INFLUENCE OF NUTRIENT APPLICATION ON ROOT PROLIFERATION IN THE FERTILIZER REACTION ZONE AND UPTAKE OF ADDED NUTRIENTS

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ABSTRACT

The objective of this study was to investigate the effects of nutrients applied in the band on root proliferation in the fertilizer band and the relationship between this root proliferation and uptake of added nutrients.

Root proliferation in the applied fertilizer zone was varied with nutrient added. Nitrogen and phosphorus when applied alone or in combination resulted in intensive root proliferation in the fertilizer band. Application of potassium alone or in combination with nitrogen and/or phosphorus resulted in no or only slight root development in the band.

Utilization of added nitrogen and phosphorus was closely related with the extent of root growth in the fertilizer band. Uptake of potassium was not closely related to the magnitude of root growth in the fertilizer band. These studies indicated that when nitrogen and phosphorus fertilizers are added in a band they should be combined for efficient root development in the band and efficient uptake of these nutrients. It was also shown that the beneficial effects of nitrogen on phosphorus uptake, when these two nutrients are combined in one band, may be partly due to the increase in root growth in the phosphorus fertilizer band when nitrogen is added.

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CHAPTER I

INTRODUCTION

During recent years, much attention has been given to the manner in which plants take up mineral elements, the exact nature of the processes involved, and the underlying reasons for variations among different species in their absorption of essential and non-essential mineral elements. The amounts of the various nutrient elements that can be absorbed by plants are strongly influenced by the ratios of various elements in the medium as well as by the absolute quantities present in available form in the root zone.

Nitrogen, phosphorus and potassium, alone or in combination, contribute differentially to root development. Kalra and Soper (39) reported differences among plant species in utilizing applied phosphorus. Later, Strong and Soper (73) demonstrated that variations in root development in the reaction zone and the absorption capacity of the root was mainly responsible for the variations in applied phosphorus uptake among plant species. It was emphasized that, with some plant species, proliferation of roots within the fertilizer reaction zone was responsible for increased phosphorus uptake.

The objective of this study was to determine the influence of nitrogen phosphorus and potassium fertilizers on the growth of roots within the fertilizer reaction zone and the influence of root proliferation in the fertilizer zone on the utilization of added nutrients. Wheat, buckwheat, flax and rape were used as test crops and a soil considered to be deficient in nitrogen, phosphorus and potassium was used for study.

CHAPTER II

LITERATURE REVIEW

A. Factors affecting root proliferation in Fertilizer bands.

The density of roots in the fertilizer band has a large influence on the rate at which nutrients are absorbed from the band. Since the fertilizer band volume is very small, it is inconceivable that a plant could utilize large amounts of fertilizer when only one percent or less of its root surface is in contact with the available nutrients. However, some plants utilize relatively large quantities of nutrients supplied in a band application. The quick growth or proliferation of roots within the fertilizer band, however, is essential. The extent of root development in the fertilizer band is influenced to varying degrees by the nutrient applied and plant species grown (54). Phosphorus and nitrogen appear to be the two plant nutrients which cause the greatest root proliferation.

Nitrogen or phosphorus applied in a band alone did not cause root proliferation in the band even though the other nutrient was supplied at high levels to the rest of the root system. Both had to be added to the band for efficient root proliferation (54). Soil phosphorus level did not affect the recovery of fertilizer phosphorus from the band provided there was root proliferation in the fertilizer band.

Schnapinger *et al.* (68) compared the relative effects of phosphorus and potassium on root proliferation and suggested that phosphorus is more effective than potassium. Racz *et al.*, (61) using a P^{32} injection technique for measuring root development, noted an enhanced root development of wheat in the vicinity of the phosphorus band. Effect of potassium alone on root growth is almost negligible (50).

Ohlrogge (55) suggested certain distinct advantages of band applications of fertilizers at planting time for corn provided certain requirements were met: (i) Fertilizers must be placed where it will intercept secondary roots. The most efficient placement would be 2.54 - 7.62 cm to the sides of the seed and 2.54 - 7.62 cm below the seed. (ii) Nitrogen and phosphorus must be mixed together in the band for rapid root proliferation and efficient nutrient uptake.

Wilkinson et al. (80) showed that soybean secondary roots respond to localized placements of nitrogen and phosphorus with increased lateral root development. Nitrogen fertilizers increased endogenous auxin content which was thought to be invaluable in increased root branching. In root extract, tryptophan was found and root-growth activity was associated with it. Extent of root-growth activity was greater at high nitrogen levels than at low nitrogen levels. Wilkinson et al. (81) later reported that nitrogen fertilized roots had higher root-growth activity than roots fertilized with phosphorus or roots not fertilized with phosphorus or nitrogen. Root extracts from roots fertilized with nitrogen and phosphorus tended to promote lateral root branching more than did root extracts from roots not fertilized with nitrogen and phosphorus, or with nitrogen and phosphorus alone.

Miller and Ohlrogge (47), working with corn plants, observed that nitrogen mixed with phosphorus increased the utilization of phosphorus from the band at all soil phosphorus levels. The development of roots in the area of nitrogen and phosphorus placement appeared to be the most important mechanism responsible for these effects. Duncan and Ohlrogge (20) observed very little effect of nitrogen and phosphorus on root development when not added in a mixture. The root proliferation they noted, was the result of a rapid growth of smaller roots. The rate of growth of primary roots was not affected. Proliferation of smaller roots was unaffected by salt concentration. The rate of growth in fertilized soil was much greater than in unfertilized soil and continued to grow for 10-12 days. Roots in unfertilized soil stopped growing after a short period of time. In other green house experiments (21), they observed that the fertilized-soil volume had no effect on fertilizer uptake when phosphorus was applied alone, but it caused significant increases in uptake when nitrogen was added to the fertilizer. Uptake of phosphorus increased with the amount and surface area of roots in the fertilized soil and with the amounts of phosphorus applied but tended to decrease with increases in the phosphorus content of the plant.

Grunes (27) observed that oat root tips were damaged in one portion of the fertilizer zone. The findings indicated that plant roots did not grow into any of the fertilizer zones except the 2 to 3 and 3-4 cm zones when the source of phosphorus was monocalcium phosphate. In another experiment, he found that roots did not penetrate the static fertilizer zone. The average distance of root growth from the fertilizer was 2, 8 and 6 cm for MCP, MCP+ NH_4Cl, and MCP+Kcl, respectively.

Stanford and Dement (72) reported that roots of intact, nitrogen deficient oat plants proliferated rapidly when placed in contact with both nitrogen fertilized and unfertilized soils.

B. <u>Placement of nitrogen, phosphorus and potassium</u>

Widdowson and Cooke (79) suggested that P, PK, and NPK beside the seed were superior treatments than broadcasting these fertilizers for a number of crops. Prummel (60) compared broadcast and banded methods of application of increasing levels of nitrogen, phosphorus, and potassium. In general, banding was better than broadcasting. For cereals, banding of nitrogen was 1.20 times as effective as was broadcast applications, while banding of phosphorus was 2.45 times superior to broadcast applications. Prevention of fixation and better early growth as a result of localization of fertilizers near the seed at an adequate depth were given as some of the reasons for the sucess of the banded placements. Dudley (19) reported similar findings with superphosphate for wheat in Kansas. He noticed that row application of superphosphate was twice as effective as was a broadcast application.

Rich et al. (64) obtained very small differences in yield as a result of different methods of fertilizer placement on silage corn. The band application was fully as effective as plow-sole or other deep placements of either all or part of the fertilizer. They obtained more early growth of the crop by band placement than by deep placement.

Stanford and Nelson (70), using P^{32}, observed that the percentage of phosphorus derived from the fertilizer was influenced by the position of the fertilizer with respect to the seed. Placement of fertilizers at seed depth and in bands on one or both sides of the seed generally resulted in greater utilization of the applied phosphorus by the plant than when placed in a single band above the level of the seed or in a single band three inches below the seed. Stanford et al. (71), in experiments with phosphorus and potassium, found very low recoveries of top dressed phosphorus. Dewitt (16), however, contradicted the findings of the above workers and suggested that at the higher rates relatively more phosphorus may be taken up from broadcast than from row applied fertilizer.

McVickar *et al.* (45) stated that banding potassium is highly beneficial on soils which are high potassium fixers, especially when low rates of potassium are applied. Band and broadcast methods were equally effective in influencing crop yields when higher rates of potassium were applied on soils with little potassium fixing capacity. Welch *et al.* (77) observed in their experiment with corn that less potassium was required to obtain a given yield when potassium was banded than when broadcast. In some cases, no rate of broadcast potassium equaled the yield produced by a given rate of banded potassium.

Nyborg and Henig (53) compared placement of fertilizers for barley, flax, and rapeseed. They obtained higher yields when fertilizers at high rates were placed away from the seed. Efficiency of phosphorus-fertilizers varied considerably with placement. Placing the phosphorus 2.5 cm directly below the seed was the best for both barley and flax and was superior to placing the fertilizer 5.0 cm from the seed. Placing the fertilizer 2.5 cm below the seed was better than placing it 2.5 cm to the side of the seed. Flax made much better use of both ammonium phosphate and triple superphosphate when placed 2.5 cm below the seed than when placed 2.5 cm to the side of the seed.

C. Phosphorus Uptake

Phosphorus uptake by plants grown in soil is affected by both soil and plant characteristics. Hagen and Hopkins (32), working with excised barley roots, observed an inverse relationship between the pH of the medium and phosphorus absorption by barley. They attributed this relationship to competitive inhibition of hydroxyl ions on phosphate uptake. Other workers (46), however, did not find any direct effect of pH on phosphorus absorption by intact plants over the pH range of 3 to 7. At pH 8, however, absorption of phosphorus was markedly reduced.

1. Soil Phosphorus Uptake

Utilization of native soil phosphorus is governed by a number of factors: viz. type of colloidal system (26), soil moisture (17), and soil volume (4).

Cornfield (15) noted a correlation in phosphorus uptake by oats, ryegrass, kale and tomato plants with their rooting intensities (root mass per mass of soil) in the soil in which they were grown. On increasing the soil volume in which the plants were grown, there was a reduction in the rooting intensity of each crop.

The nature of the crop species grown is also a determining factor in native phosphorus utilization. Kalra and Soper (39) showed that crops which made good utilization of soil phosphorus could not necessarily make good use of added phosphorus. They observed that soybeans utilized soil phosphorus to a larger extent than did rape. On the other hand, rape utilized more of the added phosphorus than did soybeans. Other workers (24, 51) have presented similar findings for a number of crops.

Fried and Shapiro (25) suggested the following relationships for phosphorus absorption by plants:

P- Minerals

$\downarrow\uparrow$

P-(Soil solution) $\underset{\text{Bulk movement}}{\overset{\text{Diffusion}}{\rightleftharpoons}}$ (Mass flow (vicinity of roots) $\underset{\text{Passive}}{\overset{\text{Active}}{\rightleftharpoons}}$ (In root)

$\downarrow\uparrow$

P-Adsorbed

$\overset{\text{Phloem}}{\rightleftharpoons}$ P (In top)

$\underset{\text{Xylem}}{\rightarrow}$

P = Phosphate ion.

They pointed out that the main process for phosphorus movement towards roots was mass flow but diffusion also accounted for part of the movement. Any factor that affects the conversion of phosphorus from solid to solution phase affects phosphorus uptake. Roots are in quilibrium only with solution phase phosphorus.

Hunter (35) concluded that the silicate ion, when present in large amounts, increased the availability of soil phosphorus by anion exchange.

2. Fertilizer Phosphorus Uptake

There are a number of factors which influence the utilization of added phosphorus. Some of them are: pH, moisture content of the soil, temperature, nature of the phosphorus fertilizer carrier, crop species, method and rate of phosphorus application, and nature of the fertilizer materials applied with phosphorus.

Lai and Lawton (43) stated that corn utilized more fertilizer phosphorus than the inter-planted crops of sesame or beans. The reason for the high phosphorus utilization by corn was attributed to the extensiveness of the corn root system. Hoagland (34), however, indicated that the magnitude of the root system does not necessarily represent the total active root absorbing surface.

Considerable evidence indicates that the percent uptake of fertilizer phosphorus by plants is inversely related to the level of soil phosphorus (12, 76).

An increase in phosphorus absorption has been observed with increases in soil moisture content (31, 78). Boatwright et al. (9) noticed that wheat plants did not absorb fertilizer phosphorus from dry soil. Alfalfa, however, was found to be able to absorb phosphorus from dry soil (18).

The influence of temperature on phosphorus availability has been studied by Barber (5). He found in laboratory studies that increases in incubation temperature of the soil increased subsequent availability of soil and fertilizer phosphorus to millet. Also, in field experiments, some relationship between the mean temperature and phosphorus availability was noticed. At low soil temperatures, reduced uptake of phosphorus has been observed (40, 44). Decreased permeability of root cells at low temperature was given as the reason for the decrease in absorption (42).

Bishop and MacEachern (7) studied the effect of rate of nitrogen, phosphorus, and potassium application on the uptake of these nutrients and found that the effect of increasing rates on the levels of these nutrients in plant tissues was predominantly linear. Increases in nitrogen levels in the plant were of much greater magnitude than increases in either phosphorus or potassium levels. Jacob et al. (37) also obtained increased percent utilization of added fertilizer phosphorus by increasing the rates of application.

a. Effect of Nitrogen on Phosphorus Uptake

The influence of added nitrogen on fertilizer phosphorus availability has been studied by a large number of workers for a variety of crops. (22, 28, 30, 48, 57, 66).

The influence of the NH_4^+ ion in increasing the fertilizer phosphorus uptake by crops has been described in various ways (2, 8, 11, 63). Blancher (8) concluded that the NH_4^+ ion increased the capacity of the plant to absorb phosphorus and did not affect the soil phosphorus availability. Caldwell (13) also found that nitrogen fertilizer increased the uptake of phosphorus. He cited the following possible reasons for the increased phosphorus uptake: (1) the influence of the nitrogen salt on the solubility of phosphorus material, (2) the interaction of ions in the culture medium, (3) some modification in the physiology of the plant, (4) root proliferation. He found the effect of various nitrogen carriers to be as follows: Ammonium Sulphate $>$ Ammonium Nitrate $>$ Calcium Nitrate. Thus the effect was primarily due to the function of the NH_4^+ ion. His results suggested that the effect of nitrogen on phosphorus absorption was brought about by chemical reactions between the nitrogen and phosphorus salts. Grunes (29) also found that the effect of nitrogen in increasing the phosphorus concentration in oat tops was due in part to increasing root growth, especially of fine roots which were high in absorbing capacity per unit weight.

Cole *et al.* (14) observed that increasing the levels of nitrogen increased phosphorus uptake by corn plants. The stimulation of the rate of phosphorus uptake with higher nitrogen levels suggests a connection between nitrogen metabolism and phosphorus uptake processes. Increased phosphorus uptake by nitrogen application was also found by Fine (23). Bouldin and Sample (10) noted the following sequence of fertilizer phosphorus uptake with different salts on two soils. The sequence on the soil with a pH value of 5.2 was: concentrated superphosphate $<$ concentrated superphosphate + potassium chloride $\leq$ concentrated superphosphate + Ammonium Chloride $\leq$ concentrated superphosphate + Ammonium Nitrate $<$ concentrated superphosphate + Ammonium Sulphate $\leq$ concentrated superphosphate + Potassium Nitrate. On the Soil with a pH value of 6.6, the order was: concentrated superphosphate $<$ concentrated superphosphate + Potassium Chloride $<$ concentrated superphosphate + Ammonium Sulphate $\leq$

concentrated superphosphate + Ammonium Chloride $\leq$ concentrated superphosphate + Ammonium Nitrate $\leq$ concentrated superphosphate + Potassium Nitrate.

Miller, Mamaril and Blair (49) found that ammonium sulphate had a large effect on the availability of phosphorus to corn plants. Nelson et al. (52) observed the effect of NP, and K in combination on the yield of oats. Nitrogen and phosphorus together were equally as responsive as was NP and K in combination. Olson and Dreier (57) also emphasized the superiority of the NH_4^+ ion over that of the NO_3^- ion in increasing fertilizer phosphorus utilization. Rennie and Mitchell (62) noted increased phosphorus uptake from ammonium phosphate and triple superphosphate as the amount of added nitrogen was increased. Riley and Barber (65), observed that ammonium fertilized soybeans absorbed more phosphorus and had a higher phosphorus concentration than nitrate fertilized soybeans.

Zuev and Golubeva (82) observed that depletion of nitrogen in winter wheat plants sharply inhibited phosphorus absorption and decreased the ratio of its inclusion in fractions of organic compounds. Transport of absorbed phosphorus from roots to shoots was also inhibited by the nitrogen deficiency. Similar results have been reported by Thien and McFee (74) for corn. The results of these workers suggested the existence of a nitrogen requiring metabolite in influencing the efficiency of phosphorus absorption and translocation mechanisms.

b. Effect of Nitrogen with Potassium on Phosphorus Uptake

Heslep and Black (33) observed increased phosphorus uptake by admixture with nitrogen and potassium salts. Similar results were obtained by Grunes

CHAPTER III

MATERIALS AND ANALYTICAL METHODS

1. SOIL: A Pine-Ridge soil was used in all the green house experiments conducted. The soil was collected from the 0 - 15 cm depth on September 25th, 1969. It was air dried, crushed, sieved through a 0.63 cm screen and thoroughly mixed. A sub-sample of 2.0 kg was passed through a 2.0 mm sieve and retained for analysis. Some characteristics of the soil used are given in Table I.

2. SOIL ANALYSIS:

(a) Soil texture: Soil texture was determined by the pipette method (41).

(b) pH: Soil pH was determined on a soil-water saturated paste using a glass and calomel electrode on a pH meter.

(c) Cation exchange capacity: The cation exchange capacity of the soil was determined as outlined by Peech *et al.* (58).

(d) Total nitrogen: A method outlined by Jackson (36) was used to determine the total nitrogen content of the soil.

(e) Sodium bicarbonate extractable phosphorus: The soil was extracted using 0.5 M $NaHCO_3$ at pH 8.5 and the phosphorus extracted determined colorimetrically (56).

(f) Conductivity: The electrical resistance of an extract from a saturated soil-water paste was measured using a conductivity bridge.

(g) Organic matter: The organic matter content of the soil was determined by the CO_2 method described by Peech *et al.* (69).

(h) $CaCO_3$ equivalent: The carbonate content of the soil was determined by the manometric method described by Skinner *et al.* (69).

TABLE I

SOME CHARACTERISTICS OF THE EXPERIMENTAL SOIL

Soil Association	Texture	Total N (%)	NO_3-N (ppm)	Na HCO_3 extractable-P (ppm)	NH_4-Ac extractable-K (ppm)	pH	$CaCO_3$ equivalent (%)	Conductivity (mmhos/cm)	C.E.C. (me/100g.)	Organic Matter (%)	Field Capacity (%)
Pine-Ridge	Loamy Sand	0.187	3	3	35	7.8	0.84	0.4	15	3.63	20.6

(i) <u>NO_3 - N</u>: The nitrate nitrogen content of the soil was determined using the phenoldisulphonic acid method (67).

(j) <u>NH_4 - Ac Extractable K</u>: Exchangeable potassium was determined by extracting the soil with 1.0 N NH_4 Ac. The potassium extracted was determined by using a Baird-Atomic KY-22 flame photometer (59).

(k) <u>Field capacity</u>: Field capacity moisture content was determined by saturating the soil with water, allowing for free drainage and then determining the moisture content of the soil.

3. EXPERIMENTAL DESIGN: All experiments were placed in a completely randomized block design and conducted in the greenhouse. All treatments in each experiment were replicated four times.

4. CROPS: In the first greenhouse experiment, the following crops were used:

   i. Wheat (Triticum aestivum, L.) var. Manitou.
   ii. Buckwheat (Fagopyrum esculentum, Moench.) var. Tokio
   iii. Flax (Linum usitattissimum, L.) var. Noralta.
   iv. Rape (Brassica napus) var. Target.

Wheat and rape were grown in the 2nd and 3rd experiments. Only wheat was grown in the 4th experiment.

5. PREPARATION OF P^{32} LABELLED PHOSPHORUS FERTILIZER:

Carrier-free P^{32} was obtained from the Atomic Energy of Canada, Ltd., Ottawa. P^{32} labelled sodium dihydrogenphosphate monohydrate and monocalcium phosphate monohydrate were used in experiments III and IV, respectively. The preparation of the fertilizers is briefly outlined below:

Adequate quantities of Na $H_2PO_4 \cdot H_2O$ or $Ca(H_2PO_4)_2$ H_2O were dissolved in a small volume of distilled water. Carrier free P^{32}, H_3PO_4 in HCl, was added so that a solution of approximately 10 μc P^{32} per 40 mg of P^{31} was prepared. All solutions were prepared in polyethylene containers. The solutions were evaporated to dryness on a sand bath and the isotopically labelled crystals ground.

6. GREEN HOUSE TECHNIQUES:

In all experiments, 2.0 kg of air dried soil was placed in one-half gallon glazed porcelain pots. The seeds were placed at a depth of 1.27 cm. Twenty seeds per pot were planted for flax and eight seeds per pot were planted for the remainder of the crops. The amount and placement of nitrogen, phosphorus, and potassium are discussed along with the result obtained for each experiment. The nutrients were mixed throughout the soil or placed into plastic cylinders (2.8 cm internal diameter and 3.6 cm long) containing a small volume of soil.

After planting and fertilization, the pots were watered to field capacity. The amount of water required to maintain the soils at or near field capacity was determined by weighing the pots. The plants were watered daily or as required.

The crops were thinned to four plants per pot except for flax in which the number of plants per pot was twelve.

7. HARVESTING AND PREPARATION OF THE PLANT SAMPLES:

The plants were harvested by cutting the stems close to the soil surface. Harvesting was done 34 days after seeding in experiment I. The duration between seeding and harvesting was 48 days for the remaining experiments. The plants were then cut into small pieces, air dried, and dried in an oven at 65° C for 36 hours. The plants were weighed and finely ground. The plant roots were separated from the soil by placing the soil from each pot or plastic cylinder on a 2.0 mm sieve and washing with water. The roots retained on the sieve were dried at 65^{o} c and weighed.

8. ANALYSIS OF PLANT MATERIAL:

(a) Total nitrogen: The total nitrogen content of the roots and tops was determined by the Kjeldahl method as outlined by Jackson (36).

(b) Phosphorus:

(i) Total phosphorus: (wet ashing procedure). The total phosphorus content of the plant material was determined colorimetrically by the Vanadomolybdate yellow colour method (36).

(ii) P^{32} labelled phosphorus (fertilizer phosphorus): Radioactivity in the wet ashed plant solutions and standard solutions (a solution of the isotopically labelled fertilizer) was determined by using a liquid DM6 GM tube attached to a binary scaling unit, Nuclear Chicago Model 161A. The radioactivity of the standard solution was measured within one hour of determining the radio activity present in the plant samples. The amounts of fertilizer phosphorus utilized (mg) by the plants was calculated using the following equation:

$$\frac{\text{Radioactivity of plant sample (C.P.M.)}}{\text{Radioactivity of standard (C.P.M.)}} \text{ X amount of fertilizer added} \text{ X } \frac{\text{Sample weight}}{\text{Yield per pot}}$$

Fertilizer phosphorus absorbed by the plants when subtracted from total phosphorus absorbed by the plants represented the amount of soil-phosphorus taken up by the plants.

(c) Total potassium: One-half g of finely ground plant tops were shaken on a reciprocal shaker for one hour with 100 ml of 1.0N NH_4 Ac.

adjusted to pH 7.0 and containing 250 ppm Li as $LiNO_3$. One-tenth or 0.2 g samples were used when roots were analyzed. The potassium extracted was determined by using a Baird-Atomic KY-22 flame photometer.

CHAPTER IV

PRESENTATION OF EXPERIMENTAL METHODS AND RESULTS

Experiment I

Several workers (39, 73, 75) in Manitoba have conducted field and green house trials to investigate the phosphorus feeding habits of a number of crops. They studied the effect of method of application, sources of phosphorus, and amounts of added fertilizer phosphorus on the utilization of added phosphorus by plants. In greenhouse experiments, they noted that crops differed in their fertilizer phosphorus utilizing capacity. They attributed the differences in fertilizer phosphorus utilization among plant species to variations in the amounts of roots within the fertilizer band and to variations in the phosphorus absorption capacity of the roots.

An experiment was thus conducted to determine if nutrients other than phosphorus would enhance root growth in a fertilizer band. Potassium was selected for study using wheat, buckwheat, flax and rape as test crops. An attempt was made to observe if there existed some relationship between root growth in the band and potassium uptake.

The main source of nitrogen used was ammonium nitrate (NH_4NO_3). Phosphorus was applied as monoammonium phosphate ($NH_4H_2PO_4$) and potassium as potassium chloride (KCl). Ammonium sulphate was used to supply 10 ppm sulphur. Nitrogen and phosphorus were added at rates of 80 and 20 ppm, respectively. The amount of nitrogen supplied by the ammonium phosphate and ammonium sulphate was calculated and the remaining quantity added as ammonium nitrate. All the nitrogen, phosphorus, and sulphur was mixed throughout the soil.