Micronutrients – Determining Crop Responses

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Introduction

Early work on micronutrients in Manitoba dates back to the sixties and identified zinc (Zn), copper (Cu) and manganese (Mn) as potential problem micronutrients. Early work also identified organic (peat) soils as a primary target for micronutrient deficiencies. Work on mineral soils would produce significant yield responses in the growth chamber or greenhouse (Akinyede 1977; Tomlinson et al. 1990), but verification of these responses under field conditions, even on soils that produced responses in the growth chamber was rarely successful (McGregor 1972; Smid and Spratt 1974a; Loewen-Rudgers et al. 1978; Nyaki 1981; Ridley et al. 1985).

Currently, a number of products and practices are being used or recommended for use without proper experimentation or through experimentation carried out in other parts of North America or the world. Occasionally, use of a product or a practice is recommended simply by deduction. An example of a deductive practice is: a single application of 3.5 to 5 lb of actual Cu/acre to the soil (broadcast and incorporated) is effective on Cu deficient soils, therefore, yearly applications of 1 to 1.5 lb Cu/acre (seed-placed) over a period of three to five years will produce the same result. Micronutrient maintenance or maintenance of an appropriate nutrient "balance" are also often quoted reasons for micronutrient applications without any experimentation to support such claims. In addition, recent marketing of micronutrient products has resulted in a significant and mostly unjustified widening of the "marginal" levels for micronutrient responses.

The objective of this report is to provide review of micronutrient soil and plant testing criteria as well as methods of placement currently in use in western Canada in general and Manitoba in particular.

Identification of Micronutrient Deficient Environments

In spite of the soil and/or plant tissue criteria utilized by various laboratories that service western Canada, the best way to define a deficient environment remains by *Yield Responses*. This becomes a critical issue, especially because not all micronutrient methodology and/or criteria currently in use by Laboratories have been verified under western-Canadian prairie soil conditions. Often criteria imported from other regions are irrelevant to the conditions or crop varieties of western Canada. The methodology and criteria in use for assessment of each micronutrient in western Canada is discussed below. The author attempted to collect all available information from western Canada published either in scientific journals or in proceedings of workshops and conferences. Inadvertently, some information may have been overlooked.

Boron

Boron represents one of the least studied micronutrients in prairie soils in general and in Manitoba soils in particular. Earlier studies had to content with inefficient and often cumbersome chemistries for determination of this nutrient. The advent of ICP (Inductively Coupled Plasma Spectrometry) has allowed development of routine techniques for determination of low boron levels in soils. No calibration work has taken place in western Canada on boron. Hot-water extractable boron, initially developed by Berger and Truog (1939), and subsequently modified by Wear (1965) and Gupta (1979), still remains the prevalent method for assessing soil "available" boron. Hot-water soluble levels of <0.35 ppm are generally considered as deficient (Sims and Johnson 1991). A preliminary survey-type study carried out by Western Co-operative Fertilizers Limited in 1999 (unpublished data) on eighteen sites combined with field data from fifteen tests in 2000 (Karamanos, Goh and Walley unpublished data) in the three prairie provinces suggests that hot-water extractable boron is probably of little or no value in assessing the boron status of western Canadian soils (Figure 1).

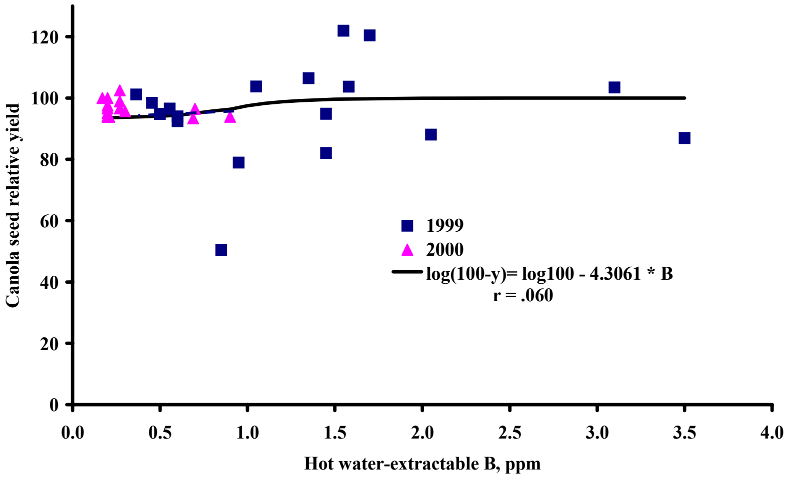

Figure 1. Relative yield of canola (*Brassica napus*) in relation to hot-water extractable boron levels in the 0-6" depth of eighteen sites across western Canada in 1999 and 2000 (Westco University of Manitoba and University of Saskatchewan unpublished data).

Inclusion of hot-water extractable levels in the 0-12" or 0-24" depth did not improve the correlation with relative canola seed yields significantly.

Plant analysis on canola tissue from the eighteen 1999 sites sampled at early flowering offered no viable alternative in interpreting the obtained yield results (Figure 2).

An attempt to calibrate N NH4Oac-extractable boron by Tomasiewicz et al. (1989) using 19 sites the majority of which contained "available" boron levels of less than 0.35 ppm and growing canola, mustard, wheat and flax was unsuccessful.

Copper

In contrast to boron, copper represents the micronutrient that most research has been carried out on in western Canada. This is to be expected since three million acres in Alberta (Penney et al. 1988) and just over one million acres in Saskatchewan (Kruger et al. 1985) have been identified as potentially deficient in copper. In Manitoba, Dowbenko et al. (1989) estimated that approximately 300,000 acres of organic soils are under cultivation and studies by Reid (1982) and Tokarchuk (1982) established that Cu deficiency is a major limitation to small grain production on these soils. Copper deficiencies have also been established on organic (peat) soils in Alberta (Hartman 1992) and Saskatchewan (Karamanos et al. 1985a; 1991).

Mineral soils

Karamanos et al. (1986) developed a critical level of 0.4 ppm for spring wheat and 0.35 ppm for canola grown on northern prairie soils. The authors found soil test levels to be a more reliable tool compared to plant tissue levels at either Feekes 6 or 10 for cereals or at flowering or bud stage for canola or pre-blossom or middle-blossom stage for flax. Alberta Agriculture, Food and Rural Development in a recent publication (1999) also use 0.4 ppm as a critical level for copper deficiency without any specific reference to plant species. Karamanos et al. (1985b) proposed marginal range of 0.4-0.8 and 0.4-0.6 ppm for Gray and Brown soils, respectively. Alberta Agriculture Food and Rural Development have proposed a marginal range of 0.4 to 0.6 ppm but also have inserted an unusual range of 0.6-1.0 ppm as "deficient in some instances". The latter may be considered as a redundancy since soil testing criteria are based on a statistical assessment ($P<0.05$ or $P<0.1$) which infers that responses to a nutrient can indeed be obtained on soils with adequate levels of the nutrient and vice versa. In Manitoba, Ridley et al. (1985) placed the critical level at 0.3 to 0.4 ppm of DTPA-extractable Cu using data from two growth chamber studies. However, field experiments on three soils containing 0.26, 0.34 and 0.42 ppm pf DTPA-Cu did not result in significant yield responses to Cu application. Mineral soils in Manitoba are generally considered as containing sufficient levels of Cu except possibly the Almasippi loamy fine sands and Gilbert sandy loams. The data from Ridley et al. (1985) were fitted in a Mitcherlich type of growth curve and a critical level of 0.3 ppm was thus derived (Figure 3).

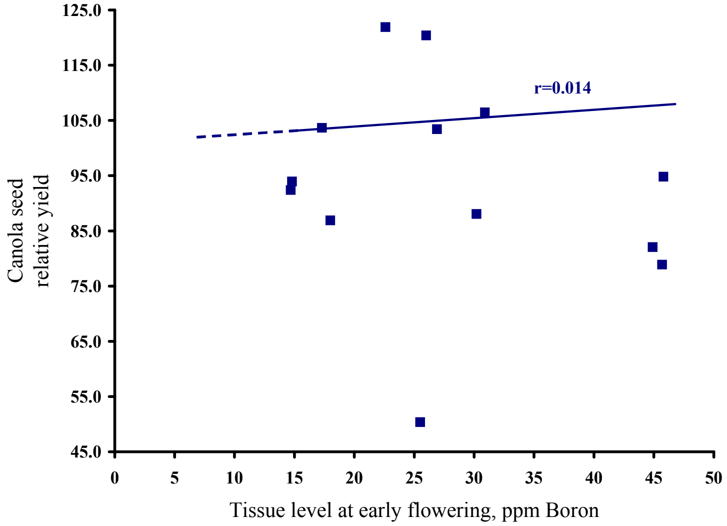

Figure 2. Relative yield of canola (*Brassica napus*) in relation to plant tissue levels at early flowering of eighteen sites across western Canada in 1999 (Westco unpublished data).

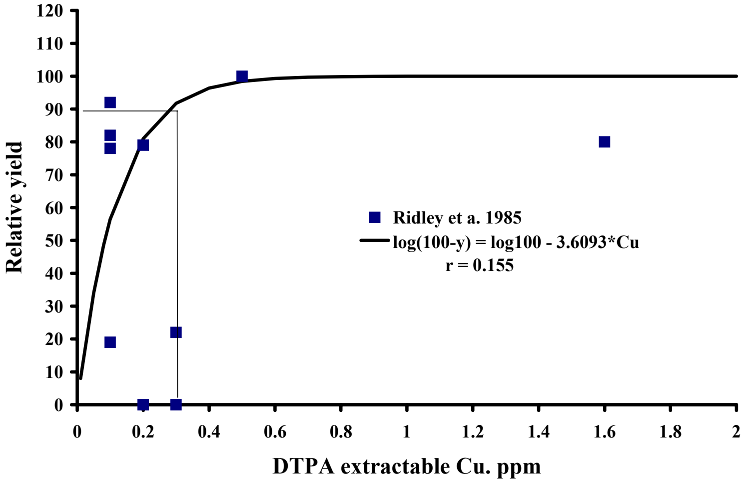

Figure 3. Relative yield of wheat (Triticum aestivum) in relation to DTPA-extractable copper levels in the 0-6" depth of soils (calculated from data by Ridley et al. 1985).

A compilation of research data on wheat barley and canola from Saskatchewan and Alberta is shown in Figures 4, 5 and 6, respectively. Work on copper in Manitoba has been extensively carried out on organic soils only and is not included in this correlation.

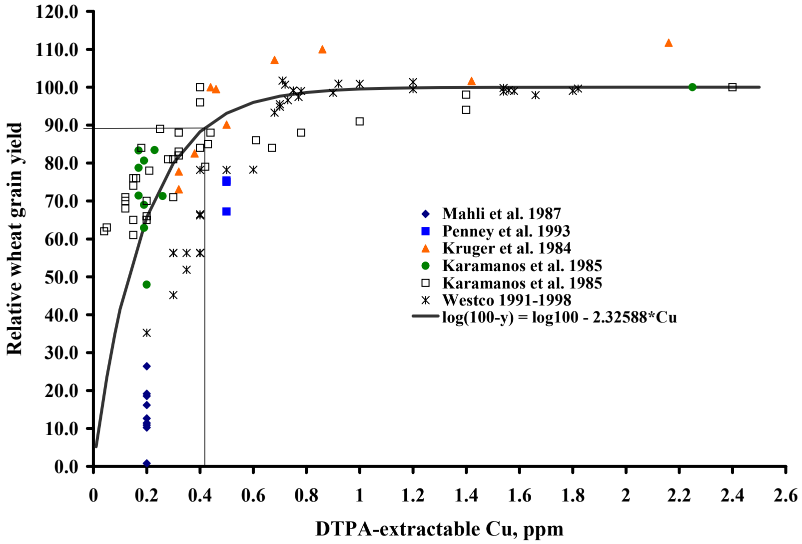

Figure 4. Relative yield of wheat (Triticum aestivum) in relation to DTPA-extractable copper levels in the 0-6” depth of soils across western Canada.

Compilation of data from field studies from a number of independent sources lead to confirmation of 0.4 ppm as a critical level for wheat and barley (Figures 4 and 5). A critical level of 0.30 ppm for canola was derived from Figure 6. Although responses to copper were reported for other crops, such as oats (Malhi et al. 1987), alfalfa (Kruger et al.1984) and flax (Karamanos et al. 1986), the database for these crops is insufficient to draw critical levels from. Karamanos et al. (1986) derived a critical level for flax of 0.3 ppm using data from individual plots of two separate experiments.

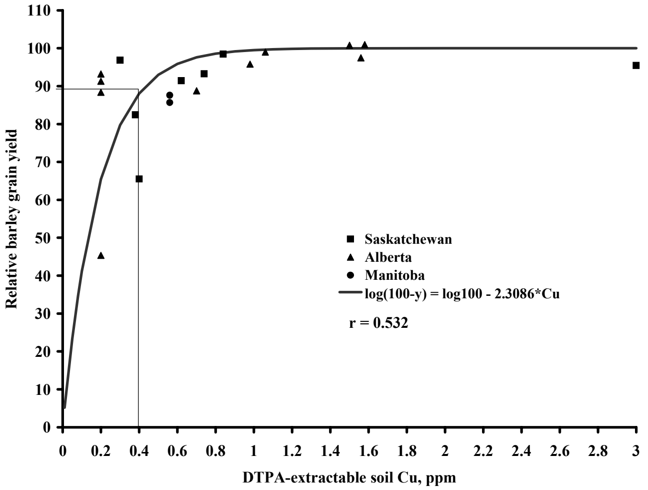

Figure 5. Relative yield of barley (*Hordeum vulgaris*) in relation to DTPA-extractable copper levels in the 0-6” depth of soils across western Canada.

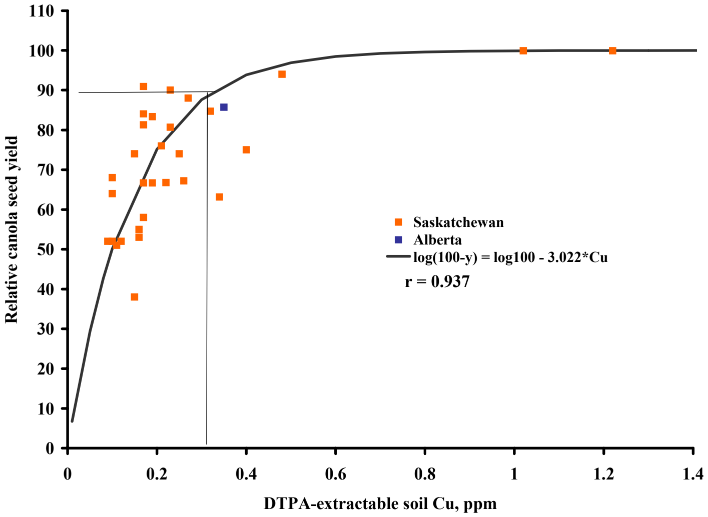

Figure 6. Relative yield of canola (*Brassica napus*) in relation to DTPA-extractable copper levels in the 0-6” depth of soils across western Canada.

Although the criteria derived from these studies are applied equally to all types of soils, clay soils do not respond as readily as sandy loams or loamy sands (Penney et al. 1988). Liang et al. (1991b) showed a close relationship between “available” copper and soil clay content using sequential fractionation techniques. Penney et al. (1993) showed very little differences in sensitivity to copper deficiency among five commonly grown varieties in Alberta over seven site-years.

Organic soils

Early work in Manitoba established that organic soils were most likely to be copper deficient (Loewen-Rudgers et al. 1978). Tokarchuk et al. (1979) demonstrated significant yield responses to barley, wheat and rapeseed to Cu applications on organic soils. The authors further indirectly demonstrated the need for a Cu x Mn balance in crop nutrition. The effect of Cu and Mn was also examined by Reid and Racz (1980) in field experiments conducted in 1978 and 1979, and concluded that only Cu had an impact on wheat yields. Tokarchuk (1982) found significant correlations between Cu levels in wheat and soil extractable Cu levels with a variety of extractants only when both fertilized and non-fertilized soils were included in the relationship. However, none of the extractants adequately assessed plant available soil Cu in organic soils not fertilized with Cu. Further, Tokarchuk reposted that on a number of Manitoba organic soils, Mn concentration in wheat usually decreased when Cu was applied at high levels. Ewanek (1988) reported very large responses of barley to Cu fertilization in three of six organic soils in Manitoba. However, crop response to Cu did not appear to be related to the amount of “available” Cu in the soils. In this study, the site with the lowest Cu level yielded no significant yield response to Cu fertilization.

Dowbenko et al. (1989) carried out a comprehensive field study to calibrate DTPA-extractable Cu and assess residual effects of CU-sulphate fertilization of crops. The authors employed a Langmuir function to calibrate the test and concluded that the critical level was 7 ppm with marginal levels occurring between 8 and 16 ppm. The data from this work were re-drawn in a Mitcherlich type growth curve (Figure 7). A critical level of 5 ppm was thus derived.

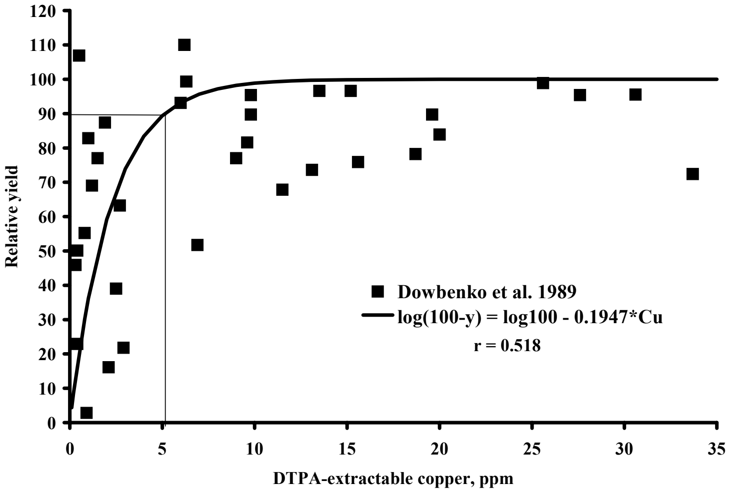

Figure 7. Relative yield of wheat (*Triticum aestivum*) in relation to DTPA-extractable copper levels in the 0-6" depth of organic soils in Manitoba (data re-drawn from Dowbenko et al. 1989).

Karamanos et al (1985a) demonstrated a very strong Cu x Mn interaction in a growth chamber study with spring wheat grown on organic soils. Later on, Karamanos et al. (1991) verified the same interaction with barley grown on organic soils in field experiments. Karamanos et al (1985a) were able to separate Cu-responding and Mn-responding from non-responding organic soils in the growth chamber experiment, however, the had to modify the DTPA extraction (Lindsay and Norvell 1978) by widening the soil:extractant ratio from 1:2 to 1:5. At Mn/Cu ratios below 1 and above 15, yield reduction and death of wheat plants occurred due to Mn and Cu deficiency, respectively. Yield reductions in the field with barley grown on organic soils occurred at Mn/Cu ratios below 10 and above 20 (Karamanos et al. 1991).

Iron and Molybdenum

Iron and molybdenum are the two least researched micronutrients in prairie soils primarily because the parent material from which these soils have been developed is rich in these micronutrients. There are anecdotal reports of calcium induced iron chlorosis in trees and garden vegetables in certain areas as well as copper-molybdenum imbalances in east central Saskatchewan and west central Manitoba due to excessive levels of molybdenum in pasture soils that result in molybdenosis in cattle (Stewart and Racz 1977; Tokarchuk and Loewen-Rudgers 1981; 1985). No calibration work has been carried out on these two micronutrients.

Manganese

Responses of common crops to manganese on mineral soils in the prairies are extremely rare. Therefore, researchers have been unable to compile enough soils and/or sites to carry out calibration work. On the contrary, extensive work has been carried out on organic (peat) soils in all three prairie Provinces (Reid 1982; Loewen-Rodgers et al. 1983; Karamanos et al. 1985a; Karamanos et al. 1991; Hartman 1992). Karamanos et al. (1985a, 1991), as mentioned in the Copper Section, have proposed the use of Mn/Cu ratio to assess the status of organic soils in these two micronutrients. Ratios of Mn/Cu less than 1 indicate Mn and those above 15 Cu deficiency, respectively. This approach, however, requires modification of the extraction ratio used in the DTPA method from 1:2 to 1:5 soil:DTPA-extractant. Germida et al. (1985) developed a simple microbial bioassay to assess the manganese status of organic soils. Tu et al. (1993) demonstrated that the solubility of both native and applied Mn was affected by application of KCl most likely due to the formation of Mn-Cl complexes.

Zinc

Extensive work on zinc was carried out with beans in Alberta (McKenzie et al. 1999), corn (Racz 1967; Smid and Spratt 1974b), beans (McKenzie 1979) and flax (Smid and Spratt 1974a; Grant 1988), wheat (Nyaki and Racz 1989) in Manitoba and a variety of crops in Saskatchewan (Karamanos et al. 1984b; Kruger et al. 1984; Singh 1986; Singh et al. 1987). McGregor (1972) suggested that soils containing less than 1.3 ppm DTPA-Zn may be suspect of being Zn deficient, while soils containing 0.8 ppm DTPA-Zn were moderately Zn deficient. Singh et al. 1987 carried out 17 field trials on soils containing as low as 0.25 ppm DTPA-extractable Zn but were unable to verify the commonly used critical level of 0.5 ppm as a valid criterion to assess cereal responses to zinc. Since responses could not be obtained with cereals on soils containing as low levels of zinc as 0.25 ppm, the authors concluded that the critical level for cereals (except corn) on prairie soils is no greater than 0.25 ppm. In subsequent studies using ^{65}Zn and fractionation techniques, Liang et al (1990; 1991a) demonstrated that DTPA is unsuitable for assessment of “available” zinc in Saskatchewan soils. However, no further work has since been carried out to derive an appropriate criterion for assessing “available” zinc in prairie soils.

Undoubtedly, lack of responses of common crops to zinc provided no incentive for further research in this area. A project recently completed on dry bean production in southern Alberta derived a critical level of 3.0 ppm in coarse soils and 1.5 ppm in medium to fine soils in the region (McKenzie et al. 1999). However, earlier work with irrigated wheat, barley and canola in southern Alberta showed no responses of these crops to zinc (McKenzie and Middleton 1991). Recent work in Manitoba (Goh et al. 2000) showed significant yield responses of Pinto beans to both soil and foliar applications of Zn on a soil containing 0.38-0.48 ppm DTPA-Zn but no responses on a soil containing 0.94-0.95 ppm DTPA-Zn.

Summary of Interpretive Criteria for Western Canadian Prairie Soils

Results of calibration work of micronutrient soil tests carried out in western Canada are summarized in Table 1.

Table 1. Soil testing criteria for assessing “available” micronutrients in prairie mineral soils.

Nutrient	Extraction method	Crop(s)	Level, ppm	Description	Comments
Boron	Hot-water	All	Unknown	Inappropriate method of assessment	Criterion of 0.35 ppm irrelevant
			>3.5	Toxic	Unconfirmed
Copper	DTPA[1]	Cereals	<0.4	Deficient	Not fully confirmed for clay soils
			0.4-0.6	Marginal	No economic responses
		Oilseeds	<0.25	Deficient	Not fully confirmed for clay soils
			0.25-0.4	Marginal	
Manganese	DTPA	All	Unknown	Unconfirmed	Criterion of 1 ppm irrelevant
Zinc	DTPA	Cereals, oilseeds	<0.25	Marginal	Inappropriate method of assessment
		Corn	<0.5	Marginal	

[1] Lindsay and Norvell (1978)

What Does a Marginal Micronutrient Soil Test Mean in Prairie Soils?

Interpretation of a marginal level can take a different meaning in prairie soils due to the extremely high spatial variation of these nutrients (Singh 1986; Singh et al. 1985). The transect in Figure 8 that was sampled every one meter clearly demonstrates the extreme variability in copper levels. Inadvertently, mixing samples from areas with deficient levels with those of sufficient levels may generate a level that is characterized as "marginal". However, in this instance response of a crop to copper will not be in the marginal range. Rather there will be a high probability of receiving a yield increase in the deficient areas and no yield increase in the areas with sufficient copper levels.

The existence of a "marginal" range is seriously questioned. Karamanos, Walley and Goh (unpublished data) have compiled data from 102 field tests across the prairies containing "marginal" and "deficient" soil Cu levels. Agronomic responses on "marginal" soils were obtained in 16 percent of cases compared to 94 percent of cases on "deficient" soils. The range of responding "marginal" soils was from 0.41 to 0.66 ppm DTPA-Cu with an average of 0.59±0.08 ppm, whereas non-responding "marginal" soils contained 0.41 to 1.2 ppm with an average of 0.68±0.16 ppm. In contrast, the range of responding "deficient" soils was from 0.04 to 0.4 ppm with an average of 0.24±0.09 ppm DTPA-Cu. There were no "economic" responses to Cu application on "marginal" soils, when the price of wheat was between $3.5 and $5.00/bu (only one case for >$5.00/bu) compared to sixty-two percent of "deficient" soils.

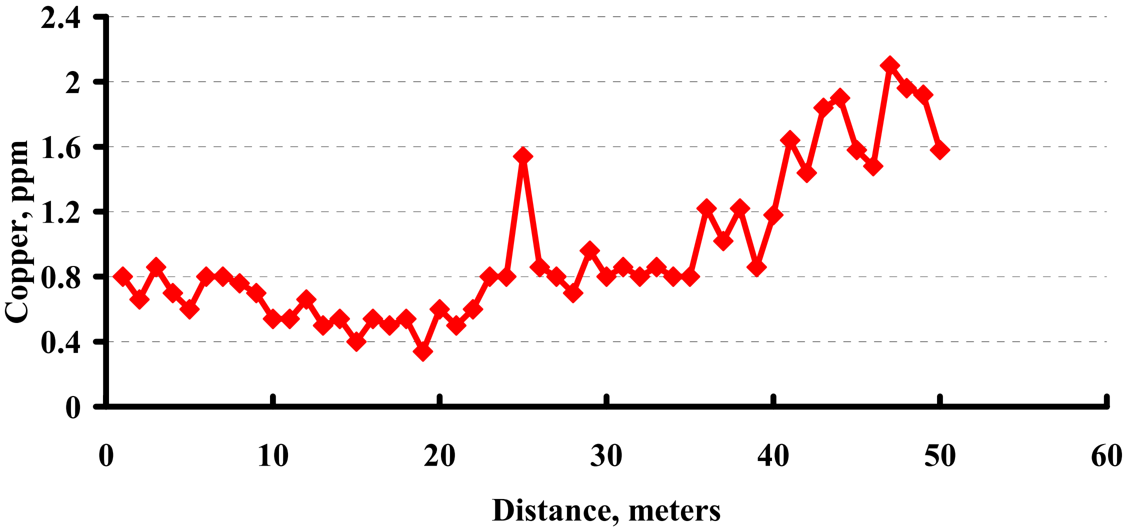

Figure 8. Distribution of DTPA-extractable Cu in the A horizon of a 46 m transect of soil sampled every meter (adapted from Singh et al. 1985).

Impact of Environmental Conditions of Micronutrient Soil Test Levels

The response to micronutrients can be greatly modified by environmental conditions. Thus, cool and wet seasons tend to promote deficiencies. Normally, most early spring deficiency symptoms will disappear later on (July). Economic responses may not always be obtained. Annual variations in micronutrient responses can also be expected.

Soil test databases have always been a useful tool in deriving trends of soil nutrients from year to year. Increased numbers of micronutrient soil tests over the last five years have allowed drawing trends for certain areas on the prairies. For example, the number of soil micronutrient tests in northeast Saskatchewan (District 8) was approximately 35% of all samples (Karamanos, 1997b). This has allowed recognition of a close relationship between median soil pH and "available" soil copper and zinc in that area for the period between 1992 and 1996 (Figures 9 and 10). The change in pH was probably due to extreme changes in the soil redox potential. In any event, the observed changes in soil pH could have strongly affected the solubility of copper and zinc (Lindsay, 1991).

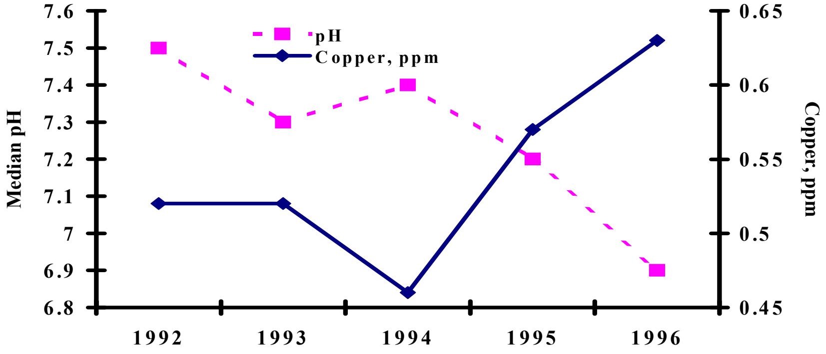

Figure 9. Relationship between mean "DTPA-available" copper and median pH in the soils of northeast Saskatchewan.

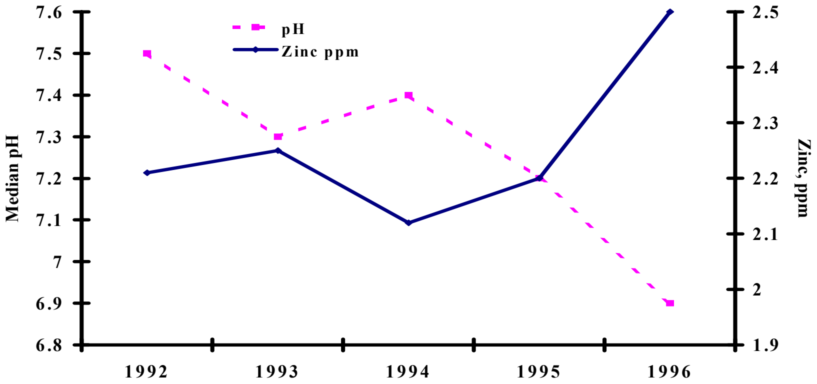

Figure 10. Relationship between mean "DTPA-available" zinc and median pH in the soils of northeast Saskatchewan.

Plant Analysis

Calibration work for plant tissue test criteria with western Canadian varieties and under prairie conditions is extremely limited. Provincial soil fertility sub-councils or sub-committees have derived a variety of criteria from research in other regions of North America or the world and with some varieties that may be irrelevant to western Canada. Oddly enough some "provincial" criteria thus derived appear very strongly impeded in today's agronomic practices in the prairies. Karamanos et al. (1984a) were successful in deriving diagnostic criteria for manganese in oats but Karamanos et al. (1986) and Penney et al (1993) were not successful in establishing plant tissue tests for copper in cereals, canola and flax in western Canada. Therefore, much work is needed in this area if "relevant" plant tissue criteria for western Canada are to be derived.

Correction of Micronutrient Deficiencies

Correction of micronutrient deficiencies using soil-applied fertilizers is quite different from that of macronutrients. Although yield responses to both macro- and micronutrients can be described by yield curves, application rates of micronutrients do not reflect a change in the nutrient requirement based on a soil test level, as is the case for macronutrients. Rather, application rates for micronutrients represent a requirement for adequate physical distribution of the product so that it does become accessible to the roots of all plants. An example of fertilizer nitrogen rate application as a function of soil nitrogen levels is illustrated in Figure 11.

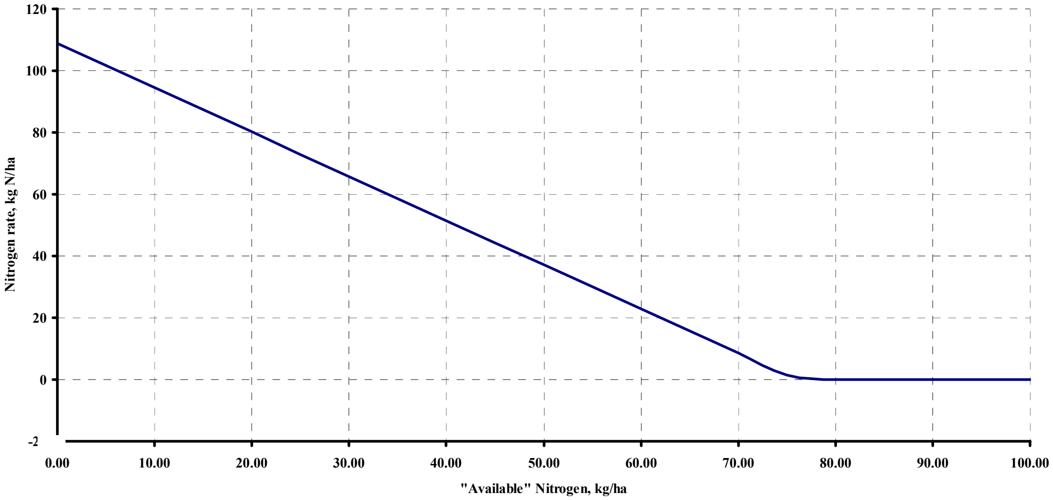

Figure 11. Mean N application rate of Moist Dark Brown soils as a function of N soil testing levels.

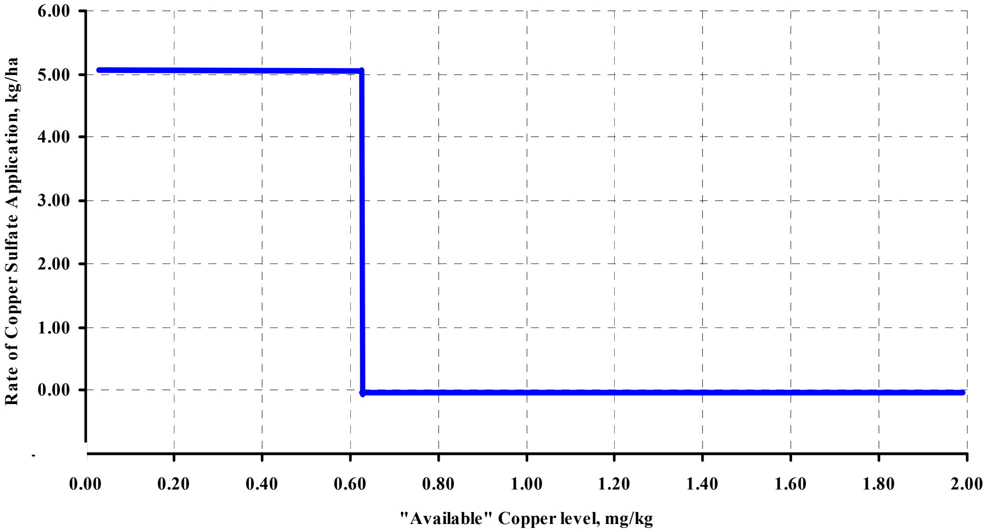

Figure 12. Cu application rate of Moist Dark Brown soils as a function of Cu soil testing levels.

However, the rate of copper (and of any other micronutrient to that effect) application is dictated by product distribution in the field and would be better represented in Figure 12. Therefore, application of copper at lower rates that those recommended would only lead to inefficient physical distribution of the product, minimization of the chances for a response and waste of money. This also presents a major challenge if anyone is attempting variable application rate of a fertilizer blend containing micronutrients (Karamanos 1997a).

Responses to micronutrients may be obtained either as a result of soil deficiencies or because of physiological effects in the plants. Physiological effects may be the result of either variety requirements or interactions between nutrients, e.g. P X Zn interaction (Racz and Haluschak 1970; Singh et al. 1986; 1988; Tu and Goh 1989; Grant and Bailey 1990).

Providing there is a deficiency, various crops will respond differently to the same micronutrient (Table 2). However, response of a crop to a micronutrient is often confused with sensitivity of the crop to the same micronutrient. For example, although canola is not as prone to copper deficiency as wheat and barley, which is illustrated by the lower soil testing critical level (Table 1), response when soils are indeed deficient can be of the same magnitude as that of barley and spring wheat (Karamanos et al., 1986).

Table 2. Response of Some Common Crops to Micronutrients under Soil or Environmental Conditions Favorable to a Deficiency

Crop	Boron	Copper	Manganese	Molybdenum	Zinc
Alfalfa	**High**	**High**	Medium	Medium	Low
Barley	Low	**High**	Medium	Low	Medium
Canola	Medium	Medium	Medium	Low	Medium
Clover	Medium	Medium	Medium	**High**	Medium
Corn	Low	Medium	Low	Low	**High**
Oats	Low	**High**	**High**	Medium	Low
Peas	Low	Low	**High**	Medium	Low
Wheat	Low	High	**High**	Low	Low

The response to micronutrients can be greatly modified by environmental conditions. Thus, cool and wet seasons tend to promote deficiencies. Normally, most early spring deficiency symptoms will disappear later on (July). Economic responses may not always be obtained. Annual variations in micronutrient responses can also be expected (Figures 9 and 10).

A complete micronutrient fertilizer program includes (i) identification of the deficiency, (ii) selection of products and method of placement, and (iii) costs. Identification of micronutrient deficiencies has already been dealt with.

Method of Placement

Earlier work (Karamanos et al. 1985b) had established broadcast and incorporation as the most efficient and in most cases the only effective method of applying micronutrients (copper and zinc) to Saskatchewan soils. The high cost of these products, however, has been prohibiting to broadcasting them, especially on soils that are perceived to be marginal in micronutrient levels; hence, no economic response to a broadcast rate of a micronutrient can be obtained. Consequently, the practice of seed-placing smaller and more economic amounts with the seed was adopted as an alternative. However, very little research has been carried out in support of this practice. The need for granular products so that blending of small amounts can be effective further complicated the practice.

Work initiated by Western Co-operative Fertilizers Limited in 1995 on a number of sites in Alberta and in 2000 on a number of sites in Saskatchewan and Manitoba has been designed to address this issue in conjunction with evaluation of a number of products for their suitability as sources of "available" copper to crops. The results of two of these studies are presented here to address the issue of seed-placement versus broadcast and incorporation and foliar application. The results of the study in Manitoba are reported elsewhere in these Proceedings by Goh et al. 2000).

Three products were seed-placed at a site in Lacombe, Alberta on a soil containing 0.35 ppm DTPA-extractable copper/acre, namely, an oxysulphate, a granular chelated (EDTA) and a sulphate product containing copper. Seed-placement of 2 lb Cu/acre was repeated on the same plots every year for four years (1995-1998) and was compared to a 4 lb Cu/acre broadcast and incorporation application (Figure 13). Significant responses ($P<0.05$ and $P<0.01$) to copper applied by broadcast and incorporation were obtained every year. Seed-placement of the chelated and sulphate products resulted in significant ($P<0.05$) responses in 1998 only. Broadcast and incorporation of copper always resulted in maximum yield every year.

The experiment was continued in 1999, however, no further copper applications were employed in an attempt to assess the residual effect of the applied treatments.

Final yields of wheat grown on these residual copper plots (Figure 14) are shown for all copper rates employed in this experiment. Broadcast and incorporation of 4 lb Cu/acre produced the highest yield. Although significant responses were indeed obtained with annual seed-placed rates of 3.6 lb Cu/acre, this rate defeats the purpose in attempting to effectively and economically correct a copper deficiency, since a single broadcast and incorporation of 4 lb Cu/acre has an effective residual effect.

Conversely, broadcast and incorporation of less than 3.6 lb Cu/acre are equally ineffective to a seed-placement. However, seed-placement of 1.8 lb Cu/acre of either a chelated or a sulphate product did produce a significant yield increase and conceivably can be considered an alternative for direct seeding recognizing, of course, that it will not lead to a maximum yield.

An alternative to this practice will be a combination of seed-placement of either a chelated or a sulphate product with a foliar application of an appropriate copper product. In separate experiments, foliar application of copper at 0.2 lb Cu/acre proved to be extremely effective providing the soil was not severely deficient in copper (Figures 15 and 16). However, when a soil is severely deficient a foliar application may not be sufficient to alleviate a copper deficiency (Figure 17). In cases of a severe copper deficiency the producer should be seeking a long-term economic solution and even be willing to sacrifice a direct seeding operation in order to correct a micronutrient problem. Broadcast and incorporation of a copper sulphate product could only achieve this. The economic return from the products used in the Lacombe five-year study reported here is shown in Figure 18.

A number of reasons are being contemplated for the inability of seed-placed copper products to provide maximum or consistent yields increases. For example, physical distribution of 1 to 1.5 lb of Cu/acre in a band leads to fertilizer granules being at great distances from each other and inability of roots to access copper. Hot bands or a P X Cu interaction are also contemplated but none of these mechanisms have ever been proven as being responsible.

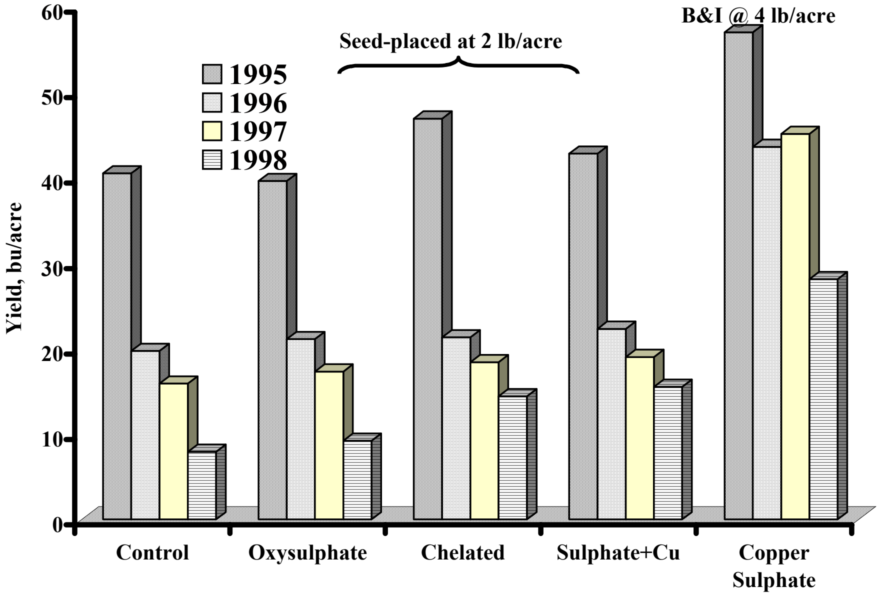

Figure 13. Yield responses to annual application of seed-placed and broadcast and incorporated copper products at Lacombe, Alberta.

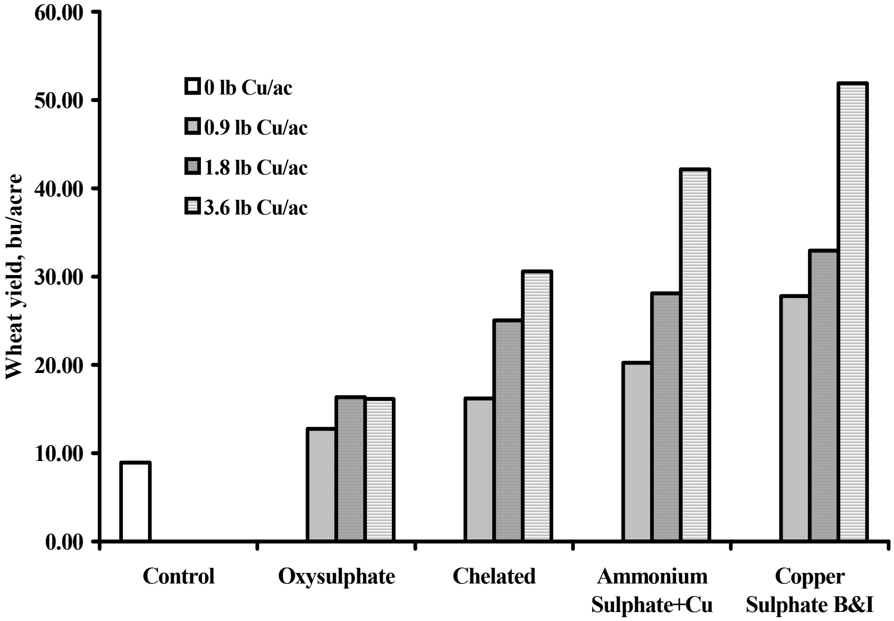

Figure 14. Yield responses of wheat grown on residual treatments of seed-placed and broadcast and incorporated copper products at Lacombe, Alberta in 1999.

Micronutrient Products

Nutting (2000) examines the choice and availability of micronutrient products in western Canada in general and in Manitoba in particular, elsewhere in these proceedings. Mention of products here is only in relation to the agronomic practices examined. A summary of the recommended methods of application of some general categories of products is provided in Table 3.

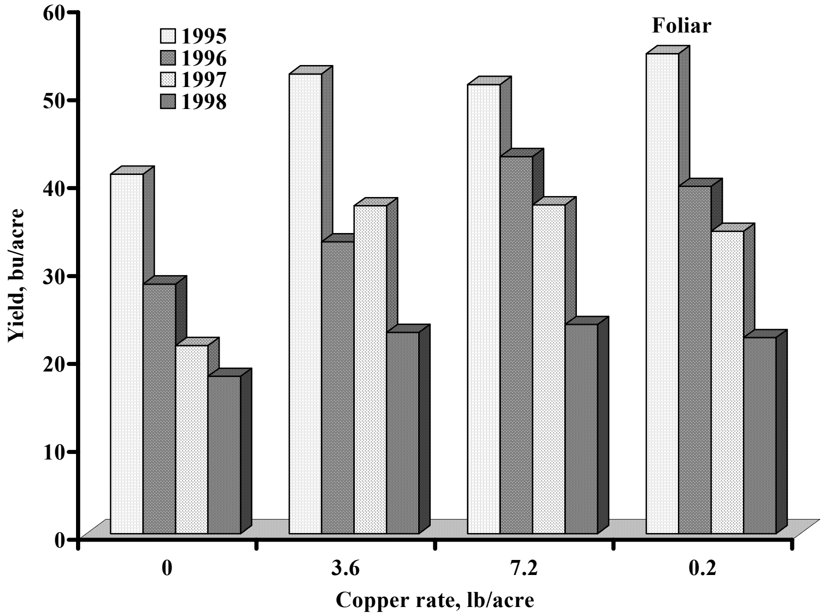

Figure 15. Comparison of foliar to broadcast and incorporated application of copper.

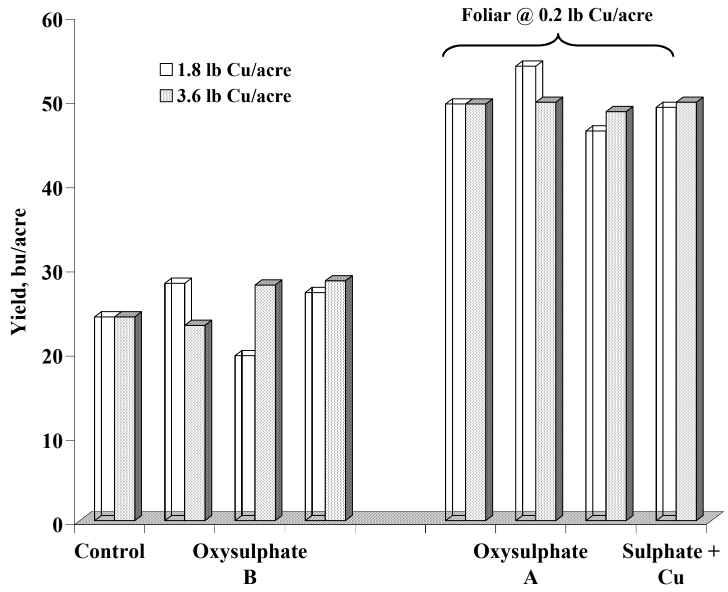

Figure 16. Application of foliar copper alleviates copper deficiency as a result of the inability of seed-placed copper to correct the deficiency.

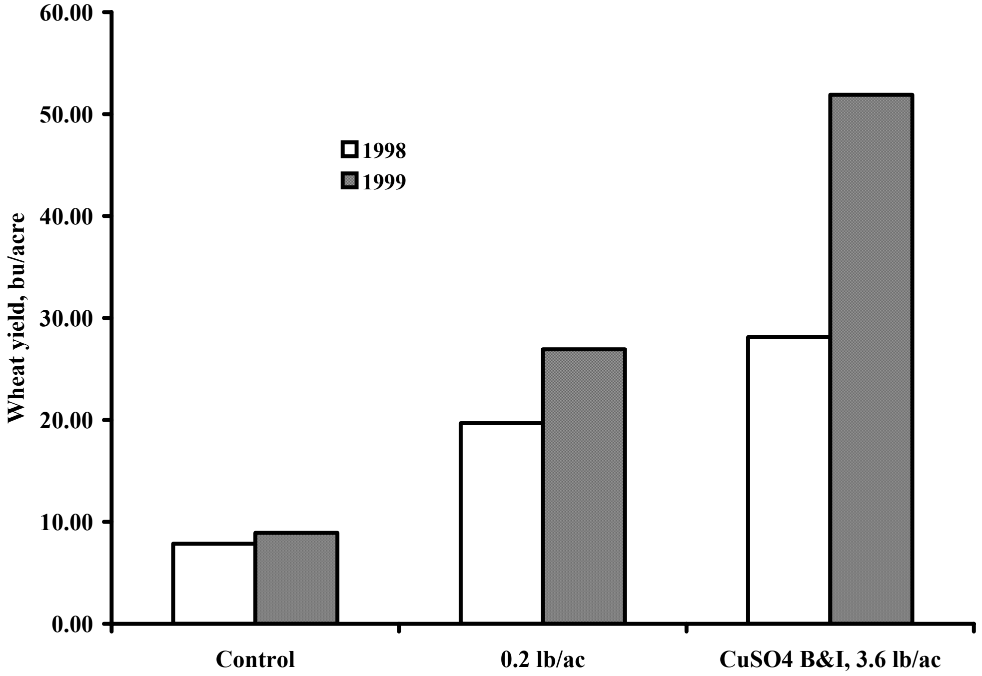

Figure 17. Application of foliar copper to a severely deficient copper crop cannot completely alleviate copper deficiency.

Table 3. Recommended methods of application of generalized categories of micronutrients products.

Nutrient	Fertilizer form	Time of soil application	Broadcast & Incorporate	Band	Seed-place	Foliar	Selected References
Copper	Sulphate	Spring or fall	3.5 –5 lb Cu/acre	Not recomm.	Not recomm.	Not recomm.[1]	Karamanos et al. 1985b Karamanos et al. 1986 Penney et al. 1988
	Oxysulphate <50% solubility	Fall	5 lbCu/acre	Not recomm.	Not recomm.	Not recomm.	Karamanos et al. 1986 This paper
	Chelated	Spring	0.5 lb Cu/acre	Not recomm.	Needs verification	0.2-0.25 lb Cu/acre	Karamanos et al. 1985b Karamanos et al. 1986 Penney et al. 1988 This paper
Zinc	Sulphate	Spring or fall	3.5 –5 lb Zn/acre	Not recomm.	Not recomm.	Not recomm.	Singh et al. 1987
	Oxysulphate <50% solubility	Fall	5-10 lb Zn/acre	Not recomm.	Not recomm.	Not recomm.	Westfall et al. 1998
	Chelated	Spring	1 lb Zn/acre	Not recomm.	Needs verification	0.3-0.4 lb Zn/acre	Karamanos et al. 1984b Singh et al. 1986
Manganese	Sulphate	Spring	50-80 lb Mn/acre[2]	Not recomm.	4-20 lb Mn/acre	Not recomm.	Karamanos et al. 1984a Karamanos et al. 1985 b Karamanos et al. 1991
	Chelated	Spring	Not recomm.	Not recomm.	Not recomm.	0.5 – 1 lb Mn/acre	Karamanos et al. 1984a Karamanos et al. 1985 b Karamanos et al. 1991
Boron	Sodium Borate	Spring	0.5 –1.5 lb B/acre	Needs verification	Not recomm.	0.3 – 0.5 lb/acre	Karamanos et al. 1984a

[1] Although foliar applications of copper sulphate are effective, the product is extremely corrosive.

[2] Broadcast and incorporated rates of manganese are generally uneconomical

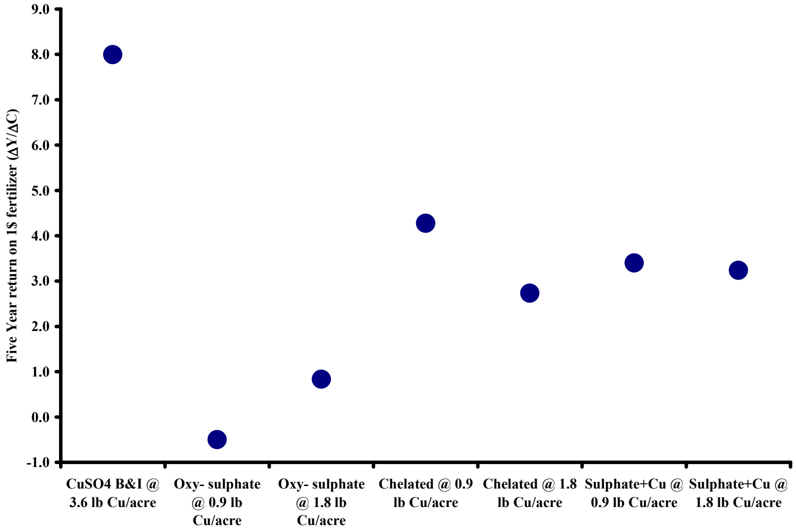

Figure 18. Five-year economic returns of seed-placed and broadcast and incorporated copper products at Lacombe, Alberta in 1999.

Are Micronutrients Needed on Micronutrient Sufficient Soils for "Optimum" Balance to Achieve Maximum Yields?

The mean results of nineteen maximum yield experiments carried out by Western Co-operative Fertilizers Limited between 1989 and 1998 in an attempt to achieve 200 bushels of barley are shown in Figure 19. The average yield in these experiments was 160 bu/acre and average yield increase of over 100 %. The overall benefit of "non-targeted" application of micronutrients was insignificant.

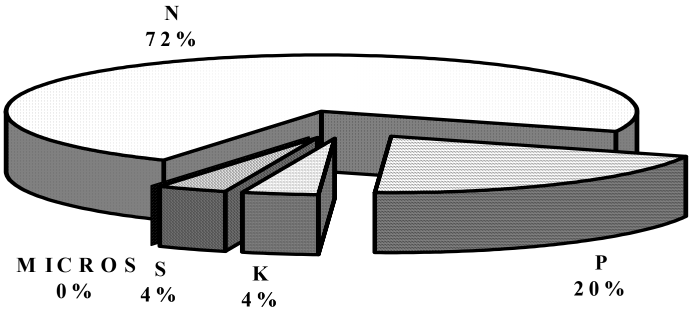

Figure 19. Average contribution of essential nutrients to the yield increase of barley.

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