MICRONUTRIENTS IN NORTHERN CLIMATES

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Introduction

Early work on micronutrients in northern US dates back to the late thirties and early forties and dealt primarily with boron (B) (Cook 1939; Cook and Millar 1940; Pierre and Allaway 1941). In Manitoba, it was initiated in 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 and Racz 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 kg of actual Cu ha^{-1} to the soil (broadcast and incorporated) is effective on Cu deficient soils, therefore, yearly applications of 1 to 1.5 kg Cu ha^{-1} (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 northern climates, which for the purpose of this paper include western Canadian prairies and especially Manitoba, Montana, North Dakota, South Dakota, Minnesota, Illinois, Wisconsin and Michigan.

Identification of Micronutrient Deficient Environments

In spite of the soil and/or plant tissue criteria utilized by various laboratories, 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 agroecological conditions of the regions involved. Often criteria imported from other regions are irrelevant to the conditions or crop varieties in the region. The methodology and criteria in use for assessment of each micronutrient is discussed below.

Boron

Earlier studies on boron (B) 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 B levels in soils. Hot-water extractable boron (HWEB), 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 mg kg^{-1} soil are generally considered as deficient (Sims and Johnson 1991). Recent work (Karamanos et al. 2003b) demonstrated that canola did not respond to B application on 40 sites, even on soils containing <0.15 mg kg^{-1} HWEB and with control canola yields of up to 3530 kg ha^{-1} (63 bu/acre), thus suggesting that responses to B are rare on prairie soils and in any event hot water extractable B is not an appropriate index to identify B deficiencies (Figure 1).

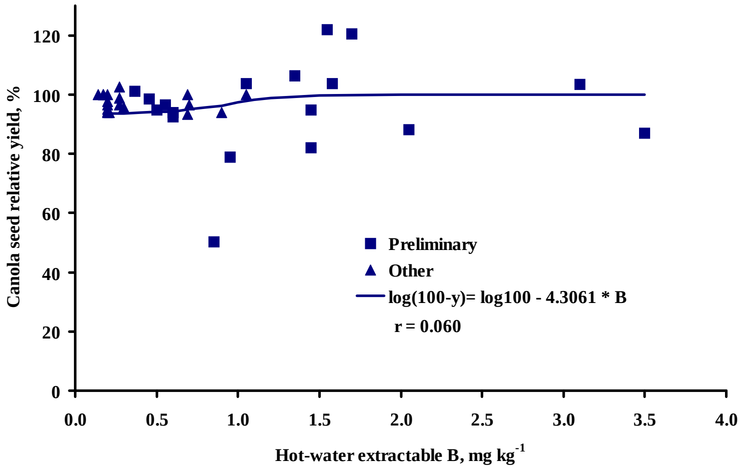

Figure 1. Relative yield of canola (*Brassica napus*) in relation to hot-water extractable boron levels in the 0-15 cm depth of forty-two sites across western Canada (Karamanos et al. 2003b).

Inclusion of hot-water extractable levels in the 0-30 cm or 0-60 cm depth did not improve the correlation with relative canola seed yields significantly.

In Minnesota, a response to B is expected on soils that have a sandy loam, loamy sand, or sand texture and low organic matter content (Rehm et al. 2002). Boron deficiencies have not been identified in Iowa, where corn is the primary crop (Sawyer 2004), but have been identified in Illinois and Michigan on light textured soils especially when alfalfa and specialty crops are grown (Hoeft 2004; Vitosh et al. 1997) and are considered the most common micronutrient deficiencies in Wisconsin (Kelling 1999).

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).

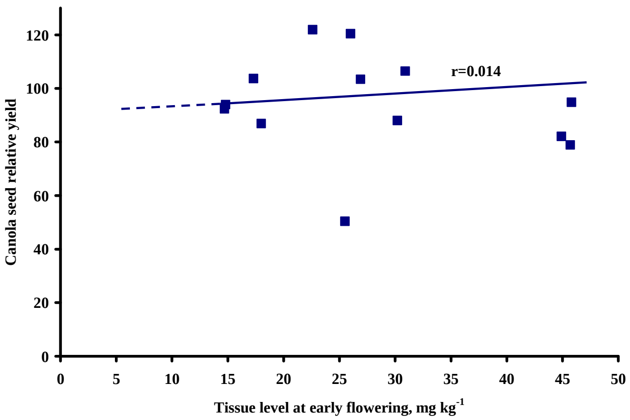

Figure 2. Relative yield of canola (*Brassica napus*) in relation to plant tissue levels at early flowering of eighteen sites across western Canada in 1999 (Karamanos, 2000).

Copper

Approximately 2.2 million hectares have been identified as potentially deficient in copper in western Canada (Penney et al. 1988, Kruger et al. 1985); of those, approximately 250,000 hectares are organic (peat) soils and studies by Reid (1982), Tokarchuk (1982), Hartman (1992) and Karamanos et al. (1985a;1991) established that Cu deficiency is a major limitation to small grain production. Copper responses of crops grown on organic soils have been documented in other areas of North-Central US (Nelson et al. 1956; Rehm and Schmitt 2002a). Recently, Malhi and Karamanos (2006) carried out a review of Cu fertilizer management for optimum yield and quality of crops in the Canadian Prairie Provinces. The authors indicated that sensitivity of crops to Cu deficiency is usually in the order of (wheat, flax, canary seed) > (barley, alfalfa) > (timothy seed, oats, corn) > (peas, clovers) > (canola, rye, forage grasses) and offered strategies to alleviate the impact of Cu deficiency on crop growth. Copper fertilization has recently been found to prevent Fusarium Head Blight in North Dakota, although yield responses have been inconsistent (Franzen et al. 2008).

Mineral soils

Karamanos et al. (1986) developed a critical level of 0.4 mg kg^{-1} soil for spring wheat and 0.35 mg kg^{-1} soil for canola grown on northern Great Plains 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. Karamanos et al. (1985b) proposed marginal range of 0.4-0.8 and 0.4-0.6 mg kg^{-1} soil for Gray and Brown soils, respectively. In Manitoba, soils are generally considered as containing sufficient levels of Cu except possibly the Almasippi loamy fine sands and Gilbert sandy loams. Goh and Karamanos (2006) established that in those soils DTPA-extractable Cu levels of less 0.2 mg kg^{-1} soil are deficient, whereas DTPA-extractable Cu levels of greater than 0.2, but less than 0.4 mg kg^{-1} are marginal. This is similar to a critical level of 0.3 mg kg^{-1} soil that was derived from data from earlier research by Ridley et al. (1985) that were fitted in a Mitcherlich type of growth curve.

A compilation of research data on wheat barley and canola from northern Great Plains is shown in Figures 3, 4 and 5, respectively. Compilation of data from field studies from a number of independent sources (Karamanos et al. 2003a) lead to confirmation of 0.4 mg kg^{-1} soil as a critical level for wheat and barley (Figures 3 and 4). A critical level of 0.3 mg kg^{-1} soil for canola was derived from Figure 56. 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 mg kg^{-1} soil using data from individual plots of two separate experiments. 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.

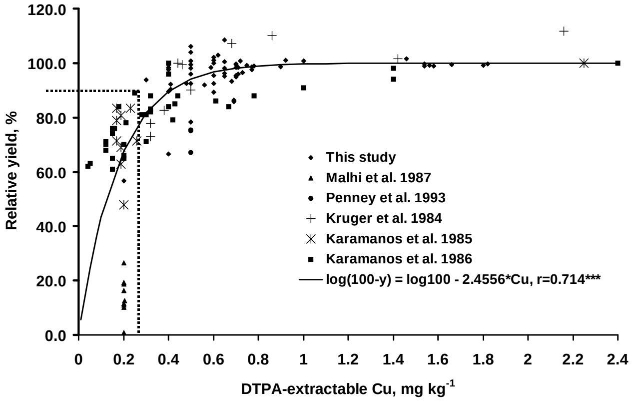

Figure 3. Relative yield of wheat (Triticum aestivum) in relation to DTPA-extractable copper levels in the 0-15 cm depth of soils across western Canada (Karamanos et al. 2003a).

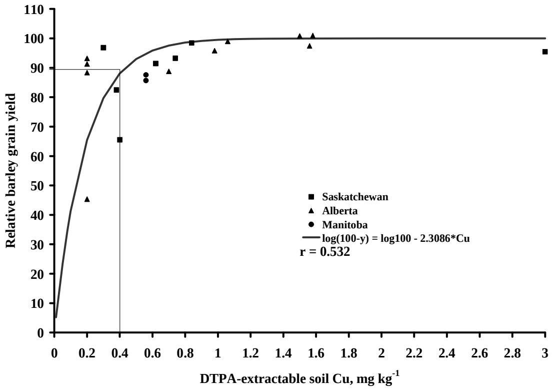

Figure 4. Relative yield of barley (*Hordeum vulgaris*) in relation to DTPA-extractable copper levels in the 0-15 cm depth of soils across western Canada.

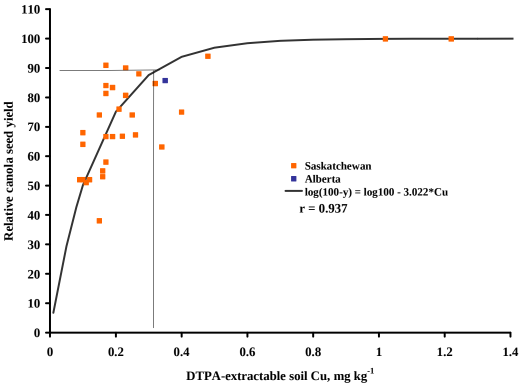

Figure 5. Relative yield of canola (*Brassica napus*) in relation to DTPA-extractable copper levels in the 0-15 cm depth of soils across western Canada.

Organic soils

Early work in Wisconsin (Nelson et al 1956) suggested sugar beet and especially oat crops essentially could not be grown on organic soils with Cu additions; the authors reported decreasing response in the order wheat, barley, oats, corn, carrots, red beets, onions, spinach, alfalfa, and cabbage. In Manitoba it was also 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 mg kg^{-1} soil with marginal levels occurring between 8 and 16 mg kg^{-1} soil. The data from this work were re-drawn in a Mitcherlich type growth curve (Figure 6). A critical level of 5 mg kg^{-1} soil was thus derived.

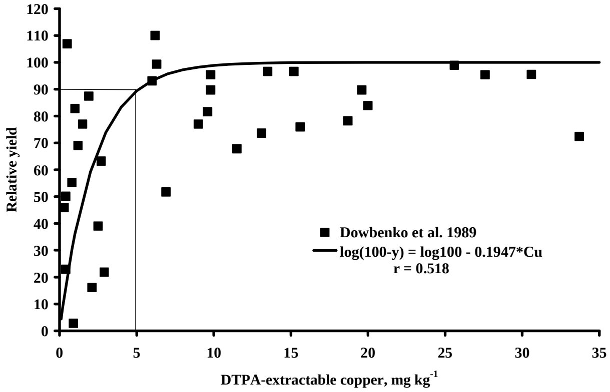

Figure 6. Relative yield of wheat (*Triticum aestivum*) in relation to DTPA-extractable copper levels in the 0-15 cm depth of organic soils in Manitoba (data re-drawn from Dowbenko et al. 1989).

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

Iron research in the region is scant in relation to other micronutrients either because the parent material from which soils in the region have been developed is rich in this micronutrient or the soil pH is high enough to self-eradicate any Fe deficiency. Hoeft (2004) reported that often Fe deficiency is indeed confused with Mn, as symptoms tend to be similar. Although soil pH could be a good predictor of possible Fe deficiency responses to Fe are not well correlated to soil test Fe. Presence of lime in the soil may induce iron chlorosis, which is common in North-Central US soils (Inskeep and Bloom, 1984; Franzen and Richardson, 2000; Goos and Johnson 2000; Hansen et al. 2003, Petersen 2007). Goos and Johnson (2000) concluded that cultivar selection was the most practical control measure for Fe-deficiency chlorosis of soybean grown in narrow rows. Screening of some 130 soybean cultivars for resistance to Fe deficiency is ongoing at North Dakota State University (Goos 2009).

Molybdenum

Early research focused on developing methodology for identifying molybdenum (Mo) deficient soils (Haley and Melsted 1957). There are anecdotal reports of molybdenum deficiency in vegetable crops and alfalfa, however there are documented 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 1982; 1985).

Manganese

Responses of common crops to manganese on mineral soils in the eastern Great Plains are extremely rare. Therefore, researchers have been unable to compile enough soils and/or sites to carry out calibration work. Responses of soybeans growing on calcareous soils to Mn in North Dakota have been reported as a result of Mn induced deficiency by FeEDDHA and low soil temperature (Moraghan 1985). In Illinois, soybeans and oats grown on strongly alkaline soils often exhibit Mn deficiency symptoms (Hoeft 2004) but available tests are not correlated to crop yield responses. 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 corn (McGregor et al. 1974; Grunes et al. 1961; Racz 1967; Smid and Spratt 1974b Rehm et al. 1984; Rehm and Schmitt 2002b; Varsa et al. 2005; Hernandez et al. 2005; 2006), beans (McKenzie 1979; McKenzie et al. 1999; Goh and Karamanos 2004), and flax (Smid and Spratt 1974a; Grant 1988), wheat (Nyaki and Racz 1989). McGregor (1972) suggested that soils containing less than 1.3 mg DTPA-Zn kg^{-1} soil may be suspect of being Zn deficient, while soils containing 0.8 mg DTPA-Zn kg^{-1} soil were moderately Zn deficient. Singh et al. (1987) carried out 17 field trials on soils containing as low as 0.25 mg DTPA-extractable Zn kg^{-1} soil but were unable to verify the commonly used critical level of 0.5 mg kg^{-1} soil 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 mg kg^{-1} soil, the authors concluded that the critical level for cereals (except corn) on prairie soils is no greater than 0.25 mg kg^{-1} soil. 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. Recently, Goh and Karamanos (2004) confirmed 0.5 mg kg^{-1} soil as a critical level for Zn deficiency in beans in Manitoba.

What Does a Marginal Micronutrient Soil Test Mean?

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 7 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 was seriously questioned by Karamanos et al. (2003a), who compiled data from 115 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 87 percent of cases on “deficient” soils. The range of responding “marginal” soils was from 0.41 to 0.66 mg DTPA-Cu kg^{-1} soil with an average of 0.59±0.08 mg kg^{-1} soil, whereas non-responding “marginal” soils contained 0.41 to 1.2 mg kg^{-1} soil with an average of 0.68±0.16 mg kg^{-1} soil. In contrast, the range of responding “deficient” soils was from 0.04 to 0.4 mg kg^{-1} soil with an average of 0.24±0.09 mg DTPA-Cu kg^{-1} soil. There were virtually no “economic” responses to Cu application on “marginal” soils and those on “deficient” soils were sensitive to the price of wheat and very much dependent on soil texture.

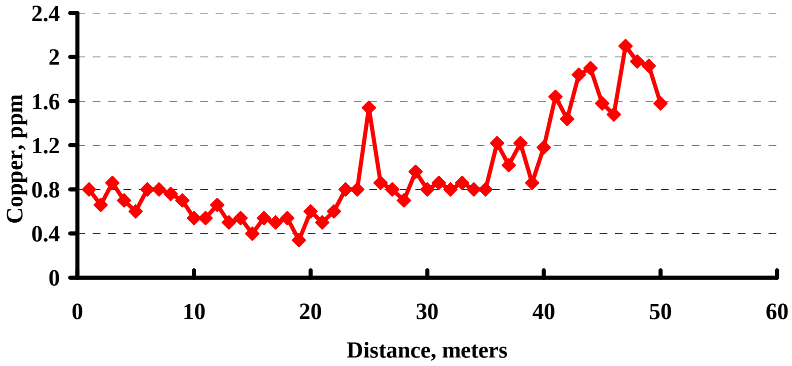

Figure 7. Distribution of DTPA-extractable Cu in the A horizon of a 46 m transect of soil sampled every meter (adapted from Singh et al. 1985).

Summary of Interpretive Criteria for Western Canadian Prairie Soils

A summary of interpretive criteria for micronutrient soil tests carried is presented in Table 1.

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 8.

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 9. 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 1997).

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

Nutrient	Extraction method	Crop(s)	Level, mg kg^{-1} soil	Description	Comments	Economic benefit
Boron	Hot-water	All	Unknown	Inappropriate method of assessment when SOM >1.5%	Criterion of 0.35 mg kg^{-1} soil irrelevant	None
			>3.5	Toxic	Unconfirmed	--
Copper	DTPA[1]	Cereals	<0.3	Deficient	Sandy to loamy soils	60-80% probability >95% when <0.2 mg kg^{-1} soil
			0.3-0.6	Marginal	Sandy to loamy soils	<10% probability
		Oilseeds	<0.2	Deficient	Sandy soils	<25% probability
			0.2-0.4	Marginal	Sandy soils	None
Manganese[2]	DTPA	All	Unknown	Other areas 1 mg kg^{-1} soil	Not adequately calibrated	None on mineral soils
Iron	DTPA	All	Unknown	Other areas 4.5 pp mg kg^{-1} soil m	Not adequately calibrated	
Zinc	DTPA	Cereals, oilseeds	<0.25	Marginal	Inappropriate method of assessment	<10% probability
		Beans and corn	<0.5	Deficient	Calibrated	75% probability
			0.5-1.0	Marginal		50% probability

[1] Lindsay (1991)

[2] Strong Mn X Cu interaction on organic soils.

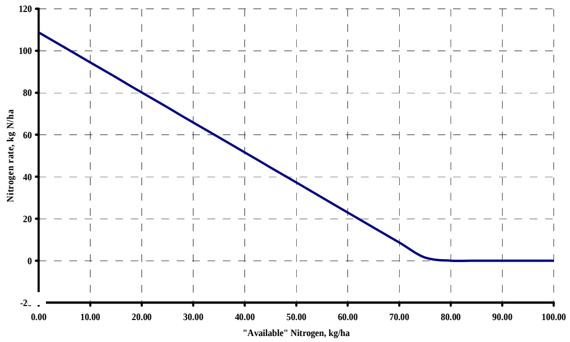

Figure 8. An example of mean N application rate as a function of N soil testing levels.

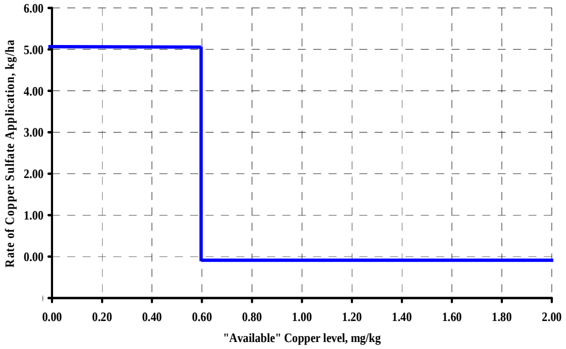

Figure 9. Cu application rate as a function of Cu soil testing levels.

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

Crop	Boron	Copper	Manganese	Molybdenum	Zinc
Alfafla	Medium	**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 10 and 11).

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.

Micronutrient Products

A summary of the recommended methods of application of some general categories of products is provided in Table 3.

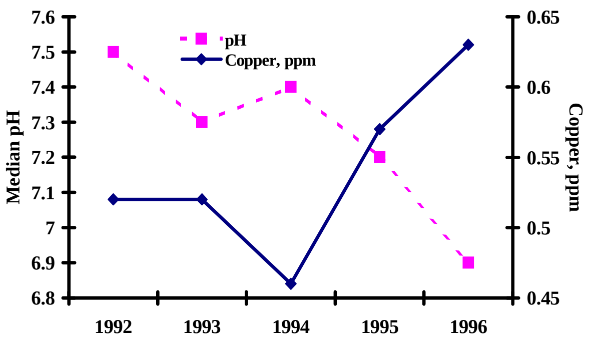

Figure 10. Relationship between mean "DTPA-available" copper and median pH in the soils of northeast Saskatchewan.

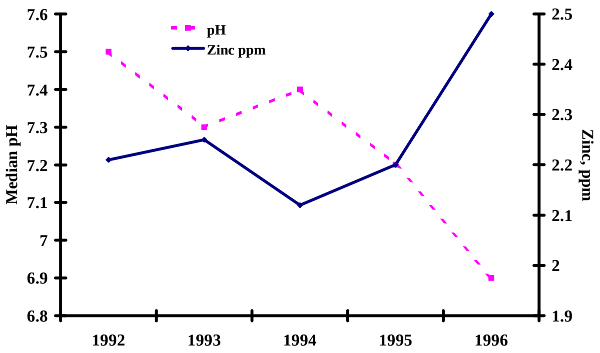

Figure 11. Relationship between mean "DTPA-available" zinc and median pH in the soils of northeast Saskatchewan.

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

A number of either soil or foliar applied multi-micronutrient products that are extensively used in other parts of the world have penetrated the western Canadian market based on the premise that their use aids a holistic approach to growing crops. Further claims address an optimum "balance" of all nutrients and especially micronutrients in achieving maximum yields.

Karamanos and Flore (2000) carried out thirteen experiments with wheat and twenty-one with barley from 1989 to 1994 to ascertain whether "targeted" or "non-targeted" use of a single foliar application of 15-20-20 (Table 8) provided an effective means of alleviating micronutrient deficiencies or simply increased yield due to a "balanced" nutrition. A product with similar analysis (18-20-20, identical micronutrient content) is currently marketed in western Canada. Application of 15-20-20 to wheat and barley crops resulted in statistically significant yield increases in two of thirteen, five of twenty-one, respectively (Figures 12 and 13).

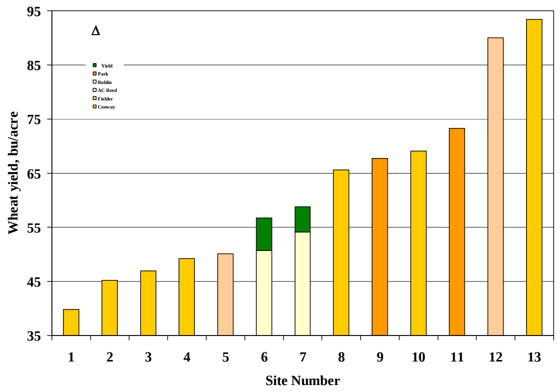

Fig. 12. Responses of wheat to foliar application of 15-20-20.

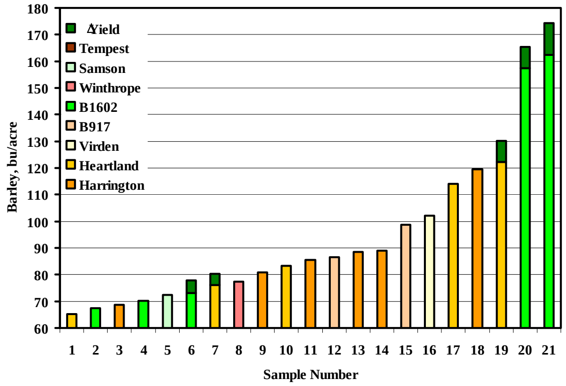

Fig. 13. Responses of barley to foliar application of 15-20-20.

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	Sulfate	Spring or fall	3.5 –5 kg Cu ha^{-1}	NR[a,b]	NR	NR	Karamanos et al. 1985b Karamanos et al. 1986 Penney et al. 1988
	Oxysulfate <50% solubility	Fall	5 kg Cu ha^{-1}	NR	NR	NR	Karamanos et al. 1986 Karamanos et al. 2005
	Chelated	Spring	0.5 kg Cu ha^{-1}	NR.	0.5 kg Cu ha^{-1}	0.2-0.25 kg Cu ha^{-1}	Karamanos et al. 1985b, 1986, 2004 Penney et al. 1988 Pomareski et al. 2003
Zinc	Sulfhate	Spring or fall	3.5 –5 kg Zn ha^{-1}	2 kg ha^{-1}	NR	NR.	Singh et al. 1987
	Oxysulfate <50% solubility	Fall	5-10 kg Zn ha^{-1}	NR	NR	NR	Westfall et al. 1998
	Chelated	Spring	1 kg Zn ha^{-1}	2 kg ha^{-1}	Needs verification	0.3-0.4 kg Zn ha^{-1}	Karamanos et al. 1984b Singh et al. 1986
Manganese	Sulfate	Spring	50-80 kg Mn ha^{-1}[c]	NR	4-20 kg Mn ha^{-1}	NR	Karamanos et al. 1984a Karamanos et al. 1985b, 1991
	Chelated	Spring	NR.	NR.	NR	0.5 – 1 kg Mn ha^{-1}	Karamanos et al. 1984a Karamanos et al. 1985b, 1991
Boron	Sodium Borate	Spring	0.5 –1.5 kg B ha^{-1}	Needs verification	NR	0.3 – 0.5 kg ha^{-1}	Karamanos et al. 1984a

[a] NR = not recommended.

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

[c] Broadcast and incorporated rates of manganese are generally uneconomical.

Table 4. Nutrient content of the product used in the study.

Constituents		Stage of application	Rate of application
N 15%	Fe 0.10%	Tillering and Boot stage	5.5 kg ha^{-1}
P 15%	Mn 0.10%		
K 20%	B 0.08%		
S 2%	Mo 0.0005%		
Cu 0.15%	Zn 1.00%		

Economic returns, excluding application cost, are shown in Figures 14 and 15. "Non-targeted" application of micronutrient mixes at all sites to provide a "balanced" nutrition of crops proved both agronomically inefficient and economically nonviable under western Canadian conditions. Yield increases were both small and unpredictable even when exceptionally high yields were obtained and are similar to those obtained in a study with 23 experiments where two cent coins were thrown on a plot to simulate a "$5.50 per acre treatment" (Figure 16) and were contrasted to an "untreated" control, i.e., they represent random events not related to the treatment (Karamanos and Flaten 2004).

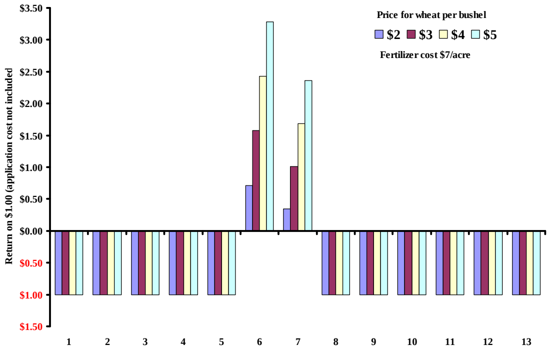

Fig. 14. Responses of barley to foliar application of 15-20-20.

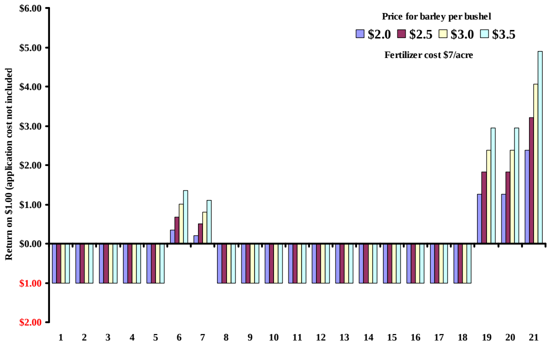

Fig. 15. Responses of barley to foliar application of 15-20-20.

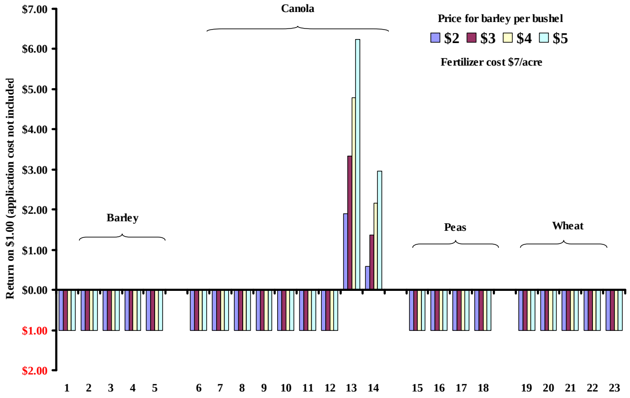

Fig. 16. Responses of crops to "two-penny" per plot treatment.

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