Feasibility of copper fertilization for optimum crop yield in the Canadian Prairies

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Background

In the Canadian prairie soils, deficiency of Cu is not widespread but whenever it occurs it can cause a drastic reduction in seed yield and quality of most cereals, especially wheat. In wheat, Cu deficiency symptoms include yellowing and curling of young leaves, pigtailing of leaf tips, limpness or wilting, delay in heading, aborted heads and spikelets, head and stem bending, as well as stem melanosis disease in certain wheat cultivars.

In organic (peat) soils, Cu deficiency is a major limitation to small grain production and often these soils respond dramatically to Cu fertilization. In mineral soils, Cu deficiency usually occurs in coarse textured soils, in irregular patches within fields. In Saskatchewan, approximately 1 million acres are estimated to be potentially deficient in Cu for optimum yield. For economic reasons, a reliable prediction of plant-available Cu in soil during the crop growing period is needed in order apply Cu fertilizers at appropriate rates, using proper Cu sources (Table 1). In western Canada, DTPA-extractable Cu is a good measure of available Cu in soil. Seed yield response of wheat to Cu fertilizer is expected in soils containing $< 0.4$ ppm Cu (Figure 1). However, soil tests for Cu do not always provide an accurate indication of available Cu in soil, especially on soils mildly deficient in Cu or soils with heavy texture. For example, Cu deficiency symptoms and seed yield response of wheat to Cu fertilizer has been also observed on soils containing 0.8 mg Cu kg\(^{-1}\); on the other hand, clay soils with Cu levels below the critical level did not respond to Cu additions. In-crop assessment of Cu deficiency also has potential to improve crop yield. Visual symptoms usually occur when the crop is moderately to severely lacking in Cu. In addition, visual symptoms can be confused with those caused by herbicide injury or frost. Nevertheless, visual diagnostic can be an effective tool when combined with soil and tissue testing (Table 2). Plant tissue testing can also be used to determine Cu deficiency in plants, but information provided by this method may be too late to correct the Cu deficiency problem and restore seed yield to the optimum level for the current crop.

Crop species vary in their sensitivity to Cu deficiency, cereals being more sensitive than other crops (Tables 3 and 4). Furthermore, cultivars within the various cereal crops species differ in their sensitivity to Cu deficiency. Increasing supply of P, N and Zn can increase severity of Cu deficiency in crops. High levels of P, Zn, Fe, Mn and Al in soil can restrict Cu absorption by plant roots and induce Cu deficiency in crop plants, and high level of N in soil can delay the translocation of Cu in crop plants. Application of N alone to a situation of mild Cu deficiency (absence of visual Cu deficiency symptoms) can result in severe Cu deficiency symptoms and loss of seed yield. This is most likely due to delay in translocation of Cu from older leaves to new leaves, thus enhancing the severity of Cu
deficiency.

**Table 1. Characteristics of Cu fertilizer products used in field experiments**

<table>
<thead>
<tr>
<th>Cu fertilizer product</th>
<th>Trade name</th>
<th>Chemical formulation</th>
<th>Cu content or concentration</th>
<th>Product producer or distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu lignosulphonate (granular)</td>
<td>Micro Tech</td>
<td>Cu lignin sulphonate</td>
<td>5%</td>
<td>RSA Micro Tech, Seattle, WA, USA</td>
</tr>
<tr>
<td>Cu sulphate (granular)</td>
<td>Copper sulphate</td>
<td>Cu SO$_4$SH$_2$O</td>
<td>25%</td>
<td>Pestell Minerals and Ingredients, New Hamburg, ON, Canada</td>
</tr>
<tr>
<td>Cu oxysulphate I (granular)</td>
<td>Cu 15% Micro Mix</td>
<td>Cu treated with H$_2$SO$_4$</td>
<td>15%</td>
<td>Cameron Chemicals, Inc., Portsmouth, VA, USA</td>
</tr>
<tr>
<td>Cu oxysulphate II (granular)</td>
<td>Frits-220G</td>
<td>Cu treated with H$_2$SO$_4$</td>
<td>20%</td>
<td>Frit Industries, Ozark, AL, USA</td>
</tr>
<tr>
<td>Cu chelate-EDTA liquid</td>
<td>Tiger EDTA</td>
<td>Cu EDTA$^2$</td>
<td>93.5 g/L</td>
<td>Tiger Industries, Calgary, AB, Canada</td>
</tr>
<tr>
<td>Cu sequestered I (liquid)</td>
<td>Tiger foliar</td>
<td>Cu complexed with lignin sulphonate</td>
<td>61.1 g/L</td>
<td>Tiger Industries, Calgary, AB, Canada</td>
</tr>
<tr>
<td>Cu sulphate/chelate (granular dissolvable)</td>
<td>Pro-Sol Cu CAC</td>
<td>Copper sulphate citric acid EDTA</td>
<td>20%</td>
<td>Frit Industries, Ozark, AL, USA</td>
</tr>
<tr>
<td>Cu sequestered II (liquid)</td>
<td>PhosynCoptrel 500</td>
<td>Cu oxychloride</td>
<td>500 g/L</td>
<td>Phosyn Canada, Grand Falls, NB, Canada</td>
</tr>
</tbody>
</table>

$^2$The use of trade names, proprietary produce or vendor does not imply endorsement by authors or Agriculture and Agri-Food Canada.

**Figure 1.** Yield increase of wheat for deficient (■, DTPA-Cu <0.4 ppm) and sufficient (▲, DTPA-Cu >0.4 ppm) soils (adapted from: Karamanos, R. E. and Goh, T. B. 2004. Effect of rate of copper application on the yield of hard red spring wheat. Comm. Soil Sci. Plant Anal. 35: 2037-2047).

Deficiency of Cu is also associated with crop diseases. In the Canadian prairies,
spring wheat (cv. Park) grown on Cu-deficient soils was found highly susceptible to stem melanosis, which was effectively controlled by the application of Cu (Tables 3 and 4). Incidences of other diseases of wheat, such as take-all, powdery mildew and ergot, have been reduced when Cu was added to Cu-deficient soils: however, Cu deficiency in itself is not the cause of these diseases. Wilting of leaves in alfalfa has also been induced by Cu deficiency in soil. This report summarizes results of Cu fertilizer management experiments conducted in the Canadian Prairies to prevent and/or control Cu deficiency in crops for optimum yield.

Table 2. Copper concentration (ppm Cu) in whole plant (WP) and youngest fully emerged leaf (YFEL) of barley at mid-tiller (GS 25) to stem elongation (GS 39) from Cu-responsive and non-responsive sites (prepared from Solberg et al. 1996)

<table>
<thead>
<tr>
<th>Site</th>
<th>DTPA-extractable Cu in soil (ppm Cu)</th>
<th>Cu-responsive sites</th>
<th>DTPA-extractable Cu in soil (ppm Cu)</th>
<th>Non-responsive sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YFEL Cu- Cu+ YFEL Cu- Cu+ WP Cu- Cu+ WP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.5 3.2 3.2 2.9 2.9 0.5</td>
<td>5.3 5.2 2.8 2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.5 3.4 4.0 3.0 2.9 0.6</td>
<td>6.7 6.5 3.6 3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.7 3.7 5.5 3.1 2.8 1.8</td>
<td>5.0 5.6 3.5 3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.5 4.9 4.8 3.0 3.1 0.3</td>
<td>6.5 6.4 3.5 3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.55 3.8 4.4 3.0 2.9 0.80</td>
<td>5.9 5.9 3.3 3.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Comparisons of six wheat cultivars for stem melanosis severity and seed yield with and without added copper in a field experiment on a Black Chernozemic sandy loam soil at Lacombe, Alberta in 1985 (prepared from Piening et al. 1989)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Disease severity (%)</th>
<th>Seed yield (bu/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without Cu With Cu</td>
<td>Without Cu With Cu</td>
</tr>
<tr>
<td>Wheat</td>
<td>Park</td>
<td>100 96</td>
<td>0.1 22.7</td>
</tr>
<tr>
<td></td>
<td>Neepawa</td>
<td>15 8</td>
<td>0.2 29.3</td>
</tr>
<tr>
<td></td>
<td>Leduc</td>
<td>0 0</td>
<td>58.9 63.2</td>
</tr>
<tr>
<td></td>
<td>Galt</td>
<td>0 0</td>
<td>50.9 51.3</td>
</tr>
<tr>
<td></td>
<td>Klages</td>
<td>0 0</td>
<td>37.0 81.6</td>
</tr>
<tr>
<td></td>
<td>Bonanza</td>
<td>0 0</td>
<td>59.4 67.2</td>
</tr>
<tr>
<td>Barley</td>
<td>Dumont</td>
<td>0 0</td>
<td>26.7 66.4</td>
</tr>
<tr>
<td></td>
<td>Cascade</td>
<td>0 0</td>
<td>38.3 60.4</td>
</tr>
<tr>
<td></td>
<td>Athabasca</td>
<td>0 0</td>
<td>49.8 65.9</td>
</tr>
<tr>
<td></td>
<td>Calibre</td>
<td>0 0</td>
<td>37.7 72.1</td>
</tr>
</tbody>
</table>

Table 4. Comparison of cultivars of cereals for stem melanosis severity and seed yield with and without added copper in a field experiment on a Cu deficient Black Chernozemic sandy loam soil at Lacombe, Alberta in 1986 (prepared from Piening et al. 1989)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Disease severity (%)</th>
<th>Seed yield (bu/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without Cu With Cu</td>
<td>Without Cu With Cu</td>
</tr>
<tr>
<td>Wheat</td>
<td>Park</td>
<td>100 96</td>
<td>0.1 22.7</td>
</tr>
<tr>
<td></td>
<td>Neepawa</td>
<td>15 8</td>
<td>0.2 29.3</td>
</tr>
<tr>
<td></td>
<td>Leduc</td>
<td>0 0</td>
<td>58.9 63.2</td>
</tr>
<tr>
<td></td>
<td>Galt</td>
<td>0 0</td>
<td>50.9 51.3</td>
</tr>
<tr>
<td></td>
<td>Klages</td>
<td>0 0</td>
<td>37.0 81.6</td>
</tr>
<tr>
<td></td>
<td>Bonanza</td>
<td>0 0</td>
<td>59.4 67.2</td>
</tr>
<tr>
<td>Barley</td>
<td>Dumont</td>
<td>0 0</td>
<td>26.7 66.4</td>
</tr>
<tr>
<td></td>
<td>Cascade</td>
<td>0 0</td>
<td>38.3 60.4</td>
</tr>
<tr>
<td></td>
<td>Athabasca</td>
<td>0 0</td>
<td>49.8 65.9</td>
</tr>
<tr>
<td></td>
<td>Calibre</td>
<td>0 0</td>
<td>37.7 72.1</td>
</tr>
</tbody>
</table>
Summary of Findings

Prevention and/or correction of Cu deficiency in crops on Cu-deficient soils has a dramatic effect on seed yield and quality of cereals, especially wheat, and occasionally yield increases up to 400% are observed with Cu fertilization. Source, rate, formulation, time and method of Cu application, and proper balancing of Cu with P, Mn, N or other nutrients in soil all affect seed yield of wheat on Cu-deficient soils. Where Cu deficiency in soil is expected in advance, seed yields are usually optimized with broadcast/incorporation application of granular Cu fertilizers at 2.7-5.06 lb Cu/acre at seeding on most soils (Table 5). Soil incorporation of granular Cu fertilizers up to 1.8 lb Cu/acre was not generally effective in increasing seed yield of wheat in the year of application, but it became effective after three annual applications. Surface-broadcast application of granular Cu fertilizers without incorporation was much less effective in preventing Cu deficiency and improving seed yield of wheat than incorporated Cu fertilizers. The requirement of Cu for optimum seed yield and quality on Cu-deficient soils tended to increase with increasing amount of P in soil and rate of applied P.

Table 5. Seed yield response of wheat to broadcast and incorporation of different rates of granular Cu fertilizers on Cu-deficient soils (prepared from Solberg et al. 1996; Flaten 2002; Karamanos et al. 2005; Malhi et al. 2005)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cu source</th>
<th>Seed yield (bu/acre) at Cu rates (lb Cu/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karamanos et al. 2005</td>
<td>Cu sulphate</td>
<td>0.0 1.8 3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49.8 59.1 59.4</td>
</tr>
<tr>
<td>Flaten 2002</td>
<td>Cu sulphate</td>
<td>0.0 5.0 10.0</td>
</tr>
<tr>
<td></td>
<td>Cu sulphate</td>
<td>2.8 8.3 8.3</td>
</tr>
<tr>
<td></td>
<td>Cu sulphate</td>
<td>3.1 12.1 14.2</td>
</tr>
<tr>
<td>Malhi et al. 2005</td>
<td>Cu lignin sulphonate</td>
<td>0.0 0.4 1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.3 23.5 27.1</td>
</tr>
<tr>
<td>Solberg et al. 1996</td>
<td>Cu sulphate</td>
<td>0.0 5.0 10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.5 43.5 49.8</td>
</tr>
<tr>
<td></td>
<td>Cu sulphate</td>
<td>0.0 2.5 5.0 7.5 10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.5 22.6 29.3 30.2 29.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.3 32.4 28.5 33.9 32.3</td>
</tr>
</tbody>
</table>

Compared to granular Cu fertilizers, surface spray broadcast application followed by incorporation of solution Cu fertilizers into the soil at 0.45 to 1.8 lb Cu/acre was found much more effective in preventing Cu deficiency and increasing wheat seed yield in the year of application (Table 6). Seedrow-placed granular Cu affords neither agronomically nor does economically acceptable yield increase; however, chelated product can provide maximum yields, albeit at a greater cost compared to broadcast and incorporation. The findings also suggest that seed dressing or banding is not a desirable method of application for Cu fertilizers, because it reduces availability of Cu to plant roots due to poor distribution of granules with low rates of Cu fertilizer. Some Cu fertilizers (e.g., Cu oxide) were not effective in increasing seed yield in the year of application, and were still generally less...
effective than other fertilizers even after a series of annual applications (Table 7). Application of Cu fertilizers at high initial rates can maintain or build-up Cu levels in soils and give residual benefits for a number of years (Table 8).

If Cu deficiency in wheat appears during the growing season, foliar application of Cu fertilizer at low rates (about 0.18-0.25 lb Cu/acre) between first node visible (Feekes 6) and flag-leaf can be used to correct Cu deficiency and restore seed yield considerably (Table 9). But foliar applications at very early or very late growth stages were not effective or much less effective. In some cases on soils with extreme Cu deficiency, two foliar applications (one at late tillering or first node formation and the other at flag-leaf or boot stage) of Cu fertilizer or a combination of both soil and foliar applications were found to produce maximum seed yield.

The sensitivity of crops to Cu deficiency is usually in the order of (wheat, flax, canary seed) > (barley, alfalfa) > (timothy seed, oat, corn) > (peas, clovers) > (canola, rye, forage grasses) (Solberg et al. 1996). Spring wheat was most sensitive to stem melanosis, while other cereals were not affected by this disease. Stem melanosis in wheat was associated with deficiency of Cu in soil and the disease was reduced substantially with application of Cu fertilizer (Tables 3 and 4).

Soil analysis for DTPA-extractable Cu in soil can be used as a good diagnostic tool to predict Cu deficiency on Cu-deficient soils, but the soil test may not provide reliable prediction of Cu fertilizer recommendation for optimum yield and economic returns on $ invested on Cu fertilizer on soils with soil tests above the critical level of 0.4 ppm Cu (Table 10). Plant tissue testing usually had a poor relationship between total Cu concentration in shoots and degree of Cu deficiency, but youngest leaves gave higher correlation than whole plants.

**Conclusions**

For immediate correction of Cu deficiency in wheat, foliar application of low rates of some Cu fertilizers at late tillering to flag-leaf growth stage can be used, but soil incorporation of Cu fertilizers prior to seeding is suggested for optimum seed yield. Since Cu deficiency in crops often occurs in irregular patches within fields, foliar application may be the most practical way to correct Cu deficiency in wheat during the growing season.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cu source</th>
<th>Rate (lb Cu/acre)</th>
<th>Seed yield (bu/acre) with different placement methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Broadcast-incorporated</td>
<td>Sidebanded</td>
</tr>
<tr>
<td>Karamanos et al. 2005</td>
<td>Cu sulphate</td>
<td>3.6 Yr-1</td>
<td>48.9(^z)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6 Yr-2</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6 Yr-3</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6 Yr-4</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yr-5(^x)</td>
<td>23.1</td>
</tr>
<tr>
<td>Malhi et al. 2005</td>
<td>Cu lignosulphonate</td>
<td>Yr-1</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yr-2</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yr-3</td>
<td>18.8</td>
</tr>
<tr>
<td>Karamanos et al. 2004</td>
<td>Cu sulphate</td>
<td>Yr-1</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yr-2</td>
<td>19.5</td>
</tr>
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<td></td>
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<td>Yr-3</td>
<td>19.3</td>
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<tr>
<td></td>
<td></td>
<td>Yr-4</td>
<td>14.3</td>
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<tr>
<td></td>
<td></td>
<td>Yr-5(^x)</td>
<td>18.3</td>
</tr>
<tr>
<td>Malhi et al. 2005</td>
<td>Cu lignosulphonate</td>
<td>Plus Foliar</td>
<td>0.2 lb/acre</td>
</tr>
<tr>
<td></td>
<td>Cu chelate</td>
<td>1.8</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Cu sulphate</td>
<td>8.9</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td>4.4</td>
</tr>
<tr>
<td>Flaten 2002</td>
<td>Cu sulphate</td>
<td>3.1</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0 lb Cu/acre</td>
<td>12.1</td>
</tr>
<tr>
<td>Karamanos et al. 2005</td>
<td>Cu sulphate</td>
<td>Control</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Broadcast-incorporated</td>
<td>10.0 lb Cu/acre</td>
</tr>
</tbody>
</table>

\(^z\)Average of control for three placement treatments.  
\(^y\)Residual effect only in year 5.  
\(^x\)Third year of a 3-year experiment with annual seedrow application of Cu.  
\(^+\)Feekes 6 = first node visible.  
\(^\)Feekes 10 = sheath of last leaf completely out.
Table 7. Effect of Cu sources on seed yield of wheat on Cu-deficient soils (prepared from Flaten 2003b; Karamanos et al. 2004; Malhi et al. 2005)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method of application</th>
<th>Rate of Cu (lb Cu/acre)</th>
<th>Seed yield (bu/acre) from different Cu sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oxysulphate</td>
</tr>
<tr>
<td>Karamanos et al. 2004</td>
<td>Seedrow-placed</td>
<td>0</td>
<td>40.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8</td>
<td>39.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td>Broadcast-incorporated</td>
<td>3.6</td>
<td>57.0</td>
</tr>
<tr>
<td></td>
<td>Seedrow-placed</td>
<td>0</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9</td>
<td>14.8</td>
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<td>1.8</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>18.7</td>
</tr>
<tr>
<td>Flaten et al. 2003</td>
<td>Broadcast-incorporated</td>
<td>0</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Broadcast</td>
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<td></td>
<td>5.0</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Malhi et al. 2005</td>
<td>Broadcast-incorporated</td>
<td>1.8 Yr-1</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8 Yr-2</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8 Yr-3</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>Seedrow-placed</td>
<td>0.9 Yr-1</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9 Yr-2</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.9 Yr-3</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>Foliar flag-leaf</td>
<td>0.22 Yr-1</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22 Yr-2</td>
<td>24.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22 Yr-3</td>
<td>18.8</td>
</tr>
</tbody>
</table>
Table 8. Residual effect of copper chelate applied at 2.7 lb Cu/acre in 1984, on stem melanosis incidence and seed yield of Park wheat grown in 1985 to 1987 on a Cu-deficient Black Chernozemic sandy loam soil at Lacombe, Alberta soil (prepared from Malhi et al. 1989)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Percent disease</th>
<th>Seed yield (bu/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>3</td>
<td>45</td>
</tr>
<tr>
<td>Cu + Zn</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Cu + NPK</td>
<td>8</td>
<td>36</td>
</tr>
<tr>
<td>Cu + Zn + NPK</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>Zn</td>
<td>76</td>
<td>97</td>
</tr>
<tr>
<td>Zn + NPK</td>
<td>76</td>
<td>100</td>
</tr>
<tr>
<td>NPK</td>
<td>70</td>
<td>97</td>
</tr>
<tr>
<td>Control</td>
<td>78</td>
<td>93</td>
</tr>
<tr>
<td>LSD&lt;sub&gt;0.05&lt;/sub&gt;</td>
<td>26</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 9. Effect of time of foliar application of Cu fertilizers (0.18-0.25 lb Cu/acre) on seed yield of wheat on Cu-deficient soils (prepared from Solberg et al. 1996; Karamanos et al. 2004; Malhi et al. 2005)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cu source</th>
<th>Seed yield (bu/acre) with foliar-applied Cu at different growth stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malhi et al. 2005</td>
<td>Cu chelate Yr-1</td>
<td>Control 23.3 Cu at 4-leaf 27.4 Cu at flag leaf 40.3</td>
</tr>
<tr>
<td></td>
<td>Cu chelate Yr-2</td>
<td>Control 24.1 Cu at 4-leaf 36.3 Cu at flag leaf 39.8</td>
</tr>
<tr>
<td></td>
<td>Cu chelate Yr-3</td>
<td>Control 18.8 Cu at 4-leaf 44.9 Cu at flag leaf 39.3</td>
</tr>
<tr>
<td>Solberg et al. 1996</td>
<td>Cu chelate</td>
<td>Control 9.5 Cu at 4-leaf 40.1 Cu at flag leaf 12.0</td>
</tr>
<tr>
<td></td>
<td>Cu sulphate</td>
<td>Control 9.5 Cu at 4-leaf 32.8 Cu at flag leaf 8.0</td>
</tr>
<tr>
<td>Karamanos et al. 2004</td>
<td>Cu citric acid</td>
<td>Control 34.1 Cu at 4-leaf 47.7 Cu at flag leaf 51.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control 19.5 Cu at 4-leaf 32.2 Cu at flag leaf 30.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control 18.3 Cu at 4-leaf 23.5 Cu at flag leaf 32.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control 3.4 Cu at 4-leaf 5.3 Cu at flag leaf 21.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control 17.3 Cu at 4-leaf 21.4 Cu at flag leaf 24.4</td>
</tr>
</tbody>
</table>

<sup>z</sup>Late boot refers to growth stage when one-fourth of the heads were out and heading refers to when all heads were out.

<sup>y</sup>Feekes 2, Fekes 6 and Fekes 10 growth stages refer to beginning of tillering, beginning of stem elongation and sheath of last leaf completely out, respectively.
Table 10. Effect of DTPA-extractable Cu in soil (0-6 in) and soil texture on seed yield of wheat and its response to applied Cu fertilizer (based on 115 experiments conducted in the three Prairie Provinces. (prepared from Karamanos et al. 2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Seed yield (bu/acre)</th>
<th>Return $ invested on Cu fertilizer at wheat price ($/bu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Cu</td>
<td>+ Cu</td>
</tr>
<tr>
<td>Soil Cu level (ppm Cu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0.4</td>
<td>27.6</td>
<td>40.6</td>
</tr>
<tr>
<td>0.4-0.8</td>
<td>42.6</td>
<td>46.8</td>
</tr>
<tr>
<td>&gt;0.8</td>
<td>53.2</td>
<td>52.9</td>
</tr>
<tr>
<td>Soil texture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loamy sand</td>
<td>36.5</td>
<td>54.2</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>18.0</td>
<td>35.1</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>29.0</td>
<td>38.8</td>
</tr>
<tr>
<td>Loam</td>
<td>51.6</td>
<td>53.7</td>
</tr>
</tbody>
</table>

Future Research Needs
The findings suggest the need for future research to consider ways of increasing dispersion/dissolution of Cu ions from granules and their uniform distribution into the soil, and to develop Cu fertilizer products/formulations that can be used on a commercial scale to prevent and/or correct Cu deficiency in the growing season and optimize seed yield and quality. Management decisions for use of Cu fertilizers should consider both immediate and long-term effects of Cu fertilizer on crop yield, seed quality and economics. Research is also required to determine the long-term effects of balanced application of Cu with P, Mn or N and other nutrients on accumulation and distribution of nitrate-N and other nutrients in the soil profile, along with nutrient, water and energy use efficiency. More research should be conducted in relation to soil/plant tissue testing issues. Copper deficiency in plants affects the amount of live pollen produced, which can result in partially filled or even empty heads on plants which are apparently healthy. This issue needs to be verified to find if Cu indeed is involved in pollination/fertilization, especially in grass species.

References


