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MAXIMUM PRODUCTION OF WHEAT AS AFFECTED BY RATE AND PLACEMENT OF PHOSPHORUS

By

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ABSTRACT

A field experiment was conducted over a three year period on Almasippi, Elm Creek and Rignold soils with low, medium and high levels of available P respectively. Effects of rates and placement method of P on maximum yield of wheat (Triticum aestivum cv. Columbus) were investigated. The first year, four rates (0, 50, 100, 200 kg P/ha) of phosphorus fertilizer (0-46-0) were broadcast and incorporated into the soil at two depths (0-7.5 and 0-15 cm). Each year, an extra 17 kg P/ha banded with the seed was applied on one half of all treatment plots. Samplings to determine yields were done at five stages of growth during the season. Results reported are for the second year.

At all sites, depth of incorporation of the P fertilizer did not affect the yields.

It was found that wheat responded well to applied P on the Almasippi soil. Maximum dry matter and grain yields were only obtained when at least 100 kg P/ha broadcast with an extra 17 kg P/ha banded with the seed were applied to the soil. Banded P was more efficient than broadcast P in improving the yields but was not sufficient by itself for yield maximization. Final grain yield was significantly correlated to the amount of P accumulated in the shoot prior to the heading stage.

Results indicated that on the Elm Creek and Rignold soils, vegetative responses to high amounts of P broadcast prior to the soft-dough and heading stages respectively were not reflected in final yields. High grain yields obtained at both sites were associated with an early P accumulation in the shoot; as much as 96% of the maximum P content in

the shoot was accumulated prior to the heading stage.

A field experiment, carried out on the Almasippi soil, was designed to investigate the effect of zinc and copper additions (0, 15 kg Cu/ha, 15 kg Cu + 20 kg Zn/ha) on yield of wheat at high rates of P applications. Treatments were split into halves; one half received on extra 17 kg P/ha seed placed.

Wheat responded well to addition of P for all micronutrient treatments. No severe yield depression was observed when no micronutrients were added but harvest indices, zinc and copper concentrations decreased with increasing rate of P fertilization. Copper addition improved the yields only marginally but with the addition of copper plus zinc, yields increased substantially.

Two growth chamber experiments were carried out on the Almasippi soil to investigate the effect of rate and method of placement of phosphorus on yield of wheat with and without added copper and zinc.

For both mixed and banded placement of the P, wheat responded significantly to addition of P and wheat yields followed an asymptotic relationship. The superiority of the mixed placement at low P rates became negligible as amounts of P applied increased. Phosphorus addition depressed zinc and copper concentrations by dilution and a phosphorus-copper interaction. Highest yields were recorded when both zinc and copper were applied to the soil.

A growth chamber experiment was undertaken on the Almasippi soil to look at the effect of rate and placement of phosphorus on maximum yield of wheat under low and high (14° and 23°C) soil temperature regimes.

Grain and dry matter of wheat was significantly increased with addition of P under both soil temperatures. The low soil temperature resulted in relatively low dry matter yields and particularly low grain yields, as compared to the high soil temperature. The highest grain yields were produced in the warm soil when P was banded as compared to the mixed placement. Method of phosphorus placement did not influence the yields at low soil temperature.

INTRODUCTION

Phosphorus (P) is an essential element for plant growth. Most Manitoban soils are deficient in P and consequently, phosphorus fertilization is required for maximum production. Phosphorus fertilizer research on cereals has largely been restricted to studying the response to fertilizer phosphorus in terms of efficient use. Little research has been undertaken to study how to produce maximum yields of wheat.

Considering P as the only restricting nutrient, increasing the amount of phosphorus fertilizer application would seem to be the answer to getting maximum yields if economy is not the primary concern. This study was undertaken to examine P as a limiting factor in the maximum production of wheat under rain-fed conditions. Three field sites were selected according to their soil available P levels and two growth chamber experiments were carried out to investigate the effects of rates and placements of P fertilizer on maximum yields of wheat. Results from this study could lead to recommendations for maximum production of wheat based on the soil phosphorus level.

When dealing with heavy P applications, the nutrient balance of the plant could be disturbed and attention should be paid to other nutrients, especially micronutrients (Touchton et al., 1980; Yadav and Shukla, 1982). A field study and a growth chamber experiment were undertaken to investigate the interaction between phosphorus and some micronutrients. This work could emphasize the importance of micronutrients for maximum production of wheat.

Power et al. (1964b) and Gingrich (1965) reported that soil temperature significantly influenced plant growth and P uptake and should also be of some concern if maximum production is intended. In a further attempt to investigate limiting conditions for maximum yields, a soil temperature experiment was undertaken in a growth chamber.

LITERATURE REVIEW

A. EFFECT OF RATE AND PLACEMENT METHODS OF PHOSPHORUS FERTILIZER ON YIELD OF WHEAT

Voluminous research to evaluate the effect of different fertilizer placement methods on the subsequent availability and efficiency of P applied to the growing crop has been reported. Numerous placement methods have been studied in order to reduce the competition between soil constituents and the applied P fertilizer, but also provide the crop with sufficient amount of available P throughout the growing season. In general, all of these placement methods may be considered as some variation of the standard broadcast or band placement. Definitions of the two methods of fertilizer placement were given by Bailey et al. (1980):

> "Broadcast involves a uniform distribution of the fertilizer over the surface of the soil. This may be followed by shallow or deep cultivation, thus permitting a mixing of the fertilizer throughout a prescribed depth of soil. The technique is intended to provide a condition in which the concentration of applied fertilizer is relatively even in a specific volume of soil ... The practice of applying a high concentrated source of nutrient in a restricted soil volume in the vicinity of plant roots is called banding ... Band application includes the placement of fertilizer at all combinations of distances to the side of and below the seed ... In general, banding fertilizer occurs at time of seeding."

In the following review, broadcast will refer to fertilizer mixed throughout the surface layer of soil and banding will include any shallow banding at various distances from the seed as well as seed-row placed fertilizer.

When phosphorus fertilizer is applied to the soil, reactions occur between the soil constituents and the fertilizer, resulting in a decrease of phosphates solubility (Sample et al., 1980). The main constituents responsible for this fixation in acidic soils are iron and aluminum, either present in the form of free oxides (Lindsay et al., 1962) or supplied by dissolution of clay minerals (Philen and Lehr, 1967). In alkaline soils, the fixation of added phosphorus as calcium phosphate is known to occur (Strong and Racz, 1970; Larsen and Widdowson, 1970).

The phosphorus uptake of cereals depends on its availability in the soil, therefore it has to be present in the soil in sufficient quantities but also be available for the use of plants (Singh, 1962). Band placement of fertilizer is a way of avoiding rapid fixation of phosphorus and yet providing the plant with enough nutrients to accomplish maximum growth (Dibb, 1978).

Studies indicate that phosphorus placed in contact with the seed is more available for plant absorption at least during the early stages of growth, than phosphorus mixed throughout the soil (Coe, 1926; Lawton and Davis, 1960; Morden and Racz, 1983). Placement where the phosphorus fertilizer is mixed thoroughly throughout the soil results in greater fixations than band placement (Prummel, 1957; Bailey et al., 1980).

Generally seed-row placed P fertilizer has been found to be superior to broadcast application because it is more efficiently utilized due to a better positional availability (Lutz et al., 1961; Sherrell et al., 1964). High P uptake as well as high yields obtained under band conditions are usually explained by a greater availability of phosphorus (Terman et al., 1961; MacLeod et al., 1975).

Cereal grains are usually fertilized by placement of the phosphorus in the seed row because they are fairly tolerant to seed damage, and because relatively small amounts of fertilizer are employed. Heavy applications of phosphate placed in contact with small seeds at time of planting have been shown to reduce germination and delay emergence (Sherrell et al., 1964; MacLeod et al., 1975).

Lawton and Davis (1960) applied 49 kg P/ha with the seed and noticed a delay in growth of wheat seedlings for the three weeks following emergence due to retarded germination and root development. Final plant dry weight values for this placement were 30 to 40% below those where seed and fertilizer were separated. Nyborg and Hennig (1969) showed that increasing rates of phosphorus added in the seed row delayed emergence. Delay of a few days did not cause any substantial reduction in the number of plants that finally emerged, and final yields were usually not reduced unless the number of plants was decreased by 50% or more.

Fertilizer injuries to roots can be of two types. If the osmotic pressure of the soil solution becomes too great, water in cells near the root tip will be drawn into the soil and they will die due to dehydration (Klepper et al., 1983). A chemical toxicity can occur with some chemical forms of the nutrients (Lawton and Davis, 1960). With moderate rates of fertilizer applied in the seed row, any damage caused by a direct toxic effect and/or increased osmotic pressure in the soil solution may be offset by the advantage of having the phosphorus in contact with the seed where it is usually more efficiently taken up

(Nyborg and Hennig, 1969).

If high rates of phosphorus fertilizer are to be placed in the seed row, Prummel (1957) concluded that the width of the fertilizer band should not be too narrow, thus decreasing the concentration. Sherrell et al. (1964), Lawton and Davis (1960) concluded, from several experiments in field and greenhouses, that a placement below and slightly to the side of the seed row would be better than a placement directly to the side or with the seed.

In some cases, the superiority of row application over broadcast application of phosphorus fertilizer is not so prominent. Yield response to increasing rates of phosphorus fertilizer is usually curvilinear (Rudd and Barrow, 1973; Dibb, 1978). This means that a high quantity of available phosphorus can promote plant-luxury absorption of phosphorus without increasing crop yield (Singh, 1962; Alessi and Power, 1980). Terman et al. (1961) reported that wheat exhibited definite limiting yields which they defined as:

> "The highest yield obtained as the quantity of phosphorus is increased indefinitely at a given level of other growth factors."

Therefore, at high levels of phosphorus application, yields will not indicate the best placement because of the highly available phosphorus in both cases (Sherrell et al., 1964; Hamid and Sarwar, 1977; Morden and Racz, 1983). Differences between placements at high rates of phosphorus fertilizer added might be evident in plant uptake through tissue analysis (Lutz et al., 1961), residual effects (Alessi and Power, 1980), or experiments with radioisotopes (Mitchell, 1957).

In 1957, Prummel found that yields given by a single dressing of phosphate placed in bands were about equal to the yields given by a double dressing of broadcast fertilizer. Morden and Racz (1983) restricted this statement to soils low in native P and only when small amounts of phosphorus were compared. When the soils were richer in soil P or when larger applications (over 100 kg P/ha) of P were used, the plants obtained enough nutrients with either method of placement.

The relative efficiency of broadcast versus banded phosphorus appears to be related to the initial phosphorus status of the soil to which the phosphorus is applied (Sherrell et al., 1964; Welch et al., 1966). Several authors, (Rudd and Barrow, 1973; Alessi and Power, 1980) reported that when the fertility level of the soil is raised by fertilization, the advantage of band application as compared to broadcast application would be expected to decrease. Barber (1958) found that band and broadcast application of phosphorus gave similar wheat yields where soils had near adequate levels of available phosphorus. Arriving at the same conclusion in their field experiments, Sherrell et al. (1966) found that yields were not influenced by either placement of phosphorus fertilizer due to a high level of soil phosphorus.

Peterson et al. (1981) grew winter wheat at different locations with various soil phosphorus levels, and calculated ratios of broadcast to row applied rates to obtain equal grain yields. Although they got positive responses to phosphorus applications, the ratios were not constant. A ratio of 2:1 would indicate that yields given by a single dressing of phosphate placed in a band were equal to yields produced by a double dressing of broadcast fertilizer, as often reported in the literature. When locations were ranked from low to high soil P levels, ratios ranged from 3:1 for low soil P to 1.2:1 and 1:1 for rich soils.

Phosphorus fertilization each year may increase the soil phosphorus pool as well as providing the crop with nutrients. In soils rich in phosphorus, there is no need for building up the soil phosphorus pool and only maintenance levels required to satisfy the crop are needed (Read et al., 1977; Bailey et al., 1977). Although there are no yield differences between the two placements where the soils are rich, if small quantities are to be applied, they should be banded to avoid rapid immobilization (Bailey et al., 1980).

In soils low in P, banding is usually recommended to efficiently provide the crop with enough available nutrients. However, if build-up of the soil phosphorus pool is of some concern, broadcasting large amounts seems to be the preferred method of phosphorus application (Welch et al., 1966; Read et al., 1977; Bailey et al., 1977). However, precautions about monitoring other nutrients should be taken when large amounts of fertilizer are applied. Decreases in yields have been observed by several workers with large applications of phosphorus (Lutz et al., 1961; Ridley and Tayakepisuthe, 1974; Morden and Racz, 1983).

B. EFFECT OF ROOT DEVELOPMENT ON PHOSPHORUS UPTAKE

Dalal and Hallworth (1976) showed that dry matter yield production of wheat was significantly correlated to P uptake. Greater uptake (Prummel, 1957) especially during early stages of growth (Lawton and Davis, 1960) as well as higher yield responses (Olsen and Dreier, 1956; Singh and Gupta, 1969; Peterson et al., 1981) were found where the fertilizer was banded as compared to broadcast. As the availability of the phosphorus fertilizer decreased with time, P uptake derived from the fertilizer decreased and P derived from the soil become more important (Kalra and Soper, 1968). Proliferation of the root system outside the fertilized zone was influenced by the availability of phosphorus within the zone and consequently affected P uptake (Hamid and Sarwar, 1977).

Boatwright and Viets (1966) demonstrated the importance of early phosphorus uptake. They grew spring wheat in a nutrient culture with phosphorus available only during the first five weeks (up to heading stage) and obtained the same maximum dry matter yield as when phosphorus was available during the whole growing season. In accordance with the above results, Brenchley had already found in 1929 that for maximum barley growth, available phosphorus was necessary only for the first six weeks. In 1961, Boatwright and Haas showed that most of the phosphorus translocated to the grain was absorbed prior to heading. Experiments with 32 P have pointed out that plants obtained most of their phosphorus from the fertilizer during the earliest stages of growth (Dion et al., 1949; Rennie, 1956) and more phosphorus was absorbed prior to heading when the fertilizer was placed rather than broadcast (Mitchell, 1957).

Therefore, early phosphorus uptake and availability of the fertilizer could be of major importance for grain production (Boatwright and Haas, 1961). Mitchell (1957), Nye (1977), Anghinoni et al. (1981), showed that the rate of phosphorus uptake increased up to the heading stage and then, with increased plant age, there was a reduction of the rate of uptake. Concentrations of phosphorus in the plants have been reported to follow the same pattern, reaching a maximum at heading stage (Rennie, 1956; Boatwright and Haas, 1961). Lutz et al. (1961), Hamid and Sarwar (1977), showed that when phosphorus was banded, mid-season harvests were higher in yields than when the fertilizer was broadcast.

However, in spite of early differences in yield, authors have found that the final yields (Hamid and Sarwar, 1977) as well as the phosphorus concentrations (Rennie, 1956; Lutz et al., 1961) were identical. In some cases (Boatwright and Haas, 1961) the grain still showed differences in phosphorus concentrations due to placements. Dion et al. (1969) reported from an experiment using radioactive phosphorus that during the earliest stages of growth, the plant obtained most of its phosphorus from the fertilizer. Later on, the soil supplied the greatest proportion of phosphorus to the plant. Several workers have noticed that the absorption of soil phosphorus continued to a later date than that from fertilizer phosphorus (Kalra and Soper, 1968), sometimes resulting in similar yields between fertilized and unfertilized treatments (Rennie, 1956), or equal nutrient concentrations for different yields (Prummel, 1957). Decreasing phosphorus availability in the fertilized zone (Kalra and Soper, 1968) as well as root proliferation outside of the fertilized zone (Lutz et al., 1961) explain greater soil phosphorus uptake by the crop during later stages of growth.

Various studies on the response by crops to phosphate fertilizers have indicated that the growth response is related to the ability of the plant to recover applied phosphorus (Racz et al., 1965; Kalra and Soper, 1968). Strong and Soper (1973) demonstrated that the feeding habits of various crops for phosphorus from a fertilized band could be explained on the basis of the root behavior in the reaction zone.

Both banded and broadcast phosphorus are placed in a soil zone that would be penetrated by roots, but the root development might differ for the two placement methods by a time factor and by an intensity factor (Welch et al., 1966). Low utilizations of banded fertilizer phosphorus by wheat as compared to rape or buckwheat could be attributed to the low proliferation of wheat roots in the reaction zone (Strong and Soper, 1974a). Root proliferation in the band seems to depend on the contrast between phosphorus availabilities inside and outside the reaction zone (Strong and Soper, 1974b).

Gunary and Sutton (1967) reported that the absorption of phosphorus consisted in the removal of most of the labile phosphate in the root zone and later, phosphorus uptake was due more to exploitation of fresh soil by root extension rather than a more intensive uptake from the same soil. P is one of the few ions supplied mainly by diffusion, and P ions diffuse through soil considerably more slowly than other ions (Barber, 1962). Replenishment of depleted zones by diffusion is therefore very slow (Lewis and Quirk, 1967). Therefore, the proportion of root mass which feeds in the fertilizer reaction zone has a significant effect on the recovery of phosporus (Newman et al., 1973; Strong and Soper, 1976a; Bailey et al., 1980). Lewis and Quirk (1967), Barley and Rovira (1970) presented data showing that the presence of root hairs influences extraction of phosphorus from the soil. Root hairs allow the root system to absorb phosphorus at a faster rate from a given soil by increasing the absorption area of the root system (Olsen and Kemper, 1968). However, Bole (1973), growing wheat varieties which differed in their root hair development, indicated that root hairs did not enhance phosphorus supply to roots. All workers (Lewis and Quirk, 1967; Bailey and Rovira, 1970; Bole, 1973) grew spring wheat in greenhouses or growth cabinets where the conditions were very similar. The different results obtained in these experiments where diffusion was the major supply mechanism could be explained by the fact that diffusion rate and therefore supply to roots is strongly dependent on the level of phosphorus addition to the soil (Lewis and Quirk, 1967). The latter authors were using rates considerably lower than Bole (1973).

C. EFFECT OF TEMPERATURE ON PHOSPHORUS UPTAKE

In studying the behavior of phosphorus fertilizer under different soil temperatures, one must distinguish between plant factors and soil factors. Soil temperature affects the physiological activity of plant in addition to such factors as solubilities, reaction rates, equilibrium constants and diffusion rates of nutritional elements in the soil.

Knoll et al. (1964) reported that the optimum temperature for plant growth varies with the species of plant. Plants native to warm climates such as corn, are favored by relatively high soil temperatures at the early growth stage, whereas cold weather plants such as some cereals are restricted in their development by high soil temperatures. Power et al. (1963) found some physiological disorders in barley caused by high soil temperature (26.7°C).

It is of common knowledge that reduced soil temperatures generally reduce the rate of morphological development in a plant. Consequently, in experiments in which plants of equal calendar age are compared, results are altered by differences in physiological and morphological maturity. Power et al. (1964b) and Gingrich (1965) noticed reduced growth and P uptake at low soil temperatures and explained it by a slower phenological development of plants at these temperatures. And so, in short-term experiments, if plants are harvested according to calendar dates, erroneous conclusions could be drawn. A major argument in favor of harvesting by stage of growth is that most plants produced for economic purposes are harvested according to a stage of growth (Power et al., 1970).

Even though wheat can be considered a cold-weather plant, germination is affected by cold soil temperatures. Read and Beaton (1963) reported that germination was slower at 5.5°C than at higher temperatures (16.1 and 26.7°C), but percentage of germination was slightly less at 26.7°C.

Several workers (Gingrich, 1964; Mack, 1965; Follet and Reichman, 1972) have found the maximum amount of dry matter produced by barley occurred at soil temperature around 15°C, whatever the rate of fertilizer P added. Temperatures above 26°C or under 10°C seemed to reduce markedly straw and grain yields (Gingrich, 1964; Mack, 1965). Power et al. (1970) reported that the greatest top growth occurred at 22°C soil temperature for the first few weeks and at 15.5°C thereafter, and by maturity, top growth at 15.5°C was greater than at 22°C. The same workers had found in 1963 that the growth rate at 15.5°C was rather slow for the first week, but then increased rapidly and soon surpassed growth at high temperatures (26.7°C). Dry matter yields in short-term experiments would be in favor of a higher soil temperature, whereas final yields at 15°C are the best, even if more time was required for plants at low soil temperatures to achieve maximum growth rates than at warmer temperatures (Power et al., 1963).

It has been noted that phosphorus uptake at low temperatures is improved where the fertilizer is placed in a band rather than mixed throughout the soil (Robinson et al., 1959; Case et al., 1964). The phosphorus mixed with the soil was utilized less efficiently at lower temperatures. Knoll et al. (1964) indicated that a greater temperature response was obtained when the fertilizer was mixed with the soil than when it was layered in the soil. Gingrich (1964) agreed with these previous results and both workers found that banding the fertilizer gave higher dry matter yields and that the difference was greater in cold soil than in warm soil. However, Knoll et al. (1964) and Gingrich (1964) harvested their plants at five weeks and three and a half weeks respectively.

P content varies with plant species and harvesting time. Knoll et al. (1964), Grant et al. (1972) reported increasing P content of corn with increasing soil temperature. Gingrich (1964, 1965) reported that total P content of wheat was greater at 15.5 and 21.1°C soil temperatures than it was for the 10°C where the yields were also very low. Conversely, Power et al. (1970) found a decreasing total P content with increasing temperature. They however reported, in agreement with Gingrich (1964, 1965), that the highest percent P occurred at the lowest temperature. Differences reported by Gringich and Power et al. could be explained by the date of harvest, 24 days in the case of Gingrich and maturity for Power et al. As previously mentioned, the P uptake and growth rate vary with time for the same temperature.

Davis and Lingle (1951) proposed that endogenous mechanisms may be involved by which variations in root temperature may induce differential production of root-produced substances having shoot regulatory activity. They also suggested that cool soil temperature may retard movement in the phloem, resulting in a congestion of substances in the shoot, thus depressing metabolic activity and salt accumulation.

Results published by Power et al. (1964a) suggest that with an unlimited supply of P, above optimum temperatures would not seriously affect potential yield, but below optimum temperatures would. Slow phenological development due to low temperature would be the prime factor in yield reduction. However, it has been shown that the addition of phosphate fertilizer would, at least in some circumstances, overcome the reduction in plant growth at low temperatures (Mack, 1965). The beneficial effect of phosphate fertilizer could result from the fertilizer increasing the quantity of available P present at the low temperature. That is to say, a more proportionate uptake would come from phosphate fertilizer compared to soil phosphate at low temperature (Sutton, 1969).

Root yields depend on the stage the plants are harvested. Also, as mentioned previously, temperature affects the phenological development of plants. Therefore, response to treatments when temperature effects are studied can vary dramatically with the age of the plant. In short-term studies, working with nutrient solutions, Bowen (1970), Sheppard and Racz (1984 a,b) found that root weight increases with an increase in temperature. Bowen (1970) found a decrease in root growth in a phosphate deficient solution only at low temperatures when compared with a phosphate sufficient solution. The influence of high temperature being that of increasing lateral root production and increasing primary root length for both solutions.

When plants were grown to maturity, root growth was found to be the lowest at higher temperatures and highest with cold soil temperatures (Mack, 1965; Gingrich, 1965; Follet and Reichman, 1972). Power et al. (1963) noticed that low temperatures restricted top growth more than root growth, but the opposite occurred at high temperatures. Follet and Reichman (1972) hypothesized that the greater root growth at low temperatures compared to high temperatures could be a survival mechanism whereby some species maintain their root system at the expense of top growth.

Power et al. (1963), Sheppard and Racz (1984a) found an increasing root weight with increasing phosphate fertilization, at all temperatures. However, the root to shoot ratio decreased with P addition, indicating an even higher top growth with P fertilization. Follet and Reichman (1972) explained this by a shift in the distribution of total weight toward the plant top with P fertilization.

In general, increased P supply broadened the soil temperature range over which up to 80% of maximum plant growth occurred (Power et al., 1964a). Sutton, in 1969, concluded that low soil temperature could reduce the quantity of available phosphate from soils. Some authors (Arambarry and Talibudeen, 1959) reported that an increase in soil temperature may raise the concentration of soluble soil and fertilizer P by increasing the rate of mineralization of organic P or the chemical decomposition of inorganic forms of P. However, Case et al. (1964) showed that beneficial effects from increasing the soil temperature were already evident in the crop after five to eight days, a period they reported to be too short to allow appreciable contribution from mineralization. They explained the responses they observed by a direct effect of the temperature on the physiology of the plants due mainly to increased translocation of P from the roots to the shoots.

Mineralization being of negligible importance in explaining the positive plant response to temperature, other factors such as P concentration and P solubility in the soil solution might be involved. Arambarry and Talibudeen (1959) found that the equilibrium concentration of P in solution was raised by the higher soil temperatures. Power et al. (1964b) wrote that warmer soil temperatures probably increased the rate of diffusion of soluble P to root surfaces. Consequently, at a given level of soluble P, the amount of soluble P present at the root surface for a period of time would be greater at warm temperatures. However, higher soil temperatures (27°C) might reduce P solubility by increasing the rate of immobilization and chemical fixation of P in the soil (Hinman et al., 1962; Beaton and Read, 1963).

D. PHOSPHORUS AND MICRONUTRIENTS INTERACTIONS

In crop production, phosphorus-induced zinc deficiencies are generally the primary concern with excessive phosphorus applications (Brown et al., 1970; Yadav and Shukla, 1982). It has been recognized that high levels of available phosphorus in the soil contribute to Zn deficiency. Because of low solubility of zinc phosphate, it was first supposed that Zn deficiency resulted when applied phosphates reacted with Zn to reduce the level of plant available Zn in the soil (Biddulph and Woodbridge, 1952; Spencer, 1960). Other investigations have indicated that the zinc-phosphorus interactions were physiological in nature due to root surface absorption phenomena or reduced translocation within the plant (Loneragan, 1951; Warnock, 1970). Brown et al. (1970) working with corn, found that applications of phosphorus tended to accentuate Zn deficiency symptoms where no Zn was applied, and conversely, Zn applications tended to accentuate phosphorus deficiency symptoms on any plants where no phosphorus was supplied. Warnock (1970) found P/Zn ratios of nutrient concentrations in corn leaves ranging from 743 to 11 when 520 ppm P + no Zn and, no P + 40 ppm Zn were added respectively; thus demonstrating the antagonistic effect of phosphorus fertilization on Zn uptake and vice versa. Warnock (1970) established from his experiments that a level of 12 ppm Zn or less in corn could be considered to be deficient. Melstead et al. (1969) stated that 15 ppm Zn in wheat was near the level at which a growth stress may occur. Yadav and Shukla in 1982, reported that total Zn uptake increased considerably with addition of phosphorus (50 ppm P and 5 ppm Zn), and then decreased with further increases in phosphorus level, but never below the Zn level obtained when no P was added. In many cases, the application of phosphate stimulated plant growth to such an extent that it diluted the amount of Zn in the plant and so induced Zn deficiency (Boawn et al., 1954; Yadav and Shukla, 1982).

There are some evidences of an antagonistic P-Cu relationship in cereal crops (Brown and Clark, 1977; Touchton et al., 1980). Application of phosphorus decreased plant copper content significantly and might have affected the utilization of copper by the plant (Bingham, 1963). Shukla and Singh (1979) reported a response to Cu application but 50 ppm of copper decreased plant yields and brought the P concentration down to levels sometimes lower than when no Cu nor P were added. High soil pH might be conducive to the formation of $Cu_3(PO_4)_2$ and a decrease in copper availability could be expected (Singh and Swarup, 1982). Beside the decreased copper availability in soil, an interaction at the absorption site and during translocation from roots to shoots could be expected (Racz and Haluschak, 1974; Singh and Swarup, 1982). When large amounts of P were applied, Bingham (1963) proposed that copper deficiency could be due to precipitation within the plant as a result of abnormal amounts of P being present in plant. Touchton et al. (1980) observed that a decrease in Cu concentration was primarily due to a dilution effect. Shukla and Singh (1979), Singh and Swarup (1982) in experiments with wheat, concluded that a proper balance between P and Cu was necessary for maximization of yield.

Interactions among trace elements may also be important. As early as 1945, Lucas found that Zn fertilizers may depress copper concentration in the tops of plants. Zinc might therefore induce copper deficiency causing a drastic depression in grain yields of cereals (Fleming and Delaney, 1961; Hooper and Davis, 1968). Chaudry and Loneragan confirmed these conclusions in 1970 when they reported that application of zinc alone accentuated copper deficiency symptoms in wheat. They also found that the relative effects of Zn fertilizer ($ZnSO_4$) in depressing Cu concentration in plants were greatest where plants did not receive Cu application and negligible only in plants receiving Cu fertilizer which gave a luxury concentration of Cu in the plant.

Copper fertilizers may also decrease zinc concentrations in plant tops (Lucas, 1945) and induce or accentuate the response of plants to zinc by promoting plant growth (Riceman, 1948; Dunne and Throssell, 1948). Chaudry and Loneragan (1970) reported that copper fertilizer had its greatest effect on Zn absorption when Zn was in limiting supply. When Zn occurred in luxury amounts, they found that copper actually enhanced zinc absorption. Later, in 1975, Loneragan indicated that Zn^{2+} and Cu^{2+} might compete in physiological absorptions.

MATERIALS AND METHODS

A. GROWTH CHAMBER EXPERIMENTS

I. Soil Preparation

The soil used for the three growth chamber experiments was collected from a 0-15 cm depth at the field experimental site in the Haywood area. After air drying, the soil was passed through a 2 mm sieve and mixed thoroughly prior to use. Physical and chemical characteristics of the soil are given in Table 1. All the pots in the three growth chamber experiments were filled with 6000 g of soil.

II. First Growth Chamber Experiment

The first growth chamber experiment was designed to study the effects of placement and rate of P fertilizer (H_3PO_4) on the uptake of P by wheat. Two placements representing two extreme situations were studied: a mixed placement where the phosphorus fertilizer was mixed throughout the entire volume of soil, and a band placement where a very narrow band of fertilizer was situated to the side and below the seed.

The mixed placement consisted of spreading 6000 g of soil of each pot on a sheet of strong paper and sprinkling 20 ml of prepared phosphorus solution with a pipette. The soil was then mixed thoroughly, however, globs of wet soil due to the method of sprinkling were noticeable. The band placement consisted in filling each pot with 5000 g of soil and adding 20 ml of phosphorus treatment in a narrow band (1.5 cm in width) following the diameter of the pot, and then adding the remaining 1000 g on top of it, thus placing the band 5 cm under the soil surface.

TABLE 1: Physical and Chemical Characteristics of Soil Used in Growth Chamber Experiments

Location	Haywood
Soil series	Almasippi
Type	Gleyed Carbonated Rego Black
Texture	L.F.S
pH	8.1
Salinity (ds/m)	0.2
NO_3.N (ppm)	13.3
$NaHCO_3$ ext. P (ppm)	2.9
Avail K (ppm)	72.0
Sulphate sulphur (ppm)	7.8
DTPA extractable copper (ppm)	0.75
DTPA extractable zinc (ppm)	5.5
Organic Matter (%)	2.28
Carbonate Content	Low
Field Capacity (%)	23

Phosphorus was applied as phosphoric acid (H_3PO_4). A 1000 ml stock solution was first made and aliquots were then drawn and diluted with various amounts of distilled water to obtain the different rates for the experiment (20, 40, 80, 120, 160, 200, 240 ppm). A check treatment containing no phosphorus, but all other growth factors, was included. Each treatment was replicated three times, thus giving 48 pots placed at random in the growth chamber and regularly rotated for a complete randomization. Phosphorus treatments were labelled with a radioactive isotope ^{32}P in the form of orthophosphoric acid in 0.02 N hydrochloric acid in order to monitor the amount of phosphorus taken up by the plant from the fertilizer. One millicurie of ^{32}P obtained from New England Nuclear was diluted into the stock solution.

Basal fertilizer treatment consisted of N as NH_2CONH_2 and K as K_2SO_4 at a concentration of 100 ppm each, 5 ppm of Cu as $CuSO_4.5H_2O$ and 10 ppm of Zn as $ZnSO_4.7H_2O$. The nutrients were supplied prior to planting in 20 ml aliquots drawn from a 1000 ml solution. Later, during the growing period, at 25 and 50 days, each pot received an extra addition of N as NH_2CONH_2 and K as KCl at a concentration of 100 ppm each.

The control instruments in the growth chambers were set to get a temperature of 22°C during the day, 17°C during the night and a day-length of 16 hours. The humidity control being out of order, the humidity was measured with a hygrometer indicating 100% during the night and 75% during the day. A light intensity of 500 to 550 microeinsteins $.m^{-2}.sec^{-1}$ within and above the canopy was recorded. The pots were brought to field capacity before planting.

Eight seeds, in four groups of two seeds, of spring wheat (*Triticum aestivum* cv Columbus) were sown in each pot 2.5 cm under the soil surface, 5 cm away from the side of the band, and 10 cm from each other. The same disposition was kept for mixed treatments using an imaginary band to place the seeds in the same spots for each pot.

Sowing was done on December 24th, 1982, however, five days later no emergence was observed due to rotten seeds thought to be because of the pots being at field capacity or above. Reseeding was accomplished on December 29th, 1982, and 100% emergence was observed after a few days. The seedlings were thinned to four per pot shortly after emergence. The pots were maintained between 3/4 field capacity and field capacity throughout the growing period. The daily loss of moisture from the pots was estimated by weighing and the soils restored to the field capacity by the addition of distilled water.

The experiment was carried out up to the heading stage where the tops were harvested and oven dried at 60°C for 48 hours. The samples were weighed and ground for chemical analysis.

III. Second Growth Chamber Experiment

Results from the first growth chamber experiment brought out some doubts about the method used for mixing the phosphorus throughout the soil. Sprinkling with a pipette could have given pellet zones of high fertilizer concentration and therefore could not be considered as being thoroughly mixed throughout the soil.

This growth chamber experiment was carried out in cooperation with Miss C. Newman, a student whose undergraduate work dealt with placements and rates of phosphorus, as well as the interaction between phosphorus and micronutrients. The experiment was divided into two parts that were conducted at the same time in the same growth environment. The experiment was carried out on a bench up to the heading stage and then continued in a growth chamber to maturity.

In the growth chamber, the humidity control was out of order resulting in a very high air humidity of 80% during the day and 100% at night. The daylength was set to be 16 hours long on both the bench and in the growth chamber. The temperature recorder on the bench indicated 30°C during the day and 20°C at night; in the growth chamber, the temperature control was set to maintain 22°C during the day and 17°C at night. The light intensity was measured to be 375 and 500 microeinsteins $.m^{-2}.sec^{-1}$ on the bench and in the growth chamber respectively.

The treatment structure of the first part of the experiment was similar to the design used in the growth chamber run in December 1982 - March 1983. However, no radioactive phosphorus was used and therefore phosphorus derived from fertilizer could not be directly calculated. Five rates of phosphorus fertilizer applied as phosphoric acid (H_3PO_4) (30, 60, 120, 180, 240 ppm) and a check receiving no phosphorus were replicated three times. All soil in pots received N as NH_2CONH_2 and K as K_2SO_4 at concentrations of 100 ppm each before planting and two extra additions of 100 ppm N as NH_2CONH_2 and 100 ppm K as KCl at tillering and heading.

The second part of the experiment was carried out to study the interactions between phosphorus and micronutrients, specifically copper and zinc. The same methods of placements were looked at, but only one rate of phosphorus was applied. A decision was taken to use a rate of 120 ppm of P because it corresponds to the rate of phosphorus normally added in growth chamber experiments. The basal treatment was common to both parts of the experiment. In part II, copper or zinc, or copper plus zinc were also sprayed and mixed throughout the soil, at rates of 10, 20 and 10 + 20 ppm respectively. The check pots with no micro-nutrients were in part one of the experiment and the data were used for both parts.

The same placements as in the first growth chamber experiment were employed. The band placement was executed in the same way, however, the mixed placement was slightly different. Instead of sprinkling the treatment solution with a pipette, a spray bottle was used. The drops were infinitely smaller and better dispensed throughout the volume of soil. The soil was mixed during the spraying operation to ensure an even better mixing procedure. The correct amount of fertilizer added was determined by weight. The whole experiment, consisting of 54 pots, was laid out as a randomized complete block design.

The pots were brought to half field capacity and twelve seeds of spring wheat (*Triticum aestivum* cv Columbus) were planted on September 16th, 1983, in four groups of three seeds in the same manner as the first growth chamber experiment. Emergence was observed a few days later and the plants were thinned to four per pot. The pots were then brought to field capacity and maintained between 3/4 field capacity and field capacity throughout the growing period, using the same method as described previously.

The tops were harvested at maturity, oven dried at 60°C for 48 hours and weighed. Each sample was threshed, the grain was weighed and ground for analysis.

IV. Third Growth Chamber Experiment

The results from the first and second growth chamber experiments showed a difference between methods of fertilizer application in favor of the mixed placement. In field trials in Manitoba, banding of phosphorus is recognized to be a more efficient method for phosphorus fertilization as compared to broadcast and mixed placements. Temperature is known to be a significant factor in the study of phosphorus placement, and hence a third experiment was conducted to study the interactions among soil temperatures, placements and rates of applied phosphorus.

Two methods of phosphorus placement were employed. Band and mixed placements were accomplished as described in the second growth chamber experiment. The phosphorus treatments consisted of one check and three rates (50, 100, 200 ppm). In order to measure the amount of phosphorus taken up by the plant derived from fertilizer, phosphorus was tagged with radioactive ^{32}P in the form of orthophosphoric acid in 0.02 N hydrochloric acid. One millicurie of ^{32}P obtained from New England Nuclear was diluted in the stock solution as previously described. Each treatment was replicated three times except for the checks, thus giving a total of 20 pots per bath. In each bath, the pots were arranged in a completely randomized design and rotated regularly.

Each pot received N as NH_2CONH_2 (100 ppm), and potassium (100 ppm), zinc (20 ppm), copper (10 ppm) as sulfate compounds. Extra additions of

N as urea (100 ppm) and K as KCl (100 ppm) were provided at tillering and heading. The growth conditions set in the growth chamber were the same as in the first growth chamber experiment. The humidity was recorded to be 30% at night and 40% during the day.

The pots were brought to half field capacity and placed into two water baths which regulated the soil temperature at 14 and 23°C (see Appendix A for description of the water bath). Planting was effected on February 2nd, 1984. Eight seeds of spring wheat (*Triticum aestivum* cv Columbus) were placed as described in the first growth chamber experiment and thinned to four plants shortly after emergence. The pots were brought to field capacity and maintained between 3/4 field capacity and field capacity throughout the growing period by weighing them regularly. The water, as well as the pots, were covered with styrofoam packing material to thermally insulate the soil. Thermocouples were placed into two pots per bath to record the temperature variations in the soil at four different depths (1, 2.5, 7.5, 12.5 cm from the soil surface) (see Appendix B).

Plant tops were harvested at maturity and oven dried at 60°C for 48 hours. The total dry weights were taken before threshing and grain weights were recorded after. Straw weights were obtained by subtraction. Each sample was ground for laboratory analysis.

B. FIELD EXPERIMENTS

Two field studies were undertaken during the summer of 1983. One of them was the second year of a three-year project conducted at three different sites in Manitoba. The aim was to look at how rates and placements of phosphorus fertilizer were affecting maximum grain yield of spring wheat (Triticum aestivum cv Columbus). The results of the first year have been the object of a thesis written by Modestus (1984). They showed, on two of the three sites, a decrease in grain yield with increasing rates of fertilizer phosphorus applied. The explanation for that decrease, supported by laboratory analysis, was thought to be a phosphorus-induced micronutrient deficiency. The second field experiment was carried out to study the interaction between phosphorus and micronutrients.

I. The First Field Experiment: Phosphorus Study

The three sites for the experiment had been chosen on the basis of their available soil phosphorus contents. They ranked from low for Haywood, to medium-high for Elm Creek, to high for Winkler. Table 2 shows the soil characteristics of the three sites. The data presented in Table 2 are based on soil analyses done in the spring of the year the experiment was initiated, just prior to seeding.

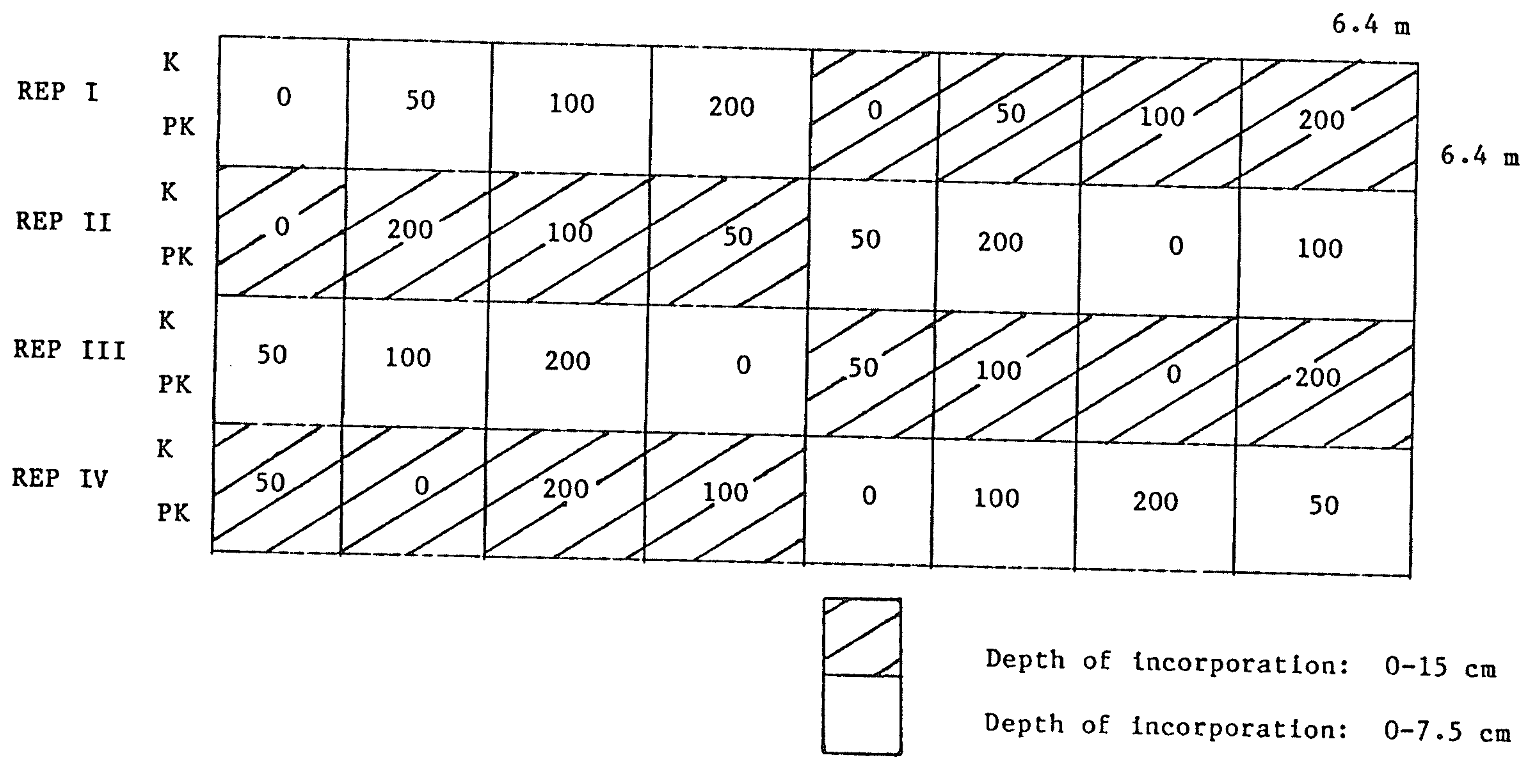
The same field lay-out was used at each site. It was a factorial experiment that consisted of four rates of broadcast phosphorus fertilizer (MCP) (0, 50, 100, 200 kg P/ha), two depths of fertilizer incorporation into the soil (0-7.5, 0-15 cm) and two band treatments. A diagram of the lay-out is shown in Figure 1. The design consisted of four replicates, each 51.2 m long and 6.4 m wide. Each replicate was divided into two subplots (25.6 x 6.4 m) corresponding to the different depths; the broadcast fertilizer was worked into the soil the first year. The subplots were split into four units (6.4 x 6.4 m). Phos-

TABLE 2: Physical and chemical characteristics of the soils used for the field studies.

Locations	Haywood[1]	Elm Creek[1]	Winkler[2]
Soil Series	Almasippi	Elm Creek	Rignold
Sub-group	Gleyed-Carbonated Rego Black	Orthic-Black	Gleyed Black
Texture	L.V.F.S	F.S.-L.V.F.S	V.F.S.L.
Carbonate Content	Low	Low	Low
pH	8.1	8.2	8.0
NO_3-N (kg/ha) (0-60 cm)	84	42	125
Avail. P (kg/ha) (0-15 cm)	6	25	31
Avail. K (kg/ha) (0-15 cm)	146	449	602

1. Soil classification by Michalyna and Smith (1972).

2. Soil classification by Smith and Michalyna (1973).



0, 50, 100, 200 = Rate of P Broadcast in kg P/ha.
K = K banded with the seed at 33 kg K/ha.
Pk = P + K banded with the seed at 17 kg P + 33 kg K/ha.

FIGURE 1: Field plan for the phosphorus experiment.

phorus fertilizer (0-46-0) was broadcast at random on each unit, and incorporated into the soil down to the desired depth. The replicates were split lengthwise into halves, each year one half received an extra 17 kg P + 33 kg K/ha banded with the seed and the other half received only 33 kg K/ha seed placed.

The statistical design of the experiment cannot be called a split-split plot because the banding treatment was not applied at random for facility purposes. The statistical analyses are discussed in a following chapter.

Nitrogen and potassium had been hand broadcast and rotor-tilled the first year. At all three sites, potassium was added at the rate of 200 kg/ha. Nitrogen was added at the rate of 150 kg/ha at Haywood and Winkler sites, and 200 kg/ha at the Elm Creek site. The second year, potassium was supplied in the band either alone or in association with phosphorus at a rate of 33 kg K/ha as KCl. Nitrogen was added based on soil analysis done in the spring of 1983. Large amounts of NH_4NO_3 were hand broadcast and incorporated so that phosphorus would be the only limiting nutrient (100 kg/ha at Winkler, 200 kg/ha at Elm Creek, 150 kg/ha at Haywood). Since micronutrient deficiencies were observed at Haywood and Winkler the first year, copper and zinc were sprayed and worked in at rates of 15 kg Cu/ha of $CuSO_4.5H_2O$ and 20 kg Zn/ha of ZnCl. Soil samples were taken in the spring from a depth of 0-15 cm on each treatment for phosphorus analysis.

Round up herbicide was applied at Haywood in spring for Quack Grass control a week before seeding. Columbus wheat was seeded with a nine row seed drill at a rate of 100 kg/ha, on May 17th at Winkler, May 18th at Elm Creek and May 26th at Haywood. The 1983 summer has been reported to be dry, however, at the three sites, no sign of water stress was observed during the growing season. Monthly rainfall, as well as total soil moisture in spring and fall to a depth of 120 cm, are reported in Table 3. Each site was sprayed with Hoe Grass and Diamine 80 during the season for weed control.

The above ground portion of wheat was regularly sampled. One square meter was harvested on each treatment at five different physiological stages. See Table 4 for the growth stages. The samples were oven dried at 60°C for 48 hours and dry matter yield determined. For the final harvest, after oven drying, the samples were weighed, threshed and the grain yields recorded. The straw yield was obtained by subtraction. A representative subsample was taken out of each harvested sample and bulked according to treatments. The composite sample, made up of four replicates, was then ground for N, P, K, Cu, Zn, Fe and Mn laboratory analysis. Elements apart from phosphorus were analysed to determine if they were not limiting factors in the experiment.

II. The Second Field Experiment: Micronutrient Study

This experiment was carried out to study the interaction between phosphorus and micronutrients, and more specifically, between phosphorus and copper. Results from the first year of the study described above showed that in some instances at high rates of phosphorus, the grain yields were decreasing. Declining trends of harvest index but no significant dry matter yield depression as well as a copper concentration in the grain down to two ppm in some cases supported the conclusion of a

TABLE 3: Monthly rainfall and total soil moisture to a depth of 120 cm at the three sites in 1983.

SITE	MONTHLY RAINFALL (cm)			TOTAL SOIL MOISTURE TO A DEPTH OF 120 cm (cm)	
	June	July	August	Spring: Seeding Time	Fall: Final Harvest
Haywood	8.08	-	1.65	32.99	20.68
Elm Creek	8.67	3.84	0.60	34.52	21.99
Winkler	5.86	4.65	2.59	29.28	24.14

TABLE 4: Physiological stages of wheat at tissue sampling time (three field sites).

SAMPLING #	STAGE OF GROWTH
1	Early Tillering
2	Bootstage
3	Heading
4	Milk - Soft-Dough
5	Maturity

possible interaction between phosphorus and micronutrients. Interactions between phosphorus and copper or zinc has been recognized for some time. In this experiment, more emphasis was put on copper than zinc because more evidence indicated a Cu-P interaction than a Zn-P interaction.

The Haywood site was selected for the field trial. The experiment consisted of 12 treatments arranged in a factorial design. The treatments were a combination of four rates of phosphorus fertilizer (0, 50, 100, 200 kg P/ha) and three micronutrient treatments (none, 15 kg Cu/ha, 15 kg Cu + 15 kg Zn/ha). The soil's characteristics are shown in Table 2. As no significant difference was found in the first year of the previous experiment between the two depths of fertilizer incorporation, a decision was taken to use only one depth of mixing for the micronutrient experiment (0-7.5 cm). The experimental plot was designed as a split-block with four replicates. The plan of the plot is illustrated in Figure 2. Each replicate was 76.8 m long and 6.4 m wide. It was divided into 12 treatments of 6.4 x 6.4 m. Phosphorus was applied as 0-46-0 hand broadcast randomly in each subplot, copper and zinc were sprayed on the soil at random on each subplot with a back sprayer as $CuSO_4 \cdot 5H_2O$ and $ZnCl_2$ respectively. Nitrogen as NH_4NO_3 (250 Kg N/ha) and K as KCl (200 kg K/ha) were also applied based on spring soil analysis in order to produce at least 5000 kg of grain per hectare. The soil was then worked with a rotor-tiller to a depth of 7.5 cm. On top of these treatments, each replicate was split lengthwise into two halves. One half received an extra 17 kg P + 33 kg K/ha banded with the seed, the other half receiving only 33 kg K/ha seed placed.

		200 P 15 Zn 15 Cu	100 P 0 Zn 0 Cu	50 P 0 Zn 0 Cu	0 P 15 Zn 15 Cu	200 P 0 Zn 15 Cu	100 P 0 Zn 0 Cu	50 P 15 Zn 15 Cu	0 P 0 Zn 15 Cu	200 P 0 Zn 0 Cu	100 P 15 Zn 15 Cu	50 P 15 Zn 0 Cu	0 P 0 Zn 0 Cu
REP I	K PK	12	11	10	9	8	7	6	5	4	3	2	1
REP II	K PK	7	2	9	6	11	6	1	8	3	10	5	12
REP III	K PK	10	9	8	7	6	5	4	3	2	1	12	11
REP IV	K PK	5	4	3	2	1	12	11	10	9	8	7	6

K = K banded with the seed at 33 kg k/ha.
PK = P + K banded with the seed at 17 kg P + 33 kg k/ha.

FIGURE 2: Field plan for the micronutrient experiment.

Potassium was added as KCl.

Columbus wheat was seeded on May 26th with a nine row-seed drill at rate of 100 kg/ha. The crop was sprayed with Hoe Grass and Diamine 80, during the growing season for weed control. Data collection from this trial was done the same way as in the field experiment described in the previous chapter. The same physiological stages of growth were used for sampling.

C. ANALYTICAL PROCEDURES

I. Plant Analysis

a. Digesting procedure.

Tissue samples from all experiments were oven dried at 60°C, and ground in a Wiley mill. One gram of a representative sample was digested using a nitric and perchloric acid digestion. The resulting digest was diluted with distilled water to 25 ml and centrifuged in an IEC model HN-SII centrifuge for 10 mn at 3/4 of the maximum speed to allow the precipitate to settle down. To ensure consistency, the same solution was used for all analyses (P, K, Cu, Zn, Mn, Fe).

b. Micronutrient analysis.

To avoid any contamination of the digested samples, micronutrient analyses were performed first using a Perkin-Elmer 560 Atomic Adsorption Spectrophotometer. The digested samples were then analyzed for macro-nutrients.

c. Phosphorus analysis.

The complexing reagent used in phosphorus analysis was made of 20 ml of ascorbic acid solution and 80 ml of acid molybdate-antimony solution (previously prepared). The ascorbic acid solution was obtained by dissolving 2.5 g of ascorbic acid in 100 ml of distilled water.

A 0.5 ml aliquot was taken from the digest and diluted with 9.5 ml of distilled water. Another similar dilution followed. Two ml of complexing reagent previously prepared was added to all samples in order to develop a blue color, as described by Stainton et al. (1974). The color intensity is proportional to the concentration of phosphorus in the sample. Within three hours, readings were taken on a spectrophotometer at 885 nm. A standard curve was obtained at the same time by using phosphate solutions ranging from 0.1 ppm to 10 ppm and following the same procedure. Percent phosphorus could then be calculated based on the standard curve and corrected for the dilutions.

d. Pdff.

In experiments involving ^{32}P, the emission as beta particles from the decaying radioisotope was detected using a Beckman model 7500 scintillation counter. This analytical system had the advantage that the sample could be used for further analysis. Therefore, the digesting procedure was the same and from each sample, 15 ml was drawn and put into scintillation vials for counting.

The program used in the scintillation counter included background subtraction, half-life correction during the counting session, counting during a determined time or to 2% error, and calculation of the sample channel ratio. Percent phosphorus derived from fertilizer was calculated as follows:

$$\% \text{ Pdff} = \frac{\text{specific activity of sample}}{\text{specific activity of standard}} \times 100$$

e. Potassium analysis.

The digest was shaken to mix the precipitate with the solution. A 0.5 ml aliquot was taken from the mixture and diluted with 9.5 ml of distilled water. A 0.5 ml aliquot from the diluted solution was drawn and diluted with 1.0 ml of a 2500 ppm $LiNO_3$ solution and 8.5 ml of distilled water. The K concentration was then determined using a Perkin-Elmer 560 Atomic Adsorption spectrophotometer.

f. Total nitrogen analysis.

Total nitrogen was determined by a modified Kjeldahl method (Jackson, 1958).

II. Soil Analysis

a. Soil texture.

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

b. pH.

Soil pH was determined by the method described by Peech (1965). A 1:1 ratio soil water paste is stirred and then allowed to sit for 30 minutes with one mixing during that period. The pH of the suspension was read on a Beckman zeromatic pH meter.

c. Organic matter.

Organic matter was determined by the Walkley-Black (1934) method as described by Allison (1965). An automatic titrator was used to back titrate excess $K_2Cr_2O_7$ with $FeSO_4$.

d. Nitrogen.

Nitrate-nitrogen was determined by Harpers' (1924) modified phenoldisulphonic method. Ten grams of air-dried soil were mixed with 50 ml of extracting solution containing 125 g of $CuSO_4 \cdot 5H_2O$ and 6 g of Ag_2SO_4 per liter. Nitrogen was measured colorimetrically as the nitrate form of phenoldisulphonic acid in an alkaline medium with a spectrophotometer at 415 mm.

e. Phosphorus.

Phosphorus was determined by a modified Olsen et al. (1954) method. Five grams of air-dried soil were extracted with 100 ml of 0.5 M $NaHCO_3$ at pH 8.5. The molybdate-phosphorus heteropoly complexes formed were then reduced with the ascorbic-molylodate reagent to form a characteristic blue color the intensity of which is proportional to the phosphorus concentration in the sample (Murphy and Riley, 1962). The absorbance was read using a spectrophotometer at 885 nm. Appropriate calculations based on a standard curve and accounting for the various dilutions gave the $NaHCO_3$ extractable phosphorus in the sample.

f. Water-extractable P.

Five grams of air-dry soil were shaken with 50 ml of distilled water for five minutes. The solution was centrifuged and filtered repeatedly until a clear extract was obtained. The phosphorus was then determined colorimetrically following the same procedure as outlined for $NaHCO_3$ extractable soil phosphorus by Murphy and Riley (1962).

g. Potassium.

NH_4OAc extractable K was determined using the modified procedure described by Pratt (1965). Five grams of soil sample were shaken with 100 ml of a solution containing 1.0 M NH_4OAc and 250 ppm $LiNO_3$ for one hour. The solution was filtered and a reading determined on a Perkin-

Elmer 303 atomic adsorption spectrophotometer.

h. Copper, zinc.

DTPA (diethylenetriaminepentacetic acid) extractable Cu and Zn were determined by the method described by Lindsay and Norwell (1969). Twenty-five grams of soil were shaken with a DTPA extracting solution (0.005 M DTPA, 0.01 M $CaCl_2$ and 0.1 M triethanolamine) for two hours. The solution was filtered and determinations were made on a Perkin-Elmer 560 atomic adsorption spectrophotometer.

III. Statistical Analysis

All the statistical analyses involved in this study will not be discussed here, but some experimental designs depart from the traditional lay-out used in the field and need some explanations.

In the third growth chamber experiment, there were no replicates of the water baths because of the lack of space. The temperature effect could not therefore be tested. Details about this experiment are given in Appendix C.

In the field study, the P banding treatment was applied on the same side of each replicate and hence no randomization. The design was not therefore a true split-split plot, but could be called a "split-block-split-plot" design. A modified anova table was used to analyze this experiment (see Appendix D).

The F-test using this new anova table showed no significant difference between the two depths of mixing at any site or any stage. A decision was taken then to treat the three sites as a split-block design with eight replicates. The anova table for this analysis is shown in

Appendix E. All the data reported in the results and discussion concerning the three-year project come from a statistical design based on a split-block design with eight replicates.

All statistical analysis in this thesis were done with the Anova procedure of Statistical Analysis System (S.A.S. 1982).

RESULTS AND DISCUSSION

A. GROWTH CHAMBER EXPERIMENTS

I. Study I: Effect of Rate and Placement of P Fertilizer on Dry Matter Yield and P Uptake

Banding phosphate fertilizers has been generally recognized to give higher dry matter and grain yields than broadcasting, and has the advantage of saving fertilizer (Coe, 1926; Prummel, 1957; McLeod et al., 1975). The object of this experiment was to compare these two extreme placements at various rates of fertilizer application. To avoid seed damage, the banding placement was situated below and slightly to the side of the seed.

a. Dry matter yield.

The most notable feature of the data reported in Table 5 and Figure 3 is the curvilinear response to the rate of P applied. Both placements showed the same type of response curve. In each case, an addition of 20 ppm gave more than a two-fold increase in dry matter yield. Statistically, a supply of 80 ppm either banded or mixed was enough to achieve maximum yield. Further addition of fertilizer did not substantially increase the dry matter yield and the response curve leveled off. Figure 3 displays the response curves with the plateau starting at 92.11 ppm for banded placement and 83.22 ppm for the mixed placement. The plateaus correspond to the maximum yields achieved for each placement. Maximum yields were 48.96 g/pot and 52.32 g/pot for the mixed and band placement respectively. Before the plateau was reached, yields for each placement were increasing with supply of fertilizer following quadratic regressions:

TABLE 5: Dry matter yield (g/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	14.92	35.94	39.73	51.28	49.63	54.56	56.52	50.05	48.25A
Banded	13.15	33.05	36.78	44.60	47.37	49.97	51.53	49.88	44.74B
Main Effect	14.03A	34.50B	38.26B	47.96C	48.50C	52.27C	54.03C	49.97C	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

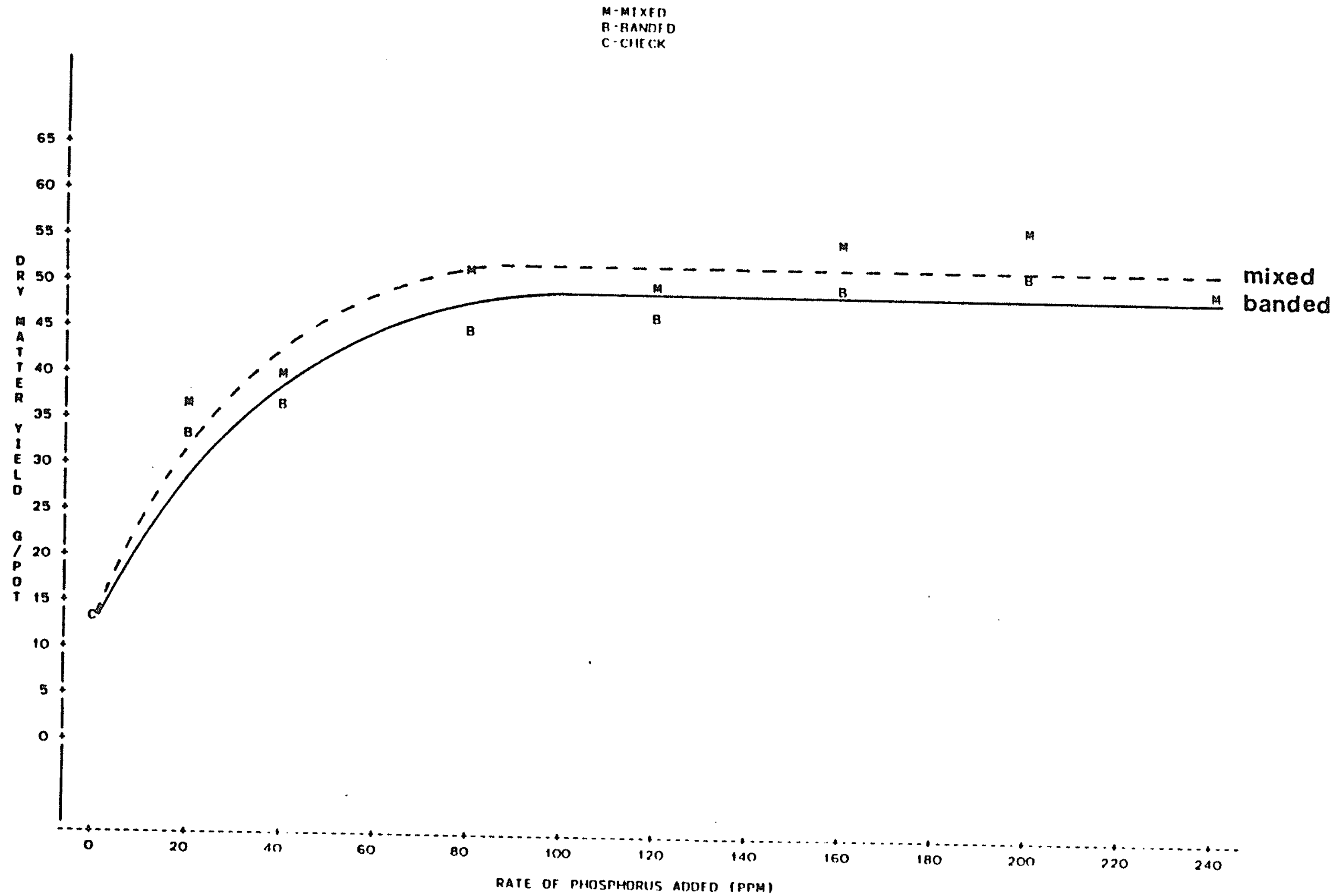


Figure 3: Relationship between dry matter yield, rate and placement of P added to the soil.

Banded Placement: Yield = 15.444 + 0.728 Rate - 0.004 Rate^2

Mixed Placement: Yield = 16.575 + 0.859 Rate - 0.005 Rate^2

The mixed placement as a main effect gave significantly higher yields than banding fertilizer. It is often reported in the literature (Prummel, 1957; Sherrell et al., 1964) that banding phosphorus with or near the seed gives higher yields in field studies. This experiment was conducted in a controlled environment where moisture conditions as well as temperature were not representative of field conditions. Gingrich (1964) demonstrated that with increasing soil temperature, the advantage of band placement for dry matter yield became negligible. This might explain why in this experiment the banding treatment did not produce more than the mixed treatment. No differences between placements were significant at each rate of fertilization probably due to a lower number of replications than for the main effect.

b. P content.

Nutrient uptake of cereals and P uptake in particular, depends on the availability of the nutrients in soil, therefore they have to be present in sufficient quantities but also be available to plants. Placement of phosphorus has been shown to influence its availability (Sherrell et al., 1964; Nyborg and Hennig, 1969; Morden and Racz, 1983). Figure 4 presents the relationship between the dry matter yield and the total P content in the shoots. The curves representing the two placements were very similar with low total P contents corresponding to low dry matter yields. Poor P contents were achieved at the lower levels of P added. It was, however, noticeable at these rates, although not significant, that a slightly higher yield was obtained for the same

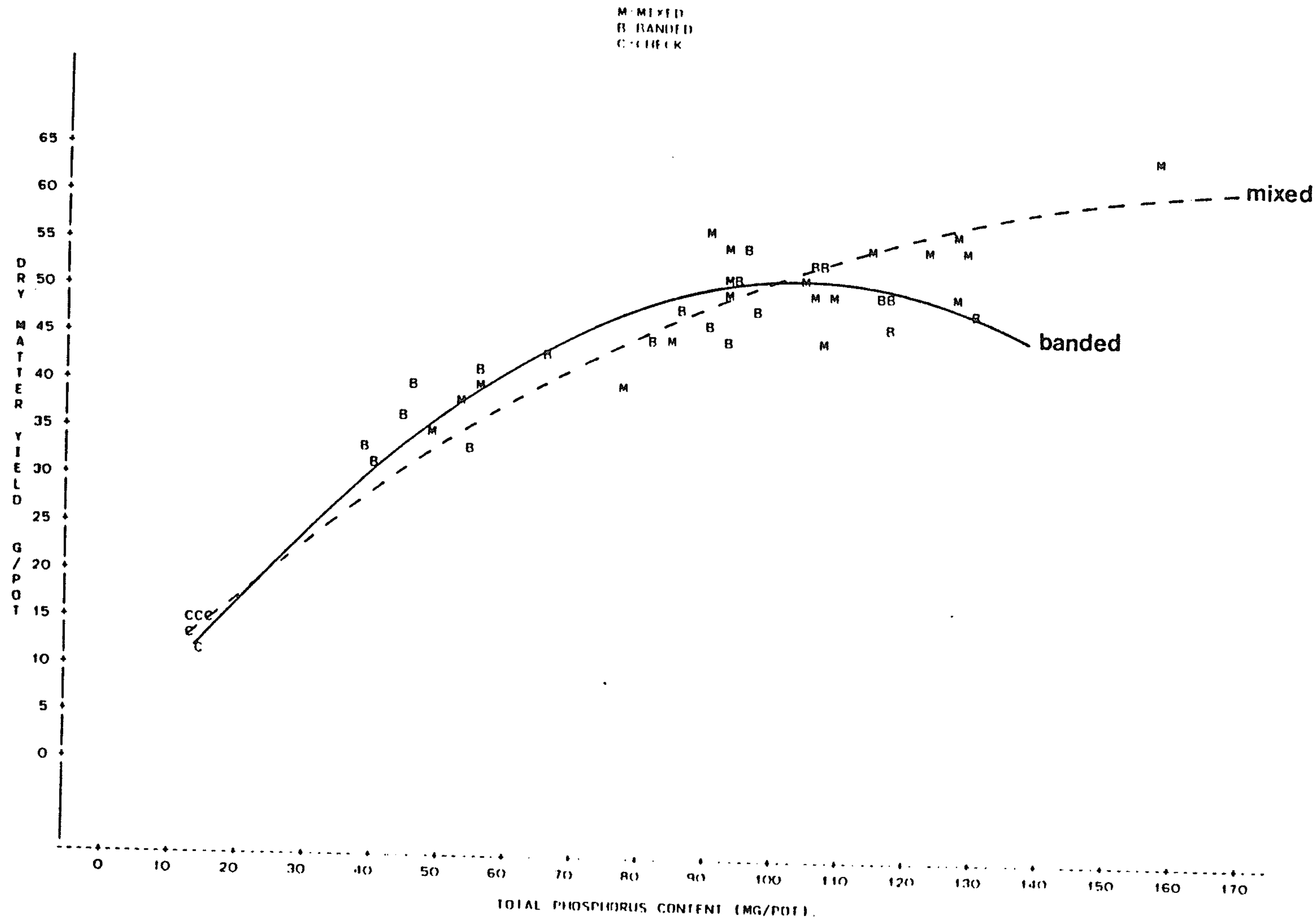


Figure 4: Relationship between dry matter yield and total P in the plant.

P content when the fertilizer was placed in a band. This could be due to a higher availability of banded P compared to mixed when low rates were employed.

At higher rates of P applied, which resulted in higher total P contents in the shoots, the mixed placement gave better yields whereas banded P had a tendency to decrease yields. A limiting factor that occurred mainly when P was banded might be responsible for the declining trend in yield with high P content. Maximum total P content, without decreasing yields, was calculated from the equations of the curves on Figure 4. Values of 167 mg P/pot for mixed placement and 107 mg P/pot when P was banded were derived from the equations. Any further increase in P content beyond the maximum values calculated would not result in any gain in yield and could be considered as luxury consumption. Maximum yields obtained from these curves were slightly higher (59.97 g/pot when P was mixed and 51.01 g/pot when P was banded) than the values calculated from the Figure 7 (52.32 g/pot and 48.96 g/pot for mixed and band treatment respectively), mainly because the latter values accounted for the yield reduction and the previous values would represent a potential yield attainable with no growth limiting factor.

P contents for both placements (Table 6) responded to additions of phosphorus but increased only slightly with a further increment of fertilizer above 80 ppm. The mixed placement as an overall effect gave a higher total P content than the band placement. The differences in P contents could be due to reduced accessibility of the fertilizer by the plant. In this experiment, the mixed placement seemed to improve P uptake.

TABLE 6: Total P (mg/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	15.41	52.78	62.27	97.41	102.24	103.57	128.21	120.92	95.34A
Banded	13.58	44.53	47.56	70.25	91.92	101.61	106.11	114.20	82.31B
Main Effect	14.49A	48.65B	54.91B	83.83C	97.08CD	102.59CD	117.16D	117.56D	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

The fertilizer was tagged with ^{32}P, thus the proportion of P derived from the fertilized (Pdff) in the shoot could be determined (Table 7). Phosphorus derived from the soil (Pdfs) in the shoot (Table 8) was calculated by the difference between the total phosphorus content and Pdff. Pdfs stayed rather constant over all rates of phosphorus added. The addition of P did not enhance the uptake of soil phosphorus as noticed by Mitchell (1957) with wheat and Bullen (1980) with soybeans. The latter suggested that as plant size increased, the root development was ensured, thus permitting the exploration of larger volumes of the soil and the extraction of larger amounts of soil phosphorus. In this experiment, where the rates of phosphorus were up to 240 ppm, Pdfs did not vary and it could mean that the plants had reached their potential soil P absorbing capacity even at the lower rates of P supplied, which may not have been the case in Bullen's study concerning soybeans.

The percentage of phosphorus derived from the fertilizer ranked from 62.18% and 67.15% at 20 ppm to 87.57% and 89.74% at 240 ppm when mixed and banded respectively. Figure 5 presents the partitioning of the phosphorus in the plant in functions of the rates of P added. Not as in most reported studies (McLeod et al., 1975; Dibbs 1978; Bailey et al., 1980), a higher Pdff content in the shoot was found when P was mixed. Whatever the placement, Pdff increased in the same manner as total P where the effect of increasing rate of fertilizer gradually disappeared. At each rate, Pdff when P was mixed was greater than when the fertilizer was banded and as a main effect, placement had a significant effect on Pdff. This meant that P was more available from the mixed

TABLE 7: Total P derived from fertilizer (mg/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)							MAIN EFFECT
	20	40	80	120	160	200	240	
Mixed	32.84	43.31	76.16	81.71	86.58	113.02	105.30	76.99A
Banded	29.64	34.37	54.73	73.64	86.64	89.68	101.72	67.21B
Main Effect	31.24A	38.84A	65.45B	77.78B	86.61BC	101.35C	103.51C	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 8: P derived from soil (mg/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	15.41	19.94	18.96	21.25	20.54	16.99	15.19	15.61	18.35
Banded	13.58	14.89	13.19	15.82	18.28	14.97	16.43	12.48	15.11
Main Effect	14.49	17.41	16.07	18.38	19.41	15.98	15.81	14.05	

Rate of Phosphorus Added: Non Significant
Placement: Non Significant
Rate x Placement: Non Significant

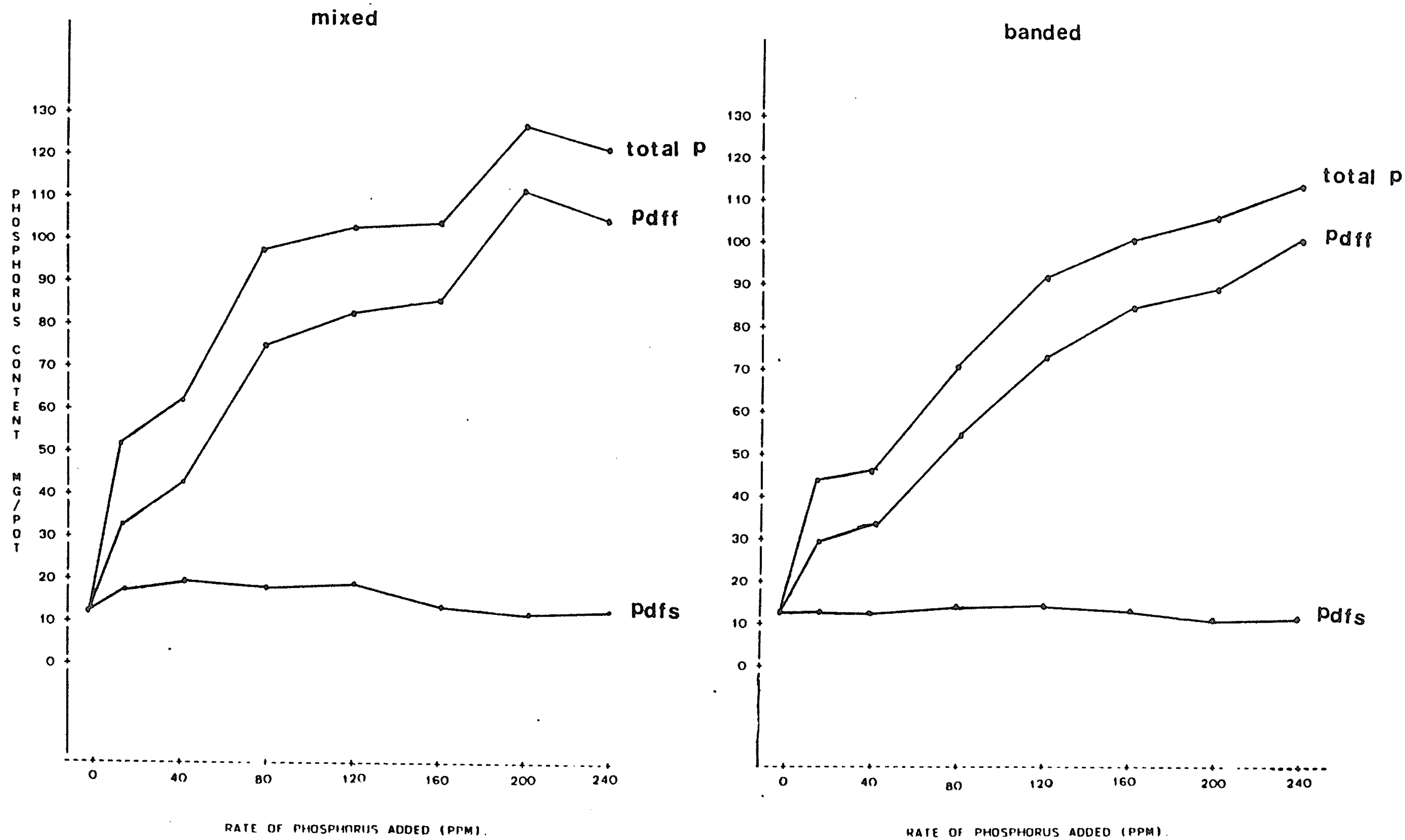


Figure 5: Partitioning of P in the plant as affected by rate and placement of P added to the soil.

treatment. Banding fertilizer is known to reduce fixation and therefore increase its availability to plants but in this experiment, the contrary seemed to happen. In this study the size of the band must be taken into consideration. Strong and Soper (1973) showed that the uptake of phosphorus from a band was dependent on the ability of a plant to develop roots in the band. The narrowness of the band utilized in this experiment could account for some of the difficulties the roots had in permeating the band and therefore limiting the uptake capacity of the plant.

c. Micronutrients content in the shoot.

Singh reported in 1962 that for maximum absorption of nutrients from the soil, nutrients must first of all be present and available for the use of the plant, but also a proportionate supply of these nutrients must be provided to the plant. Application of high amounts of P fertilizer might induce a micronutrient inbalance or immobilization (Racz and Haluschak, 1974; Ridley and Tayakepisuthe, 1974) and precautions should be taken to monitor micronutrients in soil when heavy applications of phosphorus are employed. Micronutrient analyses were carried out and zinc and copper concentrations are presented in Tables 9 and 11 respectively. There was a significant decline in micronutrient concentrations with additions of phosphorus.

Placement of fertilizer had no effect on the zinc concentration in shoots. Zinc concentrations decreased significantly with a supply of 20 ppm of phosphorus, and with further additions, reached a level that averaged 15 ppm. This figure is equal to the 15 ppm level mentioned by Melstead et al. (1969) at which a growth stress might occur. In this experiment, the level was reached at 40 ppm but no visible sign of stress was detected on these plants nor at higher rates of P where the zinc concentration was even lower. At the same growth stage, the Manitoba Provincial Soil Testing Laboratory suggested a critical level of 10 ppm zinc in the shoot at heading. Zinc concentrations never attained that level. Ten ppm could be closer to the real critical value and would partly explain the absence of any visible sign of growth stress. Addition of phosphorus increased the total zinc content (Table 10) of the plant and hence the decrease in zinc concentration was mainly due to dilution.

Copper concentration was also affected by addition and placement of phosphorus (Table 11). Higher copper concentrations were obtained when the fertilizer was mixed than when phosphorus was banded. The concentration of copper decreased steadily with increasing rates of banded phosphorus whereas when the phosphorus was mixed it decreased first and then increased again for unexplained reasons. It seemed that copper could have been limiting growth at high rates of banded phosphorus. Copper concentrations averaged 2.08 and 2.17 ppm which would suggest that the 5 ppm critical level given by Melstead et al. (1969) was a little high and the critical level of 3 ppm proposed by McAndrew (1979) was closer to the reality. This means that for the mixed treatment copper was deficient at 80 and 120 ppm and deficiencies occurred at 160 ppm and above when P was banded. Total Cu content (Table 12) increased significantly over the check treatment with additions of phosphorus, but stayed at a constant level although the yields increased considerably, indicating a dilution effect on the concentration. An improper balance

TABLE 9: Shoot zinc concentration (ppm) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	39.25	24.00	15.08	16.83	16.08	13.83	13.25	15.58	16.38
Banded	33.75	19.83	14.92	15.25	14.50	15.50	12.33	14.42	15.25
Main Effect	36.50A	21.92B	15.00C	16.04C	15.29C	14.67C	13.96C	13.83C	

Rate of Phosphorus Added: Significant at 1%
Placement: Non Significant
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 10: Shoot total zinc content (ug/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	585.68	859.65	602.16	858.10	798.69	748.83	886.72	658.95	773.30
Banded	443.32	656.03	541.05	684.65	687.50	777.20	633.58	709.03	669.86
Main Effect	514.50B	571.60A	757.84AB	771.37A	743.10AB	763.02A	760.15A	683.99AB	

Rate of Phosphorus Added: Significant at 1%
Placement: Non Significant
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 11: Shoot Cu concentration (ppm) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	4.83	4.33	3.50	2.42	2.58	3.00	3.33	3.50	3.24A
Banded	4.58	3.58	3.25	3.25	3.17	2.08	2.08	2.17	2.80B
Main Effect	4.71A	3.96AB	3.38BC	2.83BC	2.88BC	2.71C	2.54C	2.83BC	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Significant at 1%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 12: Shoot total Cu content (ug/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)								MAIN EFFECT
	0	20	40	80	120	160	200	240	
Mixed	72.08	155.30	139.50	124.33	128.25	163.65	189.61	173.72	153.51A
Banded	60.74	118.37	119.31	144.82	150.07	103.91	107.46	108.90	121.83B
Main Effect	66.41B	136.84A	129.40A	134.68A	139.16A	133.78A	148.53A	141.31A	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Significant at 1%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

between Cu and P has often been given as a cause of yield depression (Shukla and Singh, 1979; Singh and Swarup, 1982). Table 13 presents the ratios of P to Cu concentrations in the grain. Ratios over 7000 correspond to low copper concentrations in the grain as observed for 80 and 120 ppm of P mixed and rates over 160 ppm when P was banded. The ratios reached over 9000 at the highest rates of P banded. These high ratios would indicate that the P-Cu interaction was more a plant factor than a precipitation in the soil. Banding P exaggerated the effect of the Cu deficiency resulting in yield depressions.

d. Conclusion.

In a soil poor in native P, additions of phosphorus as low as 20 ppm dramatically improved dry matter yields. Banding P seemed to be more efficient in increasing P content at lower levels of fertilization, although it did not yield as much as when P was mixed. To obtain maximum yields, 92 ppm and 83 ppm were necessary when P was banded and mixed respectively. A higher maximum yield was obtained when P was mixed as compared to banding P, and for both placements, further additions of P fertilizer did not increase the yields significantly. Micronutrient levels were determined and copper could have been limiting the growth, especially when P was banded. Micronutrients concentration decreased with increasing rates of P fertilization, mainly due to dilution.

II. Study II: Phosphorus and Micronutrients Interactions

Singh et al. (1982), Tiwari et al. (1982), reported that phosphorus decreased micronutrients content significantly in wheat and affected the utilization of micronutrients by the plant.

TABLE 13: P to Cu ratios as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)							
	0	20	40	80	120	160	200	240
Mixed	2138	3399	4464	7822	7972	6329	6762	6961
Banded	2236	3762	3986	4857	6125	9779	9874	10487

If the interaction is a soil factor and precipitation reactions occur, placing the fertilizer in a narrow band would diminish P micronutrients reactions and hence give higher micronutrients concentration than if the fertilizer were mixed throughout the soil. Conversely, if the concentrations are not affected by P placements, the plant itself should be considered as the major site of interaction.

This growth chamber study was divided into two experiments. In both experiments, plants were harvested at maturity. A lack of space allowed only for three pots for the check treatments in the first part, and statistical analysis on the placement were run using the same anova table but without the check.

a. Part I: Effect of rates and placements of P on yield, P and micronutrient contents in wheat.

In this part of the experiment, the effect of rate and placement of phosphorus on grain yield, P and zinc and Cu uptake was investigated when no micronutrients were added to the soil.

1. Dry matter yield.

Dry matter yields are presented in Table 14. There was a significant response to P added for both placements. For all the treatments, mixing P throughout the soil gave a significantly higher yield than banding P. The most important feature was the rates at which maximum yields were reached for each placement. Maximum yields, extrapolated from the response curve were achieved at 51 ppm and 124 ppm for mixed and placed P respectively, were nearly identical (46.25 g/pot when mixed and 44.21 g/pot when banded). The steeper slope of the response curve when P was mixed, indicated that for the same rate, a higher dry

TABLE 14: Dry matter yield (g/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)						MAIN EFFECT
	0	30	60	120	180	240	
Mixed	19.82	41.87	44.82	45.99	46.34	47.86	45.38A
Banded		34.88	35.50	42.72	43.24	46.97	40.66B
Main Effect	19.82A	38.37B	40.16B	44.35BC	44.79BC	47.42C	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

matter yield was obtained with that placement. The rates of 30 and 60 ppm mixed, gave significantly higher yields compared to the same amounts banded. The yield advantage due to mixing P disappeared progressively with increasing supplies of P. Several authors, (Lutz et al., 1961; Hamid and Sarwar, 1977), found that yield differences due to placement were noticeable only at low rates and as rates of P fertilizer increased, placement was not an important factor in affecting yields.

2. Grain yield.

The grain yield (Table 15) was significantly increased with addition of phosphorus and, in the same manner as dry matter yield, was affected by placement of the fertilizer. The mixed placement gave the highest yield in all cases, and as an overall effect, was significantly better than the band placement. At rates of 30 and 60 ppm of phosphorus, yields obtained when P was mixed were significantly higher as compared to the band placement. The difference in yield between placements gradually diminished as phosphorus rate applied increased. At highest rates of phosphorus (180 and 240 ppm), yields could be considered identical, thus showing the importance of fertilizer placement at low rates of P only. It seemed that with large applications, the plants obtained sufficient P regardless of the method of placement. Several authors (Sherrell et al., 1964; Morden and Racz, 1983) have reported the importance of phosphorus placement for grain yield, especially at low levels of fertilization. The maximum yields determined statistically were 25.73 g/pot obtained with 53 ppm P and above when mixed and 25.67 g/pot achieved when 157 ppm P or more were banded.

3. Phosphorus content in the grain.

TABLE 15: Grain yield (g/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)						MAIN EFFECT
	0	30	60	120	180	240	
Mixed	10.22	22.81	24.83	26.00	25.64	26.46	25.15A
Banded		18.33	19.56	23.92	24.67	27.25	22.74B
Main Effect	10.22A	20.57B	22.19BC	24.96CD	25.15CD	26.85D	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Significant at 1%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

Grain phosphorus analyses were carried out and grain yields were related to the percent phosphorus in the grain by the equations:

For mixed: Grain Yield = 56.811 (% P) - 7.041 $r^2 = 0.88$

For banded: Grain Yield = 186.1709 (% P)^2 - 110.218 (% P) + 26.667 $r^2 = 0.82$

However, as previously mentioned, the check treatment was not included in the statistical analysis for the placement of phosphorus and if it is omitted in the calculation of the above equations, the relationship is not significant.

Also, Figure 6 presenting relation between grain yields at each placement and percent P in the grain indicates clearly two clouds of points and any regression drawn from that type of data should be taken with caution. Grain total phosphorus was then calculated and grain yields as a function of total P are presented in Figure 7. Grain yields were related to the total P content by the equations:

For mixed: Grain Yield = 0.135 (Total P) + 5.864 $r^2 = 0.988$

For Banded: Grain Yield = 0.135 (Total P) + 5.708 $r^2 = 0.987$

The two equations are very similar which indicates that whatever the placement, grain yield was highly correlated to the amount of phosphorus taken up, and demonstrates the importance of high phosphorus content for maximum grain yield. This means that as long as phosphorus is in sufficient quantities, placement is not important. However, when phosphorus uptake was limiting the growth, it seemed that mixing the fertilizer throughout the soil provided more available P for the plant than a narrow band. This is in contradiction with most of the work reported in this area (Sherrell et al., 1964; Welch et al., 1966) where

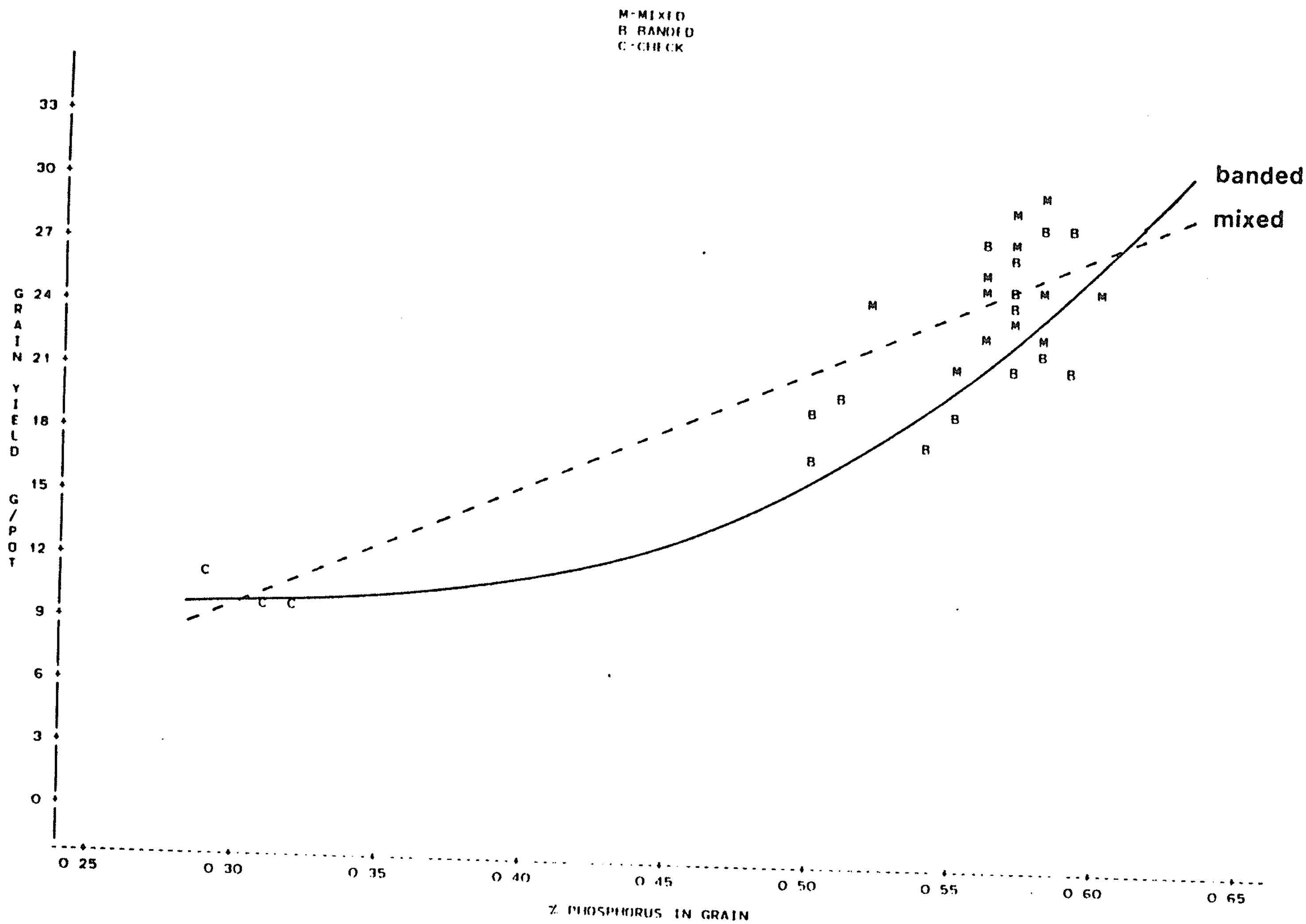


Figure 6: Relationship between grain yield and %P in the grain as affected by placement of P added to the soil.

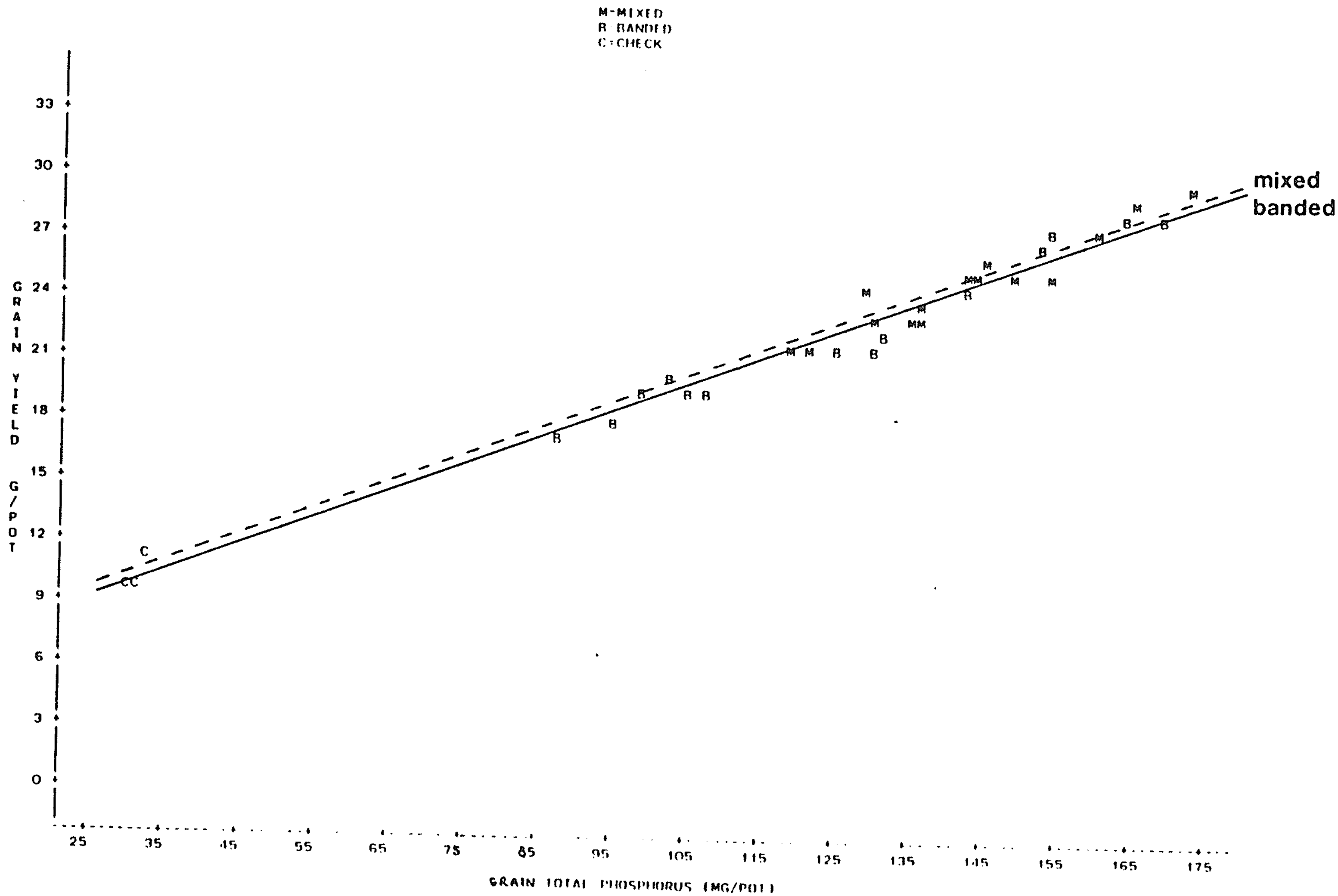


Figure 7: Relationship between grain yield and total P in the grain as affected by placement of P added to the soil.

banding was supposed to provide the roots with readily available phosphorus, whereas mixing P delayed uptake by the time it would take the plant to develop a well expanded root system.

From the total P content data presented in Table 16, it seemed that the lower rates of mixed P induced a better utilization of the phosphorus than when banded. Assuming that because of the extremely low P content in the soil, soil P had only a small influence on P uptake, the difference in P content is due to placement. The narrowness of the band has already been mentioned and could be responsible for a lower phosphorus content in the grain. Bailey et al. (1980) reported that increases in absorption could occur only if the capacity of the roots to absorb P increases, or if there is an increase in root proliferation in the band. At low rates of P application, P uptake would be limited by an intensity factor (Welch et al., 1966) that would not provide enough available nutrients to the roots, and therefore uptake would not reach the full absorbing capacity of the plant. Strong and Soper (1973) indicated that reaction zone root behavior had a direct bearing on the recovery of band applied P, and considering that P absorption consisted in the removal of most of the labile P in the root zone and later P uptake was more due to exploitation of fresh soil by root extension rather than a more intensive uptake from the same soil (Gunary and Sutton, 1967), root development could have also been limiting P uptake.

The position of the band itself compared to the seed location might have delayed P uptake by a time factor. Various placements are possible, however, Lawton and Davis (1960), Sherrell et al. (1964) found that a placement 2.5 cm below the seed or 2.5 cm to the side and below

TABLE 16: Grain total P (mg/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)						MAIN EFFECT
	0	30	60	120	180	240	
Mixed	31	123	139	148	148	154	142 A
Banded		94	105	136	142	158	127 B
Main Effect	31A	108B	122BC	142CD	145CD	156D	

Rate of Phosphorus Added: Significant at 1%
Placement: Significant at 1%
Rate x Placement: Significant at 1%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

the seed, were among the most efficient placements for root penetration. In this study, the band was 5 cm away and 2.5 cm below the seed, distances that might have delayed root penetration of the band. The delay was probably overcome only at high rates of P fertilizations.

4. Micronutrient contents in the grain.

Copper concentration in the grain (Table 17) decreased from 6.3 ppm for the check, to 2.83 ppm with 240 ppm P mixed. No visible sign of a deficiency was observed during the growing period. The concentrations decreased with increases in P supply for both placements, however, when the fertilizer was mixed, it stayed above the critical value of 2.5 ppm suggested by King and Alston (1975) for wheat grain when P was added. A level of 60 ppm of P banded was sufficient to bring the copper concentration close to the critical value indicating that banding P had a stronger effect on copper concentration than mixing P in the soil when no copper was added.Similar results were reported in the first growth chamber study where 5 ppm copper had been supplied prior to planting. It shows that the phosphorus-copper interaction was more a plant factor than a soil factor, since the copper was uniform in the soil. The total copper content for each treatment was statistically the same, indicating a dilution effect on the copper concentrations with increasing rates of P (Table 18). A significant difference between placements was observed; mixing P resulted in total copper content higher than the check whereas banding P gave content lower than the check treatment.

Zinc concentrations were determined and ranked from 60.53 ppm for the check, to 27.60 ppm and 26.13 ppm when 240 ppm P were banded and mixed respectively. Zinc never seemed to be limiting and soil zinc

TABLE 17: Grain copper concentration (ppm) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)						MAIN * EFFECT
	0	30	60	120	180	240	
Mixed	6.33	3.77	2.93	2.83	2.97	2.83	3.07 A
Banded		2.93	2.57	2.50	1.80	2.57	2.47 B
Main Effect	6.33A	3.35B	2.75BC	2.70C	2.67C	2.38C	

Rate of Phosphorus Added: Significant at 5%
Placement: Significant at 5%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

* Means and stat. done without 0 treatment.

TABLE 18: Total copper content in grain (mg/pot) as affected by rate and placement of P added to the soil.

PLACEMENT	RATE OF PHOSPHORUS ADDED (ppm)						MAIN * EFFECT
	0	30	60	120	180	240	
Mixed	64.70	85.32	72.73	72.82	77.30	74.67	76.57A
Banded		53.39	50.02	60.56	44.02	69.29	55.46B
Main Effect	64.70	69.36	61.38	66.69	60.66	71.98	

Rate of Phosphorus Added: Non Significant
Placement: Significant at 1%
Rate x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

* Means and stat. done without 0 treatment.

might have been high enough to provide the plant with a sufficient supply when no copper was added.

5. Conclusion.

Grain yield responded significantly to addition of phosphorus fertilizer. Mixing the fertilizer was clearly more efficient for grain production, especially at lower rates of application. Grain yields were highly correlated to P content whatever the placement. Placement affected P uptake at low rates of P; with higher rates there was probably enough P available for maximum growth regardless of the placement. The narrowness of the band and perhaps its position away from the seed, seemed to be largely responsible for the greater yield response when P was mixed.

Micronutrient concentrations decreased with addition of P mainly due to dilution. Zinc did not appear to be limiting in this experiment. On the other hand, copper concentration was depressed below the critical level with P addition and might have affected the grain yield. Placement of the fertilizer in a band significantly decreased copper uptake. The interaction between P and copper was probably due to a plant factor that had a greater influence when P was banded.

b. Part II: P-micronutrient interactions.

In the second part of the experiment, phosphorus-micronutrient interactions were studied with micronutrients added prior to planting. Because it represented the rate usually utilized in growth chamber experiments, a constant rate of 120 ppm P was applied using the two methods previously described. Micronutrient effects are usually more evident on grain yield and grain chemical composition, so this study looked more at the grain yield than the dry matter. Zinc and copper are often mentioned as being two important micronutrients interacting with phosphorus and were chosen for that reason.

1. Dry matter yield.

Dry matter yield data are presented in Table 19. As an overall effect, mixing the phosphorus gave a significant higher yield as compared to the banded treatment, but at each treatment the effect of the placement was not significant. The significance of the difference between placements as a main effect might be due to a larger number of replicates.

Addition of zinc alone or copper alone did not affect the yield significantly for either placement. Both micronutrients were required in order to significantly improve the dry matter production. The yields obtained when P was mixed were slightly higher, though not significantly better than when P was banded. The increase in yield, compared to the check given by the addition of micronutrients, was very similar for both placements (6.18 g for mixed and 6.33 g for banded). Supplying zinc and copper together, although not different than having copper alone, was the only treatment that improved significantly yields over the control. This would indicate that for the maximization of dry matter yield, supplying only one micronutrient is not sufficient.

2. Grain yield.

Grain yield data (Table 20) indicate the same type of response to micronutrient treatments as for the dry matter production. For each treatment, yields were higher when P was mixed, and as an average over the whole experiment, mixing P was significantly different from banding

TABLE 19: Dry matter yield (g/pot) as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	46.68	45.99	48.74	52.17	48.40 A
Banded	41.73	42.72	43.66	49.16	44.33 B
Main Effect	44.22A	44.35A	46.20AB	50.66B	

Treatments: Significant at 5%
Placement: Significant at 1%
Treatments x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 20: Grain yield (g/pot) as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	23.59	26.00	29.17	32.41	27.74 A
Banded	23.38	23.92	26.50	30.09	26.03 B
Main Effect	23.49A	24.96AB	27.83B	31.25C	

Treatments: Significant at 1%
Placement: Significant at 5%
Treatments x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

the fertilizer. More replications gave a better estimate of the experimental error and provided a more precise measure of treatment effect.

Using the check treatment as a reference, the zinc treatment slightly decreased the yields while the copper treatment increased them a little. However, although they do not differ from the check, zinc and copper treatments were significantly different. Furthermore, addition of zinc and copper significantly improved the yields indicating that addition of only one micronutrient might not give any significant yield increase and might, in the case of zinc application alone, decrease grain yield. In 1970, Chaudry and Loneragan reported that application of zinc alone accentuated copper deficiency symptoms in wheat. One of the symptoms being a reduction in grain yield. For both placements, the zinc treatment depressed grain yield below the maximum yield.

3. Percent P and total P content in the grain.

If there is an interaction between phosphorus and micronutrients, addition of zinc or copper or zinc plus copper should either depress or enhance P uptake by the plant and thereby affect the P content. Percent P in the grain (Table 21) was not significantly influenced by the addition of micronutrients. It varied from 0.57% for the check, to 0.587% when zinc was added alone. Total P content in the grain, presented in Table 22, followed the same trend as the grain yield with the zinc and copper treatment being significantly different from the check. The zinc treatment gave the highest P concentration but due to a low grain yield, resulted in the lowest total P content. Mixing P was significantly better than banding P. Shukla and Singh (1979) observed that the adverse effect of high copper application was neutra-

TABLE 21: Percent P in the grain as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	0.587	0.570	0.573	0.583	0.578
Banded	0.580	0.570	0.570	0.580	0.575
Main Effect	0.583	0.570	0.572	0.582	

Treatments: Non Significant
Placement: Non Significant
Treatments x Placement: Non Significant

TABLE 22: Total P content in grain (mg/pot) as affected by zinc and copper treatment and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	13.75	14.81	16.72	18.91	16.05 A
Banded	13.71	13.62	15.10	17.43	14.97 B
Main Effect	13.73A	14.22AB	15.91B	18.17C	

Treatments: Significant at 1%
Placement: Significant at 5%
Treatments x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

lized with the application of 100 and 250 ppm P, particularly in case of grain. They hypothesized that Cu would stimulate P absorption due to some reaction outside the root. They suggested 5 ppm Cu and 50 ppm P as being a proper balance between P and Cu for maximum grain yield. In this experiment, rates of 10 ppm Cu and 120 ppm P were employed which gave a ratio very close to the conditions given by the previous authors. Yadav et al. (1981) noticed that with 250 ppm P, zinc addition would enhance utilization of P by chickpeas. The data suggested that at the rate of phosphorus used (120 ppm) addition of micronutrients actually increased P uptake by the plant. It seemed that in studying interactions between P and micronutrients, the rate of phosphorus applied was an important factor. Low rates of P would not provide the plant with enough available P because of competition with the micronutrients and very high rates would decrease the micronutrient concentrations mainly through dilution. An intimate equilibrium between the nutrients seemed to be necessary in order to accomplish maximum growth.

4. Cu concentration in the grain.

Table 23, presents copper concentrations in the grain. There is a significant response in copper concentration to addition of copper. Whatever the placement of P, when copper and zinc were added, Cu concentrations were identical to when copper alone was applied, thus demonstrating that there was no significant zinc-copper interaction where they were both in sufficient supply. Addition of zinc alone strongly depressed the copper concentrations as compared to the check where no micronutrients were added.

If a level of 2.5 ppm (King and Alston, 1975) is considered to be

TABLE 23: Grain copper concentration (ppm) as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	1.43	2.83	7.87	7.83	4.99 A
Banded	1.53	2.50	6.43	6.93	4.35 B
Main Effect	1.48A	2.67B	7.15C	7.38C	

Treatments:	Significant at 5%
Placement:	Significant at 1%
Treatments x Placement:	Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

critical, the control plants when P was banded as well as the zinc treatments were in a situation where a growth stress might occur. The grain yields, obtained when Cu concentrations were below 2.5 ppm, were lower than when copper or zinc plus copper were applied to the soil indicating that copper deficiency might have been partly responsible for yield limitations in the first part of this experiment. However, copper was not entirely responsible because addition of copper alone did not significantly increase the yields over the check. Other factors beside copper might have been limiting the production for maximum yield. One of these limiting factors could have been a soil zinc level not high enough for maximum production as indicated by the yield difference between the copper and zinc plus copper treatments.

Comparing the check and the zinc treatment showed that copper concentration decreases dramatically without causing a significant grain yield depression. Considering that the low copper concentration in the control was mainly due to dilution, the significantly lower concentration in the zinc treatment could have resulted from an adverse effect of added zinc or copper. Addition of zinc alone depressed severely copper uptake probably due to an interaction at the absorption site. This interaction could be overcome only if both elements are highly available. Chaudry and Lonergan (1970) also found that the effects of zinc fertilizer in depressing copper concentration in plants, were greatest where plants did not receive a copper application and negligible only in plants receiving Cu fertilizer.

The overall greater Cu concentration when P was mixed instead of banded, would indicate that phosphorus did not affect copper uptake because of precipitation in the soil. Mixing the phosphate in the soil might have lowered the pH throughout the soil and increased the solubility of copper.

5. Zinc concentration in grain.

There was a dramatic response in zinc concentration to zinc application either alone or in association with copper at each P placement (Table 24). Placement of the fertilizer P did not affect zinc concentration at the rate used in this study. Copper additions did not decrease zinc concentrations significantly whether applied alone or with zinc. This would indicate that if zinc had a negative effect on copper concentration when applied alone, copper addition had no influence on zinc concentration. However, as shown with the grain yield data, zinc addition was necessary to get a significant yield increase. It seemed that even though zinc was not deficient, zinc level in the soil was not high enough to allow for maximum grain production.

6. Harvest index.

In their study, Brown and Clark (1977) demonstrated that copper deficient plants failed to develop spikes and produced very low or no grain yield. The plants described by the previous authors developed visible signs of copper deficiency. In this experiment, no visible signs were observed even on the zinc treatment that had an average copper concentration of 1.48 ppm. Harvest indices are presented in Table 25. Treatments containing copper increased the harvest indices significantly over the zinc treatment, however, only the zinc plus copper treatment significantly improved the harvest indices over the check. Addition of zinc alone slightly decreased the harvest indices.

TABLE 24: Grain zinc concentration (ppm) as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	89.97	27.10	32.87	83.73	58.42
Banded	86.87	33.67	30.57	82.57	58.42
Main Effect	88.42B	30.38A	31.72A	83.15B	

Treatments: Significant at 1%
Placement: Non Significant
Treatments x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 25: Harvest index (%) as affected by zinc and copper treatments and placement of P added to the soil.

PLACEMENT	TREATMENTS				MAIN EFFECT
	Zn	0	Cu	Zn + Cu	
Mixed	49.80	56.47	59.82	62.17	57.07
Banded	56.47	55.93	60.76	61.21	58.59
Main Effect	53.14A	56.20AB	60.29BC	61.69C	

Treatments: Significant at 1%
Placement: Non Significant
Treatments x Placement: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

The results explain the relatively larger response in grain than in dry matter. It seemed that a level of 1.48 ppm Cu did not affect grain production to the extent described by Brown and Clark (1977) or McAndrew (1979).

7. Conclusion.

Phosphorus content of grain seemed to be enhanced with addition of micronutrients and no negative interaction could be observed in this study. Grain yield was affected by addition of micronutrients; zinc depressed slightly the yields probably by affecting the copper concentration and decreasing the harvest indices. Cu addition alone only slightly improved grain yields; and both micronutrients were necessary to significantly increase the yields. Cu addition resulted in significantly higher Cu concentrations in the grain. It seemed that zinc had a strong influence on Cu uptake probably because of a low soil Cu level. In some instances, copper concentrations were below critical levels without inducing drastic grain yield reduction. Zinc concentrations did not seem to be affected by Cu fertilization, but significantly increased with zinc addition. Soil zinc level could have been marginal in this experiment, because even though zinc did not seem to be limiting the grain production, zinc addition in association with copper was necessary for yield maximization.

III. Study III: Effect of Soil Temperature, Rate and Placement of P Fertilizer on Wheat Yield and P Uptake

Temperature affects plant growth by changing the rate of morphological development. Low temperatures usually delay growth rate (Read and Beaton, 1963; Mack, 1965) and decrease P uptake (Power et al., 1964a; 1970). Besides plant growth rate, low soil temperature can also reduce the availability of phosphate to plants and might contribute significantly to reduction in P uptake by the plant (Power et al., 1964b; Sutton, 1969). Fertilization has been shown to improve P availability to plants and overcome the adverse effect of low temperature and low available P (Power et al., 1964a,b; Follet and Reichman, 1972). It has been noted that P uptake at low temperature was improved where the fertilizer was placed rather than mixed throughout the soil (Gingrich, 1964; Case et al., 1964).

The experiment was carried out to look at the effect of temperature on yield and P uptake when different P rates and placement methods were used. Soil temperature was controlled using water baths. The fertilizer was tagged with ^{32}P to monitor the amount of P fertilizer taken up for each treatment at the temperature studied (14°C and 23°C). Plants were harvested at maturity; the same growth stage was chosen instead of the same calendar date because in the fields plants are harvested according to stage of growth.

a. Observations about the experiment.

The plants looked healthy in both baths; they were normal in color, appearance and development. Plants grown at 14°C soil temperature had normal but darker green leaves than those in the 23°C soil temperature bath. The plants in the cold bath retained some of their green leaves to maturity. The high soil temperature appeared to hasten the aging process within the plant.

The growth period in the cold bath was longer than in the warm bath. Plants growing in the cold soil needed 21 more days to reach maturity than the plants under warm soil conditions. Based on visual observation, the delay occurred mainly between seeding and emergence where it took seven more days for the plants growing in the cold soil to emerge, and also, towards the end of the growing period, after the filling stage, an extra seven days were necessary for the plants in the cold treatment to reach maturity. Between emergence and the filling stage, another seven days of delay were accumulated, making a total of 14 days from emergence to maturity, and 21 days from seeding to maturity. Only between tillering and jointing was the growth rate in the cold bath greater than in the warm bath, probably because less tillers were produced under the cold soil temperature.

When the plants were harvested, the roots were extracted for observation. The root development in the cold bath was more extended than in the warm bath; more root hairs were visible whereas the warm roots were shorter and thicker, with fewer root hairs. No study was undertaken on the roots, however, this observation was consistent with the works reported by Mack (1965), Gingrich (1965), Power et al. (1970), and Follet and Reichman (1972).

Due to a greater evapotranspiration in spite of the precautions taken, the plants in the warm bath used approximately 1.5 times more water than the plants growing at cold soil temperature.

b. Dry matter yield.

Data for dry matter yield from both temperature baths are presented in Table 26 and Figure 8. Yield data from the warm bath were generally higher than in the cold one. The higher soil temperature might have

TABLE 26: Dry matter yield (g/pot) as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACEMENT	WARM	COLD
0	-	33.02 C	27.33 B
50	Mixed	54.33 AB	43.95 A
	Banded	53.77 AB	41.57 A
100	Mixed	49.23 AB	46.23 A
	Banded	52.29 AB	44.02 A
200	Mixed	47.97 B	44.26 A
	Banded	55.99 A	47.40 A

Means followed by the same letter in each column are not significantly different at 5% Tukey's w procedure.

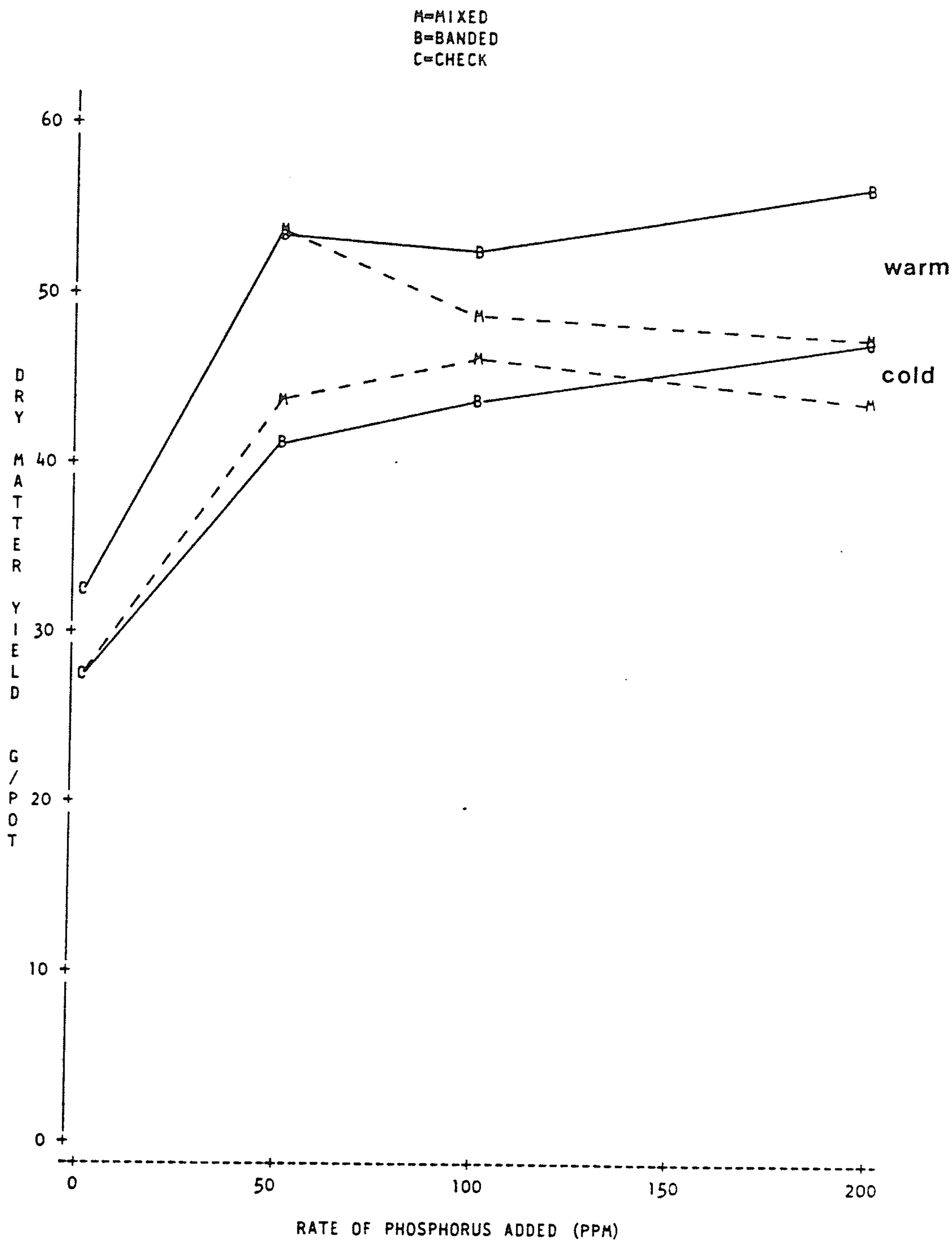


Figure 8: Relationship between dry matter yield, rate and placement of P added to the soil as affected by soil temperature.

stimulated plant growth, and more specifically top growth, whereas the low soil temperature might have been responsible for a slower phenological development of the plants and a reduced yield. The temperature range for optimum wheat production lays between 15°C and 30°C, thus the plants growing in the cold soil temperature would be situated slightly below that range and temperature might have had a direct effect on the plant growth.

In each bath, there was a dry matter yield response with additions of phosphorus. However, in the cold bath, there were no yield differences among the rates of P supplied or the placement methods.

In the warm bath, there were no significant differences among rates of P fertilization. There was only a significant difference at the 200 ppm rate between placement methods. As a general trend, banding P gave better yields as compared to mixing P at the 100 and 200 ppm rates of P supply. These results were consistent with the findings of Gingrich (1964).

As shown in Table 27, the interaction between temperature treatments and placement methods was significant, indicating yield differences between placements only in the warm bath and at each placement, warm temperature gave significantly higher yields. These results would suggest that in the cold temperature bath, the direct effect of temperature was the main cause of growth restriction and not the P availability whereas the method of placement was more critical at higher soil temperature.

c. <u>Grain yield</u>.

At each soil temperature, there was a grain yield response to addition of phosphorus (Table 28, Figure 9). There were no significant

TABLE 27: Dry matter yield (g/pot) as affected by soil temperature and placement of P added to the soil.

	MIXED	BANDED
Cold	44.81 C	44.33 C
Warm	50.51 B	54.02 A

Means followed by the same letter in each column are not significantly different at 5% Tukey's w procedure.

TABLE 28: Grain yield (g/pot) as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACEMENT	WARM	COLD
0	-	12.80 C	9.00 B
50	Mixed	24.50 A	13.48 AB
	Banded	22.18 AB	15.47 A
100	Mixed	18.78 B	15.44 A
	Banded	23.15 AB	15.24 A
200	Mixed	20.82 AB	13.40 AB
	Banded	24.36 A	16.82 A

Means followed by the same letter in each column are not significantly different at 5% Tukey's w procedure.

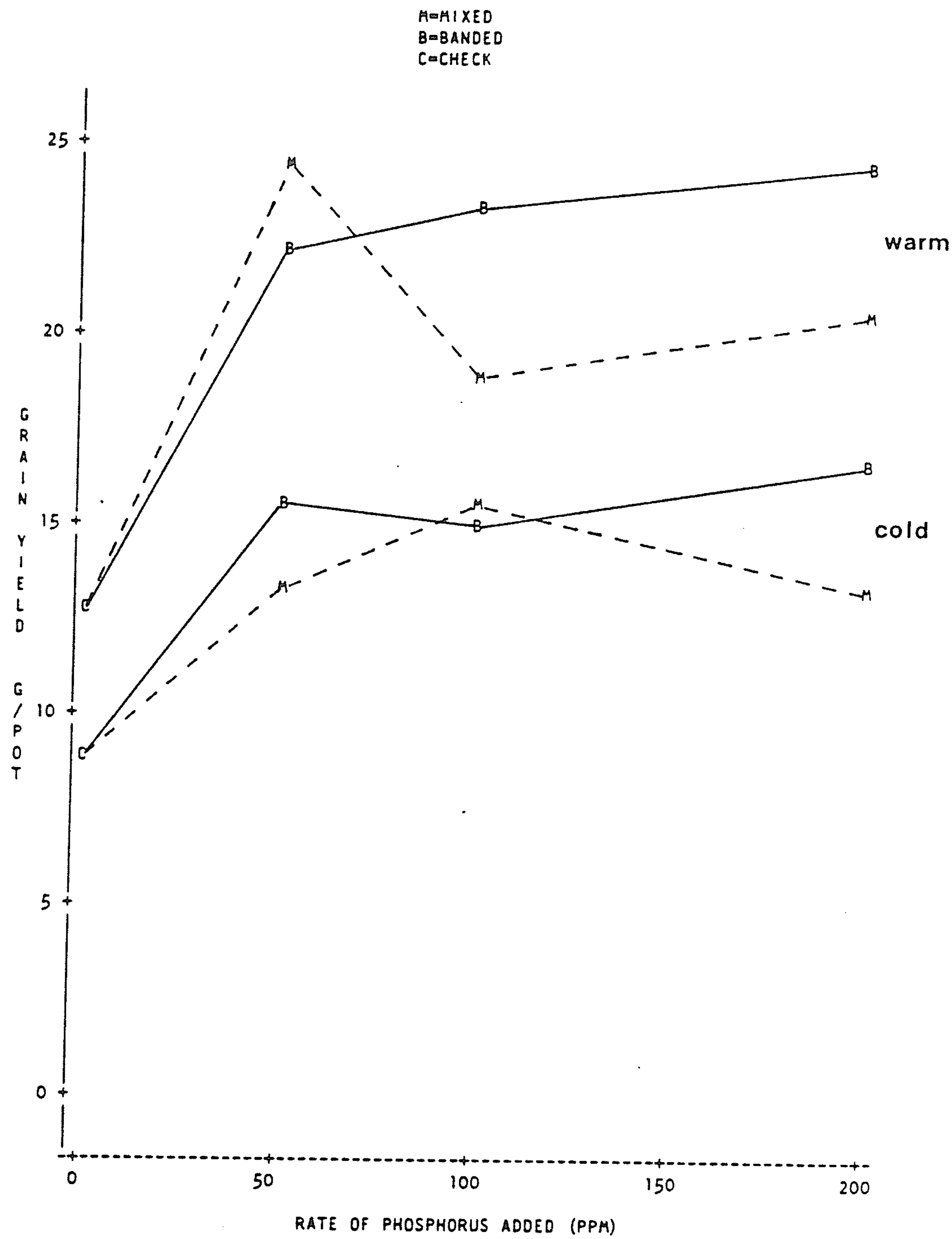


Figure 9: Relationship between grain yield, rate and placement of P added to the soil as affected by soil temperature.

differences among rates of P supply or placement of the fertilizer in the cold soil. A direct effect of the cold temperature on the plants themselves might have been responsible for the low yields reported, rather than the availability of the phosphorus. In the warm soil, the best yields were obtained at rates of 50 ppm mixed and 200 ppm banded and they were significantly different from the 100 ppm mixed treatment which was the lowest yield produced when P was added. As an overall effect, banding P gave significantly higher grain yields than mixing P in the soil. A harvest index of 42, which is considered normal for Columbus wheat, was calculated for the warm soil, and indicated optimum growth conditions. In the cold soil, the harvest index averaged 33, thus reflecting a greater difference in grain yield than in dry matter yield between the two soils.

The triple interaction temperature x placement x rate was significant and the statistics are shown in Table 29. This showed that for the check treatment, where no P was added, the yields obtained were similar. On soils low in available P, temperature had therefore no major effect on the yield. Thereafter, with addition of phosphorus, the yields obtained were significantly higher under a warm soil temperature than under cold soil conditions. For each placement, treatments in the high soil temperature produced significantly better yields.

The relationship between grain yield and total P content in the plant is shown in Figure 10. In the warm bath, high yields were observed with high P content in the plant. When P was added, P contents were all above 0.65 mg P/pot and gave yields over 18 g/pot, thus demonstrating a significant response to fertilization with regard to grain

TABLE 29: Grain yield (g/pot): statistics on interaction among treatments.

		RATE OF P ADDED IN PPM			
Temp	Placement	0	50	100	200
Warm	Mixed	12.80 CD	24.50 A	18.78 B	20.82 AB
	Banded		22.18 AB	23.15 AB	24.36 A
Cold	Mixed	9.00 D	13.48 CD	15.44 C	13.40 CD
	Banded		15.47 C	15.24 C	16.82 C

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

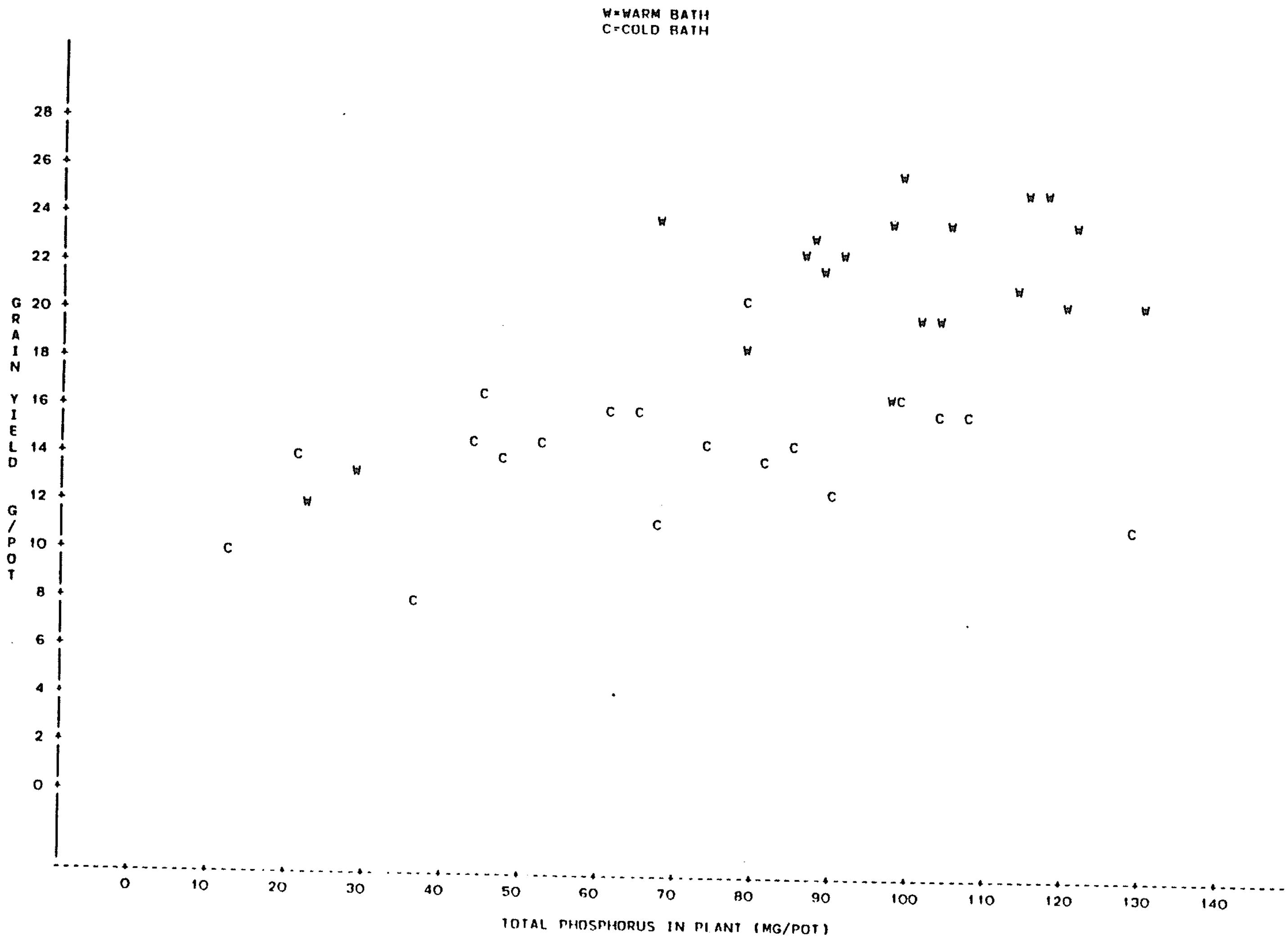


Figure 10: Relationship between grain yield and total P in the plant as affected by soil temperature.

yield and total P in the plant. In the cold bath, addition of phosphorus increased the total P content in the plant to levels similar to the plants grown under warm soil conditions. However, the increase in P content in the plant did not correspond to an increase in grain yield. It seemed that under the low soil temperature, less phosphorus was translocated to the grain even though it was present in the plant in sufficient amounts. Similar amounts in the plant under warm soil conditions gave large yield responses, thus suggesting an effect of temperature on translocation of phosphorus to the grain. It was therefore necessary to look at the relationship between grain yield and total P content in the grain (Figure 11). Two distinct populations could be identified and two regression equations, corresponding to each temperature, were calculated:

Warm Bath: Grain Yield - 9.75 + 0.16 (grain total P) $r^2 = 0.70^{**}$

Cold Bath: Grain Yield - 7.00 + 0.25 (grain total P) $r^2 = 0.63^{**}$

This means that the higher the P content in the grain, the higher the yields whatever the temperature was. However, as described by the equations, the slope of the regression line was steeper in the cold bath where lower total P contents were recorded. This indicated either a more efficient use of the phosphorus translocated to the grain under cold conditions as already demonstrated by Mack (1965) and Power et al. (1964a,b) for dry matter, or if all the data were considered, there could have been a curvilinear grain yield response to P content in the grain theoretically passing through the origin. The amount of P translocated to the grain could have been of some importance and any factor affecting P translocation would also affect the grain yields. Placement

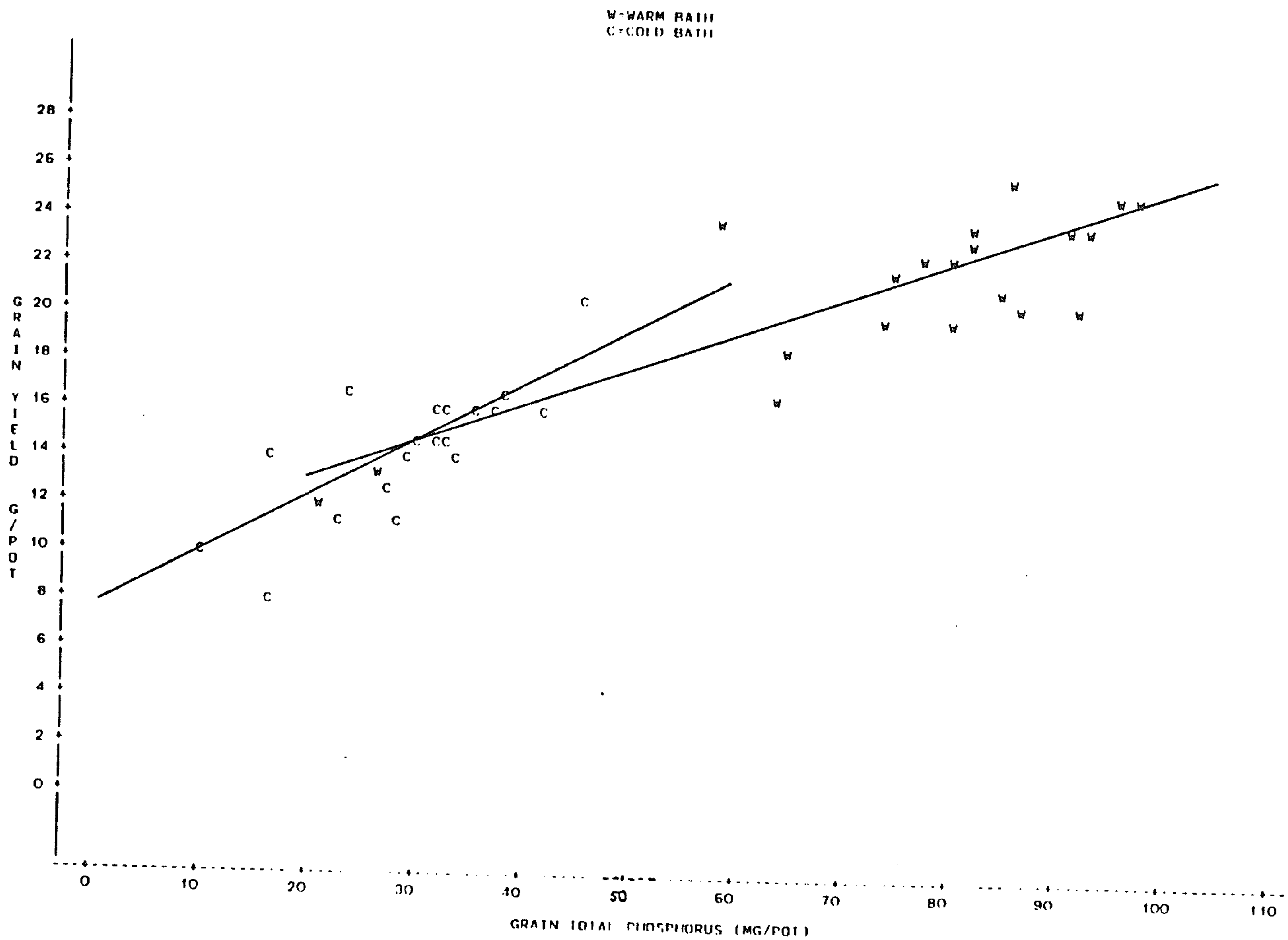


Figure 11: Relationship between grain yield and total P in the grain as affected by soil temperature.

of the fertilizer might be one of these factors. Figure 12 presents the same graph as Figure 11, but placement of the phosphorus was identified and regression equations calculated for each placement at each temperature:

Warm Bath:

Mixed: Grain Yield = 8.27 + 0.16 (grain total P) $r^2 = 0.75^{**}$

Banded: Grain Yield = 11.08 + 0.15 (grain total P) $r^2 = 0.75^{**}$

Cold Bath:

Mixed: Grain Yield = 4.69 + 0.32 (grain total P) $r^2 = 0.52^{*}$

Banded: Grain Yield = 8.53 + 0.21 (grain total P) $r^2 = 0.77^{**}$

In the warm bath the two regression lines were nearly parallel, reflecting the superiority of the banding treatment as already found for the grain yield. In the cold bath no difference between the two placements was significant, however banding P seemed to give higher grain yield when total P content was lower than 35 mg P/pot. This could be related to some field experiments reported by Morden and Racz (1983) where at low P rates, and consequently low total P in the grain, banding P was found to be superior to broadcast P and with increasing P rates and total P content in the grain, the advantage of the band placement disappeared.

d. P content.

Total P content in the dry matter and the grain are presented in Tables 30 and 31 respectively. Total P removed averaged over each temperature was greater for the warm bath than it was for the cold temperature bath for both dry matter and grain. This was in accordance with results reported previously (Gingrich, 1964).

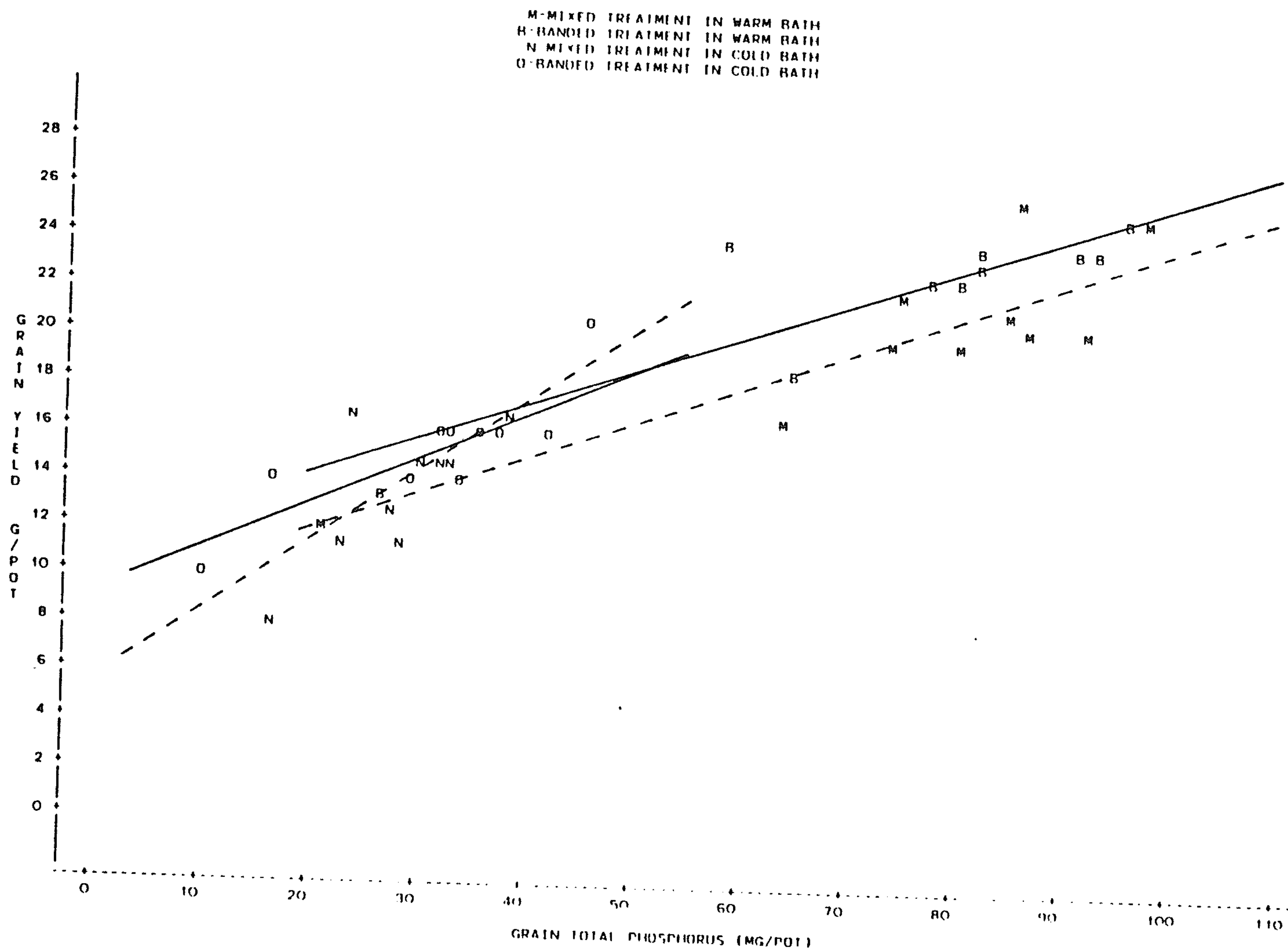


Figure 12: Relationship between grain yield and total P in the grain as affected by soil temperature and placement of P added to the soil.

TABLE 30: Total P in total dry matter (mg/pot) as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACEMENT	WARM	COLD
0	-	33.38 B	24.21 B
50	Mixed	100.75 A	105.68 A
	Banded	77.76 A	70.19 AB
100	Mixed	101.14 A	47.09 AB
	Banded	94.22 A	77.76 AB
200	Mixed	121.15 A	75.54 AB
	Banded	112.25 A	62.19 AB

Means followed by the same letter in each column are not significantly different at 5% with Tukey's w procedure.

TABLE 31: Total P in grain (mg/pot) as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACEMENT	WARM	COLD[1]
0	-	23.68 B	16.65
50	Mixed	85.83 A	31.01
	Banded	68.12 A	33.83
100	Mixed	72.60 A	27.81
	Banded	82.66 A	31.66
200	Mixed	87.41 A	29.23
	Banded	90.15 A	35.51

Means followed by the same letter in each column are not significantly different at 5% with Tukey's w procedure.

1. Not significant.

In the warm bath, there was a significant response to P addition in total P content for both dry matter and grain, but thereafter no differences among rates and placements were significant. It seemed that the mixed placement gave higher P content in the dry matter than when the fertilizer was banded probably because of the narrowness of the band as noticed in previous growth chamber experiments. The total P content of the grain was not affected by the placement of the fertilizer.

A response was observed in the cold bath for the dry matter, but only the 50 ppm mixed treatment was significantly better than the check. The very high value for that particular treatment was mainly because of a high phosphorus concentration in the straw. Experimental error did not seem to be the cause for the high value because all three replicates showed high P contents. No response was noticeable for the grain. In this latter case, though it was not significant, when P was banded, higher total P contents were recorded than when P was mixed throughout the soil. It seemed that although placement of the fertilizer had no effect on the dry matter total P content, it affected slightly the grain composition. This would suggest that at the cold temperature placement of the fertilizer had an effect on either the efficiency as shown in Figure 15 or the translocation of P, or both.

The P requirement of a plant should be considered not only in terms of the total amount of P the plant removed from the soil, or the total amount in the grain, but also in terms of the concentration in the shoot and grain. Critical levels are usually given in terms of percent P in the shoot at a specific stage of growth or in the grain. Levels of 0.40% and 0.22% P in the grain were derived for the warm and cold bath respectively. In the second growth chamber experiment, a level of 0.58% was calculated. This would indicate that depending on the soil temperature conditions, the critical level for maximum grain yield may vary. Under perfect growth conditions, the level would probably be higher and depending on the stress conditions under which the plant grows, that level could vary substantially. The critical levels given were therefore representative of a particular situation and corresponded to a potential maximum yield under those conditions.

It has been demonstrated before (Mack, 1965; Power et al., 1964a,b) that the efficiency of the dry matter production per unit weight of P taken up was decreased with increasing soil temperature. Table 32 presents the grain production per unit weight of P content in the shoot. The ratio was practically the same for both temperatures for the check, indicating, as already shown for the grain yield, that in a soil low in available P, soil P was the main limiting factor for growth and the temperature difference had no significant effect on the efficiency of P taken up. The efficiency seemed to decrease with addition of P regardless of soil temperature. As an average over each bath, the ratios were very similar, thus indicating the same efficiency in producing grain per unit weight of P taken up in the shoot. No differences among rates or placements were observable in the cold bath, whereas, in the warm one, there was a decreasing trend with addition of phosphorus on each placement. At each rate of P applied, banding P seemed to be more efficient in producing grain than mixing P and explains the better grain yields obtained when P was banded. The better grain yield obtained with the band placement could therefore be due to a better translocation of P

TABLE 32: Grain weight produced per unit weight of P taken in the plant (kg grain/g P taken up).

RATE	PLACEMENT	WARM	COLD
0	-	0.38	0.37
50	Mixed	0.24	0.13
	Banded	0.29	0.22
100	Mixed	0.19	0.33
	Banded	0.25	0.20
200	Mixed	0.17	0.18
	Banded	0.22	0.27
	AVERAGE	0.25	0.24

within the plant when P was banded. This suggests that the total amount of P in the plant was not the most determinant factor for grain production, but how the accumulated phosphorus was utilized.

Table 33 presents the repartition of the phosphorus in the plant as percentage of total phosphorus and Table 34 shows the ratios of total P in the grain to total P in the plant. The percentage of phosphorus in the grain was very similar for the check whatever the soil temperature was, indicating an identical plant behavior with regard to P utilization when the soil is very low in available P. Addition of phosphorus increased the proportion of P in the grain in the warm bath but decreased it in the cold one, thus giving ratios above the check at high temperature and below it at low temperature. Under warm soil conditions P fertilization increased P translocation towards the grain whereas under cold soil temperature it decreased % P translocated in spite of a significant grain yield increase. A slower plant metabolism could be the main reason for the reduced translocation of phosphorus. Davis and Lingle (1961) hypothesized that under cold soil temperatures retardation of movement in the phloem would result in a congestion of substances in the shoot, thus depressing metabolic activity and salt accumulation.

In the warm bath, highest yields were obtained when the ratios were above 0.80, but the highest ratio in the cold bath was obtained on the check where the lowest grain yield was obtained. It would mean that in this case, in spite of sufficient amounts of P in the shoot, highest grain yields were achieved with ratios lower than the check. P translocation might not have been the only factor affecting grain yield under cold conditions, but low temperature could have had a direct effect on

TABLE 33: Repartition of P in the plant as % of total P content as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACE	WARM		COLD	
		GRAIN	STRAW	GRAIN	STRAW
0	-	70.94	29.06	68.77	31.23
50	Mixed	85.19	14.81	29.34	70.66
	Banded	87.60	12.40	48.20	51.80
100	Mixed	71.78	28.22	59.06	40.94
	Banded	87.73	12.27	40.72	59.28
200	Mixed	72.15	27.85	38.69	61.31
	Banded	80.13	19.69	57.10	42.90

TABLE 34: Ratios total P in grain / Total P in plant as affected by soil temperature, rate and placement of P added to the soil.

RATE	PLACEMENT	WARM	COLD
0	-	0.71	0.69
50	Mixed	0.85	0.29
	Banded	0.88	0.48
100	Mixed	0.72	0.59
	Banded	0.88	0.41
200	Mixed	0.72	0.39
	Banded	0.80	0.57

grain production.

e. Conclusion.

Significant dry matter and grain yield responses with addition of phosphorus were recorded at the two temperatures studied. Placement of the fertilizer affected the dry matter yield only in the warm bath and had no effect on the grain yield.

In this investigation, it was apparent that the direct effect of temperature was the main cause of growth restriction at low temperature. Low soil temperature might have resulted in a reduced rate of morphological and physiological development resulting in low grain yields. Also, translocation of phosphorus from shoot to grain could have been responsible for the small grain yield response in spite of an increasing total P content in the plant with P fertilization.

Placing the fertilizer in a band did not improve P uptake, probably due to the narrowness of the band, however, more phosphorus was translocated giving higher grain yields.

Various critical levels were calculated under different soil temperatures demonstrating the importance of climatic conditions in determining critical levels for yield maximization.

B. FIELD EXPERIMENTS

I. Phosphorus Study: Effect of Rate and Placement of P Fertilizer on Wheat Yield and P Uptake

A three-year study was carried out to investigate two methods of fertilization and several rates of P fertilizer to be applied, in order to obtain and maintain maximum grain yield production of wheat per centimeter of water available. Band placement with the seed as well as broadcast and incorporated into the soil at two different depths prior to planting were studied in this experiment.

Large amounts of P fertilizer were broadcast the first year to investigate their individual effects in order to achieve maximum yield throughout the three years of the project. An extra 17 kg P/ha was banded on part of the treatments to look at the effect of banding extra P when maximum production is intended. Comparison among individual effects of P broadcast the first year and the additional effect of successive banding would also be investigated.

Three sites, chosen according to their phosphorus level, were selected for this three-year study.

For a better understanding of the discussion and interpretation of the data for the second year presented in this work, a short summary of the first year's conclusions seemed necessary. Results for the first year are discussed in greater detail in a thesis entitled "Phosphorus as a limiting nutrient for maximum production of wheat in Manitoba" (Modestus, 1984). Grain yield data for the first year are presented in Table 35.

a. Summary of the first year.

1. Haywood.

There was a significant curvilinear response to addition of phosphorus broadcast and incorporated into the soil, where P was either banded with the seed or not. At every rate of broadcast P, the banding treatment influenced the dry matter yields, as well as the grain production except at the 100 kg P/ha broadcast treatment. High rates of P

TABLE 35: First year: grain yield (kg/ha) as affected by rate and placement of P added to the soil for the three sites.

SITE	P BANDED kg/ha	P BROADCAST kg/ha			
		0	50	100	200
Haywood	0	1514	2238	2692	2261
	17	1961	2695	2635	1825
Elm Creek	0	3426	3456	3596	3679
	17	3654	3557	3725	3561
Winkler	0	2676	2633	2526	2252
	17	3025	2918	2823	2603

broadcast resulted in grain yield depression. Banding P with the seed accentuated the depression at high rates of P broadcast whereas it was the opposite for the lower rates. When no P was banded with the seed, an application of 50 kg P/ha was as effective as 200 kg P/ha, and when an extra 17 kg P/ha was seed placed, 200 kg P/ha broadcast decreased the yield below the check. Seedling injuries due to the fertilizer could not account for the grain yield depression observed at high rates of phosphorus because no significant dry matter yield depression occurred. Declining trends of the harvest indices, and decreasing levels of copper in the tissue as the amount of P broadcast and incorporated prior to planting increased, suggested that copper might have been deficient at high rates of P applied.

2. Elm Creek.

From the bootstage to the milk stage inclusive, dry matter yield responded to P broadcast and incorporated into the soil but yields were never affected by P banded with the seed. The absence of response at early tillering seemed to indicate that P was in sufficient supply even in the check plots. The dry matter yield at maturity nor the grain yield were significantly affected by either the rate of P broadcast or the banding treatment. The dry matter yield response to P broadcast could have likely been the result of an increasing number of tillers that dried or did not produce any grain and therefore, at maturity, no effect was noticeable. The rainfall during the growing season could have been of some influence at this site where the ground water might not have supplied the crop with sufficient moisture. Shoot chemical analysis did not indicate any nutrient deficiencies and it is likely that, even though yields were very high, water supply was the major limiting factor.

3. Winkler.

Dry matter yields did not respond significantly to rates of P broadcast and incorporated into the soil, but were affected by the fertilizer banded with the seed at all stages except for the boot and milk stages. There was a grain yield response to P banded at all levels of P broadcast, however, grain yield slightly declined as the amounts of P broadcast increased. No seedling injuries were observed at the early stages of growth and could not explain the grain yield depression. Most of the nutrients which were analyzed in the shoot were in sufficient quantities. Shoot copper concentrations at bootstage were marginal according to Melstead et al. (1969). P concentrations in shoot and grain were increased by addition of P broadcast. A severe lodging that occurred at this site at heading stage could partly account for the low grain yields and low harvest indices. However, the declining trend in grain yield could not be explained entirely by the lodging as it affected all treatments in a uniform manner. It was suggested that copper could have become a limiting nutrient at high rates of P applied.

4. Conclusion.

Recommendations for maximization of grain yield were difficult to make. At Haywood, grain yields decreased with the highest rate of P broadcast because of what may have been a micronutrient deficiency; at Winkler, where the $NaHCO_3$ extractable P was high, lodging and perhaps micronutrient deficiency resulted in a decreasing trend for grain yield with addition of P broadcast. Banding P with the seed increased the negative response of the broadcast P on the grain yield at Haywood only. No yield improvement was observed at Elm Creek whatever the treatment. Generally, applications of phosphorus increased P uptake except at Elm Creek, where the results were quite inconsistent.

It seemed that fertilization was necessary at Haywood for better yields and in the case of Elm Creek and Winkler, small amounts could have been enough to maintain high production. When large amounts of P fertilizer are applied, precautions should be taken to monitor other soil nutrients.

b. Second year.

In the second year, only the banding treatment was repeated on the same plots as the first year. Nitrogen and potassium were provided as previously described.

The purpose of the second year was to see if the phosphorus broadcast the first year could maintain high yields the second year and if an extra 17 kg P/ha seed placed was necessary to achieve maximum production. The additional effect of P banded could also be compared with the residual effect of P broadcast the previous year.

The sites selected being different in soil available P when the project was started, recommendations could be made as how to achieve maximum yield as a function of the fertility status of the soil. The same harvesting stages were kept to allow comparisons among years. Besides grain and dry matter yields, P uptake as well as N, K and micronutrient behavior were investigated.

Since the effects of the depth of phosphorus incorporation on yield response and nutrients content were not significant, treatment means for the second year at the three sites are comprised of eight observations. Details of the statistical analysis were discussed in materials and methods, and in Appendices D and E. Moisture conditions have also been previously reported.

In Spring, the water table at Haywood was 1.2 meters under the soil surface and dropped down to 1.6 m in Fall. At Winkler, the Spring water level was at 1.5 m below the soil surface and moved down to 2.1 meters when the final harvest was taken. No well was placed at Elm Creek because no water table was within a distance reachable with the equipment. No visible signs of deficiency, disease, seed damage or delayed emergence were observed during the growing season. Elm Creek and Winkler responded very similarly and a decision was taken to discuss both sites together.

1. Haywood.

1.1 Dry matter yield.

Dry matter yields are presented in Tables 36, 37, 38, 39, and 40. Final dry matter yields obtained the second year were lower than the first year. Maximum dry matter yield produced per centimeter of water used by the crop decreased from 357 kg the first year, to 307 kg the second year. A difference in water distribution as well as evapotranspiration could be responsible for the yield decrease. The yield decline could also indicate that the second year, water was not the only limiting factor for maximum production and the lower value obtained could be representative of a decline in P availability. This would suggest a slow conversion of applied P from relatively soluble compounds to rather insoluble forms. The superiority of the first year's yield

TABLE 36: Dry matter yield at early tillering stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	114	182	148	118
50	137	188	162	125
100	182	175	178	147
200	212	201	207	156
MAIN EFFECT	161	186		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 37: Dry matter yield at bootstage (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	704	943	823 A	616
50	838	951	896 AB	962
100	1089	1161	1125 BC	1180
200	1305	1254	1279 C	1348
MAIN EFFECT	984	1077		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 38: Dry matter yield at heading stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	3324	3843	3583	2802
50	3838	3953	3895	3660
100	3990	4650	4320	4322
200	4416	4335	4376	4390
MAIN EFFECT	3892	4195		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 39: Dry matter yield at soft-dough stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	4450	5536	4993 A	5601
50	4619	5874	5246 A	7354
100	5777	5903	5839 AB	7689
200	6236	6286	6261 B	8196
MAIN EFFECT	5270	5900		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 40: Total dry matter yield at maturity (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	4028 A	5838 BC	4933 A	5860
50	5119 AB	5717 BC	5418 A	7423
100	5981 BC	6592 C	6282 B	8133
200	6323 C	6772 C	6547 B	8117
MAIN EFFECT	5363	6230		

P Broadcast: Significant at 1%
P Banded: Non Significant
P Broadcast x P Banded: Significant at 5%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

was noticeable from the bootstage for the highest rates of fertilization, but not before heading for the check and only after soft-dough stage for the 50 kg P/ha broadcast treatment.

The better yields observed the second year at the early stages could be mainly due to a cumulative precipitation of 8.08 cm in June 1983, instead of 4.24 cm in June 1982. Later in the season, no rainfall was recorded in July 1983, whereas 6.13 cm fell in July 1982; thus explaining the disappearance of the yield advantage acquired in the earlier stages in 1983. Studies by Power et al. (1961), Boatwright et al. (1964) postulated that fertilizer P would not be used by spring wheat from a dry soil until water was added to the fertilizer zone.

Addition of 50 kg P/ha broadcast the first year was usually sufficient to significantly improve the yields the same year, but at least 100 kg P/ha was necessary to give a substantial increase the second year when the broadcast treatment was significantly affecting the yields. In 1982, at the earliest stages of growth only, addition of 200 kg P/ha broadcast yielded significantly more than 100 kg P/ha. A year later, no difference was observable between the two rates at any stage.

In the second year, at each harvest the increase in dry matter yield was curvilinear as a result of P broadcast and incorporated into the soil the first year. The improvement due to fertilization was significant at all stages except for early tillering and heading where high variation within the data collected would not allow a precise measure of the treatment effect.

When no P was banded with the seed, the response to broadcast treatments was more dramatic than where P was banded. The banding treatment partially masked the broadcast effect, especially at low rates and hence gave yields very similar over the all range of broadcast treatments. Taken as an overall effect, addition of 17 kg P/ha seed placed did not significantly affect the dry matter yield. The interaction among treatments was significant for the final yield because of a significant response of the banded P on the check. Highest yields were obtained at rates of 100 and 200 kg P/ha when extra P was banded with the seed, thus demonstrating that in soils low in available phosphorus, both broadcasting and banding P with the seed could be necessary for maximum production.

1.2 Grain yield.

Grain yields recorded for the second year (Table 41) were higher than the first year except for the 50 kg P/ha treatment. The better yields for the check, 100 and 200 kg P/ha broadcast treatments might be due to a response to micronutrients added in Spring 1983. This was even more dramatic on the higher rates where an apparent micronutrient deficiency the first year severely depressed the yields. A slight increase in grain yield produced per centimeter of water used by the crop (117 kg in 1982 to 126 kg in 1983) reflected the improvement due to micronutrient application. A rainfall of only 9.73 cm during the growing season with no precipitation in July, must have partially limited the grain yield response the second year. Also, when 50 kg P/ha was broadcast the first year, micronutrients did not affect the yields and a decrease in P availability the second year could be responsible for the yield decrease. The yield difference between the two years was more evident where P was banded because of the better availability of

TABLE 41: Grain yield (kg/ha) as affected by rate of P added to the soil and P banded with the seed (Haywood).

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	Yield (kg/ha) 1st YEAR
0	1633 A	2543 BC	2088 A	1738
50	2180 B	2478 BC	2329 A	2469
100	2606 BC	2904 C	2755 B	2666
200	2675 BC	2920 C	2798 B	2043
MAIN EFFECT	2273 A	2711 B		
YIELD 1st YEAR	2176	2279		

P Broadcast: Significant at 1%
P Banded: Significant at 5%
P Broadcast x P Banded: Significant at 5%

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

banded phosphorus. The first year, it resulted in a greater interaction with micronutrients thus reducing the yields more than when no P was banded, and in the second year, it provided the plant with readily available phosphorus thus providing a higher yield than on the residual treatment.

The second year there was a significant response to P broadcast as well as P banded with the seed. The interaction between the two placement methods was also significant. Banding P with the seed improved the grain yield at each rate of P broadcast but the gain was significant only on the check plot. The banding treatment the second year corresponded to the cumulated effect of two banding treatments of 17 kg P/ha each. The residual effect of the first year and the additional banding the second year, explained the large response on the check plot where the soil did not receive any fertilization. On this particular treatment a response of 447 kg/ha was recorded the first year versus an increase of 910 kg/ha the second year. The response was even more spectacular because the experiment was located on a site that had never received any previous fertilization, and had a very low soil available P level.

Banding P two years in a row was better (though not significantly) than a broadcast application of 50 kg P/ha the first year. Best grain yields were obtained at rates of 100 and 200 kg P/ha with an extra 17 kg P/ha seed placed in both cases (Figure 13). This would suggest that on a soil low in available P, both broadcasting and banding P are necessary to achieve maximum grain production of wheat. This finding is in accordance with that of Ridley and Tayakepisuthe (1974) who concluded that broadcasting large amounts of fertilizer in order to bring soils rapidly

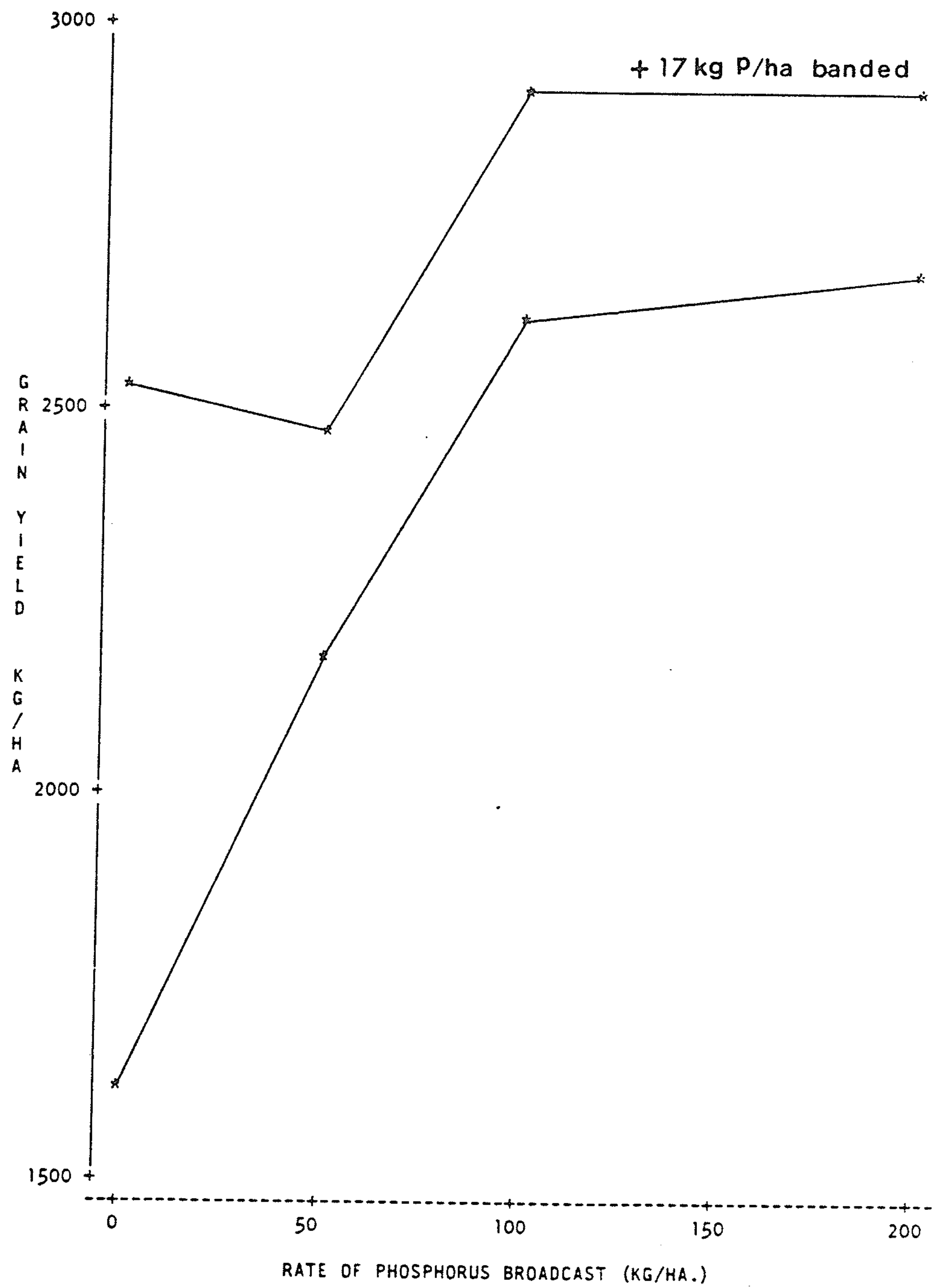


Figure 13: Relationship between grain yield, rate of P added to the soil and P banded with the seed.

to an acceptable level of available P may be a desirable practice if maximum yields are to be attained on extremely phosphate deficient soils.

1.3 P content.

The importance of early P uptake has been mentioned in previous publications. Table 42 shows how much P nutrient was required and when it was accumulated to get maximum dry matter yield and grain production. Losses in P content may be attributed to an actual loss of plant parts, to leaching, to the return of some of the phosphorus to the roots and soil, to experimental error or to a combination of all these factors.

The table shows that over 86% of the total P content was taken up before the heading stage and more than 60% was accumulated between the bootstage and heading stage. In accordance with these results, Boatwright and Haas (1961), Boatwright and Viets (1966) had found that apparently wheat plants absorbed practically all of their P prior to heading.

Maximum P uptake also corresponded to the maximum dry matter production. Nearly 50% of the total dry matter was produced between the bootstage and heading stage. This would indicate that dry matter production and consequently grain yield is related to P uptake. Grain yield was therefore plotted against total P content at heading on Figure 14. Grain yield was related to total P content at heading by the equation:

$$\text{Grain Yield} = 836.87 + 162.68\ (\text{P content}) \qquad r^2 = 0.82^{**}$$

This demonstrates the importance of an early P uptake as well as the necessity for a high P content accumulated by the heading stage in order

TABLE 42: Repartition of dry matter yield and P content, according to plant physiological stages, to produce maximum grain yield at Haywood.

STAGES	EARLY TILLERING	BOOT	HEADING	SOFT-DOUGH	MATURITY	SEASON TOTAL STRAW	SEASON TOTAL GRAIN
TIME IN DAYS AFTER SEEDING	30	45	63	75	95	95	
Dry Matter Produced:							
Between Stages (kg/ha)	199	1009	3285	1600	589	3770	2912
% of Maximum	199	1208	4493	6093	6682	6682	
Cumulative (kg/ha)	2.98	15.10	49.16	23.94	8.82	54.42	43.58
% of Maximum	2.98	18.08	67.24	91.18	100.00	100.00	
Total P Taken Up:							
Between Stages (kg/ha)	1.50	3.05	8.58	1.90	-0.08	-	-
% of Maximum	1.50	3.55	12.13	14.03	13.95	1.42	12.53
Cumulative (kg/ha)	10.69	25.30	61.16	13.54	-0.57	-	-
% of Maximum	10.69	35.99	86.46	100.00	99.43	10.12	89.31

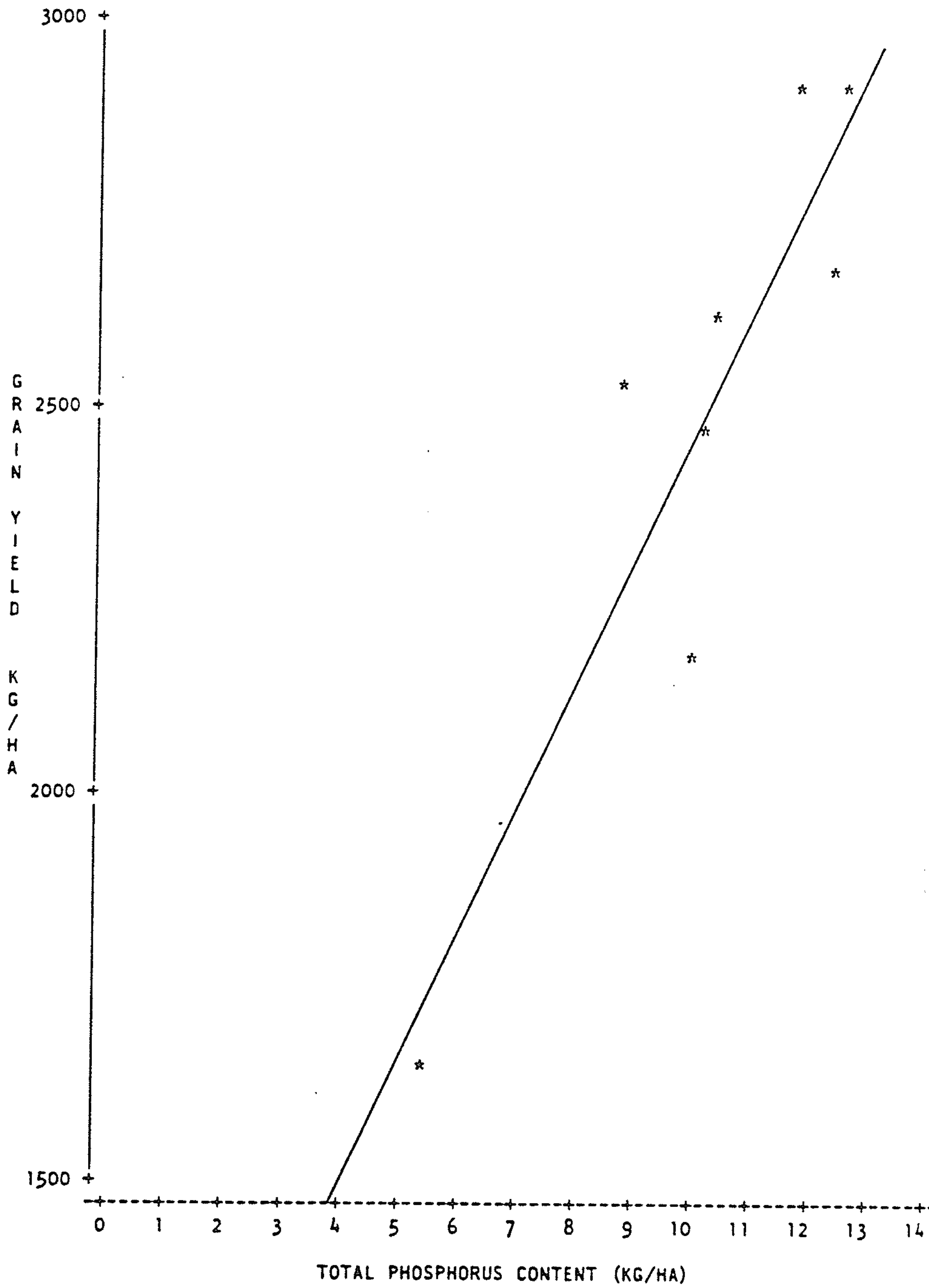


Figure 14: Relationship between grain yield and total P content in the plant at heading.

to give maximum grain yield. However, as demonstrated in the third growth chamber experiment, this equation is representative of a particular situation and corresponds to a potential maximum yield under those conditions.

P concentrations and total P contents tended to increase as the amount of P broadcast and incorporated into the soil increased (Table 43). The concentrations in the shoot recorded at the heading stage were in most cases in the 0.26-0.50% sufficient range suggested by the Manitoba Provincial Soil Testing Laboratory. Treatments where no P was broadcast, even with the extra P banded with the seed, had shoot concentrations in the 0.10-0.25% marginal range. A final yield response could be expected from the interpretations of the P analysis carried out at heading stage. Banding P with the seed generally resulted in higher P concentrations as well as total P content. The effect of banding P with the seed in improving P uptake decreased with increasing amounts of P broadcast and mixed into the soil and with time. This might suggest that banding P would provide an early uptake of fertilizer and that later in the season when the plant has a well expanded root system, it could absorb P from a larger soil volume. Also, the larger the amount of P broadcast the less the starter effect of banded P in affecting final yields. This might explain the decrease in dry matter and grain yield response to banded P observed with increasing rates of P broadcast.

1.4 Other nutrients.

The grain yield depression observed during the first year when 200 kg P/ha were broadcast did not occur the second year. The Spring application of 20 kg Zn + 15 kg Cu/ha might have provided the crop with

TABLE 43: P concentrations and total P content in wheat shoots as influenced by amount of P broadcast and P banded with the seed (Haywood).

STAGE OF GROWTH	P Banded (kg/ha)	P BROADCAST AND MIXED IN SOIL (kg P/ha)							
		0		50		100		200	
Early Tillering	0	0.40	(0.46)	0.50	(0.69)	0.44	(0.80)	0.54	(1.15)
	17	0.60	(1.10)	0.56	(1.05)	0.70	(1.38)	0.88	(1.77)
Boot	0	0.30	(2.14)	0.35	(3.12)	0.42	(4.58)	0.44	(5.74)
	17	0.37	(3.48)	0.42	(4.01)	0.46	(5.57)	0.38	(4.78)
Heading	0	0.16	(5.32)	0.26	(9.98)	0.26	(10.39)	0.28	(12.36)
	17	0.23	(8.83)	0.26	(10.28)	0.27	(12.56)	0.27	(11.70)
Soft-Dough	0	0.14	(6.24)	0.16	(7.39)	0.21	(12.13)	0.21	(13.10)
	17	0.17	(9.69)	0.22	(13.21)	0.22	(13.28)	0.23	(14.52)
Maturity: Straw	0	0.02	(0.48)	0.03	(0.88)	0.03	(1.18)	0.04	(1.46)
	17	0.03	(0.99)	0.03	(1.13)	0.03	(1.29)	0.04	(1.54)
Maturity: Grain	0	0.36	(5.88)	0.43	(9.37)	0.49	(12.77)	0.49	(13.24)
	17	0.42	(10.68)	0.47	(11.77)	0.37	(10.74)	0.49	(14.31)

Numbers in brackets = Total P content in kg/ha

Numbers outside brackets = % P

enough available micronutrients. Also, the amount of available P in the soil the second year could have been reduced dramatically as compared to the level of the first year, and consequently, the interaction with micronutrients was diminished. Nevertheless, copper and zinc analyses were carried out and the data did not show any deficiencies (Table 44). The concentrations decreased with increasing rates of broadcast P mainly due to a dilution effect. However, for all treatments, they exceeded the critical levels of 3 ppm for copper and 10 ppm for zinc suggested by the Manitoba Provincial Soil Testing Laboratory. Copper and zinc concentrations were increased the second year with applications of micronutrients as compared to the first year levels, also reported on Table 44. Other nutrient analyses were run to determine if they became a limiting factor during the growing season.

1.5 Conclusions.

On soils low in available P, broadcasting at least 100 kg P/ha as well as a yearly application of 17 kg P/ha banded with the seed was necessary to give high grain yields two years in a row. It seemed that precautions should be taken to monitor the micronutrient balance in the plant with high rates of phosphorus fertilization.

Grain yield was related to the amount of phosphorus taken up before heading and would therefore suggest that an early P uptake was necessary to achieve maximum yield. Early P uptake could be achieved through a band placement with the seed. Banding P seemed to be a more efficient way to provide the plant with P; banding 17 kg P/ha two successive years when no P was broadcast was as efficient as a broadcast application of 50 kg P/ha the first year, hence saving fertilizer.

TABLE 44: N, K, Zn, Cu, Fe, Mn concentrations at heading stage.

Only concentrations at the heading stage have been reported here because this particular stage is used by the Manitoba Provincial Soil Testing Laboratory to determine the critical level of a nutrient in the plant, as presented in the right column. Percent N in the grain was also reported.

NUTRIENT	BANDED kg/ha	RATE OF P BROADCAST (kg/ha) 0	50	100	200	CRITICAL LEVEL
%N	0	1.95	2.38	2.28	2.39	1.5
	17	2.32	2.47	2.33	2.38	
%K	0	2.36	1.71	1.79	1.51	1.0
	17	1.28	1.59	1.24	1.14	
ppm Zn	0	31.15	26.15	21.30	19.25	10.0
	17	27.90	25.00	22.00	18.80	
ppm Cu	0	6.75	7.05	5.90	4.90	3.0
	17	7.50	6.40	5.40	4.65	
ppm Fe	0	86	100	92	83	15.0
	17	88	80	92	88	
ppm Mn	0	16.15	18.30	19.15	21.80	10.0
	17	18.05	19.80	20.00	20.90	

Zinc and copper concentrations at heading stage for the first year.

ppm Zn	0	26	18	16	15
	17	18	15	16	15
ppm Cu	0	3.1	3.5	2.5	2.0
	17	2.9	3.0	2.7	1.9

% N in the grain reported at 13% moisture.

% N	0	3.21	3.01	2.80	2.85
	17	2.94	2.96	2.86	2.90

The association of both placement methods was necessary to produce maximum yields on a soil low in available P. Banding P provided the plant with readily available P and allowed for an early P uptake whereas broadcasting P built up the soil reserve and provided P throughout the growing season.

2. Elm Creek and Winkler.

2.1 Dry matter yield.

Since data from the Winkler and Elm Creek sites showed similar responses, a decision was taken to discuss both sites together. Dry matter yields are presented in Tables 45, 47, 49, 51, 53 and 46, 48, 50, 52, 54, for Elm Creek and Winkler respectively. At both sites, the final dry matter yields the second year were lower than the first year. Maximum dry matter yield produced per centimeter of water used by the crop stayed constant at Elm Creek (332 kg in 1982 and 330 kg in 1983) but increased dramatically at Winkler (from 286 kg the first year to 460 kg the second year). The drastic difference at Winkler was mainly due to a severe lodging that occurred the first year at that site thus giving a low value probably not representative of the actual situation. At Elm Creek, the same ratio was found for two years and could indicate that water was the main yield limiting factor. The yield decrease could also be partially due to a decrease in P availability however yields recorded for the second year on the highest rates of P applied were still lower than the check the first year suggesting that the decline could be mainly due to water supply. No final dry matter yield response to fertilization was observed neither the first year nor the second year. The final yields on the checks, which received no fertilization

TABLE 45: Elm Creek - Dry matter yield at early tillering stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	199	257	228	160
50	248	235	242	169
100	239	259	249	181
200	217	272	245	183
MAIN EFFECT	226	256		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 46: Winkler - Dry matter yield at early tillering stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	235	230	233 A	223
50	255	258	257 AB	243
100	271	254	263 B	249
200	262	257	259 AB	231
MAIN EFFECT	256	250		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 47: Elm Creek - Dry matter yield at bootstage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	1029	1130	1079 A	995
50	1345	1368	1356 B	1291
100	1513	1413	1466 B	1373
200	1481	1469	1475 B	1370
IN EFFECT	1348	1346		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 48: Winkler - Dry matter yield at bootstage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	1640	2058	1849 A	1454
50	2116	2076	2096 AB	1526
100	2415	2323	2369 B	1647
200	2261	2284	2273 B	1520
MAIN EFFECT	2108	2185		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 49: Elm Creek - Dry matter yield at heading stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	3720	4009	3874	3552
50	4034	4343	4188	3962
100	4278	4351	4313	3888
200	3993	4258	4125	3899
MAIN EFFECT	4015	4240		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 50: Winkler - Dry matter yield at heading stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	3500	4679	4089 A	4817
50	4298	4659	4478 AB	5121
100	4573	4789	4681 B	4786
200	4535	5136	4836 B	5111
MAIN EFFECT	4226 A	4816 B		

P Broadcast: Significant at 5%
P Banded: Significant at 5%
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 51: Elm Creek - Dry matter yield at soft-dough stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	7490	7039	7264 A	9214
50	8023	8308	8165 B	9494
100	8424	7521	7973 AB	10047
200	9011	8080	8546 B	10111
MAIN EFFECT	8237	7737		

P Broadcast: Significant at 5%
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 52: Winkler - Dry matter yield at soft-dough stage (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	6869	7626	7248	10064
50	7705	7676	7691	10307
100	7909	7879	7894	9918
200	8145	7384	7764	10006
MAIN EFFECT	7657	7641		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 53: Elm Creek - Total dry matter yield at maturity (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	8348	8490	8419	9288
50	8400	7883	8141	9005
100	8471	8518	8495	9574
200	9025	8633	8829	9356
MAIN EFFECT	8561	8381		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 54: Winkler - Total dry matter yield at maturity (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	1st YEAR
0	7921	8044	7983	9160
50	8593	8233	8413	9017
100	8497	8649	8573	8966
200	8812	8383	8597	8669
MAIN EFFECT	8456	8327		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

for two years, did not differ significantly from the other treatments, indicating that the soil provided the plant with enough available P. Both sites had been continuously fertilized for several years and the soil P pool had been increased partially offsetting the decrease in soluble P resulting from removal by continuous cropping. In 1973, Rudd and Barrow reported that few of the yield responses to P fertilizer were large on sites that had been fertilized before.

Better yields were observed the second year up to heading stage for Elm Creek and bootstage for Winkler. Later in the season, the increase in yield was greater the first year, hence giving higher final dry matter yields. The same behavior was observed on both sites and could be mainly due to the rainfall that was poor the second year.

In the second year, if the overall effect of the broadcast treatment is considered, a response to P broadcast was significant at Elm Creek only at the boot and soft-dough stages, and at Winkler at all stages except maturity. The absence of significant differences could be due partly to high variation in the data collected but also, the increasing yield trend with added P became less important as the plants matured to finally give the same yield for all the treatments. This would suggest that even though the final yields were similar, there must have been a difference in P availability in the earlier stages. Yields on the check were, up to the soft-dough stage, always the lowest indicating a delay in dry matter production that was caught up only at maturity. The better availability of fertilizer P could be partly responsible for the yield difference in the earlier stages, thereafter, the high P availability of the soils could provide the plant with a sufficient supply of nutrient. The delay would therefore correspond to the time it took the plant to develop a well expanded root system. Banding P with the seed did not affect significantly the yields on both sites except at Winkler for the heading stage for unexplained reasons.

2.2 Grain yield.

Grain yield data for the second year are reported in Tables 55 and 56 for Elm Creek and Winkler respectively. Yields obtained at Elm Creek the second year were lower than the first year whereas yields at Winkler were higher than the first year. As previously mentioned, the yield decrease at Elm Creek could be partially due to a decrease in P availability, but most of all due to a variation in water supply. The higher yields obtained at Winkler the second year could be explained by the relatively low yields of the previous year at that particular site due to a severe lodging that occurred at heading and a possible micro-nutrient deficiency which was corrected the second year. This reflected through the slight decrease of maximum grain yield produced per centimeter of water used the crop at Elm Creek (128 kg in 1982 to 123 kg in 1983) and the two-fold increase of the ratio at Winkler (from 89 kg the first year to 177 kg the second year).

In the second year, none of the treatments significantly affected the grain yield at both sites and yield averages of the sites were very close: 3157 kg grain/ha for Elm Creek and 3235 kg grain/ha at Winkler. It seemed that due to large amounts of available P present the soil, the plant obtained sufficient P regardless of the method of placement and rate of fertilization.

TABLE 55: Elm Creek - grain yield (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	YIELD (kg/ha) 1st YEAR
0	3240	3274	3257	3540
50	3150	2964	3057	3504
100	3159	2760	2959	3661
200	3416	3289	3353	3620
MAIN EFFECT	3241	3072		
YIELD 1st YEAR	3539	3623		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

TABLE 56: Winkler - grain yield (kg/ha) as affected by rate of P added to the soil and P banded with the seed.

P BROADCAST (kg/ha)	P BANDED WITH SEED (kg/ha) 0	17	MAIN EFFECT	YIELD (kg/ha) 1st YEAR
0	3153	3080	3116	2851
50	3268	3293	3280	2776
100	3271	3303	3287	2675
200	3285	3229	3257	2428
MAIN EFFECT	3244	3226		
YIELD 1st YEAR	2522	2842		

P Broadcast: Non Significant
P Banded: Non Significant
P Broadcast x P Banded: Non Significant

2.3 P content.

Table 57 shows the dry matter production and P accumulation for each stage of growth. Losses in P content may be attributed to an actual loss of plant parts, to leaching, to the return of some of the phosphorus to the roots and soil, to experimental error or to a combination of all these factors.

Over 96% of the maximum phosphorus content was accumulated before heading and more than 50% was already taken up by the bootstage. Early P uptake is therefore necessary to achieve high grain yields. The results were consistent with other published experiments (Boatwright and Haas, 1961; Boatwright and Viets, 1966).

At heading stage, 96% of the maximum P content was accumulated in the plant but only 51% of the total yield was achieved. Most of the dry matter was produced between heading and soft-dough stages, resulting in a delay between P uptake and plant growth. This would indicate that accumulation of phosphorus during the earliest stage is necessary for further maximum growth.

There was an increasing trend in P concentrations and total p contents as the amount of P broadcast and incorporated into the soil increased (Table 58). All concentrations at heading stage were in the 0.26-0.50% sufficient range suggested by the Manitoba Soil Provincial Soil Testing Laboratory. This could explain the absence of response at the final harvest. An increase of 25% in P concentrations was observed at early tillering that diminished as the plant matured. The increase was only 5.5% in the grain, thus showing no response to rates of P applied. Banding P with the seed did not seem to have any effect on P

TABLE 57: Repartition of dry matter yield and P content, according to plant physiological stages, to produce maximum grain yield (average of Elm Creek and Winkler sites).

STAGES	EARLY TILLERING	BOOT	HEADING	SOFT-DOUGH	MATURITY	SEASON TOTAL STRAW	SEASON TOTAL GRAIN
TIME IN DAYS AFTER SEEDING	30	42	58	73	95	95	
Dry Matter Produced:							
Between Stages (kg/ha)	247	1500	2577	3494	613	5235	3196
% of Maximum	2.93%	17.79%	30.57%	41.44%	7.27%	62.09	37.91%
Cumulative (kg/ha)	247	1747	4324	7818	8431	8431	
% of Maximum	2.93%	20.72%	51.29%	92.73%	100%	100%	
Total P Taken Up:							
Between Stages (kg/ha)	1.37	6.95	7.57	0.61	-1.28	-	-
% of Maximum	1.37	8.32	15.89	16.50	15.22	2.08	13.14
Cumulative (kg/ha)	8.30	42.12	45.88	3.70	-7.76	-	-
% of Maximum	8.30	50.42	96.30	100%	92.24	12.61	87.39

TABLE 58: P concentrations and total P content in wheat shoots as influenced by amount of P broadcast and P banded with the seed (Winkler and Elm Creek).

STAGE OF GROWTH	P Banded (kg/ha)	P BROADCAST AND MIXED IN SOIL (kg P/ha)							
		0		50		100		200	
Early Tillering	0	0.520	(1.09)	0.560	(1.40)	0.645	(1.63)	0.700	(1.65)
	17	0.455	(1.10)	0.465	(1.18)	0.520	(1.33)	0.610	(1.61)
Boot	0	0.335	(4.64)	0.385	(6.84)	0.435	(8.79)	0.520	(9.73)
	17	0.470	(7.63)	0.485	(8.34)	0.510	(9.57)	0.580	(11.05)
Heading	0	0.350	(12.66)	0.340	(14.12)	0.370	(16.33)	0.385	(16.40)
	17	0.325	(14.00)	0.355	(15.96)	0.390	(17.78)	0.425	(19.90)
Soft-Dough	0	0.188	(13.55)	0.220	(17.32)	0.215	(17.36)	0.218	(18.69)
	17	0.200	(14.58)	0.195	(15.60)	0.220	(16.89)	0.233	(18.06)
Maturity: Straw	0	0.033	(1.60)	0.040	(2.12)	0.040	(2.11)	0.045	(2.50)
	17	0.035	(1.79)	0.035	(1.73)	0.040	(2.22)	0.050	(2.63)
Maturity: Grain	0	0.395	(12.80)	0.415	(12.29)	0.415	(13.32)	0.413	(13.85)
	17	0.408	(12.99)	0.410	(12.76)	0.418	(12.53)	0.415	(13.54)

Numbers in brackets = Total P content in kg/ha

Numbers outside brackets = % P

concentrations or total P contents of the plant.

2.4 Comparison with Haywood.

The same amounts of P fertilizer were applied at all sites but yields at Haywood were quite different from the two other sites. At Elm Creek and Winkler, no response was observed whereas fertilization improved the yields drastically at Haywood. However, maximum grain yields produced per centimeter of water used by the crop, averaged over two years, varied from 122 kg for Haywood to 125 kg for Elm Creek and 133 kg for Winkler. This demonstrates that when P is supplied in large quantities, water was an important factor in limiting maximum production. Also, as mentioned previously, the soil available P level might have been responsible for the growth difference. At Winkler and Elm Creek the P pool might have been built up by continuous fertilization for several years whereas Haywood had never received any fertilization.

A comparison between P uptake and dry matter yield production indicates that at Haywood, P uptake and dry matter production occurred practically at the same time, showing an immediate use of the phosphorus taken up by the plant. On the high yielding sites, there was a delay between P accumulation and dry matter production. This might suggest that an apparent luxury consumption or P accumulation during the early stages is necessary for high yield production.

Also, P uptake was practically achieved by the heading stage on the rich soils indicating that the availability of the phosphorus was never limiting the uptake. Available P in solution must have been always present in larger quantities than the maximum absorption of the plant and therefore the plant itself might have been the limiting factor to P absorption. At Haywood, if compared to Elm Creek and Winkler, P uptake occurred later and was delayed or limited because 13.54% of the maximum P content was still absorbed during the soft-dough stage, versus 3.7% on soils high in available P. This would suggest that P uptake might have been limited by the rate of release of soil P from less soluble form of P to solution P and the plant did not take up nutrients at its maximum absorption capacity. An increase in P absorption could therefore correspond to exploration of fresh soil by the roots, thus explaining the similar trend between dry matter production and P accumulation.

2.5 Other nutrients.

Other nutrients analyses beside phosphorus were determined to check if they were a limiting factor during the growing season. Data for the heading stage are presented in Tables 59 and 60 for Elm Creek and Winkler respectively. It seemed that even though copper and zinc had been sprayed in Spring at Winkler, the copper concentrations at heading dropped below the critical level suggested by the Manitoba Provincial Soil Testing Laboratory on two of the treatments, however, no grain yield depression was observed at the final harvest and data from the following harvest suggested that the low values were probably due to experimental error. Otherwise, no element was in limiting supply.

2.6 Conclusion.

On soils high in available P, there was a vegetative growth response to P in the early stages that was not reflected in the final yield. A response to P in the final yield might have been possible if more water had been supplied to the crop throughout the growing season. The data suggested that there was enough P in the soil to give maximum

TABLE 59: Elm Creek - N, K, Zn, Cu, Fe, Mn concentrations at heading stage.

NUTRIENT	BANDED kg/ha	RATE OF P BROADCAST (kg/ha) 0	50	100	200	CRITICAL LEVEL
%N	0	2.49	2.70	2.74	2.67	1.5
	17	2.86	2.78	2.64	2.81	
%K	0	1.90	2.00	2.11	2.01	1.0
	17	1.95	2.01	2.08	1.93	
ppm Zn	0	22.25	16.25	14.75	15.38	10.0
	17	17.00	14.88	16.50	16.50	
ppm Cu	0	5.55	6.15	4.80	4.50	3.0
	17	4.25	4.15	3.75	3.55	
ppm Fe	0	63	89	105	64	15.0
	17	68	105	70	65	
ppm Mn	0	22.25	18.05	23.75	24.75	10.0
	17	22.50	22.25	25.50	30.25	

Zinc and copper concentrations at heading stage for the first year.

ppm Zn	0	22	21	20	22
	17	23	21	21	20
ppm Cu	0	3.7	3.4	3.0	3.2
	17	3.8	3.7	4.2	4.7

% N in the grain reported at 13% moisture.

% N	0	3.00	2.62	2.85	2.89
	17	3.15	2.99	3.05	2.98

TABLE 60: Winkler - N, K, Zn, Cu, Fe, Mn concentrations at heading stage.

NUTRIENT	BANDED kg/ha	RATE OF P BROADCAST (kg/ha) 0	50	100	200	CRITICAL LEVEL
%N	0	3.33	2.56	2.46	2.63	1.5
	17	2.42	2.59	2.42	2.51	
%K	0	2.38	2.19	2.38	2.40	1.0
	17	2.45	2.26	2.05	2.33	
ppm Zn	0	30.90	18.50	19.30	14.15	10.0
	17	30.15	23.90	21.40	20.30	
ppm Cu	0	4.01	2.50	3.05	2.25	3.0
	17	5.00	5.10	4.05	3.70	
ppm Fe	0	122	109	119	120	15.0
	17	104	104	99	93	
ppm Mn	0	25.10	29.30	31.40	24.65	10.0
	17	40.30	38.15	44.40	47.75	

Zinc and copper concentrations at heading stage for the first year.

ppm Zn	0	18	17	18	19
	17	15	19	18	15
ppm Cu	0	3.7	3.5	3.4	3.1
	17	3.6	3.6	3.6	3.5

% N in the grain reported at 13% moisture.

% N	0	3.05	3.15	3.18	3.23
	17	3.14	3.20	3.16	3.18

yield of wheat under the conditions investigated. It seemed that P accumulation in the shoot during the early stages was necessary to achieve high yields. No difference between methods of placement was observed at these sites. Both sites were high in available P and there was therefore no need for reserve build-up, but if continuous cropping is intended, maintenance level of fertilization should be considered. The quantity of fertilizer required could be determined as a function of the amount of P removed by the previous crop as estimated by tissue analysis.

II. Field Micronutrient Study: Effect of Micronutrient Treatment, Rate and Placement of P Fertilizer on Wheat Yield and Nutrients Uptake

High rates of phosphorus fertilizer application have been reported to interact with micronutrients, especially zinc and copper, and induce deficiencies (Loneragan, 1957; Spencer, 1960; Brown and Clark, 1977; Touchton et al., 1980). The first year of the phosphorus field study, grain yield depression occurred at two of the three sites. High rates of P had been applied and Cu tissue concentration at heading were below the critical level of 3 ppm suggested by the Manitoba Provincial Soil Testing Laboratory. It was therefore decided to carry out a field study on the interaction among phosphorus and micronutrients when maximum production is intended.

The experiment was on the Haywood site where data from the first year supported evidence of a P-copper interaction. The split-block design chosen for this study allowed the same phosphorus treatments as in the phosphorus study and the addition of a combination of micronutrients, thus giving 12 treatments.

a. Dry matter yield.

There was a significant curvilinear dry matter yield response to P broadcast at all stages harvested (Tables 61, 62, 63, 64 and 65). A rate of 50 kg P/ha broadcast was as effective as 200 kg P/ha broadcast in improving the yields except for two earlier stages of growth. Results for early tillering were quite inconsistent and no meaningful conclusion can be drawn from the data. Application of 200 kg P/ha broadcast was significantly better than 50 kg P/ha in improving the yields at the bootstage.

The effect of P banded was not significant as a main effect at any harvest, however, from the boot to maturity the addition of 17 kg P/ha banded with the seed when no P was broadcast significantly increased the yields. With the milk stage put aside, that particular treatment yielded as much as 50 kg P/ha broadcast.

As a general effect, an increasing trend in dry matter yield with application of micronutrients occurred from the heading stage to maturity, but the gains in yield were too little to be a significant amelioration. At heading stage, visible signs of zinc deficiency occurred on all treatments where copper alone had been sprayed before planting. Rather than a yield depression from the deficiency, there was a slight yield increase. Micronutrients analyses were carried out and results will be discussed later in a following chapter.

The beneficial effect, (though not significant) of micronutrients addition on final dry matter yields seemed to decrease with increasing

TABLE 61: Dry matter yield at early tillering (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	82	136	133	129	460	167	221	159	224	148	186
Cu	79	116	175	144	192	152	189	205	159	155	157
Zn + Cu	107	138	189	166	178	178	197	176	168	165	166
MEANS	90	130	166	147	277	166	202	180	184	156	
MEANS	110 A		156 AB		221 B		191 AB				

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

TABLE 62: Dry matter yield at bootstage (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

MICRO-NUTRIENT TREATMENT	RATE OF P BROADCAST (kg/ha) 0		50		100		200				
	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	448	1125	1242	1315	1637	1520	1690	1507	1254	1367	1311
Cu	388	975	1145	1413	1412	1535	1893	1590	1209	1378	1294
Zn + Cu	553	1295	1435	1623	1408	1530	1812	1465	1301	1478	1390
MEANS	463A	1132B	1274B	1450BC	1486BC	1528BC	1798C	1520BC	1255	1408	
MEANS	797 A		1362 B		1507 BC		1659 C				

Means followed by the same letter in each row are not significantly different at 5% with Tukey's w procedure.

TABLE 63: Dry matter yield at heading (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	2670	3937	4755	4345	5223	4680	5192	4600	4460	4391	4425
Cu	2133	4005	4232	4425	5093	5155	5507	5235	4241	4705	4473
Zn + Cu	2798	4253	5045	4990	4560	5365	5313	5110	4429	4929	4679
MEANS	2533A	4065B	4678BC	4587BC	4958C	5067C	5338C	4982C	4377	4675	
MEANS	3299 A		4632 B		5013 B		5160 B				

Means followed by the same letter in each row are not significantly different at 5% with Tukey's w procedure.

TABLE 64: Dry matter yield at soft-dough stage (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	4153	5430	6453	5745	6610	6653	6950	7068	6041	6224	6133
Cu	3885	5100	6440	6492	6755	7190	7103	6803	6046	6396	6221
Zn + Cu	4060	5230	6808	7455	7583	7223	7178	7000	6407	6727	6567
MEANS	4033A	5253B	6567C	6564C	6983C	7022C	7077C	6957C	6165	6449	
MEANS	4643 A		6556 B		7002 B		7017 B				

Means followed by the same letter in each row are not significantly different at 5% with Tukey's w procedure.

TABLE 65: Dry matter yield at maturity (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	4380	5811	5970	6048	6388	6565	7059	7220	5949	6411	6180
Cu	4384	5498	6484	6421	6770	6962	7424	7123	6265	6496	6381
Zn + Cu	4327	5342	7276	6991	7646	7572	6511	7308	6440	6803	6622
MEANS	4364A	5550B	6577BC	6487BC	6934C	7027C	6998C	7217C	6218	6570	
MEANS	4957 A		6532 B		6980 B		7108 B				

Means followed by the same letter in each row are not significantly different at 5% with Tukey's w procedure.

rates of P broadcast when P was supplied. At a rate of 50 kg P/ha broadcast, highest yields (over 6900 kg/ha) were achieved when both micronutrients were supplied. When 100 kg P/ha was broadcast, high yields were produced when both micronutrients were present but also with copper alone when an extra 17 kg P/ha was banded with the seed. Only one treatment did not yield among the highest when 200 kg P/ha was broadcast. Maximum yields could therefore be achieved at a lower rate of P broadcast when both micronutrients are supplied.

b. Grain yield.

Grain yields were significantly increased with addition of P broadcast (Table 66). However, rates from 50 to 200 kg P/ha broadcast did not differ significantly. Banding P with the seed significantly improved the yield only on the OP broadcast treatment. Figure 15 shows a weak relationship between grain yield and % P in the grain. This could indicate that phosphorus was not the only factor affecting yields.

No grain yield depressions were noticeable with increasing rates of P broadcast when no micronutrients were provided as observed during the first year of the phosphorus experiment at Haywood and Winkler. The harvest indices (Table 67) decreased significantly from the check to the 200 kg P/ha broadcast treatment. Addition of micronutrients did not improve significantly the harvest indices, even at the highest levels of P broadcast. For both micronutrient treatments the harvest index decreased with increasing rate of P broadcast, indicating that perhaps the micronutrient fertilization rates used were not sufficient in overcoming the adversive effect of high rates of P broadcast. Several authors (Shukla and Singh, 1979; Singh et al., 1982) have mentioned the

TABLE 66: Grain yield (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

MICRO-NUTRIENT TREATMENT	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	1793	2438	2410	2468	2577	2648	2690	2775	2368	2582	2475
Cu	1808	2208	2555	2568	2675	2715	2923	2718	2490	2552	2521
Zn + Cu	1765	2253	2705	2850	3098	3018	2598	2863	2541	2746	2643
MEANS	1788A	2299B	2557BC	2628BC	2783C	2793C	2737C	2785C	2466	2626	
MEANS	2044 A		2593 B		2788 B		2760 B				

Means followed by the same letter in each row are not significantly different at 5% with Tukey's w procedure.

FIGURE 15: Relationship between grain yield and %P in the grain.

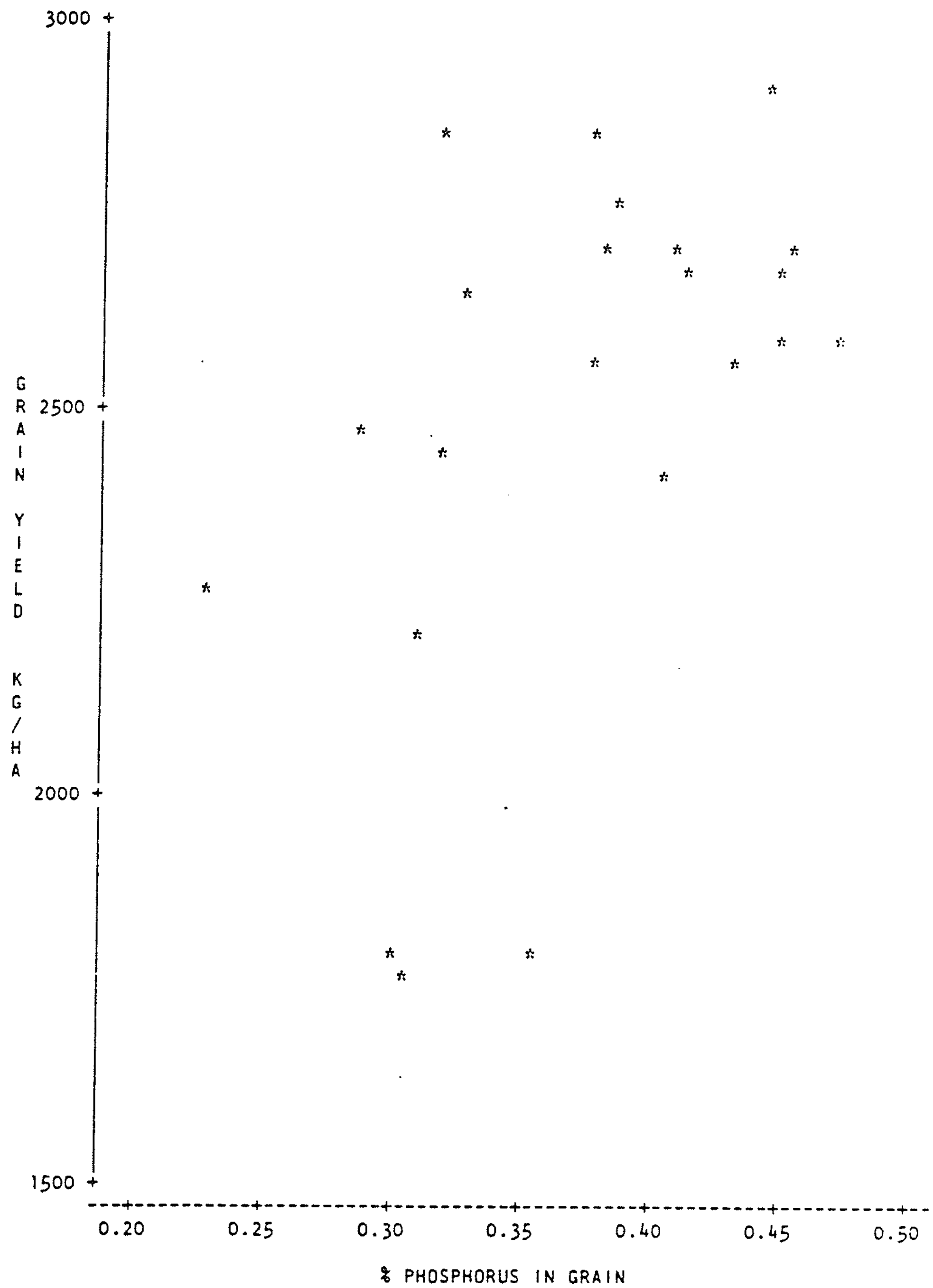


Figure 17: Relationship between grain yield and %P in the grain.

TABLE 67: Harvest index in % as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	0.41	0.42	0.41	0.41	0.41	0.41	0.38	0.38	0.40	0.40	0.40
Cu	0.42	0.40	0.39	0.40	0.39	0.39	0.39	0.38	0.40	0.40	0.40
Zn + Cu	0.41	0.42	0.37	0.40	0.40	0.40	0.40	0.39	0.40	0.40	0.40
MEANS	0.41	0.41	0.39	0.41	0.40	0.40	0.39	0.39	0.40	0.40	
MEANS	0.41 A		0.40 AB		0.40 AB		0.39 B				

Means followed by the same letter are not significantly different at 5% with Tukey's w procedure.

necessity for a proper equilibrium among P and micronutrients for maximization of yields. This balance was probably not achieved in this experiment, and in view of the data, might have been in favor of the phosphorus effect.

c. P content.

There was a response in P uptake to addition of phosphorus at all stages harvested but it was not affected by the micronutrient treatments. The Manitoba Provincial Soil Testing Laboratory bases its recommendations on tissue analysis results on the whole plant prior to filling which would correspond to the third harvest or heading stage (Table 68). According to their classification, only the treatment where no P was applied and where zinc and copper were added was under the critical level of 0.15%. Most of the data for % P at that stage were in the marginal range (0.16-0.25%) and only a few treatments were actually in the sufficient range starting at 0.26%.

Banding P with the seed always increased P concentrations in the plant as compared to when no P was banded. P concentrations above 0.26% were achieved only at high rates of P broadcast when extra P was banded with the seed. Addition of micronutrients did not affect significantly P concentrations at heading stage.

No significant relationship was found between % P at heading, % P in grain or even total P in grain (Table 69) and grain yield.

d. Copper analysis.

Copper concentrations increased with addition of copper either alone or in association with zinc. It decreased with addition of phosphorus when no micronutrients were supplied, as found by previous

TABLE 68: % P at heading stage as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

MICRO-NUTRIENT TREATMENT	RATE OF P BROADCAST (kg/ha) 0		50		100		200		MEANS		MEANS
	P BANDED WITH THE SEED (kg/ha) 0	17	0	17	0	17	0	17	0	17	
0	0.17	0.21	0.19	0.24	0.21	0.28	0.21	0.29	0.20	0.26	0.23
Cu	0.20	0.20	0.21	0.24	0.19	0.28	0.25	0.28	0.21	0.25	0.23
Zn + Cu	0.14	0.18	0.19	0.25	0.21	0.25	0.21	0.30	0.19	0.25	0.22
MEANS	0.17	0.20	0.20	0.24	0.20	0.27	0.22	0.28	0.20	0.25	
MEANS	0.18		0.22		0.24		0.25				

TABLE 69: Total P content in the grain (kg/ha) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	5.34	7.80	9.71	7.03	12.19	8.61	11.11	10.68	9.59	8.53	9.06
Cu	6.42	6.84	10.99	9.71	12.04	12.35	13.01	10.33	10.62	9.81	10.21
Zn + Cu	5.38	5.07	11.04	10.83	13.48	11.41	11.64	9.10	10.39	9.10	9.75
MEANS	5.71	6.57	10.58	9.19	12.24	10.79	11.92	10.04	10.20	9.15	
MEANS	6.14		9.89		11.52		10.98				

researchers (Loneragan, 1951; Touchton et al., 1980). Table 70 presents the copper concentrations at heading stage to allow comparison with the Manitoba Provincial Soil Testing Laboratory data. When no micronutrients were provided, rates of 100 kg P/ha broadcast and above when no P was banded decreased the copper concentration below the critical level of 3 ppm. The addition of 17 kg P/ha banded at highest rates of P broadcast raised the copper concentrations to 3.3 and 3.0 ppm, whereas at 50 kg P/ha the contrary was observed. Total copper uptake decreased with addition of phosphorus where no copper was applied, indicating that an interaction between P and copper could have been possible when no micronutrients were applied.

When copper was added, with or without zinc, all levels were above 3 ppm but increasing rates of broadcast phosphorus induced a decreasing trend to copper concentrations and kept them in the 3-4.5 ppm marginal range in most cases. The effect could be mostly explained by a dilution effect but the total copper increased with increasing rates of phosphorus showing an enhancement of copper uptake with addition of phosphorus when Cu was applied. These results are in accordance with the findings of Racz and Haluschak (1974). The data for this stage were not consistent enough to indicate any interaction between copper and zinc.

Grain copper concentrations are shown in Table 71 and basically, the same pattern as for heading stage was observed. Copper concentrations decreased with increasing rates of P broadcast, even with addition of micronutrients. Addition of micronutrients did not influence Cu concentrations when no P was broadcast. The banding treatment did not seem

TABLE 70: Copper concentrations (ppm) at heading stage as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	6.8	4.5	4.3	1.5	1.5	3.3	1.8	3.0	3.6	3.08	3.34
Cu	7.3	4.0	4.3	5.5	4.8	5.3	4.5	3.8	5.23	4.65	4.94
Zn + Cu	4.8	4.3	6.3	4.5	3.5	4.0	4.3	5.5	4.73	4.58	4.65
MEANS	6.3	4.27	4.97	3.83	3.27	4.20	3.53	4.10	4.52	4.10	
MEANS	5.28		4.40		3.74		3.82				

APPENDIX A

Description of Water Baths

The baths were constructed of 2.5 cm thick plywood. The baths measured 120 cm x 90 cm x 45 cm.

A 5 cm thick styrofoam sheet was placed in the bottom of the bath to isolate the bottoms of the pots. The baths were then lined with a plastic sheet. The baths were supported 10 cm above the growth chamber floor to ensure circulation of air in the growth chamber.

Temperature in the warm bath was maintained at 23°C by a heater (heating coil). The heater was thermostatically controlled and had a built-in pump to provide circulation of the water. A hose was hooked to the pump to force the water into the opposite corner of the bath. An additional pump with a hose was added to obtain a more homogeneous temperature throughout the bath.

In the cold bath, refrigeration was accomplished with a "dip cooling" probe placed in a plastic pipe to avoid direct contact between the probe and the pots. As there was no thermostat to control the refrigeration of the bath, two heaters were placed to counter the cooling effect and a temperature of 14°C was the result of an intimate equilibrium between cooler and heaters. Hoses were connected to the heaters to force the water at the other end of the bath, and in the tube containing the probe to avoid icing of the deep cooler and increase its efficiency. A pump with a hose, situated at the other end of the bath, improved the water circulation around the pots.

Water was added regularly to maintain the original level in both

TABLE 71: Copper concentrations (ppm) in grain as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	5.23	4.65	2.05	3.60	2.90	2.33	2.58	2.78	3.19	3.34	3.27
Cu	5.20	6.28	4.10	4.40	4.40	3.73	4.08	4.65	4.45	4.77	4.61
Zn + Cu	5.30	5.28	4.85	5.05	2.95	4.45	2.95	4.15	4.01	4.73	4.37
MEANS	5.24	5.40	3.67	4.35	3.42	3.50	3.20	3.86	3.88	4.28	
MEANS	5.32		4.01		3.46		3.53				

to have an effect on copper concentrations, except maybe on the zinc plus copper treatment. Zinc addition apparently depressed copper uptake severely when no P was banded. Banded P might have interacted with zinc uptake and inhibited the adversive effect of zinc on copper due to the presence of large amounts of available P.

Several authors (Shukla and Singh, 1979; Singh and Swarup, 1982), working with wheat, concluded that a proper balance between P and Cu was necessary for maximization of yield. With the intention of finding out a proper P-Cu blance for maximim yield, ratios of P to Cu concentrations in the grain were calculated and are given in Table 72. Ratios giving the highest yields in this experiment (above 2700 kg/ha) were identified in the table but no relationship between P/Cu ratios and maximum grain yields could be found. This would indicate that a proper balance between Cu and P might not be the main factor in maximization of yields as suggested by the previous author.

e. Zinc analysis.

There was a response in zinc concentration at all stages to the zinc sprayed and worked into the soil before seeding time. Application of phosphorus, either broadcast or banded, decreased zinc concentration at all stages harvested. The concentration followed a decreasing trend with increasing rates of P broadcast at each micronutrient treatment. Copper fertilization alone did not depress the zinc concentration as compared to the control treatment, which was contrary to the findings of Lucas (1945), Widdowson (1966), and Chaudry and Loneragan (1972). Perhaps the soil zinc level was high enough to provide the plant with enough nutrients in spite of copper fertilization. However, starting at

TABLE 72: P/Cu ratios in grain as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	570	688	1966	792	1631	1398	1601	1387*	1442	1066	1254
Cu	683	494	1049	859	1023	1221*	1091*	817*	962	848	905
Zn + Cu	575	427	841*	752*	1475*	849*	1091	766*	996	699	847
MEANS	609	536	1285	801	1376	1156	1261	990	1133	871	
MEANS	573		1043		1266		1126				

* Ratios giving highest grain yields.

heading stage, when copper alone was applied, the plants showed visible signs of zinc deficiency. Zinc concentrations at heading (Table 73) indicated levels close or below the 10 ppm critical level, suggested by the Manitoba Soil Provincial Testing Laboratory, for that particular treatment. The shoot chemical analysis indicated that the symptoms observed were definitively due to zinc deficiency. However, even though the concentrations went down to 8.8 ppm, high grain yields were still obtained when 200 kg P/ha was broadcast regardless of the banding treatment. Concentrations reported for the control treatment (no micronutrients) were very similar to the copper treatment but no zinc deficiency was apparent on the leaves. This would mean that copper did not depress zinc absorption as suggested by Chaudry and Loneragan (1970) but copper might have affected translocation of zinc within the plant after the bootstage. When zinc was supplied, it enhanced zinc uptake and increased the concentration above the critical level at all rates of phosphorus fertilization.

Total zinc contents were calculated to account for biological dilution. Addition of phosphorus had a tendency to decrease total zinc concentration hence demonstrating the presence of a phosphorus-zinc interaction at the absorption site as mentioned by Warnock (1970) and Racz and Haluschak (1974).

In light of these results, a phosphorus-zinc interaction could be an absorption phenomena whereas zinc-copper interaction would be a translocation interaction.

Grain zinc concentrations are reported in Table 74. Phosphorus application decreased the concentration in the grain, however, it

TABLE 73: Zn concentrations (ppm) at heading stage as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	25.5	20.0	11.8	13.0	11.8	11.0	9.5	9.5	14.7	13.4	14.0
Cu	24.5	17.0	11.0	13.8	9.3	10.3	8.8	9.3	13.4	12.6	13.0
Zn + Cu	35.5	30.8	29.0	23.3	23.8	20.3	20.3	22.5	27.2	24.2	25.7
MEANS	28.5	22.6	17.3	16.7	15.0	14.9	12.9	13.8	18.4	16.7	
MEANS	25.6		11.3		14.4		13.3				

TABLE 74: Zn concentrations in grain (ppm) as affected by micronutrient treatment, rate of P added to the soil and P banded with the seed (Haywood).

	RATE OF P BROADCAST (kg/ha)										
	0		50		100		200				
MICRO-NUTRIENT TREATMENT	P BANDED WITH THE SEED (kg/ha)								MEANS		
	0	17	0	17	0	17	0	17	0	17	MEANS
0	51.28	38.60	34.90	24.23	29.40	18.65	20.95	18.10	34.13	24.90	29.51
Cu	32.78	36.78	24.83	21.73	20.83	20.80	23.90	17.98	25.59	24.32	24.96
Zn + Cu	50.33	49.53	54.55	44.98	38.40	39.10	38.35	37.13	45.41	42.69	44.05
MEANS	44.80	41.64	38.09	30.31	29.54	26.18	27.73	24.40	35.04	30.64	
MEANS	44.22		34.20		27.86		26.07				

appeared that once a level of 100 kg P/ha broadcast or more was supplied, the zinc concentration remained relatively constant for each micronutrient treatment and the control. It seems that a minimum level of around 21 ppm was reached on treatments where no zinc was added. With zinc added, that level was around 38 ppm. As an overall effect, zinc application increased zinc concentration as compared to the control treatment with no micronutrients. When copper alone was added, the zinc concentrations at each rate of P broadcast were very similar to the control, except on the 0 and 50 kg P/ha broadcast where no P was banded where it seemed to depress zinc concentrations. This was not observed for the previous stages harvested. As mentioned earlier, a possible zinc-copper interaction has been reported (Dunne, 1956; Chaudry and Loneragan, 1970, 1972) and it seemed that in this experiment the adversive effect of copper fertilization on zinc was noticeable only when no zinc was supplied and at low levels of P availability, which corresponded to the lowest rates of P broadcast when no P was banded.

For the micronutrient control treatment, banding P with the seed always resulted in lower zinc concentrations than when no P was banded. The negative effect of banded P diminished with increasing rates of P broadcast indicating that the higher P availability resulting from increasing rates of P broadcast decreased the negative effect of banded P on micronutrients uptake. Zinc concentration in the plant was therefore related to the P availability to the plant, and banding placement.

Total zinc content in the grain supported these conclusions, indicating a lower content with increasing rates of P broadcast, especially when P was banded.

f. Conclusion.

Phosphorus fertilization significantly improved dry matter and grain yields. Banding P with the seed did not result in any significant increase in yield except where OP was broadcast. No grain yield depression was observed at high rates of P broadcast in this experiment, but the harvest indices decreased significantly with increasing rates of phosphorus fertilization. Environmental factors, among others, might have been responsible for the absence of a yield depression. Considering the data from the micronutrient control treatments, copper and zinc concentrations were either below or close to the critical levels suggested by the Manitoba Provincial Soil Test Laboratory indicating that Cu and Zn could eventually become limiting factors for maximum grain production and hence micronutrient levels should be monitored.

Addition of micronutrients decreased the P rates at which maximum yields were achieved, and application of micronutrients should not only be considered in terms of nutrients equilibrium but also in terms of saving P fertilizer. As a general effect, added micronutrients increased, though not significantly, dry matter and grain yields. Concentration data for Cu and Zn at heading stage, where no micronutrients were added, indicated that for maximum yield both zinc and copper are needed.

Interactions among P and micronutrients resulted in a decrease in micronutrient concentrations with increasing rates of P fertilizations. When copper alone was supplied, phosphorus application enhanced copper uptake however no P/Cu nutrient balance could be determined for maximization of yields. Copper fertilization did not depress zinc uptake as suggested by previous work but could have affected zinc translocation within the plant. Banding P with the seed resulted in a higher level of available P and might have reduced zinc absorption by the plant.

SUMMARY AND CONCLUSIONS

Field and growth chamber studies were conducted on Almasippi, Elm Creek and Rignold soils with respectively low, medium and high levels of available P, to investigate P as a limiting factor for maximum production of wheat in Manitoba. Zinc and copper additions as well as soil temperature effects on wheat yield were also studied.

A field experiment was carried out over a three year period at three sites, chosen on the basis of their available P, to look at the effect of depth of incorporation, rate and placement method of P fertilizer on yield of wheat at five stages of growth. Results reported are for the second year.

At all sites, depth of incorporation (7.5 and 15 cm) of the P fertilizer did not affect the yields.

There were no yield responses at maturity to added P on the two soils with medium and high levels of available P. A response to P broadcast in vegetative material during the early stages of growth was not reflected in the final yields, probably due to a limited water supply. Phosphorus banded with the seed generally did not influence the yields during the growing season. A lack of yield response can be explained by the high soil P availability which resulted from several years of continous P fertilization at the Elm Creek and Rignold sites. High yields obtained at both sites were associated with an early P accumulation in the shoot; as much as 96% of the total P content of the tops was taken up prior to the heading stage.

In the Almasippi soil, low in available P, a large yield response to added P was observed. At least 100 kg P/ha broadcast with an extra 17 kg P/ha banded with the seed was necessary to achieve maximum yields. Banded P was more efficient than broadcast P in improving the yields, but was not sufficient by itself for yield maximization. Thus high amounts of P broadcast were required to provide the plant with available phosphorus throughout the growing season. The yield increase due to the extra P banded with the seed was significant only for the grain. Final grain yield was significantly correlated to the amount of phosphorus accumulated in the shoot prior to the heading stage.

Results from the first year of the previous study indicated that in some cases, high rates of P fertilization induced copper deficiency and limited the potential for maximum yield. A field experiment, carried out on the Almasippi soil, was designed to study the effect of copper and zinc addition on yield of wheat at high rates of P application. Wheat responded well to addition of phosphorus for all micronutrient treatments. When no micronutrients were added, no significant yield limitation was observed at high rates of P fertilization, however, harvest indices, zinc and copper concentrations followed a declining trend with increasing amount of P broadcast. Starting at the heading stage, zinc deficiency symptoms were visible on plots which received only copper application. Responses in yield and copper concentration in the shoot were observed with addition of copper. However, highest yields were obtained when both zinc and copper were added.

Two growth chamber experiments were carried out on the Almasippi soil to investigate the effect of rate and method of placement of phosphorus on yield of wheat with and without added copper and zinc. For both placements studied, yields responded significantly to addition of P, following an asymptotic relationship. The superiority of the mixed placement at low rates became negligible as amounts of P applied increased. Increases in P supply reduced the zinc and copper concentrations in shoots when no micronutrients were added. Applications of zinc alone induced a copper deficiency and decreased grain yields. Copper fertilization by itself improved the yields only marginally. As was found in field conditions, both zinc and copper are necessary to get maximum yield.

A growth chamber experiment was undertaken on the Almasippi soil to look at the effect of rate and placement of phosphorus on maximum yield of wheat under low and high (14° and 23°C) soil temperature regimes. Grain and dry matter yields increased significantly with addition of P under both soil temperatures. Compared to high soil temperature, low soil temperature resulted in relatively low dry matter yields and particularly low grain yields. In the latter case, low grain yields were associated with a reduced P translocation from the shoot to the grain resulting in low P concentrations in the grain. Highest grain yields were obtained in the warm soil when P was banded as compared to the mixed placement. Method of phosphorus placement did not influence the yields at low soil temperature.

Under Manitoba climatic conditions, when P is the only yield limiting factor, maximum production of wheat could be obtained on a soil low in available P by adding large amounts of phosphorus broadcast and reasonable quantities of P with the seed. Results from the growth chamber and field micronutrient experiments indicated that, in some cases, adding large amounts of phosphorus severely depressed zinc and copper concentrations and limited the potential for maximum yield. Thus, at high rates of P fertilization, zinc and copper should be supplied in order to obtain maximum yield.

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baths. A handful of $CuSO_4$ was diluted in each water bath to limit algal growth.

Temperature of the water baths was recorded regularly with a thermocouple staying in permanence in the water. A temperature variation of ±1°C from the derived temperatures was maintained throughout the bath.

APPENDIX B

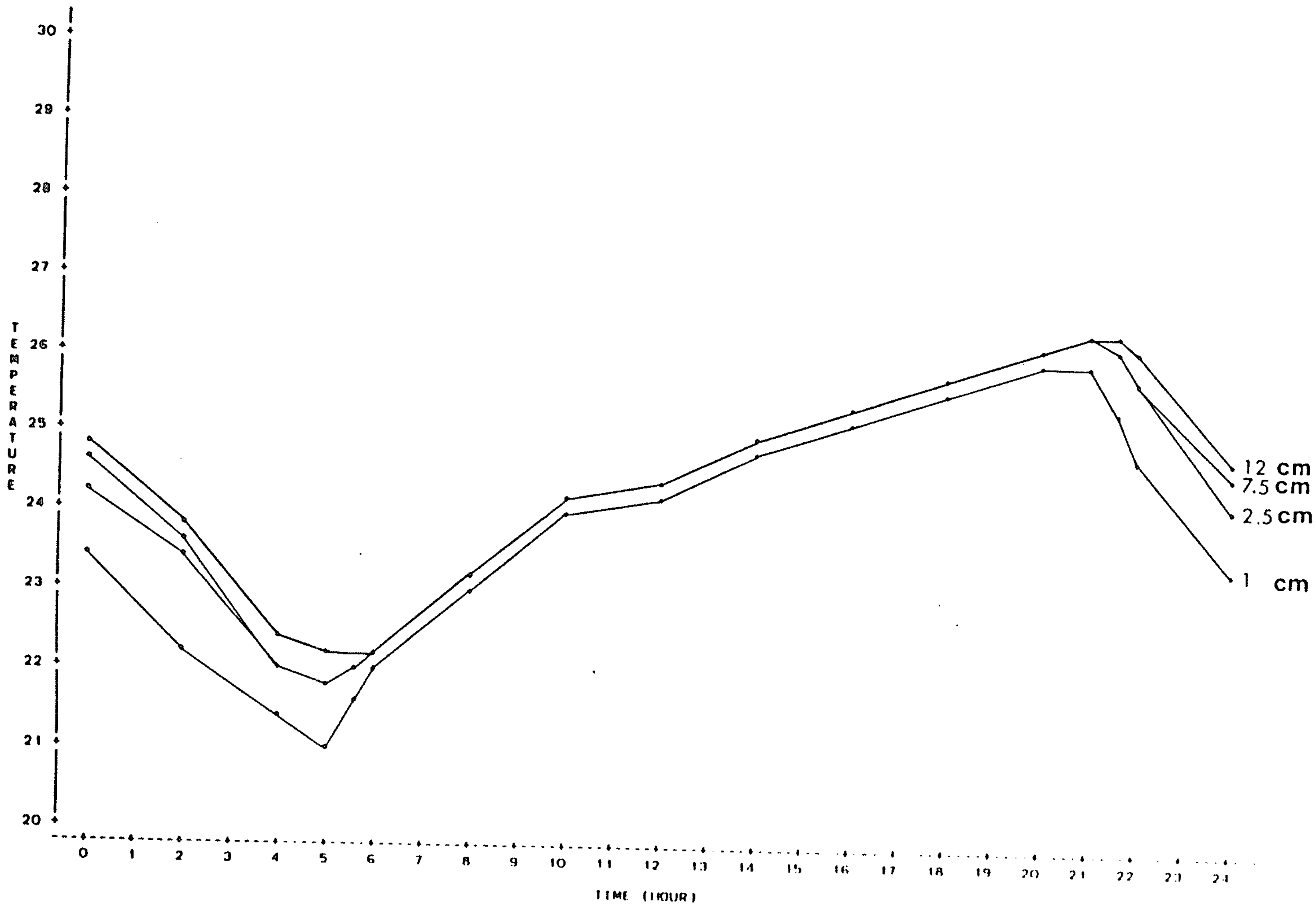

FIGURE 16: Temperature variation versus time in warm bath.

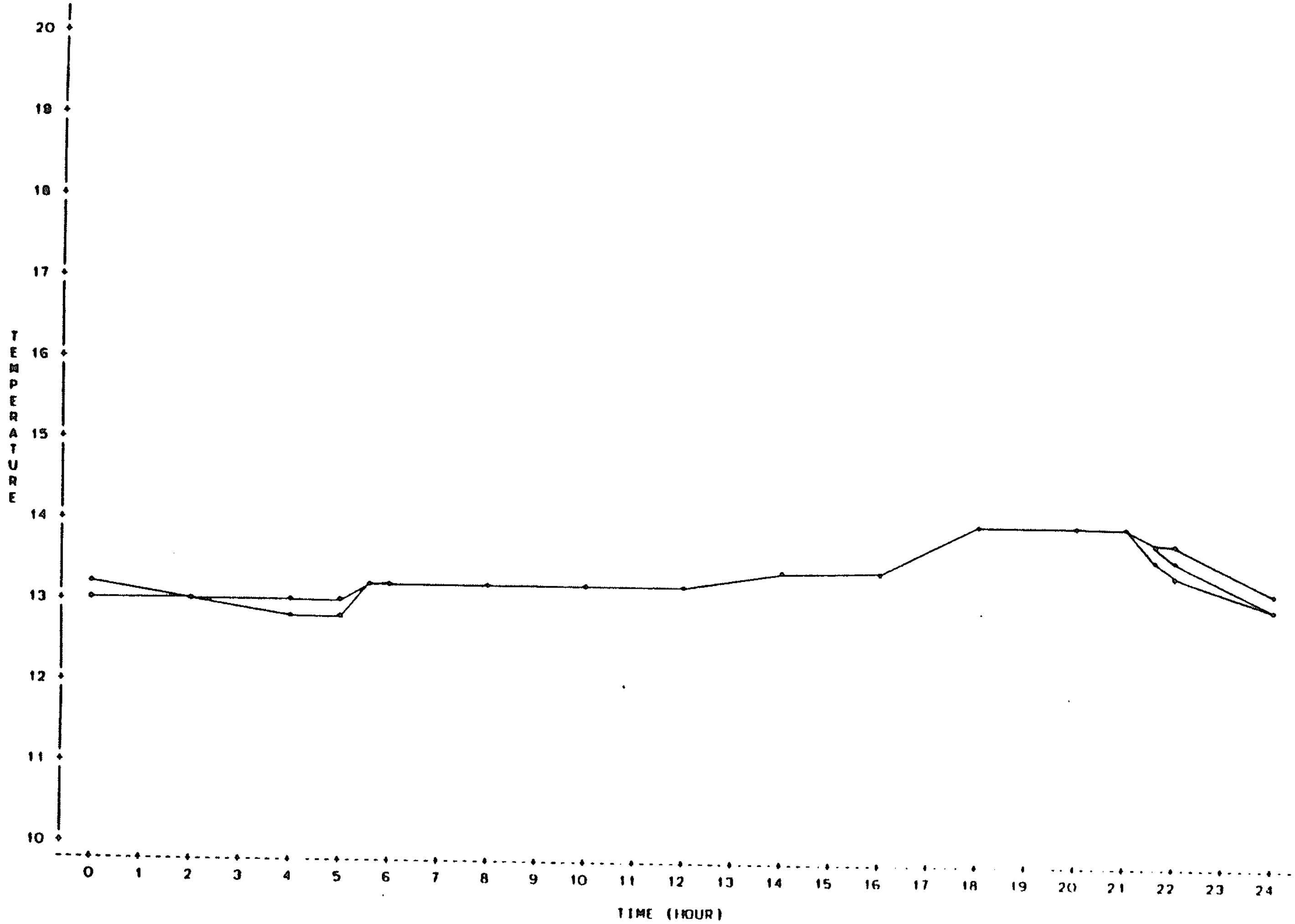

FIGURE 17: Soil temperature variation versus time in cold bath.

APPENDIX C

In the third growth chamber experiment, the effect of temperature and placement on phosphorus uptake was studied. The fertilizer response at each temperature as well as its interactions with the different temperatures were the main object of this experiment. Due to a lack of space, replication of the water bath was impossible. Consequently, a simple comparison between baths was impossible but deficiencies were expected anyway and were not the object of this study. This means that a comparison between temperatures as a main effect could not be tested statistically and a restriction error term was used in the anova table.

ANOVA TABLE

Source of variation	DF
Temperature baths	1
Restriction error	0
Phosphorus treatments	3
Placement	1
Phosphorus x Placement	3
Temperature x Placement	1
Temperature x Phosphorus	3
Temperature x Placement x Phosphorus	3
Error	32
Total	47

APPENDIX D

The anova table used for the statistical analysis of the phosphorus experiment in the field, departed slightly from a split-split plot anova table (Steel and Torrie, 1980). Both tables are presented here, side by side, to show the differences.

CONVENTIONAL SPLIT-SPLIT PLOT ANOVA TABLE

Sources of Variation	DF
Block	3
Depth	1
Error a	3
P Broad	3
Depth x P Broad	3
Error b	18
P Band	1
Depth x P Band	1
P Broad x P Band	3
Depth x P Broad x P Band	3
Error c	24
Total	63

ANOVA TABLE USED IN THIS STUDY

Sources of Variation	DF
Block	3
P Band	1
Error a	3
Depth	1
Error b	3
P Broad	3
P Broad x Depth	3
Error c	9
P Band x Depth	1
P Band x P Broad	3
P Band x P Broad x Depth	3
Error d	30
Total	63

APPENDIX E

Anova Table for a Split-Block Design with Eight Replicates

Source of Variation	DF
Block	7
P Band	1
Error A	7
P Broad	3
Error B	21
P Band x P Broad	3
Error C	21
Total	63