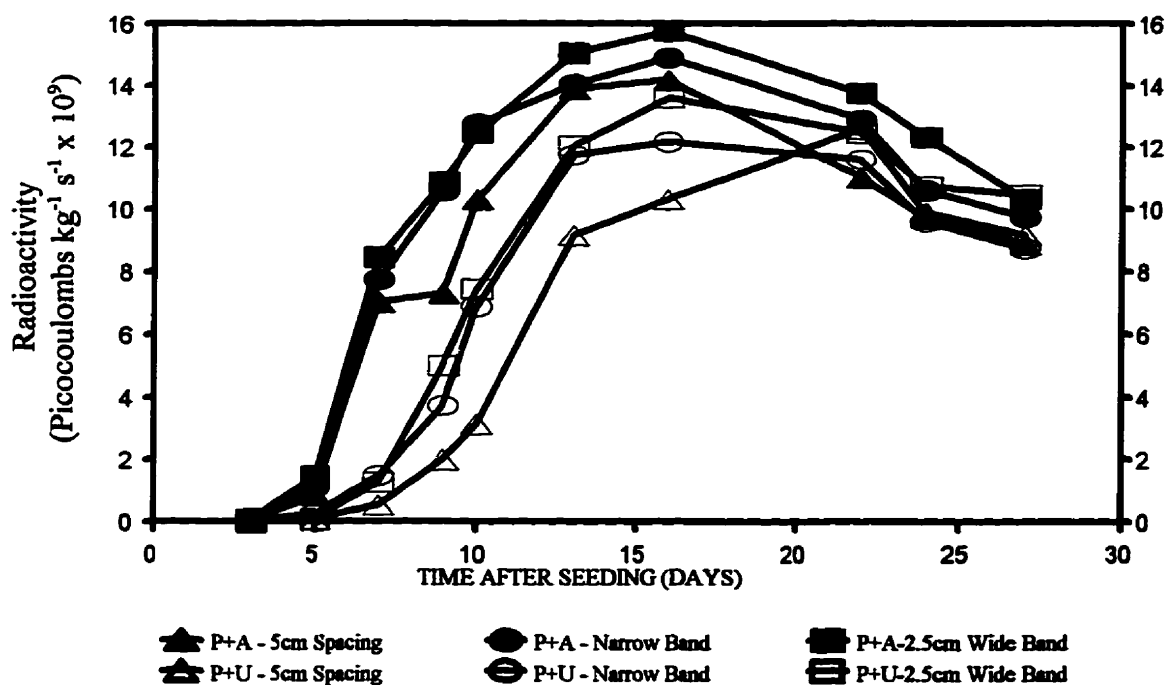
Figure 3.6 Radioactivity of canola due to P uptake from labelled MAP dual banded with either ammonium sulphate (A) or urea (U) in various band geometries.

Initiation of fertilizer P uptake by the wheat and canola was not affected by treatment except with the MAP-urea dual bands. Uptake of P from the MAP-urea dual bands during the seedling stage appeared to be delayed, particularly for the treatments with small areas or volumes of soil fertilized which would result in high concentrations of fertilizer in the reaction zone. The effect was more pronounced for canola than for wheat. The delay in P uptake during the seedling stage from dual MAP-Urea bands was also noted in previous studies by Beever (1987) and Flaten (1989). However, the delays in those studies were longer in duration, due to a combination of greater distances between the fertilizer band and the seed row and greater concentrations of fertilizer in the bands (i.e. Higher rates of MAP and urea were applied). These authors suggested that the additional delays in P uptake from dual MAP-Urea bands, as compared to separate applications placed a similar distance from the seed row, were the result of a lack of root penetration into the fertilizer band. Isensee and Walsh (1971) found that nitrite and ammonia in urea bands increased to toxic levels, and Passioura and Wetselaar (1972) indicated that the initial pH increase and resulting nitrite accumulation from the urea limited root growth to the periphery of the band up to 8 weeks after seeding.

Radioactivity of the wheat plants just prior to harvest, with MAP and N banded separately, was greatest for the 2.5 cm wide continuous band. Application of urea to the MAP band (dual banded) did not increase uptake. However, dual banding MAP with ammonium sulphate increased radioactivity in plants above that of similar treatments with MAP and ammonium sulphate banded separately, with the exception of the narrow continuous band. There were no significant differences in radioactivity of the canola

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treatments just prior to harvest. However, dual banding of MAP and ammonium sulphate did increase the radioactivity of the canola during the first 15 days after emergence.

Table 3.5 shows the results of analysis of plant tissue from the first crop of wheat and canola. In all cases yield with MAP was greater than without MAP. There was little or no difference in yield of wheat among treatments with MAP. However, canola yields decreased as a result of dual banding MAP and urea, as compared to similar band geometries with MAP applied alone or with ammonium sulphate, for all but the narrow continuous band. This trend was most significant for the greatest area of application (2.5 cm wide continuous band), and was most likely the result of the initial delay in fertilizer P uptake. Total P concentrations in canola were unaffected by the fertilizer treatments. Total P concentrations in wheat were not significantly different among treatments with MAP. Wheat treated with MAP usually had lower P contents than wheat without MAP. These differences were significant in three instances.

Generally, utilization of fertilizer P by the wheat crop increased with increasing area of MAP application, though not significantly. Both urea and ammonium sulphate tended to increase (not significantly) fertilizer P uptake when the MAP and N were dual banded in a 2.5 cm wide dual band.

Canola utilized much greater quantities of fertilizer P than wheat. Generally uptake by canola was not greatly affected by band geometry and chemistry. However, applying MAP and N separately in the smallest area of application (Treatment 3) resulted in the greatest utilization efficiency for canola. Uptake from narrow bands, however, appeared to be less than from other bands and/or spacings. Uptake of P with urea-MAP dual bands

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Table 3.5 Total dry weight, total P concentration and fertilizer P utilization efficiency of canola and wheat as affected by band geometry and dual banding with N (1st crop).

Treatments		Total Dry Weight (g)		[Total P] (mg/g)		Fertilizer P Utilization (%)	
Fertilizers	Band Geometry	Canola	Wheat	Canola	Wheat	Canola	Wheat
1. $(NH_4)_2SO_4$ alone	Continuous narrow band	3.9 e^z	2.4 bc	2.00 a	2.80 a	___	___
2. Urea alone	Continuous narrow band	3.9 e	2.3 c	2.09 a	2.69 ab	___	___
3. MAP & $(NH_4)_2SO_4$ applied separately	Row of 3 spots 5 cm apart	6.2 ab	3.1 a	2.32 a	2.46 abc	65.0 a	16.0 ab
4. MAP & $(NH_4)_2SO_4$ applied separately	Row of 6 spots 2.5 cm apart	5.9 bcd	3.2 a	2.17 a	2.33 bc	58.8 ab	16.4 ab
5. MAP & $(NH_4)_2SO_4$ applied separately	Continuous narrow band	5.8 bcd	2.9 ab	2.29 a	2.61abc	52.1 b	16.8 ab
6. MAP & $(NH_4)_2SO_4$ applied separately	Continuous 1.5 x 12.5 cm band	5.9 bcd	2.9 ab	2.15 a	2.47 abc	62.7 a	16.4 ab
7. MAP & $(NH_4)_2SO_4$ applied separately	Continuous 2.5 x 12.5 cm band	6.2 ab	3.4 a	2.08 a	2.31c	56.6 ab	17.9 ab
8. MAP & $(NH_4)_2SO_4$ dual applied	Row of 3 spots 5 cm apart	6.1 abc	2.8 ab	2.13 a	2.44 abc	59.8 ab	16.2 ab
9. MAP & $(NH_4)_2SO_4$ dual applied	Continuous narrow band	6.2 ab	3.2 a	2.15 a	2.57 abc	52.5 b	16.2 ab
10. MAP & $(NH_4)_2SO_4$ dual applied	Continuous 2.5 x 12.5 cm band	6.6 a	3.3 a	2.15 a	2.31c	55.9 ab	21.5 a
11. MAP & Urea dual applied	Row of 3 spots 5 cm apart	5.5 cd	2.9 a	2.32 a	2.30 c	59.2 ab	14.1 b
12. MAP & Urea dual applied	Continuous narrow band	5.8 bcd	3.2 a	2.30 a	2.51 abc	52.5 b	16.2 ab
13. MAP & Urea dual applied	Continuous 2.5 x 12.5 cm band	5.3 d	3.1 ab	2.34 a	2.38 bc	59.9 ab	18.8 ab
Standard Error		0.30	0.28	0.20	0.19	5.14	2.78

^{z} Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

Table 3.6 Total dry weight, total P concentration and fertilizer P utilization efficiency of canola and wheat as affected by band geometry and dual banding with N (2nd crop).

Treatments		Total Dry Weight (g)		[Total P] (mg/g)		Fertilizer P Utilization (%)	
Fertilizers	Band Geometry	Canola	Wheat	Canola	Wheat	Canola	Wheat
1. $(NH_4)_2SO_4$ alone	Continuous narrow band	0.7 ab[z]	1.2 a	1.67 b	2.64 a	___	___
2. Urea alone	Continuous narrow band	0.5 b	1.3 a	1.66 b	2.95 a	___	___
3. MAP & $(NH_4)_2SO_4$ applied separately	Row of 3 spots 5 cm apart	1.4 a	1.1 a	1.71 ab	2.85 a	2.6 abc	2.5 ab
4. MAP & $(NH_4)_2SO_4$ applied separately	Row of 6 spots 2.5 cm apart	0.9 ab	1.1 a	1.95 ab	3.31 a	2.6 abc	2.6 ab
5. MAP & $(NH_4)_2SO_4$ applied separately	Continuous narrow band	1.0 ab	1.2 a	2.10 a	2.99 a	1.9 c	2.6 ab
6. MAP & $(NH_4)_2SO_4$ applied separately	Continuous 1.5 x 12.5 cm band	1.0 ab	0.9 ab	1.95 ab	2.72 a	2.9 abc	2.6 ab
7. MAP & $(NH_4)_2SO_4$ applied separately	Continuous 2.5 x 12.5 cm band	1.2 ab	0.6 b	1.76 ab	3.04 a	2.5 abc	1.7 b
8. MAP & $(NH_4)_2SO_4$ dual applied	Row of 3 spots 5 cm apart	1.2 ab	1.2 a	1.84 ab	3.22 a	3.0 ab	3.3 a
9. MAP & $(NH_4)_2SO_4$ dual applied	Continuous narrow band	1.2 ab	1.0 ab	1.94 ab	3.11 a	2.7 abc	1.8 ab
10. MAP & $(NH_4)_2SO_4$ dual applied	Continuous 2.5 x 12.5 cm band	1.3 a	1.0 ab	1.99 ab	3.20 a	3.4 a	2.5 ab
11. MAP & Urea dual applied	Row of 3 spots 5 cm apart	0.7 ab	1.1 a	1.72 ab	2.79 a	2.0 bc	1.8 ab
12. MAP & Urea dual applied	Continuous narrow band	1.0 ab	0.9 ab	1.90 ab	3.04 a	1.9 bc	1.7 ab
13. MAP & Urea dual applied	Continuous 2.5 x 12.5 cm band	0.8 ab	1.1 a	1.91 ab	3.00 a	2.4 abc	2.8 ab
Standard Error		0.39	0.24	0.20	0.35	0.57	0.81

[z] Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

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was similar to that with ammonium sulphate-MAP dual bands. Dual banding MAP with N fertilizer resulted in P uptake similar to that with separate bands.

Table 3.6 shows the results for the second crop (i.e. after reseeding of the pots with no disturbance of the bands). Yields were substantially lower than from the first harvest, particularly for canola. Total P concentration in the plants was somewhat higher, due to the poorer overall growth. Fertilizer P utilization was drastically reduced for both the wheat and canola, indicating that uptake from the first harvest and fixation reactions had depleted the levels of available fertilizer P. There were very few significant differences among treatments in yield, P concentration or fertilizer P utilization, probably because the majority of the available P had been utilized by the first crop.

The results of the preceding studies with wheat and canola showed that responses to the treatments varied for the two crops. This was not entirely unexpected, since the two crops vary considerably in both their requirements of P and their ability to utilize applied P. Canola has been shown to recover a greater proportion of its P requirement during early growth stages, while the P recovery pattern of wheat is much more gradual over the growth cycle (Racz et al., 1965). Another significant difference between the two crops relates to associations with vesicular-arbuscular mychorrizal (VAM) fungi, which can increase the volume of soil from which P is absorbed in addition to solubilizing it through acidification. While wheat is able to take advantage of these VAM fungal associations (Kucey, 1987), canola does not normally form symbiotic associations with VAM fungi (Hirrel et al, 1978). Canola instead compensates for this by its ability to acidify its rhizosphere and increase the availability of inorganic P (Grinsted et al., 1982;

Hedley et al., 1982; Moorby et al., 1985). Strong and Soper (1974a,b) showed canola to be more capable than wheat in adjusting root growth to allow greater proliferation within a small fertilizer P reaction zone. The canola roots also showed a greater absorptive capacity for P than wheat roots, allowing for more rapid uptake when they encounter a fertilizer P reaction zone. These differences may help explain some of the differences in trends observed for canola and wheat in the results of the studies outlined in this section.

Studies with canola indicated that changes in area of fertilizer application, and changes in the chemistry of the band through dual banding of MAP with either ammonium sulphate or urea, were ineffective in increasing utilization of P from applied MAP. This was in contrast to previous findings by Beever (1987), who found that dual banding with ammonium sulphate increased utilization of P from applied MAP. He suggested the increase was related to a combination of increased solubility of the P and the ammonium ion effect on biological factors. However, the fertilizer bands in his studies were placed much farther from the seed row than those described here, resulting in lengthier delays to initial fertilizer P uptake. The canola roots in this study came into contact with the fertilizer P much quicker and were able to proliferate in the fertilizer zone and scavenge the bands for fertilizer P, resulting in less opportunity for increased uptake due to increased root-fertilizer contacts.

The results for wheat, however, showed some interesting trends. In this experiment uptake of applied P increased with increased area of application. Also, utilization of added P from dual bands of MAP and ammonium sulphate was greater than when added in separate bands. This was in agreement with previous findings by Beever

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(1987). These results indicate that the increase in uptake was probably due to a combination of increased root-fertilizer contact resulting from the larger area of application and increased availability of the fertilizer P due to greater solubility and/or other ammonium ion effects relating to root growth and physiology (Beever, 1987). Urea did not significantly improve P utilization when dual banded with MAP, in contrast to results of previous studies (Beever, 1987). However, work by Flaten (1989) indicated that dual banding with urea only enhanced P utilization significantly when the distance of the band exceeded 2.5 cm below and beside the seed row.

3.4.2 Effect of band geometry and chemistry on fertilizer P uptake by wheat - P fertilizer applied in fine granular form

Figures 3.7 and 3.8 represent the radioactivity of wheat plants with time, due to uptake of P from the labelled MAP. There was a strong correlation between readings taken just prior to final harvest with the Geiger-Mueller survey metre and decays per minute readings obtained from liquid scintillation counting of the digested plant tissue extracts (Table 3.7).

Table 3.7 Correlation analysis of Geiger-Mueller survey meter readings vs. decays per minute measured by scintillation counting.

Test Crop	Pearson Correlation Coefficient	Probability > |R|
Wheat	0.96	0.0001

Figure 3.7 indicates the effect of band geometry on fertilizer P uptake patterns by wheat from treatments with MAP and ammonium sulphate dual applied in fine granular form, as compared to separate application. Figure 3.8 shows similar results for dual application of MAP and magnesium sulphate.

Initiation of uptake occurred at a similar time for all treatments, and early uptake was similar until approximately 8 days after seeding. Radioactivity in plants from dual MAP and ammonium sulphate application was greater than with the N and P applied separately after about 10 days after seeding (Figure 3.7). The greatest intensity resulted from the dual band of MAP and ammonium sulphate with the greatest surface area of application (2.5 x 1.0 x 12.5 cm). Radioactivity from dual MAP and magnesium sulphate application was also greater than with the MAP applied separately (Figure 3.8). The greatest intensity occurred from the 1.5 x 1.0 x 12.5 cm band. However, both the effect of band geometry and the overall intensity with magnesium sulphate appeared to be less than for treatments with ammonium sulphate.
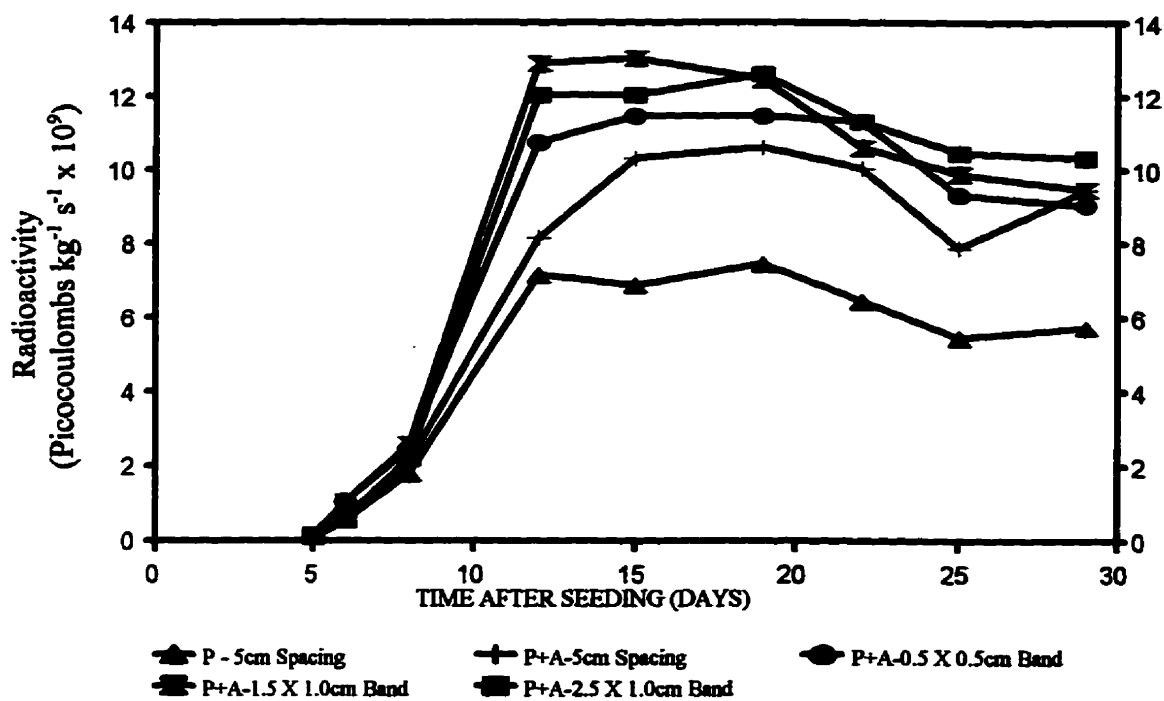
Figure 3.7 Radioactivity of wheat due to P uptake from labelled MAP in dual bands with ammonium sulphate (A) in various band geometries.
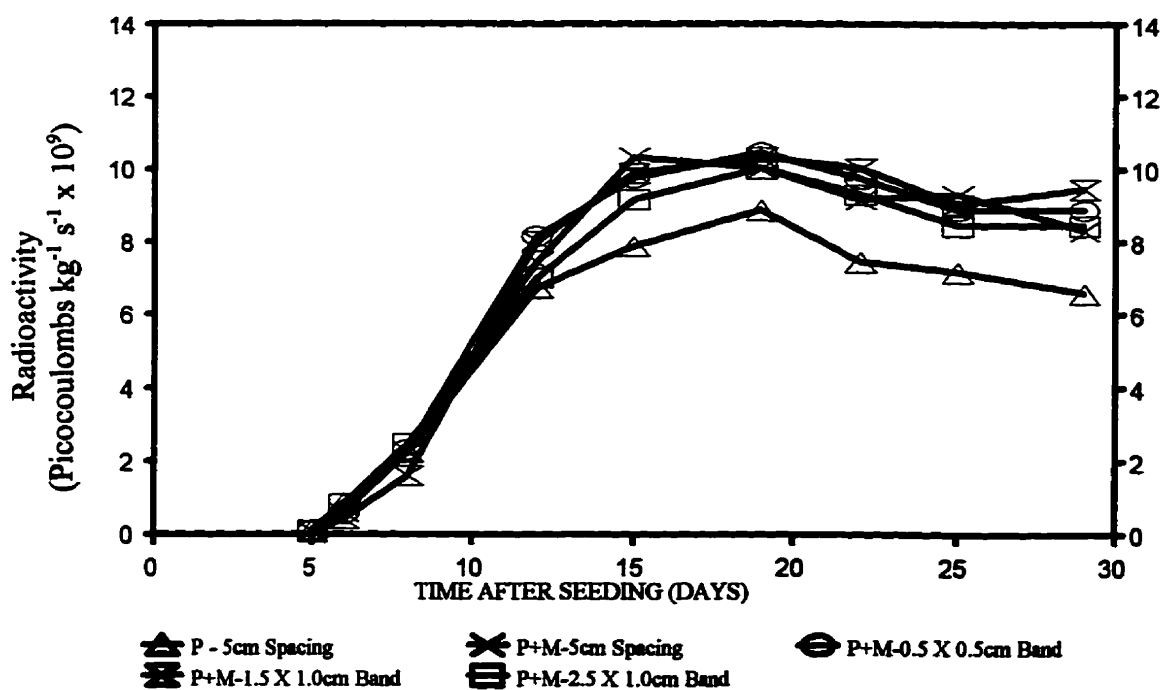
Figure 3.8 Radioactivity of wheat due to P uptake from labelled MAP in dual bands with magnesium sulphate (M) in various geometries.

Table 3.8 shows the results of plant tissue analysis. In all cases the addition of
MAP increased yield. Yield with MAP and ammonium sulphate applied in a dual band
increased with increased band size. Yield with dual application of MAP and ammonium
sulphate in the larger band widths was greater than yield with MAP and ammonium
sulphate applied separately in very localized spots. There was no difference in yield among
the treatments to which magnesium sulphate was applied. Yield with dual application of
MAP and magnesium sulphate tended to be lower than yield with MAP and ammonium
sulphate dual applied. Total P concentration in the plant tissues with MAP was less than
without MAP. The difference was significant in most cases. This indicated that biological
dilution occurred with application of fertilizer P. Utilization of applied P with dual banded
MAP and ammonium sulphate was significantly greater than when these fertilizers were
added separately. Increasing the surface area of application of the dual bands appeared to
further increase utilization, though the differences were not significant. Dual applications
of MAP and magnesium sulphate also improved utilization of applied P as compared to
applying them separately, with the exception of the largest area of application.

Table 3.8 Total dry weight, total P concentration and fertilizer P utilization efficiency of wheat as affected by band geometry and fertilizer amendments.

Treatments		Total Dry Weight (g)	[Total P] (mg/g)	Fertilizer P Utilization (%)
Fertilizers	Band Geometry^z			
1. $(NH_4)_2SO_4$ alone	0.5 x 0.5 x 12.5 cm band	2.8 de^x	1.57 ab	___
2. $(NH_4)_2SO_4$ & Mg_2SO_4	0.5 x 0.5 x 12.5 cm band	2.3 e	1.64 a	___
3. MAP & $(NH_4)_2SO_4$ applied separately	Row of 3 spots 5 cm apart	3.7 cd	1.32 bc	11.8 d
4. MAP & $(NH_4)_2SO_4$ dual applied	Row of 3 spots 5 cm apart	4.5 abc	1.23 c	20.9 ab
5. MAP & $(NH_4)_2SO_4$ dual applied	0.5 x 0.5 x 12.5 cm band	4.7 ab	1.14 c	20.5 ab
6. MAP & $(NH_4)_2SO_4$ dual applied	1.5 x 1.0 x 12.5 cm band	4.9 a	1.20 c	21.8 ab
7. MAP & $(NH_4)_2SO_4$ dual applied	2.5 x 1.0 x 12.5 cm band	5.2 a	1.16 c	24.0 a
8. MAP & Mg_2SO_4 applied separately	Row of 3 spots 5 cm apart	4.7 ab	1.24 c	14.2 cd
9. MAP & Mg_2SO_4 dual applied^y	Row of 3 spots 5 cm apart	4.4 abc	1.37 abc	20.0 ab
10. MAP & Mg_2SO_4 dual applied^y	0.5 x 0.5 x 12.5cm band	4.6 abc	1.34 bc	19.2 ab
11. MAP & Mg_2SO_4 dual applied^y	1.5 x 1.0 x 12.5cm band	4.6 abc	1.34 bc	21.3 ab
12. MAP & Mg_2SO_4 dual applied^y	2.5 x 1.0 x 12.5cm band	3.9 bc	1.35 bc	18.0 cb
Standard Error		0.53	0.16	2.65

^{z}The surface of all fertilizer bands was centered 1.25 cm below and beside the seed row.
^{y}In these treatments $(NH_4)_2SO_4$ was applied in a 0.5 x 0.5 x 12.5 cm band 1.25 cm below and to the opposite side of the seed row from the Mg_2SO_4-MAP dual bands to provide adequate N.
^{x} Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

The results of the second study confirmed some of the findings from the first study involving fertilizer solution applications. The dual banding of ammonium sulphate with the MAP again resulted in greater utilization of applied P, as compared to the N and P applied separately. This was particularly true for the larger band volumes. However, the effectiveness of magnesium sulphate, dual applied with MAP, in improving the efficiency of P utilization was also a very interesting finding in this study. While there is little direct evidence for why this occurred, previous research with other neutral salts may hold some clues. Work with KCl has shown that its application in P fertilizer bands can actually decrease P availability, through desorption of exchangeable calcium which then can undergo precipitation with the soluble P from the fertilizer (Akinremi and Cho, 1993). However, Bouldin et al. (1960) showed that addition of potassium sulphate with monocalcium phosphate reduced the precipitation of applied P at the site of application to a greater extent than potassium chloride. This appeared to result from precipitation of calcium with the sulphate, leaving less calcium available for precipitation with P. In the study reported herein the pots with magnesium sulphate treatments also received ammonium sulphate as an N source. Therefore, the levels of sulphate in these pots would have been quite high, and this may at least partly explain the effectiveness of the magnesium sulphate in improving the P fertilizer use efficiency.

3.5 Summary and Conclusions

Studies were conducted utilizing canola and wheat as test crops to investigate the effects of various band geometries and fertilizer sources on the efficiency of P utilization

from MAP. The band geometries involved ranged from three points of application spaced 5 cm apart to a volume of 2.5 x 1.0 x 12.5 cm. Fertilizer sources including ammonium sulphate, urea and magnesium sulphate were dual applied with the MAP in several of these band geometries to determine their effect on P utilization and yield.

The canola crop was extremely efficient at utilizing P from MAP when applied in the smallest area of application (three points 5 cm apart), resulting in uptake of 65% of the applied P in the first 27 days after seeding. The efficiency of use of P from MAP was not increased by dual banding with N or increasing the volume of soil fertilized.

For the wheat crop, increasing the area (or volume) of soil fertilized resulted in a small increase in P utilization. Urea was ineffective in improving P uptake when dual applied with the MAP, apparently due to initial delays in uptake resulting from the toxic effects of ammonia or nitrite in the bands. These delays were most pronounced in bands with small areas of application, due to greater concentrations. Magnesium sulphate was effective in improving utilization of applied P, but not to the extent of dual applications with ammonium sulphate. The most consistent trend noted in these trials was that the dual bands of ammonium sulphate and MAP consistently resulted in the greatest fertilizer P use efficiency for wheat.

4. EFFECT OF LIGNOSULFONATES ON UTILIZATION OF PHOSPHATE FROM MONOAMMONIUM PHOSPHATE APPLIED IN SOLUTION

4.1 Abstract

Studies were undertaken to explore the effects of chemical modifications and fertilizer band geometry on fertilizer P uptake by wheat. Various lignosulfonates (NH_4-, Ca-, and H-saturated) and ammonium sulfate were tested as chemical amendments. The lignosulfonates were applied to the bands in solution form, as were the fertilizer sources. Treatments involved low rates of lignosulfonate applied to MAP bands, as well as lignosulfonate application in dual N-P bands.

None of the forms of lignosulfonate had a positive effect on fertilizer P uptake by wheat. This was true whether the MAP was applied separately from the N source or in a dual band with the ammonium sulphate. Utilization of P was increased when ammonium sulfate was added to the P fertilizer. The greatest fertilizer P use efficiency occurred from the application of MAP, ammonium sulphate and ammonium lignosulfonate with the greatest area of application, most likely due to the greater levels of the ammonium ion.

4.2 Introduction

In recent years much research has been conducted with the aim of improving the utilization of fertilizer phosphorus. Findings have indicated that geometry and chemistry

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of fertilizer bands have a significant effect on the uptake of fertilizer P by some crops. Previous studies indicated that utilization of applied phosphorus by wheat was affected by aspects of band geometry involving both the area and uniformity of application within the fertilizer band (Section 3). Utilization of fertilizer phosphorus was also affected by chemical modification of the bands. For example, application of ammonium sulphate with monoammonium phosphate (MAP) increased phosphorus fertilizer utilization. These results sparked curiosity about other potential chemical modifications and their interaction with different band geometries.

Work by Xie et al. (1991) indicated that calcium lignosulfonate increased total P retention in soil through increased soil solution Ca^{++} concentration resulting in Ca-P precipitation, probably as hydroxyapatite. In contrast, ammonium lignosulfonate reduced P retention through competition for adsorption sites between lignosulfonate and phosphate ions. Subsequent work by Russell et al. (1991) indicated that ammonium lignosulfonate improved P uptake by corn from applied triple superphosphate. These increases were obtained utilizing very high rates of lignosulfonate (≈ 850 kg ha^{-1}). It was postulated that lignosulfonate may increase fertilizer P uptake, at much lower rates of lignosulfonate application, if the lignosulfonate was added to the micro region of fertilizer granules. Thus a study was undertaken to determine the effect on P uptake by wheat of several forms of lignosulfonate, applied at a rate of 15 kg ha^{-1} directly to the micro region of MAP application, alone or in conjunction with ammonium sulfate.

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4.3 Materials and Methods

A growth chamber experiment using wheat (*Triticum aestivum* var. Katepwa) as a test crop was conducted to study the effect of lignosulfonate and ammonium sulphate on uptake of P from applied monoammonium phosphate (MAP). The soil selected for study was a calcareous silty clay loam soil similar to that described in Table 3.1 (Section 3). Its characteristics included a gravimetric field capacity of 32%, pH of 7.9, sodium bicarbonate extractable P content of approximately 4.5 μg g^{-1}, and a cation exchange dominated by calcium. The soil was taken from the surface 15 to 20 cm of the profile, passed through a sieve with openings of 1.5 x 3.5 cm, and air dried. It was then thoroughly mixed, and 2500 gram portions of soil placed into 3.5 L pots. The top 2.5 cm of soil in each pot was removed, the remaining soil watered to field capacity, and the fertilizer and lignosulfonate treatments applied to the exposed surface.

MAP, labelled with the radioisotope ^{32}P, and ammonium sulfate were used as the sources of P and N, respectively, at rates equivalent to 7.5 kg P ha^{-1} and 50 kg N ha^{-1} (area basis). The MAP solution was labelled with 37 MBq of ^{32}P as H$_3$PO$_4$ in 0.02N HCl, such that it received 2.96 x 10^4 Bq mg^{-1} ^{31}P. Calcium-, ammonium-, and hydrogen-saturated lignosulfonate were included as chemical amendments. The calcium lignosulfonate (CaLS) was Lignosite 50 (Imperial Oil, Chemicals Division) containing approximately 2.5% calcium available for exchange. Ammoniated and hydrogenated forms were prepared from the CaLS by passing it through a cation exchange resin saturated with either NH$_4$$^+$, or H$^+$, respectively. Table 4.1 indicates the efficiency of exchange based on analysis of exchangeable calcium.

Table 4.1 Analysis of lignosulfonate sources for efficiency of exchange and pH.

Lignosulfonate	Exchangeable Ca^{++} (mg/ml)	Ion Exchange (% of Ca^{++} removed)	Lignosulfonate pH Readings
Calcium Lignosulfonate	21.0	___	5.4
Ammonium Lignosulfonate	3.63	82.7	5.5
Hydrogen Lignosulfonate	0.03	99.8	0.1

All of the fertilizers and lignosulfonates were applied to the bands in solution form. There were three replicates of fourteen treatments in the study (Table 4.2 and Figure 4.1).

After application of the fertilizer and lignosulfonates, one-half of the soil which had been previously removed from the pots was replaced, a row of twelve seeds placed along the centre of the pots, and the remaining soil replaced. The pots were then watered to field capacity, placed in the growth chamber in a completely randomized design, and watered to field capacity every 2 to 3 days. Day length was maintained at 16 hours, with a temperature and humidity of approximately 23°C and 60%, respectively. Night temperature and humidity were approximately 14°C and 80%, respectively. Plant density was thinned to 8 plants pot^{-1} on the 8th day after emergence.

Table 4.2 Description of treatments.

Treatment #	P Fertilizer	N Fertilizer	Lignosulfonate	Method of Application[z]
1	None	Ammonium Sulphate	None	N applied as a row of 3 spots 5 cm apart.
2[y]	MAP	Ammonium Sulphate	None	P applied as a row of 3 spots 5 cm apart.
3[y]	MAP	Ammonium Sulphate	None	P applied in a 2.5 cm wide continuous band.
4	MAP	Ammonium Sulphate	None	N and P applied together as a row of 3 spots 5 cm apart.
5	MAP	Ammonium Sulphate	None	N and P applied together in a 2.5 cm wide continuous band.
6[y]	MAP	Ammonium Sulphate	Calcium Lignosulfonate	P and CaLS applied together as a row of 3 spots 5 cm apart.
7[y]	MAP	Ammonium Sulphate	Ammonium Lignosulfonate	P and NH₄LS applied together as a row of 3 spots 5 cm apart.
8[y]	MAP	Ammonium Sulphate	Hydrogen Lignosulfonate	P and HLS applied together as a row of 3 spots 5 cm apart.
9[y]	MAP	Ammonium Sulphate	Calcium Lignosulfonate	P and CaLS applied together in a 2.5 cm wide continuous band.
10[y]	MAP	Ammonium Sulphate	Ammonium Lignosulfonate	P and NH₄LS applied together in a 2.5 cm wide continuous band.
11[y]	MAP	Ammonium Sulphate	Hydrogen Lignosulfonate	P and HLS applied together in a 2.5 cm wide continuous band.
12	MAP	Ammonium Sulphate	Calcium Lignosulfonate	P, N and CaLS applied together in a 2.5 cm wide continuous band.
13	MAP	Ammonium Sulphate	Ammonium Lignosulfonate	P, N and NH₄LS applied together in a 2.5 cm wide continuous band.
14	MAP	Ammonium Sulphate	Hydrogen Lignosulfonate	P, N and HLS applied together in a 2.5 cm wide continuous band.

[z]All bands were centred 1.25 cm below and 1.25 cm beside the seed row.
[y] In these treatments the N was placed in a row of 3 spots 5 cm apart to the opposite side of the seed row from the MAP.
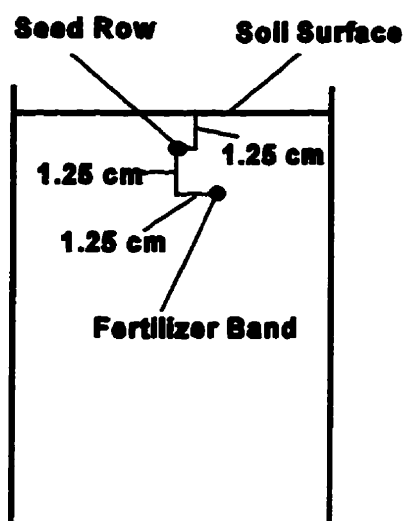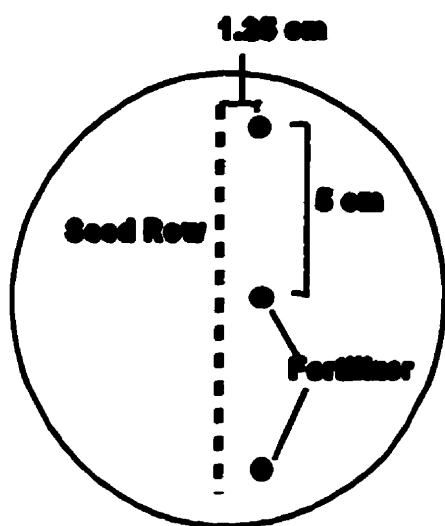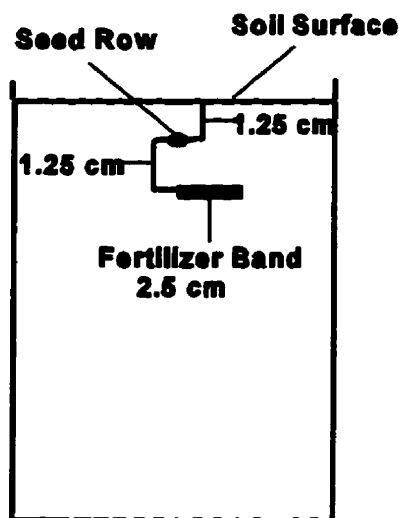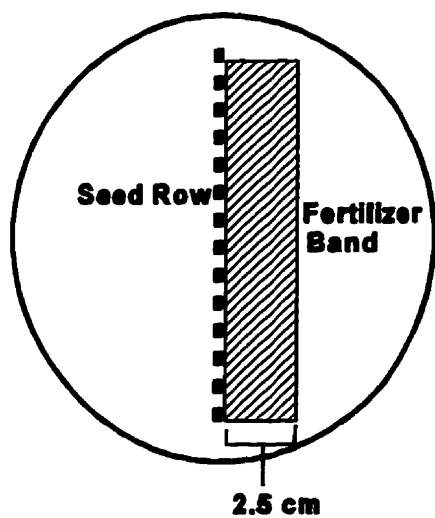
Figure 4.1 Illustration of band geometries for treatments.

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The plants were monitored for changes in radioactivity resulting from the uptake of P from the labelled MAP using a hand held Geiger-Mueller survey metre. The average intensity, observed as the metre was moved slowly over the plant surfaces, was recorded. Counts were not corrected for radioactive decay. The above ground plant material was harvested at 25 days after emergence, allowed to air dry for 1 day, and then oven dried at approximately 60°C for 3 days. The mass of the dry matter was measured, and the samples ground using a Braun (Braun Canada Ltd., 110 Matheson Blvd. W Suite 200, Mississauga, ON, L5R 3T4) AG Type KSM1 coffee grinder. Plant tissue analysis was then conducted, including determination of total and fertilizer P uptake (Appendix I). Statistical analysis of results included ANOVA, mean comparison and correlation procedures using the Statistical Analysis System (SAS Institute (Canada) Inc., BCE Place, Suite 2220, 181 Bay Street, P.O. Box 819, Toronto, ON, M5J 2T3).

4.4 Results and Discussion

The radioactivity of wheat plants, which reflects the uptake of fertilizer P with time after seeding, is shown in figures 4.2 to 4.4. Correlation analysis between the radioactivity of the plants prior to harvest and the results of liquid scintillation counting of the plant tissue extracts indicated these Geiger-Mueller survey meter readings to be a good indication of ^{32}P uptake (Table 4.3).

Table 4.3 Correlation analysis of Geiger-Mueller survey metre readings vs. decays per minute measured by scintillation counting.

Test Crop	Pearson Correlation Coefficient	Probability > |R|
Wheat	0.91	0.0001
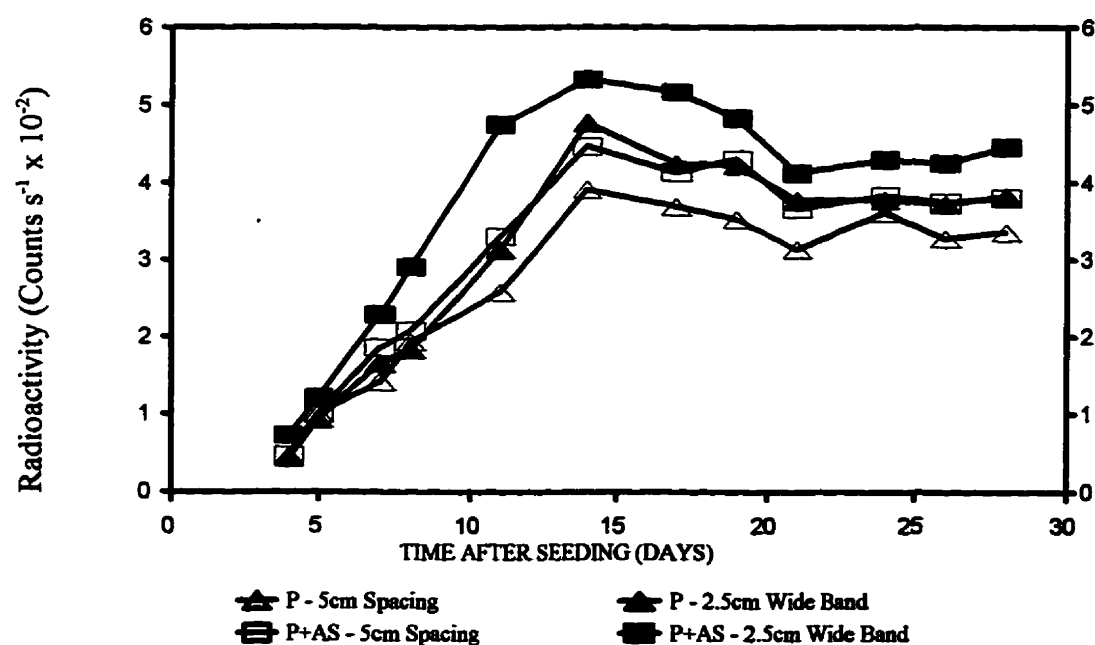
Figure 4.2 Effect of band geometry and ammonium sulphate (AS) on P uptake from labelled MAP by wheat.
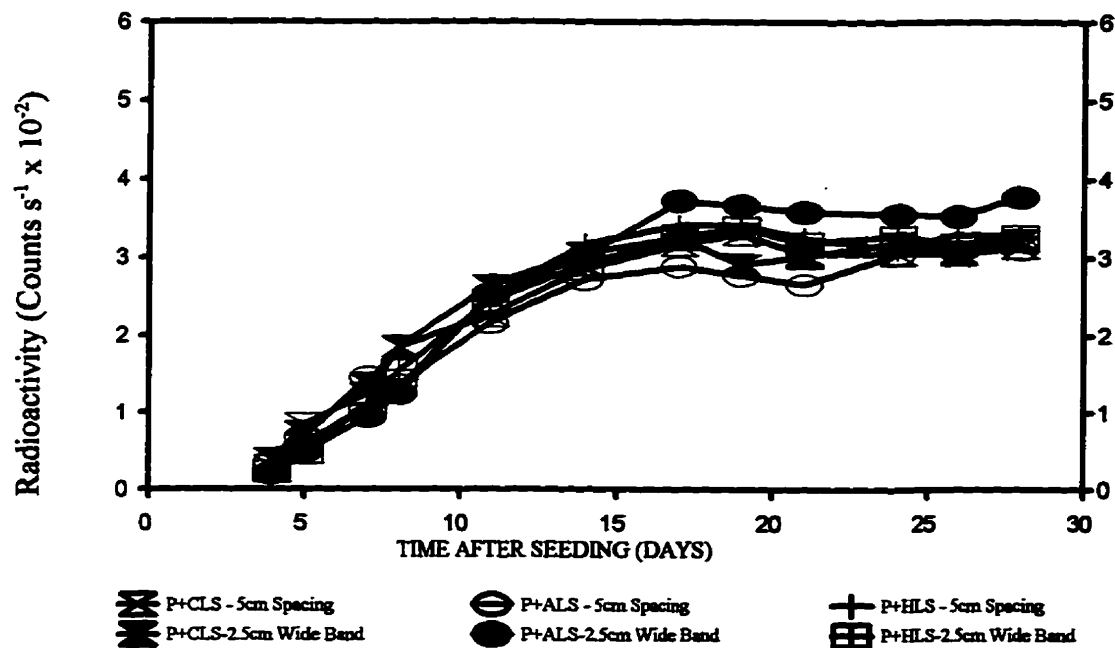
Figure 4.3 Effect of band geometry and lignosulfonate (CLS, ALS, HLS=calcium, ammonium and hydrogen lignosulfonate, respectively) on P uptake from labelled MAP by wheat.
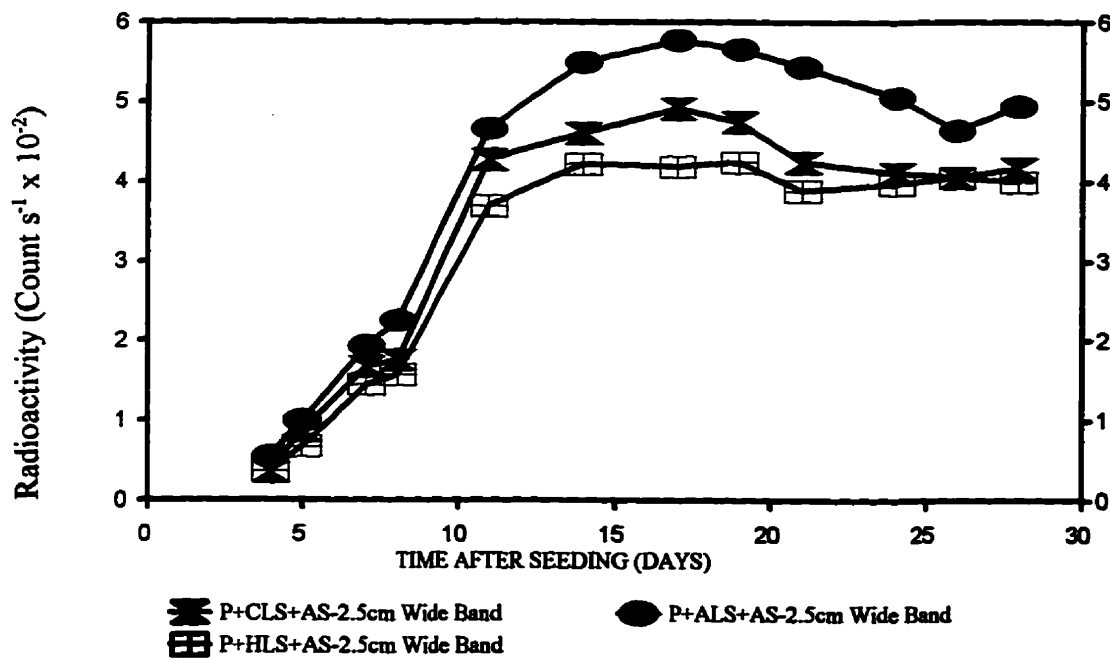
Figure 4.4 Effect of band geometry, ammonium sulphate (AS) and lignosulfonate (CLS, ALS, HLS=calcium, ammonium and hydrogen lignosulfonate, respectively) on P uptake from labelled MAP by wheat.

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The plants in the treatments involving ammonium lignosulfonate with the greatest area of application showed the greatest radioactivity among the lignosulfonate treatments. However, none of the various lignosulfonates increased fertilizer P uptake as compared to similar treatments without lignosulfonate (Figures 4.2 and 4.3). Utilization of fertilizer P increased with increased area of application when MAP was applied alone or in combination with ammonium sulphate. Dual banding of ammonium sulphate with the MAP also increased fertilizer P utilization for both band geometries (Fig. 4.2). Lignosulfonates usually had no effect on P utilization. However, it was interesting to note that the band of MAP, ammonium sulphate and ammonium lignosulfonate (ie. greatest ammonium application) and largest area of application resulted in the greatest uptake of applied P.

In all cases yield with added P was greater than without P (Table 4.4). Generally, yields increased with increases in fertilizer P utilization. Utilization of fertilizer P increased slightly with increases in area of application when MAP was applied alone. Dual banding of ammonium sulfate with the MAP increased P utilization for both band geometries. None of the forms of lignosulfonate had a positive effect on fertilizer P utilization, whether they were applied with MAP alone or with MAP and ammonium sulphate. However, the band containing MAP, ammonium sulphate, and ammonium-saturated lignosulfonate (and therefore the greatest [NH_4^+]) resulted in the greatest utilization of applied P. This indicates that the increases in P utilization were probably due to an ammonium ion effect.

The study reported herein with calcium-, ammonium-, and hydrogen-saturated forms of lignosulfonate showed that there was no positive effect on utilization of applied P

resulting from application of low rates of lignosulfonates directly to MAP fertilizer bands. Previous work (Russell et al., 1991; Xie et al., 1991) which showed that lignosulfonates reduced the retention of P from applied diammonium phosphate utilized high rates of lignosulfonate (846 kg ha^{-1} and 150 g kg^{-1} of soil, respectively). They suggested that the main mechanism of reduced P retention was competition between the lignosulfonate and phosphate ions for adsorption sites. It was hoped that the low rates of lignosulfonate used in these studies, which would be more practical for field applications, would be high enough to saturate the adsorption sites with lignosulfonate in the micro region of MAP application, but they proved to be insufficient. Xie et al. (1991) showed that calcium lignosulphonate increased Ca^{++} concentration in the soil solution resulting in Ca-P precipitation which would offset any increase in P availability. The hydrogen lignosulfonate source was extremely acidic, and may have limited root growth in bands containing this amendment. The lack of response to the ammonium lignosulfonate is more difficult to explain, but it may be due to the differences in the soils used in the studies. The other studies mentioned used an acidic soil (pH 5.7), which had a lower level of exchangeable calcium than the soil used in this study. They showed that removal of native Ca^{++} from the soil by reaction with ammonium lignosulfonate enabled the ammonium lignosulfonate to reduce P retention. In this study the combination of higher levels of exchangeable Ca^{++} and lower rates of ammonium lignosulfonate would probably leave some calcium available for precipitation with P in the soil solution.

Table 4.4 Total dry weight, total P concentration and fertilizer P utilization efficiency of wheat as affected by band geometry and chemical amendments.

Treatments			Total Dry Weight (g)	[Total P] (mg/g)	Fertilizer P Utilization (%)
Fertilizers	Lignosulfonate	Band Geometry			
1. $(NH_4)_2SO_4$	None	Row of 3 spots 5 cm apart	1.3 g ^{z}	2.23 a	___
2. MAP & $(NH_4)_2SO_4$ applied separately	None	Row of 3 spots 5 cm apart	3.3 abcde	2.07 ab	23.0 bcd
3. MAP & $(NH_4)_2SO_4$ applied separately	None	2.5 x 12.5 cm band	3.5 abc	2.07 ab	25.8 abc
4. MAP & $(NH_4)_2SO_4$	None	Row of 3 spots 5 cm apart	3.5 abc	2.17 ab	28.8 a
5. MAP & $(NH_4)_2SO_4$	None	2.5 x 12.5 cm band	3.7 a	1.85 b	29.0 a
6. MAP & $(NH_4)_2SO_4$ applied separately	Calcium Lignosulfonate	Row of 3 spots 5 cm apart	2.7 ef	2.00 ab	19.0 de
7. MAP & $(NH_4)_2SO_4$ applied separately	Ammonium Lignosulfonate	Row of 3 spots 5 cm apart	2.6 f	1.90 ab	16.9 e
8. MAP & $(NH_4)_2SO_4$ applied separately	Hydrogen Lignosulfonate	Row of 3 spots 5 cm apart	2.8 def	2.10 ab	21.1 cde
9. MAP & $(NH_4)_2SO_4$ applied separately	Calcium Lignosulfonate	2.5 x 12.5 cm band	3.0 cdef	1.97 ab	21.5 cde
10. MAP & $(NH_4)_2SO_4$ applied separately	Ammonium Lignosulfonate	2.5 x 12.5 cm band	3.0 cdef	2.03 ab	22.9 bcd
11. MAP & $(NH_4)_2SO_4$ applied separately	Hydrogen Lignosulfonate	2.5 x 12.5 cm band	2.9 cdef	2.10 ab	22.2 cd
12. MAP & $(NH_4)_2SO_4$	Calcium Lignosulfonate	2.5 x 12.5 cm band	3.6 ab	1.93 ab	29.4 a
13. MAP & $(NH_4)_2SO_4$	Ammonium Lignosulfonate	2.5 x 12.5 cm band	3.7 a	1.97 ab	30.0 a
14. MAP & $(NH_4)_2SO_4$	Hydrogen Lignosulfonate	2.5 x 12.5 cm band	3.3 abcd	2.13 ab	27.0 ab
Standard Error			0.32	0.18	2.52

^{z} Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

4.5 Summary and Conclusions

A study was conducted to determine the effect of organic amendments on the efficiency of P uptake from applied MAP. The organic compound chosen was lignosulfonate, a by-product of the sulphite pulping process. While other authors indicated this compound to be effective in improving uptake of applied P at high rates of application, this study involved lower rates of application which would be more practical under field conditions. The three lignosulfonate sources tested had calcium, ammonium and hydrogen as accompanying cations, and were applied as solution and incorporated directly into the micro region of MAP application.

None of the lignosulfonates souces incorporated into the MAP bands were effective in improving P utilization from applied MAP, when compared to similar bands with MAP applied alone. The low rates of lignosulfonate applied in this study appeared to be insufficient to allow adequate competition between lignosulpnonate and phosphate ions for adsorption sites. Also, the high level of exchangeable calcium in the soil used in this study may have been too great for the lignosulfonate to significantly reduce Ca-P precipitation.

This study did confirm the trends of previous studies by showing that ammonium sulphate was effective in improving P uptake from applied MAP when the two were applied as a dual application. The larger areas of application appeared to provide better utilization of applied P, though not significantly greater than from smaller application areas. This trend was more pronounced for MAP and N applied separately than for the MAP and ammonium sulphate in dual bands. The 2.5 cm wide band of MAP, ammonium

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lignosulfonate and ammonium sulphate applied together resulted in the greatest utilization

of applied P, but this was clearly a response to the ammonium ion effects.

5. UTILIZATION OF FERTILIZER PHOSPHORUS FROM LARGE BAND WIDTHS AND THE INFLUENCE OF P APPLICATION RATE

5.1 Abstract

Studies with band widths of up to 15 cm were undertaken using ^{32}P labelled MAP to study fertilizer P utilization from bands such as those obtained with openers designed to give wide spread patterns. The phosphorus fertilizer was added in a manner which simulated granule application. Interaction among band size, dual banding of P with urea and ammonium sulphate and rate of P applied were also investigated.

Increases in band width tended to slightly decrease fertilizer P utilization up to 15 days after seeding for the treatments involving MAP applied separately from the N source. By 29 days after seeding this trend had disappeared for these treatments. Dual banding the MAP with ammonium sulphate increased P use efficiency in all cases by 29 days after seeding. Application of the ammonium sulfate in intimate contact with the MAP was more effective than a random distribution within the band in increasing fertilizer P uptake for the largest band width. Dual banding of the MAP with urea decreased P uptake during the early stages of growth (15 days after seeding), particularly for the narrow bands. By 29 days after seeding addition of urea to the P fertilizer band had also increased the fertilizer use efficiency, as compared to the MAP and N applied separately. Trends were similar for both rates of P application. Yield of dry matter reflected trends in fertilizer P utilization.

5.2 Introduction

Most P fertilizer research has involved fertilizer placed with the seed in relatively narrow bands or placed in narrow bands with nitrogen fertilizer sources (dual banding) prior to planting. Dual banding has been shown to increase fertilizer P utilization at later stages of growth but can delay uptake during the seedling stage due to high salt and/or ammonia concentrations within the band (Beever, 1987; Flaten, 1989). Previous studies indicated that the uptake of P from applied MAP fertilizer bands increased when the band width (or area of soil fertilized) was increased (Sections 3 and 4). However, the previous studies only included band widths up to approximately 2.5 cm. Fertilizing with air seeders with openers designed to give wider spread patterns can result in very wide band widths and greater scattering of the fertilizer granules, which will affect root-fertilizer contact, salt and/or ammonia concentrations within the band, and therefore uptake of fertilizer P. Studies were conducted to determine the effect of band width, dual banding, and rate of P application on fertilizer P uptake using very wide band widths.

5.3 Materials and Methods

5.3.1 Fertilizer P Uptake by Wheat as Affected by Very Large Band Widths and Dual Banding with N

This study was conducted to determine the effect of very large band widths, such as those associated with air seeder applications, on uptake of applied P. The possibility of improving uptake from these wider bands through dual application of P with urea or ammonium sulfate was also investigated. A silty clay loam soil was used for the study (Table 5.1). The soil was collected from the surface (approximately 15 to 20 cm), sieved

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Table 5.1 Some chemical and physical characteristics of the soil.

Soil Characteristics[z]	
Soil Classification	Cumulic Regosol
Soil Association	Riverdale Association
Soil Texture	Silty clay loam
Gravimetric field capacity	32%
NaHCO$_3$ extractable P	3.7 μg g^{-1}
Inorganic Carbon	10.6 g C kg^{-1} soil
Exchangeable Cations:	
Ca^{++}	4475 μg g^{-1}
Mg^{++}	391 μg g^{-1}
K^{++}	240 μg g^{-1}
Na^{++}	27 μg g^{-1}
pH (soil-water)	7.9
Electrical Conductivity	0.30 dS m^{-1}

[z]Note: Detailed description of the soil analysis procedures is contained in Appendix II.

and air dried, as described for the previous studies (Sections 3.3 and 4.3).

An 11 kg portion of soil was placed into rectangular plastic pots measuring approximately 24 x 34 cm. The top 3.8 cm of soil was then removed, the remaining soil watered to field capacity, and the fertilizer applied to the surface. The fertilizers were applied at rates of 8.7 kg P ha^{-1} and 70 kg N ha^{-1}. The MAP was labelled with 37 MBq of ^{32}P as H$_3$PO$_4$ in 0.02 N HCl, such that it received 1.37 x 10^4 Bq mg^{-1} ^{31}P. The solution was dried at 35°C until the decrease in mass over a 24 hour period was less than 0.001 g. The dry material was ground to a powder in a glass mortar and pestle. The treatments consisted of 3 replicates of 13 treatments, using wheat (Triticum aestivum var. Katepwa) as a test crop (Table 5.2, Figure 5.1).

Table 5.2 Fertilizer treatments.

Treatment[x]	P Source[zx]	N Source[x]	Band Width	Application Method
1[y]	None	Ammonium Sulfate	------	N mixed into top 5cm of soil.
2[y]	MAP	Ammonium Sulfate	2.5	P applied to nine spots 1.9 cm below the seed row; N applied as described in treatment 1.
3[y]	MAP	Ammonium Sulfate	7.5	P applied to nine spots 1.9 cm below the seed row; N applied as described in treatment 1.
4[y]	MAP	Ammonium Sulfate	15.0	P applied to nine spots 1.9 cm below the seed row; N applied as described in treatment 1.
5	MAP	Urea	2.5	P applied to as described above; N granules scattered randomly within the MAP band.
6	MAP	Urea	7.5	P applied to as described above; N granules scattered randomly within the MAP band.
7	MAP	Urea	15.0	P applied to as described above; N granules scattered randomly within the MAP band.
8	MAP	Ammonium Sulfate	2.5	P applied to as described above; N granules scattered randomly within the MAP band.
9	MAP	Ammonium Sulfate	7.5	P applied to as described above; N granules scattered randomly within the MAP band.
10	MAP	Ammonium Sulfate	15.0	P applied to as described above; N granules scattered randomly within the MAP band.
11	MAP	Ammonium Sulfate	2.5	P applied to as described above; N granules applied in direct contact with the P.
12	MAP	Ammonium Sulfate	7.5	P applied to as described above; N granules applied in direct contact with the P.
13	MAP	Ammonium Sulfate	15.0	P applied to as described above; N granules applied in direct contact with the P.

[z]P was applied as 0.1945 g of powder split into 9 approximately equal portions, which were randomly positioned within the band.
[y]N in these treatments was mixed into top 5 cm of soil to simulate broadcast incorporation (ie. N and P applied separately).
[x]All rates were calculated based on 20 cm row spacing, and wheat was seeded at 27 kernels pot^{-1}.

Treatments 2, 5, 8, 11

Top View   End View

2.5 cm
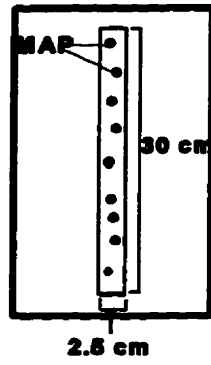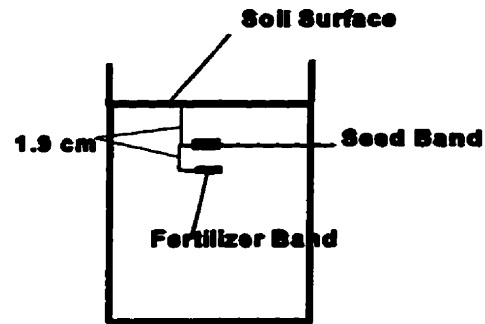
Treatments 3, 6, 9, 12

Top View   End View

7.5 cm
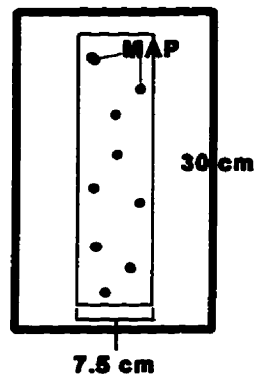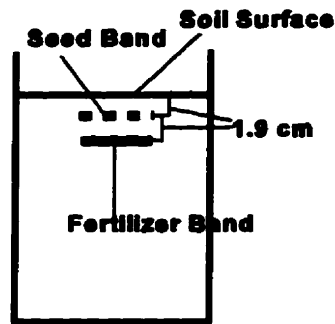
Treatments 4, 7, 10, 13

Top View   End View

15 cm
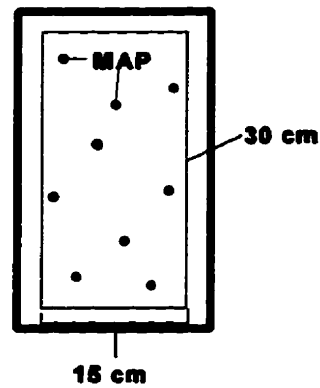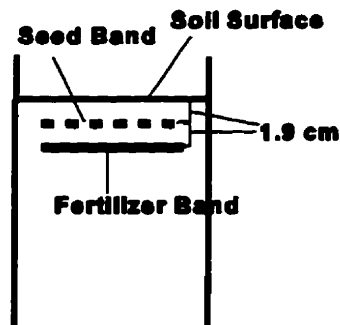
Figure 5.1 Fertilizer band geometries.

Soil equivalent to 1.9 cm depth was replaced and 27 kernels of wheat were randomly applied to a band of identical dimensions to that of the fertilizer band (ie. seeds were randomly scattered in band widths of 2.5, 7.5 or 15 cm to match fertilizer band widths of 2.5, 7.5 or 15 cm, respectively). The remaining soil was then replaced. The pots were then watered to field capacity, placed in the growth chambers in a randomized complete block design, and watered to field capacity every 2 to 3 days. The positions of the pots were changed on the days the plants were watered to help insure each received similar conditions of light, etc., throughout the course of the experiment. Day length, temperature and humidity were approximately 16 hours, 23°C and 60%, respectively, while night temperature and humidity were approximately 14°C and 80%, respectively. Plant density was thinned to 20 plants pot^{-1} on the 8th day after emergence.

The plants were monitored for changes in radioactivity from emergence to final harvest using a hand held Geiger-Mueller survey metre. The average intensity, observed as the metre was moved slowly over the plant surfaces, was recorded. Counts were not corrected for radioactive decay. The above ground plant material from 10 randomly selected plants in each pot was harvested at 15 days after seeding. At 29 days after seeding the remaining plants were harvested. Samples were allowed to air dry for 1 day, and then oven dried at approximately 60°C for 3 days. The mass of the dry matter was measured, and the samples ground using a Braun coffee grinder. Plant tissue analysis was then conducted to determine total and fertilizer P uptake (Appendix I). Statistical analysis of results included ANOVA, mean comparison and correlation procedures using the Statistical Analysis System.

5.3.2 Effect of Band Width, Dual Banding and Phosphate Application Rate on P Utilization

The soil used for this study was similar to that used in the previous study described in this section, differing only slightly in nutrient values (Table 5.3). The pots were set up as described for the previous study, and used the same band geometries (Figure 5.1). In contrast to treatments used in the previous study two rates of MAP (labelled with ^{32}P) were used and urea as an N source was eliminated. Treatments in which the MAP and ammonium sulphate were applied to the same spot (in direct contact) or randomly distributed in the fertilizer band were also included. The treatments are described in detail in Table 5.4. All other procedures and analyses were conducted as described in the previous study.

Table 5.3 Some chemical and physical characteristics of the soil.

Soil Characteristics[z]	
Soil Classification	Cumulic Regosol
Soil Association	Riverdale Association
Soil Texture	Silty clay loam
Gravimetric field capacity	32%
NaHCO$_3$ extractable P	1.7 $\mu g \ g^{-1}$
Inorganic Carbon	10.5 g C g-1 soil
Exchangeable Cations:	
Ca^{++}	4750 $\mu g \ g^{-1}$
Mg^{++}	397 $\mu g \ g^{-1}$
K^{++}	255 $\mu g \ g^{-1}$
Na^{++}	20 $\mu g \ g^{-1}$
pH (soil-water)	7.8
Electrical Conductivity	0.37 dS m-1

[z]Note: Detailed description of the soil analysis procedures is contained in Appendix II.

Table 5.4 Fertilizer treatments for study of interactions among band width, dual banding and phosphate application rate.

Treatment #	MAP Rate ^{x} (kg P ha^{-1})	Application Method
1^y	0	N mixed into the top 5 cm of soil
2^y	8.7	P applied to 9 spots in a 2.5 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
3^y	8.7	P applied to 9 spots in a 7.5 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
4^y	8.7	P applied to 9 spots in a 15.0 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
5^y	17.4	P applied to 18 spots in a 2.5 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
6^y	17.4	P applied to 18 spots in a 7.5 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
7^y	17.4	P applied to 18 spots in a 15.0 x 30 cm band 1.9 cm below the seed band; N mixed into top 5 cm of soil
8	8.7	P applied to 9 spots in a 2.5 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.
9	8.7	P applied to 9 spots in a 7.5 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.
10	8.7	P applied to 9 spots in a 15.0 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.
11	17.4	P applied to 18 spots in a 2.5 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.
12	17.4	P applied to 18 spots in a 7.5 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.
13	17.4	P applied to 18 spots in a 15.0 x 30 cm band 1.9 cm below the seed band; N applied directly to the same spots as the P.

^{z}P was applied as 0.1945 g of powder split into 9 (8.7 kg P ha^{-1}) or 18 (17.4 kg P ha^{-1}) approximately equal portions.
^{y}N in these treatments was mixed into top 5 cm of soil to simulate broadcast incorporation (ie. N and P applied separately).
^{x}All rates were calculated based on 20 cm row spacing. Wheat seeded at 27 kernels pot^{-1}.

5.4 Results and Discussion

5.4.1 Fertilizer P Uptake by Wheat as Affected by Very Large Band Widths and Dual Banding with N

Figures 5.2, 5.3 and 5.4 represent the radioactivity of wheat plants as measured

with a Geiger-Mueller survey metre, which reflected the uptake of fertilizer P with time

after seeding. Correlation analysis between the radioactivity of the plants prior to harvest

and the results of liquid scintillation counting of the plant tissue extracts indicated these

Geiger-Mueller survey meter readings to be a good indication of ^{32}P uptake (Table 5.5).

Table 5.5 Correlation analysis of Geiger-Mueller survey metre readings vs. decays per minute measured by scintillation counting for study of larger band widths (Both harvest dates).

Harvest Date (Days after seeding)	Pearson Correlation Coefficient	Probability > |R|
15	0.90	0.0001
29	0.88	0.0001
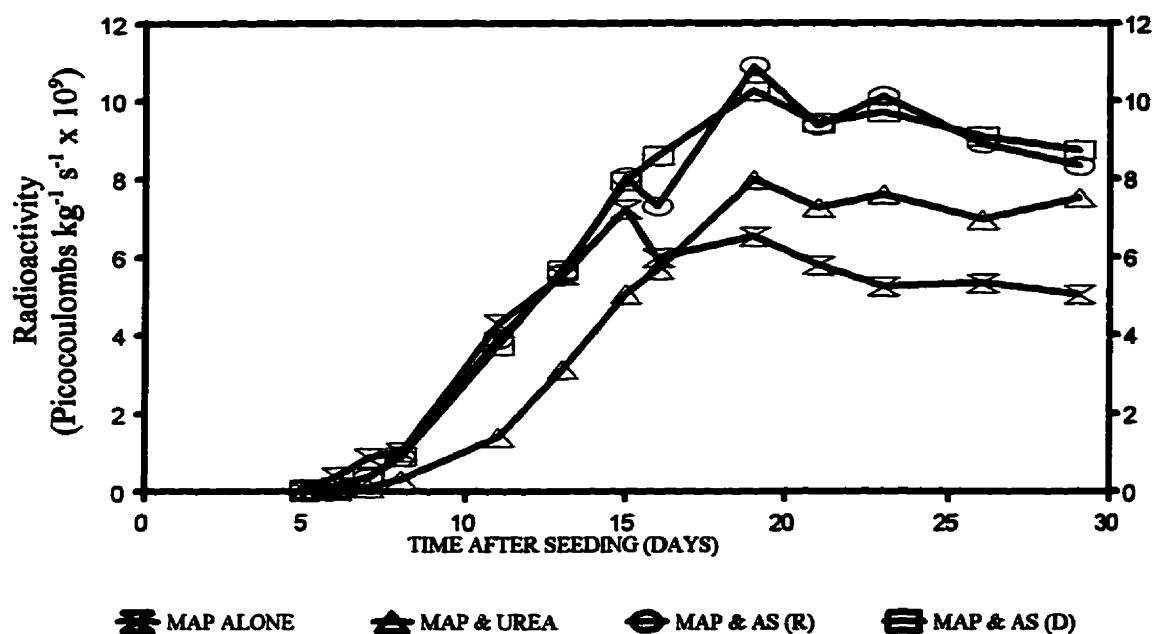
Figure 5.2 P uptake from labelled MAP applied alone or dual banded with urea or
ammonium sulphate (AS) in 2.5 cm wide bands (R=MAP & AS granules both
randomly scattered in the band; D=MAP & AS placed in direct contact).
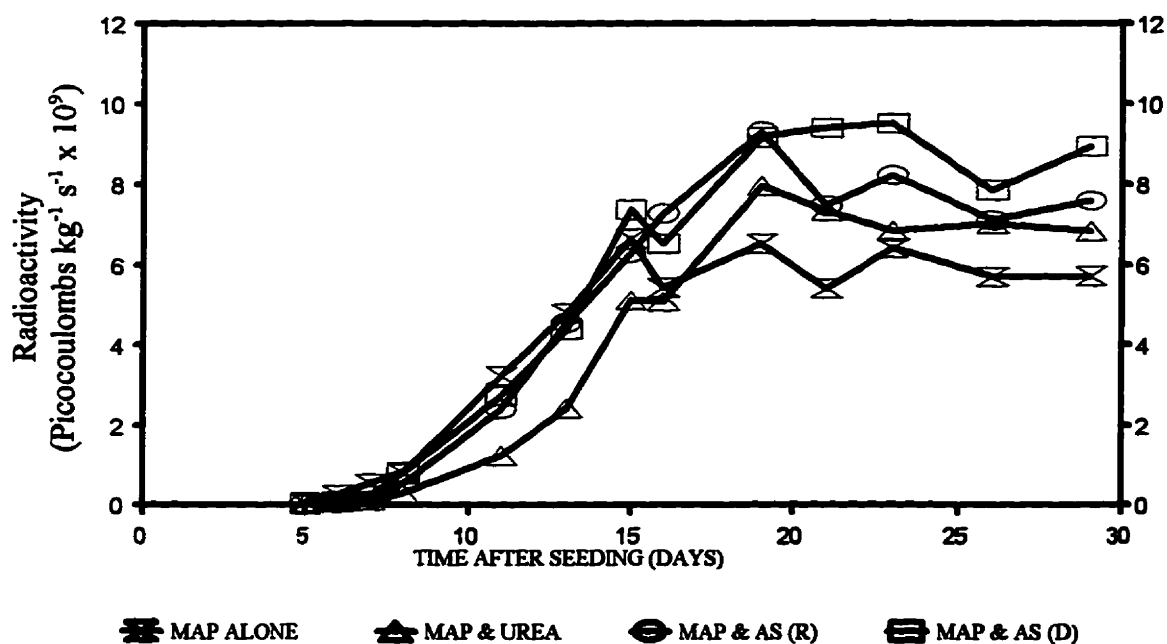
Figure 5.3 P uptake from labelled MAP applied alone or dual banded with urea or
ammonium sulphate (AS) in 7.5 cm wide bands (R=MAP & AS granules both
randomly scattered in the band; D=MAP & AS placed in direct contact).
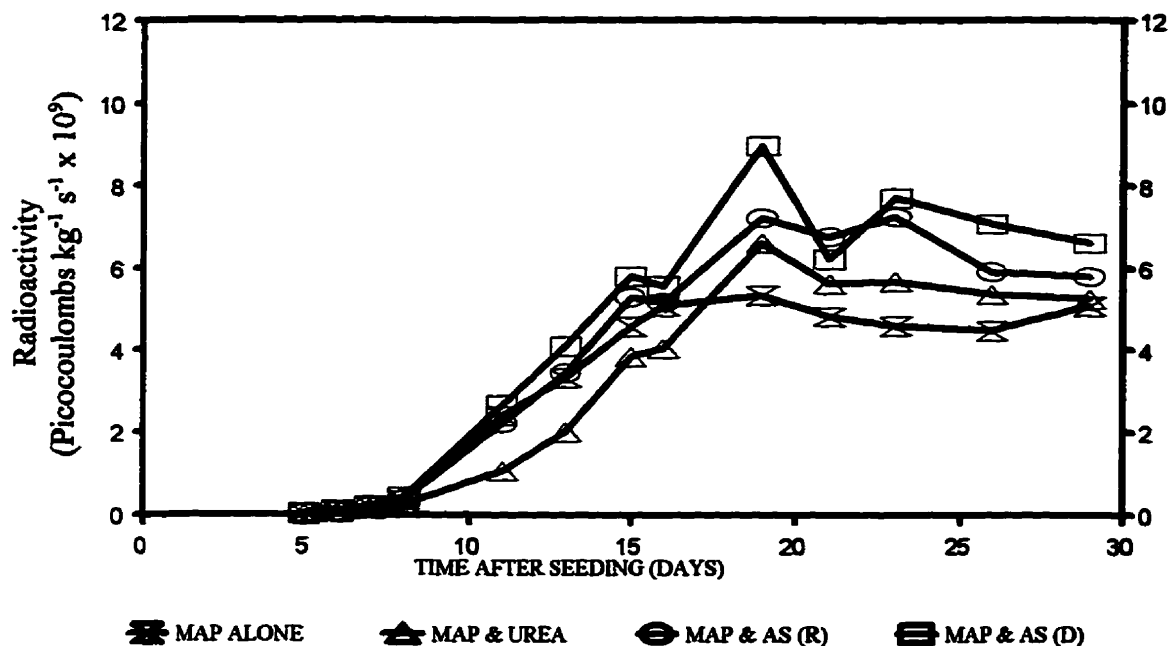
Figure 5.4 P uptake from labelled MAP applied alone or dual banded with urea or
ammonium sulphate (AS) in 15 cm wide bands (R=MAP & AS granules both
randomly scattered in the band; D=MAP & AS placed in direct contact).

The application of N to the MAP bands had a significant effect on the pattern of

fertilizer P uptake. There was a slight delay in initiation of fertilizer P uptake when urea

was applied with the MAP, as compared to the MAP applied separately from the N

source, for the 2.5 and 7.5 cm wide bands. The rate of uptake of fertilizer P by the plants

in the MAP-urea dual bands was considerably less than that for the MAP applied

separately until approximately 17 days after seeding, for all band widths. Dual applications

of MAP and ammonium sulfate increased fertilizer P uptake above that with MAP alone

for all band widths.

Band width appeared to have relatively little effect on the rate of fertilizer P uptake

by plants in treatments where MAP and N were applied separately. However, uptake of

fertilizer P by the plants for treatments involving dual applications of N and MAP

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decreased with increasing band widths. Uptake of applied P from randomly distributed MAP and ammonium sulfate was similar to that with MAP and ammonium sulphate in direct contact when the band width was 2.5 cm. However, application of the ammonium sulfate and MAP in intimate contact resulted in improved fertilizer P uptake over a random distribution with band widths of 7.5 and 15 cm.

Tables 5.6 and 5.7 represent the results of analysis of wheat tissue from plants harvested at 15 and 29 days after seeding, respectively. Yield, 15 days after seeding, with MAP was greater than without except for the yield from the 2.5 cm wide dual band of MAP and urea (Table 5.6). However, only the MAP and ammonium sulphate applied separately produced a significantly greater yield than the treatment with only ammonium sulphate. Total P concentration in the plants increased significantly with the addition of MAP. The application of ammonium sulphate with the MAP increased total P concentration over that of plants with MAP applied alone, for similar band widths, although the difference was only significant for the 7.5 cm wide band. The application of urea to the MAP band had little or no effect on P concentration. Fertilizer use efficiency for the MAP from dual application of ammonium sulphate and MAP was similar to MAP applied alone for the 2.5 cm band width. However, utilization of fertilizer P was slightly greater for the ammonium sulphate and MAP applied in direct contact for band widths of 7.5 and 15 cm (not significantly) than for the N and P randomly distributed within the band. Urea had a negative effect on fertilizer use efficiency of MAP at all band widths, with the most significant reduction occurring with the 2.5 cm wide band.

Table 5.6 Total dry weight, total P concentration and fertilizer P utilization of wheat as affected by band width and dual banding with N (First harvest).

Treatments		Total Dry Weight (g)	[Total P] (mg/g)	Fertilizer P Utilization (%)
Fertilizers	Band Geometry			
1. $(NH_4)_2SO_4$ alone	N mixed into top 5cm of soil.	0.52 bc^x	1.23 d	___
2. MAP & $(NH_4)_2SO_4$ applied separately	P in 2.5 x 30 cm band; N applied as in #1.	0.85 a	3.59 abc	5.27 ab
3. MAP & $(NH_4)_2SO_4$ applied separately	P in 7.5 x 30 cm band; N applied as in #1.	0.79 ab	3.28 c	4.40 abcd
4. MAP & $(NH_4)_2SO_4$ applied separately	P in 15 x 30 cm band; N applied as in #1.	0.75 abc	3.08 c	3.43 abcd
5. MAP & Urea dual applied^z	P and N in 2.5 x 30 cm band .	0.49 c	3.03 c	2.35 d
6. MAP & Urea dual applied^z	P and N in 7.5 x 30 cm band .	0.66 abc	3.15 c	3.33 bcd
7. MAP & Urea dual applied^z	P and N in 15 x 30 cm band .	0.58 abc	3.20 c	2.93 cd
8. MAP & $(NH_4)_2SO_4$ dual applied^z	P and N in 2.5 x 30 cm band .	0.69 abc	4.08 a	5.07 ab
9. MAP & $(NH_4)_2SO_4$ dual applied^z	P and N in 7.5 x 30 cm band .	0.75 abc	3.52 bc	4.40 abcd
10. MAP & $(NH_4)_2SO_4$ dual applied^z	P and N in 15 x 30 cm band .	0.70 abc	3.24 c	3.40 bcd
11. MAP + $(NH_4)_2SO_4$ in direct contact ^{y}	P and N in 2.5 x 30 cm band .	0.74 abc	3.96 ab	4.87 abc
12. MAP + $(NH_4)_2SO_4$ in direct contact ^{y}	P and N in 7.5 x 30 cm band .	0.76 ab	3.95 ab	5.53 a
13. MAP + $(NH_4)_2SO_4$ in direct contact ^{y}	P and N in 15 x 30 cm band .	0.78 ab	3.51 bc	4.33 abcd
Standard Error		0.14	0.29	1.07

[z]P was positioned randomly within the band, then the N granules were randomly distributed within the same band.

[y]P and N in these treatments were applied to the same randomly positioned spots within the band (in direct contact).

[x]Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

Table 5.7 Total dry weight, total P concentration and fertilizer P utilization of wheat as affected by band width and dual banding with N (Second harvest).

Treatments		Total Dry Weight (g)	[Total P] (mg/g)	Fertilizer P Utilization (%)
Fertilizers	**Band Geometry**			
1. $(NH_4)_2SO_4$ alone	N mixed into top 5cm of soil.	2.73 e	2.18 a	—
2. MAP & $(NH_4)_2SO_4$ applied separately	P in 2.5 x 30 cm band; N applied as in #1.	5.55 cd	1.77 b	10.3 f
3. MAP & $(NH_4)_2SO_4$ applied separately	P in 7.5 x 30 cm band; N applied as in #1.	5.49 cd	1.86 ab	11.5 f
4. MAP & $(NH_4)_2SO_4$ applied separately	P in 15 x 30 cm band; N applied as in #1.	5.25 d	1.82 ab	9.9 f
5. MAP & Urea dual applied[z]	P & N in 2.5 x 30 cm band .	6.30 abc	2.00 ab	17.2 ab
6. MAP & Urea dual applied[z]	P & N in 7.5 x 30 cm band .	5.76 bcd	2.15 ab	16.2 bc
7. MAP & Urea dual applied[z]	P & N in 15 x 30 cm band .	5.50 cd	2.11 ab	13.4 de
8. MAP & $(NH_4)_2SO_4$ dual applied[z]	P & N in 2.5 x 30 cm band .	6.87 a	1.78 b	19.8 a
9. MAP & $(NH_4)_2SO_4$ dual applied[z]	P & N in 7.5 x 30 cm band .	6.57 ab	1.97 ab	18.1 ab
10. MAP & $(NH_4)_2SO_4$ dual applied[z]	P & N in 15 x 30 cm band .	5.76 bcd	1.95 ab	13.6 cde
11. MAP + $(NH_4)_2SO_4$ in direct contact[y]	P & N in 2.5 x 30 cm band .	6.65 ab	1.91ab	18.5 ab
12. MAP + $(NH_4)_2SO_4$ in direct contact[y]	P & N in 7.5 x 30 cm band .	6.43 abc	1.94 ab	18.2 ab
13. MAP + $(NH_4)_2SO_4$ in direct contact[y]	P & N in 15 x 30 cm band .	6.23 abcd	1.89 ab	15.6 bcd
Standard Error		0.52	0.20	1.51

[z]P was positioned randomly within the band, then the N granules were randomly distributed within the same band.

[y]P and N in these treatments were applied to the same randomly positioned spots within the band (in direct contact).

[x]Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).

Yield at 29 days after seeding with MAP was significantly greater than without MAP in all cases (Table 5.7). Generally, trends in yield were a reflection of the trends in utilization of P from the MAP. Increasing band width tended to decrease yield for similar fertilizer treatments. However, this trend was only significant for the ammonium sulphate-MAP dual bands in which the two fertilizers were randomly distributed. Dual banding with nitrogen increased yield in all cases for similar band widths, but significant increases only occurred with ammonium sulphate applied in the narrower bands (2.5 and 7.5 cm wide). Concentration of P in the plants changed dramatically between 15 and 29 days after seeding. Plants with the treatment with no MAP increased in total P concentration, while the concentrations in the MAP fertilized treatments declined substantially. As a result significant differences between MAP treated and untreated plants were not evident at 29 days after seeding. Dual application of MAP and N sources increased utilization of applied P. The initial negative effects of urea dual banded with the MAP had been overcome by this stage and P uptake was significantly increased. Nevertheless, ammonium sulphate was still more effective (not significantly) than urea in improving P fertilizer efficiency when dual applied with the MAP. Application of MAP and ammonium sulphate in direct contact improved P utilization only slightly more than a random distribution, and only for the 15 cm band.

Dual banding with urea resulted in considerably less fertilizer P uptake from applied MAP than from similar applications of MAP and ammonium sulphate. Yield followed a similar, though less significant trend. These differences in response to dual banding from the two N sources apparently resulted from reductions in initial uptake of P

from the urea-MAP dual bands, particularly in the narrower band widths. These findings were similar to those of Beever (1987) and Flaten (1989), and are probably explained by high pH and NH_3-N concentrations in the bands with urea. These high concentrations could be toxic to root growth near the application site (Colliver and Welch 1970). Nitrite accumulation, which is toxic to plant roots, is also enhanced by high concentrations of ammoniacal N and alkaline pH which can occur in urea bands (Aleem and Alexander 1960; Court et al. 1964), and may have been a contributing factor. By the second harvest uptake rate with MAP and urea had increased above that of MAP alone, and fertilizer P utilization had increased significantly. This indicated that once nitrification had lowered the levels of ammonia and nitrite the urea significantly increased fertilizer P uptake rates, similar to the effect of dual banding with ammonium sulphate.

5.4.2 Effect of Band Width, Dual Banding and Phosphate Application Rate on P Utilization

Figures 5.5 and 5.6 represent increases in radioactivity, resulting from ^{32}P uptake by wheat with time after seeding, for P application rates of 8.7 and 17.4 kg ha^{-1}, respectively. Correlation analysis between the radioactivity of the plants prior to harvest and the results of liquid scintillation counting of the plant tissue extracts indicated these Geiger-Mueller survey meter readings to be a good indication of ^{32}P uptake (Table 5.8).

Table 5.8 Correlation analysis of Geiger-Mueller survey metre readings vs. decays per minute measured by scintillation counting for study of band width, dual banding and phosphate application rate (Both harvest dates).

Harvest Date (Days after seeding)	Pearson Correlation Coefficient	Probability > |R|
15	0.91	0.0001
29	0.88	0.0001
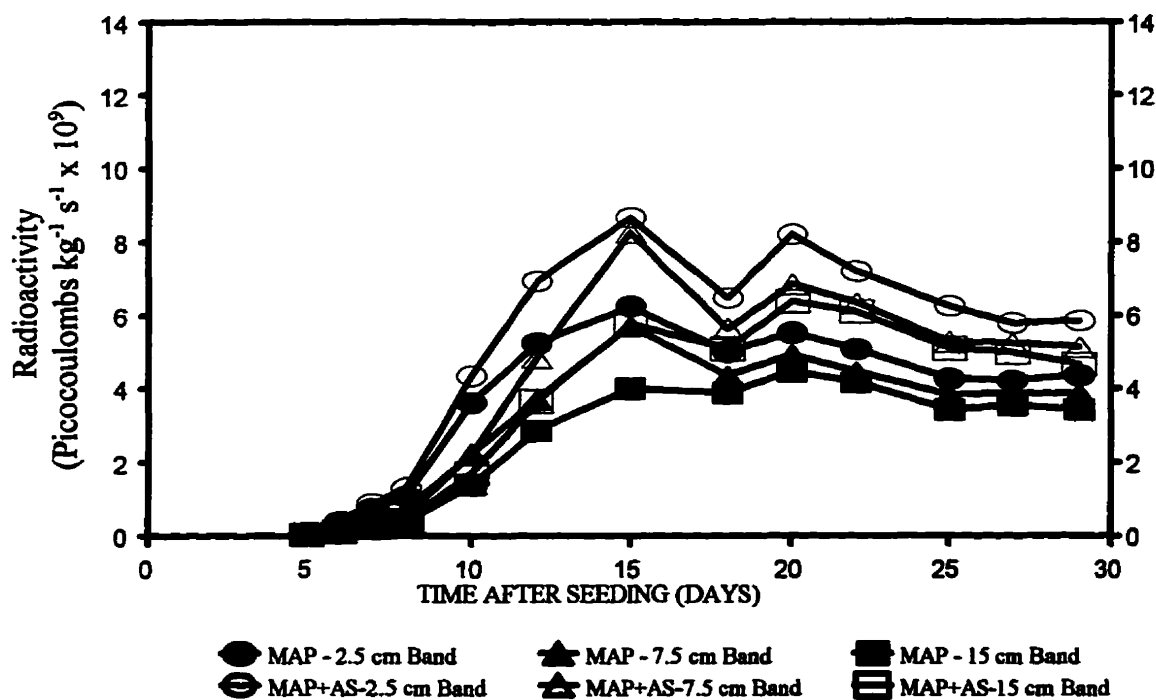
Figure 5.5 Fertilizer P uptake from labelled MAP applied at a rate of 8.7 kg P ha^{-1}, alone or dual banded with ammonium sulphate (AS).
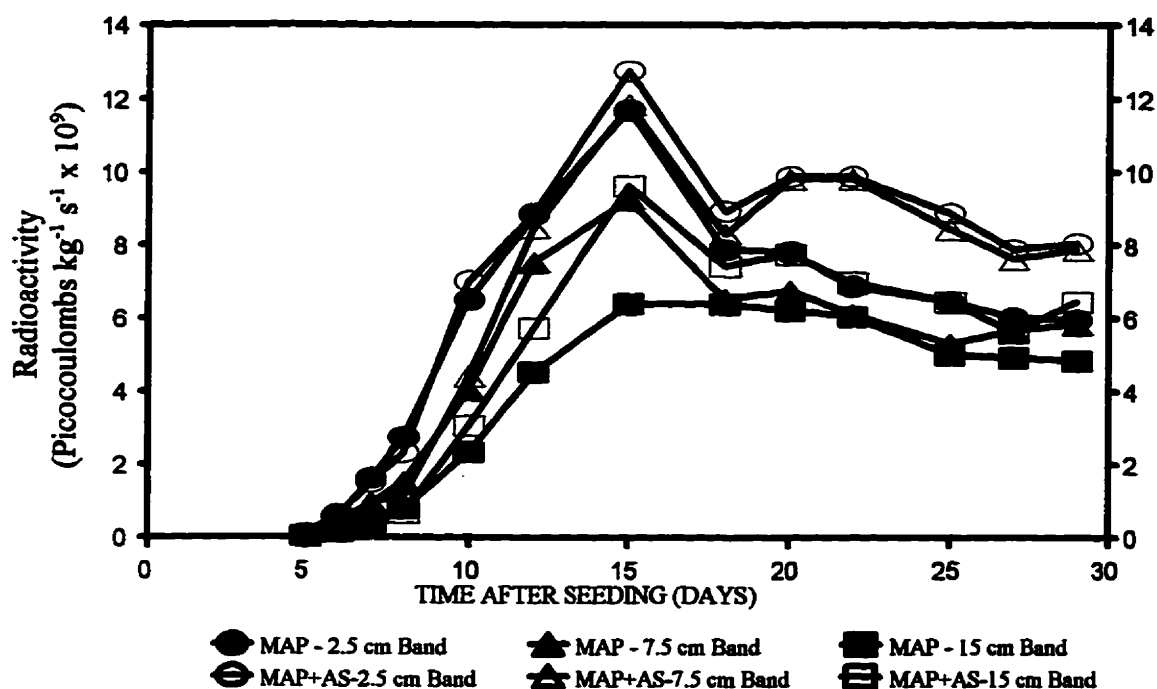
Figure 5.6 Fertilizer P uptake from labelled MAP applied at a rate of 17.4 kg P ha⁻¹, alone or dual banded with ammonium sulphate (AS).

Initiation of uptake of P from MAP occurred on the same day for all treatments. As expected, increasing the rate of MAP application resulted in increased P uptake for similar treatments. Increased band widths decreased radioactivity of the plants whether the MAP was applied separately or dual applied with ammonium sulphate. For each of the P application rates the level of radioactivity was greater from applications of ammonium sulphate and MAP applied in direct contact than for the N and P applied separately. It is interesting to note that fertilizer P uptake for the dual N-P band at a band width of 15 cm was equal to or above that with MAP and N applied separately but with the P in a narrow (2.5 cm) band, for both application rates (Figures 5.5 and 5.6).

Tables 5.9 and 5.10 indicate the results of tissue analysis of plants harvested at 15 and 29 days after seeding, respectively. MAP application increased yield above the control in all cases by 15 days after seeding, but not always significantly. When MAP was applied separately from the ammonium sulphate the yield only increased significantly for the high rate of application (17.4 kg P ha^{-1}) in the narrower band widths (2.5 and 7.5 cm). In contrast, the application of the MAP in direct contact with the ammonium sulphate significantly increased yield over that of the control for all but the low MAP rate in the widest band width (15 cm). Both increased MAP rate and dual application with N increased yield for similar treatments, but none of the increases were significant. Application of MAP increased the total P concentration in the plant tissue at 15 days after seeding, but at 29 days after seeding no significant differences among the treatments were noted. P concentration in the plants from the first harvest generally increased with rate of P application and was greater with dual N-P application than with N and P separately applied. Band width had little or no effect on P concentration. Percent utilization of the applied P was similar for the two application rates. Percent utilization was increased by dual application of the ammonium sulphate with the MAP. The magnitude of the effect of dual banding decreased with increased P rate and increased band width. There was a slight but not significant decline in fertilizer P utilization with increased band width.

Dry matter yields, at 29 days after seeding, showed a significant positive response to MAP in all cases. Increasing the rate of P application and dual banding of MAP and ammonium sulphate in direct contact tended to increase yield, but the trends were not significant. Concentrations of P in plants were similar for all treatments. Increasing

Table 5.9 Total dry weight, total P concentration and fertilizer P uptake and utilization of wheat as affected by band width and P rate (First harvest).

Treatments		Total Dry Weight	[Total P]	Fertilizer P Uptake	Fertilizer P Utilization
Fertilizers	Band Geometry	(g)	(mg/g)	(mg)	(%)
1. $(NH_4)_2SO_4$	N mixed into top 5cm of soil.	0.46 c^z	1.67 h	—	—
2. MAP (8.7 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 2.5 x 30 cm band; N applied as in #1.	0.66 bc	3.90 fg	1.93 gh	3.7 bcde
3. MAP (8.7 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 7.5 x 30 cm band; N applied as in #1.	0.62 bc	4.58 def	1.82 gh	3.5 cde
4. MAP (8.7 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 15 x 30 cm band; N applied as in #1.	0.62 bc	3.73 g	1.58 h	3.0 de
5.MAP (17.4 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 2.5 x 30 cm band; N applied as in #1.	0.77 ab	5.31 bcd	3.76 bcd	3.6 cde
6.MAP (17.4 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 7.5 x 30 cm band; N applied as in #1.	0.74 ab	5.21 cde	3.32 cde	3.2 de
7.MAP (17.4 kg ha^{-1}) & $(NH_4)_2SO_4$	P in 15 x 30 cm band; N applied as in #1.	0.69 abc	4.85 de	2.69 efg	2.6 e
8. MAP (8.7 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 2.5 x 30 cm band .	0.73 ab	4.78 de	3.00 def	5.7 a
9. MAP (8.7 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 7.5 x 30 cm band .	0.69 ab	4.95 de	2.73 defg	5.2 ab
10.MAP (8.7 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 15 x 30 cm band .	0.66 bc	4.49 ef	2.16 fgh	4.1 bcde
11.MAP (17.4 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 2.5 x 30 cm band .	0.91 a	5.85 abc	5.06 a	4.8 abc
12.MAP (17.4 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 7.5 x 30 cm band .	0.79 ab	6.36 a	4.68 ab	4.5 abcd
13. MAP (17.4 kg ha^{-1}) + $(NH_4)_2SO_4$	P & N in 15 x 30 cm band .	0.76 ab	5.96 ab	4.16 abc	4.0 bcde
Standard Error		0.12	0.40	0.57	0.85

^{z}Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).
^{y} P and N in these treatments applied to same locations (ie. in direct contact) within the fertilizer band.

Table 5.10 Total dry weight, total P concentration and fertilizer P uptake and utilization of wheat as affected by band width and P rate (Second harvest).

Treatments		Total Dry Weight	[Total P]	Fertilizer P Uptake	Fertilizer P Utilization
Fertilizers	Band Geometry[1]	(g)	(mg/g)	(mg)	(%)
1. $(NH_4)_2SO_4$	N mixed into top 5cm of soil.	2.8 c^z	2.25 a	—	—
2. MAP (8.7 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 2.5 x 30 cm band; N applied as in #1.	5.3 ab	1.93 a	5.24 e	10.0 c
3. MAP (8.7 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 7.5 x 30 cm band; N applied as in #1.	5.1 b	2.23 a	5.59 e	10.7 c
4. MAP (8.7 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 15 x 30 cm band; N applied as in #1.	5.0 b	2.17 a	5.48 e	10.5 c
5.MAP (17.4 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 2.5 x 30 cm band; N applied as in #1.	6.0 ab	2.46 a	9.91 bc	9.5 c
6.MAP (17.4 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 7.5 x 30 cm band; N applied as in #1.	6.3 ab	2.38 a	9.69 c	9.2 c
7.MAP (17.4 kg ha⁻¹) & $(NH_4)_2SO_4$	P in 15 x 30 cm band; N applied as in #1.	6.6 ab	2.36 a	10.5 bc	10.1 c
8ʸ. MAP (8.7 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 2.5 x 30 cm band .	6.2 ab	2.29 a	8.94 cd	17.1 a
9ʸ. MAP (8.7 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 7.5 x 30 cm band .	5.8 ab	2.27 a	7.86 d	15.0 b
10ʸ.MAP (8.7 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 15 x 30 cm band .	5.9 ab	2.05 a	7.53 d	14.4 b
11ʸ.MAP (17.4 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 2.5 x 30 cm band .	7.4 a	2.33 a	13.8 a	13.2 b
12ʸ.MAP (17.4 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 7.5 x 30 cm band .	7.0 ab	2.57 a	14.0 a	13.4 b
13.MAP (17.4 kg ha⁻¹) + $(NH_4)_2SO_4$	P & N in 15 x 30 cm band .	6.7 ab	2.34 a	11.5 b	11.0 c
Standard Error		1.10	0.37	0.91	1.00

[z]Values in columns with the same letter are not significantly different according to Duncan's Multiple Range Test (Alpha=.05).
[y] P and N in these treatments applied to same locations (ie. in direct contact) within the fertilizer band.

band width had little effect on fertilizer P uptake when the MAP was applied alone. Slight decreases in fertilizer P uptake and utilization efficiency were observed with increased band width for the dual bands. Uptake of fertilizer P was greater with the higher rate of application in all cases. Efficiency of fertilizer P utilization for MAP alone was similar for the two rates of application. However, percent utilization of fertilizer P was increased by application of MAP and ammonium sulphate in direct contact as compared to MAP and N applied separately. This effect was less pronounced at the higher P application rate (17.4 kg ha^{-1}), although it was still singnificant for all but the 15 cm band width.

Studies by Beever (1987) indicated that movement of P away from the site of MAP application was limited to between 2.75 and 0.75 cm for neutral to alkaline soils. Thus, for the lower application rates (8.7 kg P ha^{-1}), it can be shown that the spheres of fertilizer P affected soil around the points of application did not overlap even for the narrow band width (2.5 cm). Thus, increasing the band width beyond 2.5 cm would not increase the area of fertilizer affected soil, nor the surface area for fixation and precipitation reactions. Therefore, any reductions in P uptake were likely related to reduced probability of root-fertilizer contact, or delayed initial contact. These effects would also have been reduced by the relatively small distance between the seed row and fertilizer band, and the similar dimensions and random distribution of seed in that seed row. Beever (1987) also showed increased movement of P from the site of application when the MAP was dual applied with N (particularly ammonium sulphate). This helps to explain the greater P uptake with the dual bands as compared to the MAP applied alone. Increased continuity of fertilizer P affected soil in the narrower bands combined with ammonium ion effects spurred large

increases in P uptake. However, as band width increased less continuity combined with lowered concentration of N in the MAP reaction zone, due to distribution of the N over a greater area, would limit the effectiveness of the dual banding. Application of the N and P in direct contact offset this trend somewhat, but not significantly.

5.5 Summary and Conclusions

Two growth chamber studies were conducted to determine the effects of rate of fertilizer P application, dual banding of nitrogen and phosphate sources, and very large band widths on fertilizer P utilization. In vivo monitoring of radioactivity of the plants and tissue analysis of plants harvested at 15 and 29 days after seeding were used to assess effect on yield, total P concentration and fertilizer P utilization.

Dry matter yield was usually greater with MAP than without indicating that the soil used was responsive to P fertilization. As a result, trends in yield tended to reflect trends in fertilizer P utilization. Total P concentrations in the plants from the two harvests indicated that initial P uptake was very rapid, and was significantly increased by MAP additions. The smaller band widths resulted in greater P concentrations for all but the MAP-urea dual bands. Dual banding with ammonium sulphate also initially increased plant P concentrations when compared to the P and N applied separately. However, the rate of plant growth appeared to exceed the rate of P uptake between 15 and 29 days after seeding for treatments receiving MAP, and any significant differences in total P concentration disappeared by the second harvest.

Increased band width appeared to have very little effect on fertilizer P utilization

from bands with MAP applied alone. Increasing the band width increased the distance between application points for the MAP, but may not have increased the area of fertilizer P affected soil to any great extent. Increasing band width decreased uptake from dual N-P bands with the exception of urea at 15 days after seeding. This was most likely due to reduced concentration of N in contact with the MAP, which appeared to lessen the benefits from ammonium ion effects. The most noteable observation in these studies was the fact that in all cases fertilizer P utilization was increased through dual banding of N and P at 29 days after seeding, as compared to similar treatments with the N and P applied separately. Also, ammonium sulphate in direct contact with the MAP was more effective than randomly distributing these fertilizers as granules in the same band, for wider band widths similar to those produced by air seeder openers designed to give wide spread patterns.

6. GENERAL DISCUSSION

The studies reported herein assessed the effect of two main topics, band geometry and chemistry, on efficiency of P utilization from applied MAP. Wheat and canola were used as test crops. The aspects of band geometry studied included both the size of the bands and the continuity of application within them. The first three studies involved band geometries ranging from points of application spaced 5 cm apart to 2.5 cm wide continuous bands. The fertilizers were applied in solution or very fine granular form. In the larger bands the fertilizer was spread as uniformly throughout the band as possible. Chemical amendments introduced into these MAP bands included nitrogen sources (ammonium sulphate and urea), magnesium sulphate, and lignosulfonate with calcium, ammonium or hydrogen as accompanying cations.

Two other studies, reported herein, involved much larger band widths, ranging from 2.5 to 15 cm. The MAP was applied within these bands as randomly positioned portions of fine granular MAP to simulate commercial granular MAP applications. Granular urea or ammonium sulphate was scattered randomly within the bands to simulate a mechanical mixture of the N and P source (dual banding). Ammonium sulphate was also applied directly to the same spots as the MAP to simulate a chemical mixture of the N and P fertilizer.

The results using canola as a test crop in the first study indicated that the canola

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was extremely efficient at utilizing P from MAP applied in the band with the smallest area of application. These findings were in agreement with work by Strong and Soper (1974a,b) which indicated canola to be much more efficient than wheat at utilizing fertilizer P applied to a small area in the soil, due to greater root proliferation and adsorptive capacity. Changes in band geometry and dual banding with N were unable to enhance fertilizer P use efficiency beyond this level. This was in contrast to research by Beever (1987) which showed significant increases in utilization of P from dual banding of MAP and ammonium sulphate. The difference in results is most likely explained by the greater distance of the bands in his studies from the seed row, which would make the benefits of increased solubility and ammonium ion effects more critical.

Results obtained using wheat as a test crop were different than those obtained using canola. Increasing the surface area of fertilizer P application through increases in band width or volume increased the utilization of P from MAP applied in solution or fine granular form, although not significantly. These increases in fertilizer P uptake were probably due to increased root-fertilizer contact (Eghball and Sander 1987), or increased probability of contact between the roots and MAP (Sleight et al. 1984). The fact that this trend was not more pronounced may have resulted from the relatively small distance between the fertilizer band and the seed row used in these studies. Increasing the distance of P application from the seed row would decrease the probability of root fertilizer contact and reduce P uptake, making the area of application more critical (Eghball and Sander 1989).

Increasing band width beyond 2.5 cm for MAP distributions similar to commercial

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granular applications appeared to have little effect on the utilization efficiency of MAP

applied alone. These results may be explained by the fact that movement of P from the

point of MAP application is very limited in neutral to alkaline soils (Beever 1987). As a

result the P reaction zone formed around the points of application were probably already

independent of one another in the 2.5 cm wide band. This would mean that increasing the

band width would have little effect on the area of P affected soil, and hence little effect on

fixation reactions or root fertilizer contact.

Incorporation of lignosulfonate sources into the MAP bands had no effect on

fertilizer P utilization. This was in contrast to previous findings (Xie et al. 1991; Russell et

al. 1991), which indicated that ammonium lignosulfonate could effectively compete with

phosphate ions for adsorption sites and improve P uptake. However, their studies

involved acidic soils with lower levels of exchangeable calcium, and much higher rates of

lignosulfonate application. The calcium levels in the soil used in the studies reported

herein were probably too high for the lignosulfonate to significantly reduce Ca-P

precipitation. However, incorporation of magnesium sulphate into MAP bands was

effective in improving uptake of applied P. This may have resulted from displacement of

calcium into the soil solution followed by precipitation of calcium sulphates which would

reduce the levels of soluble calcium available for precipitation with phosphate. Studies

involving K_2SO_4 have indicated that potassium sulphate would be more effective than KCl

or KNO_3 in improving P availability due to less precipitation of applied P at the point of

application by similar mechanisms (Bouldin et al. 1960).

The most consistent trend in these studies was the enhancement of P uptake from

dual N-P bands as compared to similar applications of MAP applied separate from the N source. However, the two N sources did vary in their effectiveness, with greater increases resulting from dual bands of MAP and ammonium sulphate than from MAP-urea dual bands. The urea delayed fertilizer P uptake from the dual bands initially, but this was generally overcome by the final harvest of plant tissue (about 29 days after seeding). These initial delays in uptake were likely the result of ammonia and/or nitrite toxicity preventing root growth into the bands (Colliver and Welch 1970; Beever 1987; Flaten 1989). The effectiveness of ammonium sulphate in improving P utilization from dual bands with MAP was probably the result of increased availability due to acidification of the reaction zone as well as biological mechanisms related to the ammonium ion effect (Section 2.3.3).

7. SUMMARY AND CONCLUSIONS

The studies reported herein were designed to assess the effect of a variety of band geometries and chemical modifications to MAP fertilizer bands on P utilization and yield. Canola was found to be extremely efficient in utilizing P from MAP applied alone in bands with small zones of fertilizer application. As a result, opportunities for improving fertilizer P utilization by canola through modifications to band geometry and chemistry appeared to be much more limited than for wheat. For this reason the rest of this summary deals with findings involving wheat as a test crop.

With regard to band geometry, increasing the band width and continuity of the application within that band increased P uptake slightly from bands of MAP applied alone, for bands up to 2.5 cm wide. For distributions similar to commercial granular applications, increasing the band width from 2.5 to 15 cm appeared to have little effect. It appeared that in this calcareous soil the limited mobility of the applied P resulted in discrete reaction zones around the simulated granules in the 2.5 cm wide bands. Hence, increasing band width beyond 2.5 cm did not increase the actual area of fertilizer P affected soil significantly.

The introduction of various lignosulfonate sources into MAP bands had no effect on the uptake of fertilizer P. The lack of response was most likely due to insufficient competition of the lignosulfonate ions with the phosphate ions for adsorption sites, due to

the low rates of lignosulfonate application combined with the high levels of exchangeable calcium in the soil available for precipitation with the applied P.

Introducing magnesium sulphate into MAP bands was effective in improving fertilizer P use efficiency. This was probably the result of displacement of calcium into the soil solution followed by precipitation of calcium sulphates, making the calcium less available for precipitation with the applied P.

The most consistent trends throughout the studies conducted were the responses to dual banding of N sources with MAP, as compared to MAP and N applied separately in similar bands. In all cases dual banding of MAP with urea resulted in an initial delay in uptake. The most likely cause was poor root growth into the bands due to the build-up of high concentrations of ammonia and/or nitrite in the band from the initial increase in pH associated with urea hydrolysis. This initial delay was followed by enhanced fertilizer P uptake, resulting in similar or greater P utilization from the urea-MAP bands by 25 days after emergence. Dual banding MAP with ammonium sulphate was also effective in improving utilization of applied P. In all cases ammonium sulphate was more effective in improving utilization of P from applied MAP than urea, due to the lack of initial delays in uptake. These positive effects on P uptake were likely related to ammonium ion effects including increased availability and mobility from acidification of the reaction zone through nitrification and biological effects on root proliferation in the band and absorptive capacity of the roots.

From these findings it appears that the greatest potential for improving fertilizer P use efficiency from applied MAP may involve modifications to band geometry combined

with dual application with ammonium N sources. Future research would be required to determine the optimum band geometry in terms of the combination of area of application and the distribution of the P and N within that area, as affected by factors such as granule or droplet size. The greatest opportunity for improvement may involve bands placed greater distances from the seed row, such as when deep banding. There may also be some opportunity to enhance P uptake through a chemical mixture of N with MAP in bands with very wide spread patterns.

8. CONTRIBUTION TO KNOWLEDGE

Annual crops in western Canada are fertilized with phosphorus fertilizer in granular

or droplet form in narrow bands with or near the seed, or placed in wide bands such as

with air seeders equipped with openers giving wide spread patterns. Utilization of the

fertilizer phosphorus is usually low, particularly for crops such as the cereals. Studies

were conducted with wheat and canola, in which band geometry and chemistry were

varied in an attempt to improve utilization of fertilizer phosphorus.

The best method of phosphorus application for canola was granule application in a

narrow band with or near the seed. Dual banding of phosphorus with nitrogen such as

urea had an overall detrimental effect. Dual banding of phosphorus with ammonium

sulphate was about as effective as phosphorus alone.

The studies did show that utilization of fertilizer phosphorus by cereal crops could

be improved above present levels by altering the geometry and chemistry of the band.

Increasing the band area or volume of soil fertilized increased utilization of fertilizer

phosphorus. Placing the phosphorus near the seed row in a band about 2.5 cm wide with

the phosphorus uniformly distributed in the band was more effective than present

fertilization practices in which granules or droplets of fertilizer are placed in a narrow

band. Applying ammonium sulphate with the phosphorus enhanced uptake of the fertilizer

phosphorus. Applying the ammonium sulphate in direct contact (chemical mix) with the

phosphorus fertilizer was more effective in increasing fertilizer phosphorus uptake than applying separate granules of MAP and ammonium sulphate to the same band, for wider band widths. Field studies with cereal crops are needed to ascertain the benefits which could be obtained if present fertilization practices were altered to those noted above.

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10. APPENDICES

I. Details of Plant Tissue Analysis Procedures

1) Nitric-perchloric digestion of plant material.

A subsample of approximately 1 g of ground plant tissue was massed to three decimal places and placed in a digestion tube. Five ml of concentrated nitric acid and 2.5 ml of concentrated perchloric acid were added, and the samples allowed to pre-digest for at least 1 h. The digestion was then carried out using a Digestion System 40, 1006 Heating Unit, heated to approximately 230°C, until the solution was pale yellow to clear. The samples were allowed to cool, and transferred quantitatively to 25 ml volumetric flasks and brought to volume with deionized water. An aliquot of approximately 15 ml was then transferred to a 20 ml scintillation vial and stored for ^{31}P and ^{32}P analysis.

2) ^{32}P determination.

Radiation from ^{32}P present in the samples was analysed by Liquid Scintillation Counting using a Beckman Model 7500 Liquid Scintillation Counter. The samples were prepared by mixing 3 ml of sample with 7 ml of Beckman Ready Solv CP cocktail in a 20 ml polystyrene scintillation vial which was then placed in the counter. A 0.1, 0.2, and 0.3 ml aliquot of the original fertilizer solution, each mixed with 10 ml of scintillation cocktail, was also analysed in order to calculate the specific activity of the fertilizer solution. Using these values the total amount of fertilizer P uptake and the percent utilization were calculated using the following equations:

Fertilizer P uptake (mg)= $\frac{[(25/3)x((DPM(sample)-DPM(control))/SA\ of\ MAP)] \times DMY}{Mass\ Digested}$

Where: DPM = Decays per minute

              SA of MAP = Specific Activity of MAP solution

              DMY = Dry matter yield for the sample

Percent Utilization = $\frac{Fertilizer\ P\ uptake\ (mg)}{Total\ P\ applied\ (mg)} \times 100$

3) ^{31}P determination.

      A 0.25 ml aliquot of the sample was diluted to 5 ml with deionized water. A second

dilution of 0.25 ml in 10 ml deionized water was conducted to bring the concentration of P

into the range of 0 to 1.0 μg P ml^{-1}. Concentration of ^{31}P in solution was then determined by

the acid molybdate procedure as described by Murphy and Riley (1962). Three samples of

1 in 32 000 dilution of the original fertilizer solution were also analysed for ^{31}P for use in the

calculation of specific activity of the fertilizer.

II. Details of Soil Chemical Analysis Procedures

1) Phosphate determination.

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

2) Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) in NH_4OAc extract determination.

The cations were extracted from the soil by shaking with 1 M ammonium acetate extracting solution for 1 hour, and the extract filtered through #1 filter paper. Appropriate dilutions were made, and 1.0 ml of 5% LaO solution added to the diluent to provide Lanthanum ions to reduce ionization or interferences. Concentrations were determined on an IL-257 Atomic Absorption Spectrophotometer.

3) Soil texture.

The soil texture was determined by hand texturing methods.

4) Field capacity determination.

Field capacity moisture contents were determined by placing a known quantity of soil passed through a sieve with 2.0 mm openings into polyethylene cylinders and wetting the soil surface until the wetting front reached approximately one third the depth of the soil. The cylinders were covered with parafilm to prevent evaporation from the surface, and were allowed to equilibrate for 2 days. A sample of moist soil was taken, weighed, and then oven dried at 110°C for 2 days. Oven dry weights were then measured and the gravimetric field capacity moisture contents calculated.

5) Inorganic carbon determination.

An 8 g sample of soil was mixed with 1 drop of n-octyl alcohol in a French square bottle sealed with a rubber stopper with a glass tube through the center and a needle puncture stopper sealing the tube. A scintillation vial containing 5 ml of KOH was attached to the glass tubes. Two blanks without soil were also included. Fifty ml of air was removed using a hypodermic syringe through the rubber stopper. Samples were reacted with 20 mls of 2M HCl injected through the needle puncture stopper using a hypodermic syringe. The CO_2 produced was collected in the 5 mls of 2M KOH in a 7 ml scintillation vial attached to the glass tube inside the sealed bottle. After 16 - 20 hours at room temperature the scintillation vial was removed, capped, and stored in a refrigerator. A two endpoint titration with 0.1N HCl was conducted on the samples, with endpoints at pH's of 8.3 and 3.8, and the amount of HCl used to lower the pH from the first endpoint to the second was used to calculate the inorganic carbon content.