Spring Wheat and Durum Yield and Disease Responses to Copper Fertilization of Mineral Soils

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ABSTRACT

Copper deficiency has been linked to the incidence of a number of wheat diseases. Canadian research on mineral soils has suggested that low Cu availability, as indicated in a DTPA extraction soil test, combined with low soil organic C and coarse textures may also result in Cu deficiency of cereals. The objective of this study was to determine the yield responses of spring wheat (*Triticum aestivum* L.) and durum [*T. turgidum* subsp. *durum* (Desf.) Husn.] to Cu fertilization, and to determine whether wheat leaf rust (*Puccinia triticina* Roberge ex Desmaz f. sp. tritica), tan spot [*Pyrenophora tritica-repentis* (Died.) Dreschler], and Fusarium head blight (*Fusarium graminearum* Schwabe) incidence and severity would be reduced with these treatments. Experiments were established from 1998–2000 on 17 spring wheat sites and three durum wheat sites throughout North Dakota. Disease ratings were recorded at 10 sites.

Most experiments were sited on coarse-textured soils with organic C levels less than 20 g kg^{-1}. Yield increases were detected at 5 of 20 sites, and decreases in yield were observed at two sites. Test weight was increased at one site, while Cu treatment increased protein at one site and decreased protein at two sites. Treatments did not affect leaf rust. Tan spot incidence was reduced at one of seven sites recording infection. Fusarium head blight incidence was reduced at four of nine infected sites and increased at one site. Fusarium head blight severity was reduced at four sites. The results suggest that amending low organic matter, sandy, low Cu soils may increase spring wheat and durum yield and reduce tan spot and Fusarium head blight incidence and severity.

Copper deficiency in wheat was recognized in the United States over 40 yr ago (Younts, 1964). The requirement of crops for Cu in North America has most often been recorded in organic soils, those soils having an organic C content of greater than 100 g kg^{-1} (Younts, 1964; Wallingford, 1977; Dowbenko et al., 1990). A series of field strip studies was conducted by Oplinger and Ohlrogge (1974) on a combination of mineral and organic soils that suggested possible yield responses from Cu fertilization in corn (*Zea mays* L.) and soybean [*Glycine Max* (L.) Merr.] in mineral soils; however, a companion study on mineral soils using replicated plot studies showed yield decreases from Cu application.

Kruger et al. (1985) found consistent Cu responses in several crops, including spring wheat, in the Gray Soil Zone of Saskatchewan, in soils characterized by coarse textures, and low organic C content. The study also resulted in a response curve for spring wheat, which established a critical DTPA (diethylene triamine pentaacetic acid) Cu level of about 0.6 mg kg^{-1} surface 15-cm soil depth. Penney and Solberg (1988) conducted a survey of archived Alberta soil sample data using the 0.6 g kg^{-1} Cu level established by Kruger et al. (1985) and found that about 29% of samples were in the deficient category. A Cu fertilization trial on barley (*Hordeum vulgare* L.) by Kruger et al. (1985) on a low organic matter sandy site did not result in a significant yield response; however test weight and kernel weight were increased.

A 10-yr study that included all three Canadian prairie provinces (Karamanos et al., 2003) resulted in reducing the critical DTPA Cu level to 0.4 g kg^{-1}. Eighty-seven percent of field sites experienced yield increases with either soil applied or foliar Cu application. In contrast, an oat (*Avena sativa* L.) experiment with Cu fertilization in North Dakota on four soils with low organic C, sandy loam texture, and soil DTPA Cu less than 1 g kg^{-1} did not result in yield responses (Mosset et al., 1984). Responses to Cu fertilization can also be complicated by differential varietal response (Owuoche et al., 1994), where increases in spring wheat yield were observed in only two of eight varieties on a responsive soil.

Wheat plants with insufficient Cu have been found to be susceptible to stem melanosis, which is caused by a bacteria, *Pseudomonas cichorii* (Swingle) Stapp (Piening et al., 1989). The presence of stem melanosis was used by Kruger et al. (1985) to identify fields with possible Cu deficiency.

Increased susceptibility of cereals to diseases when Cu was deficient was reviewed by Graham (1983), and included powdery mildew (*Erysiphe graminis* f. sp. *avenae*), tan spot, ergot [*Calviceps purpurea* (Fr.) Tul.], take-all (*Gaeumannomyces graminis*), and leaf rust. All of these diseases, except ergot, are diseases of leaf or stem tissue. Copper deficiency may play a role in increased infection because Cu is necessary for cell wall lig-

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Abbreviations: DTPA, diethylene triamine pentaacetic acid; EDTA, ethylene diamine tetraacetic acid.

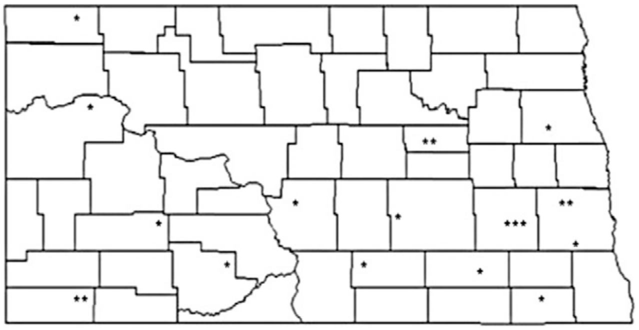

Fig. 1. Location of Cu study sites in North Dakota, 1998–2000. Each site is designated by *, with multiple asterisks indicating the number of sites within an area < 2 km in radius.

nification. When lignification is disrupted, cell walls are more susceptible to penetration by fungi (Graham, 1983).

In addition to affects on leaf disease susceptibility, evidence exists that pollen sterility and male sterility are enhanced when Cu is deficient in cereal crops (Graham, 1975). Copper-deficient plants produced smaller anthers, and the pollen had a high incidence of sterility. This might explain why a head disease of cereals, such as ergot, might have a higher incidence with Cu deficiency. If the flower is not pollinated, it has a tendency to remain open and susceptible to infection by spores of the ergot fungus for a longer time.

Fusarium graminearum Schwabe (the fungus causing head scab of wheat) is a disease organism that also infects wheat during pollination or flowering. This disease develops during periods of wet weather during flowering (McMullen and Stack, 1999). Australia and the western Canadian provinces have previously documented Cu deficiency in wheat, but not increased Fusarium head blight with Cu deficiencies. This may be due to the relatively dry or arid conditions in those regions that prevent Fusarium head scab infections. Currently there is no information available regarding the role of Cu nutrition in *Fusarium graminearum* incidence and severity.

Table 1. Site characteristics, 1999 Cu experiments.

North Dakota site	Wheat type†	Cultivar	Latitude	Longitude	OC‡	pH	DTPA Cu
					g kg^{-1}		g kg^{-1}
Charleson	D	Ben	47°59′4″ N	102°52′17″ W	33.0	7.9	0.7
New Leipzig	SW	Nora	46°28′31″ N	101°57′46″ W	31.0	6.6	1.3
Valley City	SW	NDSU 2375	46°31′5″ N	97°54′53″ W	12.0	7.3	0.4
Menoken	SW	NDSU 2375	46°54′46″ N	100°29′50″ W	35.0	7.5	0.5
Crosby	SW	McNeil	46°59′35″ N	103°9′28″ W	28.0	7.1	0.8
New Rockford	SW	NDSU 2375	47°39′10″ N	99°10′48″ W	22.0	7.3	0.3
Arthur	SW	NDSU 2375	47°6′39″ N	97°15′44″ W	26.0	8.3	0.5
Embden	SW	Oxen	46°51′44″ N	97°25′58″ W	20.0	7.9	0.3

† D = durum wheat, SW = spring wheat.

‡ OC, organic carbon.

Table 2. Site characteristics, 2000 Cu experiments.

North Dakota site	Wheat type†	Cultivar	Latitude	Longitude	OC‡	pH	DTPA Cu
					g kg^{-1}		g kg^{-1}
Taylor	SW	Keene	47°46′47″ N	102°24′44″ W	17.0	5.8	0.4
Napolean	SW	Oxen	46°29′48″ N	99°43′25″ W	37.0	7.4	0.5
Medina	SW	Butte 86	46°50′21″ N	99°17′53″ W	19.0	7.4	0.4
Valley City	SW	NDSU 2375	46°52′50″ N	97°54′53″ W	10.0	7.2	0.2
Valley City (1998)	SW	NDSU 2375	46°52′29″ N	97°54′31″ W	15.0	5.9	0.2
Rutland	SW	Russ	46°1′57″ N	97°58′31″ W	42.0	7.6	0.6
New Rockford	SW	NDSU 2375	46°40′1″ N	99°31′5″ W	18.0	7.3	0.4
Arthur	SW	NDSU 2375	47°7′16″ N	97°18′21″ W	16.0	6.2	0.2
Northwood	SW	Russ	47°45′36″ N	97°43′33″ W	20.0	6.7	0.4
Bowman (1999)	D	Ben	46°24′41″ N	103°8′31″ W	26.0	7.1	0.5
Bowman (2000)	D	Ben	46°24′40″ N	103°8′31″ W	17.0	5.8	0.4
LaMoure	SW	Russ	46°39′58″ N	98°9′46″ W	11.0	7.3	0.2

† D = durum wheat, SW = spring wheat.

‡ OC, organic carbon.

The objectives of the study were to determine the yield response frequency of spring wheat and durum wheat from Cu fertilization, and to determine the effect of fertilization on leaf rust, tan spot, and Fusarium head scab incidence and severity.

MATERIALS AND METHODS

A series of Cu fertilization studies were established from 1998 to 2000 at 20 sites (Tables 1 and 2; Fig. 1) in North Dakota. Fifteen of the soils selected for the studies were loamy sand to fine sandy loam in texture, with less than 30 g kg^{-1} organic C in the surface 15 cm. The experimental design for all sites was a randomized complete block. The 1998 study consisted of one site with two treatments, no Cu check and 5.6 kg ha^{-1} Cu as $CuSO_4$ 25% granules ($CuSO_4 \cdot 5H_2O$), applied preplant with eight replications. The 1999–2000 experiments consisted of six treatments: check, 1.4, 2.8, 4.2, 5.6 kg Cu ha^{-1} preplant as $CuSO_4$ (25% Cu) soil treatments, and a 0.56 kg ha^{-1} Cu as Cu–EDTA (ethylene diamine tetraacetic acid) foliar application at Feekes 4–5 leaf stage on plots not treated with a soil Cu amendment.

Individual plot treatment size was 3.04 m wide and 6.08 m long. Blocks were separated with 1.52-m alleys. The alleys were not mowed until the day of harvest. Dry granule treatments were applied by hand within a few days prior to planting. The corners of the entire plot area were located using a differential global positioning signal (DGPS) receiver, and large steel washers were buried at a 15-cm depth. All stakes from the area delineating individual plots and plot location were removed and the area was seeded as part of the farmer–cooperator's field. Following seeding, the plot area was located again and restaked using the DGPS information and a metal detector. The foliar treatment was applied using a hand sprayer, with the dissolved Cu chelate applied with 30.6 l ha^{-1} water at 276 kPa using a hollow-cone nozzle. The experiments were not treated with a fungicide. Disease that occurred did so naturally without inoculation.

Harvest was conducted using a plot combine with a 1.2-m cutting swath. The grain was collected, then forced air dried at 50°C for 2 d. The grain was then cleaned and weighed. Test weight was determined using a Fairbanks/Morse test weight apparatus with a 473-mL cup. Moisture was determined using a Burrows 700 digital moisture computer (Seedburo Equipment Co., Chicago, IL). Protein was determined using an Infra Tec1226 grain analyzer (Dresden, Germany).

The 1999 experiments were replicated eight times, and the 2000 experiments were replicated six times. Year 2000 yield and disease ratings were also obtained at a second site at Bowman where soil treatments were applied in 1999 as previously described, but the field was not seeded by the grower–cooperator in 1999 due to unusually wet conditions. Yield and disease ratings also were measured in spring wheat at the 1998 treatment site that was again seeded to spring wheat in 2000. These two sites are referred to as residual soil treatments. All study sites were fertilized with 112 kg ha^{-1} N as a combination of ammonium sulfate and urea, with enough ammonium sulfate to compensate for the different levels of sulfate in the $CuSO_4$ treatments, and the urea rate adjusted for the N contribution of ammonium sulfate. The treatments were incorporated and seeded by the farmer–cooperators using their choice of cultivar (Tables 1 and 2). Herbicide was applied at the discretion of the growers.

Table 3. Soil series at the 1999 Cu experimental sites.

North Dakota site	Soil series	Series description
Charleson	Williams l†	fine-loamy, mixed, superactive, frigid Typic Argiustolls
New Leipzig	Chama sil	fine-silty, mixed, superactive, frigid Typic Calciustolls
Valley City	Maddock sl	sandy, mixed, frigid Entic Hapludolls
Menoken	Manning fsl	coarse-loamy over sandy or sandy skeletal, mixed, superactive, frigid, Typic Haplustolls
Crosby	Williams l	fine-loamy, mixed, superactive, frigid Typic Argiustolls
New Rockford	Barnes fsl	fine-loamy, mixed, superactive, frigid Calcic Hapludolls
Arthur	Glyndon fsl	coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
Embden	Galchutt fsl	fine, smectitic, frigid, Vertic Argialbolls

† l = loam, sil = silt loam, sl = sandy loam, fsl = fine sandy loam.

Table 4. Soil series at the 2000 Cu experimental sites.

North Dakota site	Soil series†	Series description
Taylor	Shambo sl	fine-loamy, mixed, superactive, frigid Typic Haplustolls
Napolean	Williams l	fine-loamy, mixed, superactive, frigid Typic Argiustolls
Medina	Maddock sl	sandy, mixed, frigid Entic Hapludolls
Valley City	Maddock sl	sandy, mixed, frigid Entic Hapludolls
Valley City (1998)	Arvilla sl	sandy, mixed, frigid Calcic Hapludolls
Rutland	Forman l	fine-loamy, mixed, superactive, frigid Calcic Argiudolls
New Rockford	Arvilla sl	sandy, mixed, frigid Calcic Hapludolls
Arthur	Hecla sl	sandy, mixed, frigid Oxyaquic Hapludolls
Northwood	Arvilla sl	sandy, mixed, frigid Calcic Hapludolls
Bowman (1999)	Telfer sl	sandy, mixed, frigid Entic Hapludolls
Bowman (2000)	Telfer sl	sandy, mixed, frigid Entic Hapludolls
LaMoure	Eckman ls	coarse-loamy, mixed, superactive, Calcic Hapludolls

† sl = sandy loam, l = loam, ls = loamy sand.

In 1999, four sites were rated for foliar and head disease. At these four sites, the first four of eight blocks were rated for disease. Time constraints with the crop scouts conducting the readings did not allow for the rating of all eight blocks. In 2000, six sites, which included the residual Cu application from the 1998 Valley City site, were rated for disease. In 2000, all blocks were rated for disease. Disease ratings were made at Feekes 11.2 (soft dough stage), approximately 3 wk after pollination. Leaf scores for leaf rust and tan spot were made on flag leaves of 20 plants from the middle two rows of the plots using an estimate of flag leaf area affected by disease. The assessment was made using a modified James key (James, 1971) by L. Francl, North Dakota State University (unpublished work, 1995). Fusarium head blight disease ratings were similarly taken on 20 plants from the middle two rows of each plot. Fusarium head blight incidence was recorded as the percentage of 20 plants that showed any sign of the disease on the heads. Fusarium head blight severity was the percentage of kernels within the heads, using a modified Horsfall and Barrett (1945) scale developed by Stack and McMullen (1998, p. 1095).

Relevant soil analysis and soil series descriptions for the 1999 sites are shown in Tables 1 and 3. Relevant soil analysis and soil series descriptions for the 2000 sites, the 1998 residual site at Valley City, and the 1999 residual site at Bowman are available in Tables 2 and 4.

SAS 9.1 for windows was used for data analysis (SAS Institute, 2003, Cary, NC). Soil samples at the 0- to15cm depth were obtained prior to Cu treatments in each plot and analyzed for DTPA-extractable Cu. Due to small-scale spatial structure of soil Cu at most of the sites (data not shown), PROC MIXED, REPEATED with spatial error measures model using spatial parameters developed within GS+ 5.0 for Windows (Gamma Design Software, Plainwell, MI) was used to analyze the data. Use of this procedure accounts for spatial errors within each experiment not addressed with blocking. LS Means (least square means) were generated. A P level $\leq$0.05 was used to detect treatment differences at all sites unless otherwise indicated.

Table 5. *F* values of yield, protein, and test weight comparisons of untreated vs. any Cu treatment rates at the 1999 experimental sites.

Site	Yield	Test weight	Protein
Charleson	0.65	0.24	0.48
New Leipzig	0.11	0.28	0.36
Valley City	0.79	0.15	1.51
Menoken	2.08*+†	0.59	1.09
Crosby	2.62*+	0.16	0.69
New Rockford	3.18‡+	4.6*+	0.79
Arthur	0.96	1.41	0.55
Embden	1.57	1.86	0.41

* Significant at $P < 0.05$.

† + indicates a positive response.

‡ Significant at $P < 0.10$.

RESULTS AND DISCUSSION

Yield, test weight, and protein: There were yield differences between the check and the Cu treatments at 7 of 20 sites (Tables 5 and 6). Yields were increased at five sites with preplant Cu treatments, while yield was depressed at two sites (Taylor and Valley City, 1988) (Tables 7 and 8). The foliar treatment resulted in a yield increase at three sites and also decreased yield at one site. Test weight was increased at one site (New Rockford, 1999) with preplant treatment, but not the foliar treatment. The residual Cu treatment at Valley City (1998) increased protein in the Year 2000 experiment. Protein decreased at Rutland with the foliar treatment, but

Table 6. *F* values of yield, protein and test weight comparisons of untreated vs. any Cu treatment rates at the 2000 experimental sites.

Site	Yield	Test weight	Protein
Taylor	2.37*–†	1.93	0.84
Napolean	2.56*+ ‡	0.19	0.65
Medina	1.15	0.42	0.97
Valley City (2000)	0.95	0.54	1.13
Valley City (1998)	2.13§–	1.67	6.13*+
Rutland	0.75	0.46	2.13*–
New Rockford	1.88§+	0.96	0.72
Arthur	0.25	0.46	0.10
Northwood	0.67	1.08	0.20
Bowman (1999)	0.61	0.84	2.56*–
Bowman (2000)	0.27	0.69	1.5
LaMoure	0.74	0.78	0.85

* Significant at $P < 0.05$.

† – indicates a negative response.

‡ + indicates a positive response.

§ Significant at $P < 0.10$.

not with preplant Cu applications. The protein difference at Bowman (2000) was between the 4.2 kg ha^{-1} Cu treatment and the other Cu treatments. Therefore, only three sites recorded protein differences between the check and Cu applications, one being a positive response, and the other two negative.

Correlation of soil DTPA Cu analysis, organic matter, and surface texture of the soil series did not explain sites that responded positively to yield, protein and test weight and those that did not (data not shown). According to previous reports in Canada (Karamanos et al., 2003), a DTPA soil Cu level of 0.4 g kg^{-1} should provide a high level of confidence that a yield increase would be expected. However, of three sites in 1999 with Cu levels of 0.4 g kg^{-1} or less, only one resulted in a yield increase. Other sites with yield increases had Cu levels from 0.5 to 0.8 g kg^{-1}. Fifteen of twenty sites had organic C content below 30 g kg^{-1}. However, two of the six sites with yield increases from Cu treatments had organic C content higher than this. Fifteen of the twenty sites also had surface textures of fine-sandy loam or coarser, however, one site had a yield increase with a loam soil. From these data it is clear that yield increases, and occasionally yield decreases, are possible from Cu application from either foliar or soil treatments. However, the soil Cu analysis, soil textural class and organic C level were not consistent predictors of yield response. Based on yield and protein effects alone, application of Cu to soils with the general characteristics examined in this series of experiments (low organic matter, sandy-textured with soil DTPA Cu below 1 g kg^{-1}) would probably not be justified.

Table 7. Test weight and/or yield from sites that recorded significant responses to Cu application (1999).

	Cu treatment, kg ha^{-1}					
Site/component	0	1.4	2.8	4.2	5.6	0.56 foliar
Menoken/yield, kg ha^{-1}	2459 ab†	2379 a	2318 a	2641 b	2446 ab	2600 b
Crosby/yield, kg ha^{-1}	1431 a	1599 b	1525 ab	1626 b	1512 a	1666 b
New Rockford/yield, kg ha^{-1}	2016 ab	2049 ab	2211 b	1915 a	1888 a	1988 ab
New Rockford/test weight, kg m^{-3}	718 a	738 b	735 b	726 a	729 ab	724 a

† Values in the same row followed by the same letter are not significantly different at the probability level indicated in Table 5.

Table 8. Test weight and/or yield from sites that recorded significant responses to Cu application (2000).

	Cu treatment, kg ha^{-1}					
Site/component	0	1.4	2.8	4.2	5.6	0.56 foliar
Taylor/yield, kg ha^{-1}	2237 b†	2223 b	2170 ab	2029 a	2029 a	2002 a
Napolean/yield, kg ha^{-1}	1895 a	1988 b	2116 b	1760 a	1962 b	1915 b
Valley City (1998)/yield, kg ha^{-1}	2533 b	NI‡	NI	NI	2405 a	NI
Valley City (1998)/protein, mg kg^{-1}	139 a	NI	NI	NI	143 b	NI
Rutland/protein, mg kg^{-1}	158 b	158 b	158 b	158 b	158 b	156 a
New Rockford/yield, kg ha^{-1}	1975 a	2009 ab	2150 b	1955 a	2036 ab	2043 ab
Bowman (1999)/protein, mg kg^{-1}	144 ab	148 b	145 ab	142 a	149 b	144 ab

† Values in the same row followed by the same letter are not significantly different at the probability level indicated in Table 7.

‡ NI is treatment not included in study.

Table 9. Tan spot and incidence and severity of Fusarium head blight from sites that recorded significant responses to Cu application.

	Cu treatment, kg ha^{-1}					
Site/component	0	1.4	2.8	4.2	5.6	0.56 foliar
Valley City (1999)/ FI†, %	8.3 b‡	2.5 a	7.5 ab	4.2 ab	5.8 ab	2.5 a
Arthur (1999)/ FS, %	10.2 b	3.1 a	4.5 ab	4.7 ab	4.0 a	3.8 a
Embden (1999)/ FI, %	34.2 c	16.7 a	17.5 a	28.4 b	20.8 ab	23.4 ab
Valley City (1998)/ FI, %	63.7 b	NI§	NI	NI	32.5 a	NI
Valley City (1998)/ FS, %	22.1 b	NI	NI	NI	8.5 a	NI
New Rockford (2000)/FS, %	13.4 b	11.9 ab	9.2 ab	6.6 a	2.3 a	11.6 ab
Northwood (2000)/ TS, %	3.2 b	2.7 ab	1.5 a	1.2 a	1.3 a	2.0 ab
Northwood (2000)/ FI, %	9.8 b	10.3 b	7.2 ab	5.5 ab	2.7 a	7.8 ab
Northwood (2000)/ FS, %	0.8 ab	1.4 b	0.5 a	0.5 a	0.5 a	0.9 ab

† FI is Fusarium incidence, FS is Fusarium severity, TS is tan spot

‡ Values in the same row followed by the same letter are not statistically different at the probability level indicated in Table 9.

§ NI is treatment not included in study.

Leaf Disease: Disease ratings were obtained at four sites in 1999 and six sites in 2000. Several sites were not recorded in 2000, either because they had a complete absence of disease, or because a harvest desiccant was used that masked the presence of foliar disease. At three of the 6-yr (2000 sites), harvest desiccants prevented foliar disease ratings, however, Fusarium head blight ratings were still conducted. The sites where disease reductions were observed all had soil DTPA Cu levels of 0.4 kg ha^{-1} or below. Sites where Cu was above 0.4 kg ha^{-1} showed no disease affect from Cu fertilization.

Leaf rust was not affected by Cu treatments at any site. Tan spot was reduced with Cu treatments, including foliar, at Northwood. Since Cu fungicides are prophylactic in activity, and tan spot ratings were made on flag-leaves, any effect of foliar Cu applied at Feekes 4–5 on tan spot of the flag-leaf would have to be considered as nutritional, not fungicidal. Tan spot at Northwood ranged from 3.2% in the check to a range of 1.5 to 2.0% in soil applied and foliar treatments (Table 9). Tan spot ratings ranged from less than 5 to more than 50% between sites (data not shown), however, only one of these sites showed a response to Cu. These data agree with that of Graham (1983). Copper taken up by the roots can reduce the presence of tan spot. However, the data also show that relying on sufficient Cu to alleviate the risk of crop damage from tan spot is not reasonable. Although presence of tan spot was reduced at one site with Cu fertilization, other sites with lower or equal soil Cu levels were not affected. Reliance on Cu nutrition alone does not appear to be a viable strategy for leaf rust or tan spot prevention or cure.

Fusarium head blight: Differences in Fusarium head blight incidence were detected in 5 of 10 sites (Table 10). At four of these sites, incidence decreased with Cu treatment, while at one site, incidence increased (Arthur). At three of the positively responding sites, both foliar and soil-applied treatments decreased incidence. At one site (Northwood), only soil application decreased incidence.

Decreases in Fusarium head blight severity were detected at four sites with Cu treatment. Three of these sites were equally responsive to both foliar and soil applied treatments. One site (New Rockford) was only responsive to soil-applied Cu. Although the decreases in Fusarium are sometimes small, economic significance to growers may be large. In some years, a mycotoxin emitted by the fungus contaminates wheat and durum, decreasing its market value. Decreasing the disease below acceptable levels may have great economic value in some years (McMullen and Stack, 1999).

The frequency of positive responses for Cu application in the reduction of Fusarium head blight incidence and disease was much higher than for leaf diseases. No known work has been published on the role of Cu in the reduction of Fusarium head blight in wheat. These data support the possible role that Cu nutrition might have in suppressing this disease. The basis for a possible mechanism in disease reduction might be linked to male sterility and a longer time that the floret is open and vulnerable to infection with Cu deficiency (Graham, 1975). Wheat flowers that remain open for a longer time due to Cu deficiency during conditions favorable for disease infection would be more susceptible to infection and disease severity. In contrast to yield and protein, where surface soil texture, organic matter content and Cu did not seem to correlate well with yield increase, sandy texture, organic matter content less than 20 g kg^{-1}, and soil DTPA Cu less than 0.5 g kg^{-1}, were all present at sites with a reduction in Fusarium head blight measurements.

SUMMARY

The combined effect of Cu on yield, protein, tan spot, and Fusarium head blight incidence and severity, suggest that Cu nutrition of spring wheat and durum may need to be considered as part of a disease management plan. Although Cu did not eliminate Fusarium, its application reduced the disease at a number of sites. Soil application of Cu more consistently increased yield and decreased Fusarium head blight incidence and severity compared with foliar Cu. Foliar Cu application at Feekes 4–5 leaf stage must be considered more nutritional than fungicidal in regards to its effect on Fusarium, since it was applied before heading and is generally not considered a systemic fungicide.

Future research might investigate the combination of Cu soil application followed with a fungicide to determine whether the two combined strategies might improve plant health more than either one by itself. The literature regarding these interrelationships is nonexistent.

Table 10. *F* values between check and copper treatments in presence of leaf rust, tan spot, and incidence and severity of Fusarium head blight.

			Fusarium head blight	
Site	Leaf rust	Tan spot	Incidence	Severity
New Leipzig (1999)	NS†	NS	NS	NS
Valley City (1999)	NS	NS	2.12*+‡	NS
Arthur (1999)	NS	NS	None	2.56*+
Embden (1999)	NS	NS	3.47*+	NS
Medina (2000)			NS	NS
Valley City (1998)			29.7*+	48.4*+
Valley City (2000)	NS	NS	NS	NS
New Rockford (2000)	NS	NS	NS	2.45*+
Arthur (2000)			3.16*–§	NS
Northwood (2000)	NS	2.69*+	2.20*+	2.08*+

* Significant at $P < 0.05$, + indicates a positive response, – indicates a negative response.

† NS = nonsignificant at $P < 0.05$; blank entries indicate no measurements were possible.

‡ + indicates a positive response, which means that disease was decreased with Cu.

§ – indicates a negative response, which means that disease increased with Cu.

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