SECTION CONTENTS:

- **Introduction**
- **Micronutrient Nutrition**
- **Micronutrient Fertilizer Sources**
- **Application with Mixed Fertilizers**
- **Foliar Sprays**
- **Micronutrient Rates & Example Results**

Micronutrients

Micronutrients are elements which are essential for plant growth, but are required in much smaller amounts than those of the primary nutrients, nitrogen, phosphorus and potassium. The micronutrients are boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), and chloride (Cl). While chloride is a micronutrient, deficiencies rarely occur in nature, so discussions on supplying micronutrient fertilizers are confined to the other six micronutrients.

Deficiencies of micronutrients have been increasing in some crops. Some reasons are higher crop yields which increase plant nutrient demands, use of high analyses NPK fertilizers containing lower quantities of micronutrient contaminants, and decreased use of farmyard manure on many agricultural soils. Micronutrient deficiencies have been verified in many soils through increased use of soil testing and plant analyses.

Micronutrient Nutrition

A brief discussion of micronutrient functions and nutrient deficiency symptoms in plants and soil conditions affecting micronutrient availability serves to help understand their importance in crop production and to recognize symptoms of possible deficiencies.

Boron

A primary function of boron is related to cell wall formation, so boron-deficient plants may be stunted. Sugar transport in plants, flower retention and pollen formation and germination also are affected by boron. Seed and grain production are reduced with low boron supply. Boron-deficiency symptoms first appear at the growing points. This results in a stunted appearance (rosetting), barren ears due to poor pollination, hollow stems and fruit (hollow heart) and brittle, discolored leaves and loss of fruiting bodies. Boron deficiencies are mainly found in acid, sandy soils in regions of high rainfall, and those with low soil organic matter. Borate ions are mobile in soil and can be leached from the root zone. Boron deficiencies are more pronounced during drouth periods when root activity is restricted.

Copper

Copper is necessary for carbohydrate and nitrogen metabolism, so inadequate copper results in stunting of plants. Copper also is required for lignin synthesis which is needed for cell wall strength and prevention of wilting. Deficiency symptoms of copper are dieback of stems and twigs, yellowing of leaves, stunted growth and pale green leaves that wither easily.

Copper deficiencies are mainly reported on organic soils (peats and mucks), and on sandy soils which are low in organic matter. Copper uptake decreases as soil pH increases. Increased phosphorus and iron availability in soils decreases copper uptake by plants.

Iron

Iron is involved in the production of chlorophyll, and iron chlorosis is easily recognized on iron-sensitive crops growing on calcareous soils. Iron also is a component of many enzymes associated with energy transfer, nitrogen reduction and fixation, and lignin formation. Iron is associated with sulfur in plants to form compounds that catalyze other reactions. Iron deficiencies are mainly manifested by yellow leaves due to low levels of chlorophyll. Leaf yellowing first appears on the younger upper leaves in interveinal tissues. Severe iron deficiencies cause leaves to turn completely yellow or almost white, and then brown as leaves die.

Iron deficiencies are found mainly on calcareous (high pH) soils, although some acid, sandy soils low in organic matter also may be iron-deficient. Cool, wet weather enhances iron deficiencies, especially on soils with marginal levels of available iron. Poorly aerated or compacted soils also reduce iron uptake by plants. Uptake of iron decreases with increased soil pH, and is adversely affected by high levels of available phosphorus, manganese and zinc in soils.

Manganese

Manganese is necessary in photosynthesis, nitrogen metabolism and to form other compounds required for plant metabolism. Interveinal chlorosis is a characteristic manganese-deficiency symptom. In very severe manganese deficiencies, brown necrotic spots appear on leaves, resulting in premature leaf drop. Delayed maturity is another deficiency symptom in some species. Whitish-gray spots on leaves of some cereal crops and shortened internodes in cotton are other manganese-deficiency symptoms.

Manganese deficiencies mainly occur on organic soils, high-pH soils, sandy soils low in organic matter, and on over-limed soils. Soil manganese may be less available in dry, well-aerated soils, but can become more available under wet soil conditions when manganese is reduced to the plant-available form. Conversely, manganese toxicity can result in some acidic, high-manganese soils. Uptake of manganese decreases with increased soil pH and is adversely affected by high levels of available iron in soils.

Molybdenum

Molybdenum is involved in enzyme systems relating to nitrogen fixation by bacteria growing symbiotically with legumes. Nitrogen metabolism, protein synthesis and sulfur metabolism are also affected by molybdenum. Molybdenum has a significant effect on pollen formation, so fruit and grain formation are affected in molybdenum-deficient plants. Because molybdenum requirements are so low, most plant species do not exhibit molybdenum-deficiency symptoms. These deficiency symptoms in legumes are mainly exhibited as nitrogen-deficiency symptoms because of the primary role of molybdenum in nitrogen fixation. Unlike the other micronutrients, molybdenum-deficiency symptoms are not confined mainly to the youngest leaves because molybdenum is mobile in plants. The characteristic molybdenum-deficiency symptom in some vegetable crops is irregular leaf blade formation known as whiptail, but interveinal mottling and marginal chlorosis of older leaves also have been observed.

Molybdenum deficiencies are found mainly on acid, sandy soils in humid regions. Molybdenum uptake by plants increases with increased soil pH, which is opposite that of the other micronutrients. Molybdenum deficiencies in legumes may be corrected by liming acid soils rather than by molybdenum applications. However, seed treatment with molybdenum sources may be more economical than liming in some areas.

Zinc

Zinc is an essential component of various enzyme systems for energy production, protein synthesis, and growth regulation. Zinc-deficient plants also exhibit delayed maturity. Zinc is not mobile in plants so zinc-deficiency symptoms occur mainly in new growth. Poor mobility in plants suggests the need for a constant supply of available zinc for optimum growth. The most visible zinc-deficiency symptoms are short internodes (rosetting) and a decrease in leaf size. Chlorotic bands along the midribs of corn, mottled leaves of dry bean and chlorosis of rice are characteristic zinc-deficiency symptoms. Loss of lower bolls of cotton and narrow, yellow leaves in the new growth of citrus also have been diagnosed as zinc deficiencies. Delayed maturity also is a symptom of zinc-deficient plants.

Zinc deficiencies are mainly found on sandy soils low in organic matter and on organic soils. Zinc deficiencies occur more often during cold, wet spring weather and are related to reduced root growth and activity as well as lower microbial activity decreases zinc release from soil organic matter. Zinc uptake by plants decreases with increased soil pH. Uptake of zinc also is adversely affected by high levels of available phosphorus and iron in soils.

Chloride

Because chloride is a mobile anion in plants, most of its functions relate to salt effects (stomatal opening) and electrical charge balance in physiological functions in plants. Chloride also indirectly affects plant growth by stomatal regulation of water loss. Wilting and restricted, highly branched root systems are the main chloride-deficiency symptoms, which are found mainly in cereal crops.

Most soils contain sufficient levels of chloride for adequate plant nutrition. However, reported chloride deficiencies have been reported on sandy soils in high rainfall areas or those derived from low-chloride parent materials. There are few areas of chloride-deficient soils in the U. S., so this micronutrient generally is not considered in fertilizer programs. In addition, chloride is applied to soils with KCl, the dominant potassium fertilizer. The role of chloride in decreasing the incidence of various diseases in small grains is perhaps more important than its nutritional role from a practical viewpoint.

Plants differ in their requirements for certain micronutrients. The following table shows the estimate of the relative response of selected crops to micronutrients. The ratings of low medium and high are used to indicate the relative degree of responsiveness.

Crop Response to Micronutrients

Table 9.1: Relative Responsiveness of Selected Crops to Micronutrients

Crop	B	Cu	Mn	Zn
Alfalfa	High	Med	Low	Med
Apples	High	Med	Low	Med
Sugar Beet	High	Low	Low	Med
Cabbage	Med	Low	Med	Low
Citrus	Med	High	Med	Med
Clover	Med	Med	Low	Med
Corn	Med	Low	Low	High
Cotton	High	Low	High	Med
Grain Sorghum	Low	Med	Med	High
Grass	Low	Low	Low	Med
Lettuce	Med	High	High	Med
Oat	Low	Med	High	Med
Onion	Low	High	High	High
Peach	Med	Med	Med	High
Peanut	High	Low	Med	Low
Pecan	Med	Low	Low	High
Potato, Irish	Low	Med	Med	High
Potato, Sweet	High	Low	High	Med
Rye	Low	Low	Low	Med
Soybean	Low	Med	High	Med
Tobacco	Med	Low	Med	Med
Tomato	High	High	Med	Med
Wheat	Low	High	High	Low

Micronutrient Fertilizer Sources

Micronutrient sources vary considerably in their physical state, chemical reactivity, cost, and availability to plants. Some of the commonly used micronutrient sources are shown in Table 9.2.

Table 9.2: Micronutrient Fertilizer Sources

Source	Solubility in H_2O	Percent Element
	Boron	
H_3BO_3	Soluble	17
$Na_2B_4O_7.5H_2O$	Soluble	20
$Na_2B_4O_7.10H_2O$	Soluble	11
$Ca_2B_6O_{11}.5H_2O$	Slightly soluble	10
	Copper	
$CuSO_4.5H_2O$	Soluble	25
CuO	Insoluble	50-75
	Iron	
$FeSO_4.7H_2O$	Soluble	20
FeHEDTA	Soluble	5-9
FeEDDHA	Soluble	6
	Manganese	
$MnSO_4.4H_2O$	Soluble	24
MnO	Insoluble	41-68
Mn oxysulfate	Variable	30-50
	Molybdenum	
$Na_2MoO_4.2H_2O$	Soluble	39
$(NH_4)_2MoO_4$	Soluble	49
MoO_3	Soluble	66
	Zinc	
$ZnSO_4.H_2O$	Soluble	36
$ZnSO_4$ - NH_3 complex	Soluble	10-15
ZnO	Insoluble	60-78
Zn oxysulfate	Variable	18-50
ZnEDTA	Soluble	6-14

The four main classes of micronutrient sources are:

- inorganic products
- synthetic chelates
- natural organic complexes
- fritted glass products (frits).

Inorganic Sources

Inorganic sources include oxides and carbonates, and metallic salts such as sulfates, chlorides, and nitrates. The sulfates are the most common of the metallic salts and are sold in crystalline or granular form. An ammoniated $ZnSO_4$ solution also is used in polyphosphate starter fertilizers. Oxides of manganese and zinc also are commonly used, and are sold as fine powders and in granular form. Because oxides such as ZnO and MnO are water insoluble, their immediate effectiveness for crops is rather low in granular form. Also, the available divalent form of manganese in MnO will oxidize to the unavailable tetravalent form of manganese, so there is very little residual availability of manganese fertilizers for succeeding crops. Thus, agronomic effectiveness of granular MnO may be rather low. Since manganese in MnO_2 already is in the unavailable form, it should not be used as a manganese fertilizer.

Oxysulfates are oxides, usually industrial by-products, which have been partially acidulated with sulfuric acid, and generally are sold in granular form. The percentage of water-soluble manganese or zinc in oxysulfates is directly related to the degree of acidulation by sulfuric acid. Research results have shown that about 35 to 50 percent of the total zinc in granular zinc-oxysulfate should be in water-soluble form to be immediately effective for crops. Similar results would be expected for manganese-oxysulfate. Inorganic sources usually are the least costly sources per unit of micronutrient, but they may not always be the most effective for crops.

Synthetic Chelates

These sources are formed by combining a chelating agent with a metal through coordinate bonding. Stability of the metal-chelate bond affects availability to plants of the micronutrient metals --- copper, iron, manganese, and zinc. An effective chelate is one in which the rate of substitution of the chelated micronutrient for other cations in the soil is quite low, thus maintaining the applied micronutrient in chelated form. Relative effectiveness for crops per unit of micronutrient as soil-applied chelates may be from two to five times greater than that of inorganic sources, while chelates costs per unit of micronutrient may be five to 100 times higher. Several types of chelates are sold, so relative effectiveness values depend on the sources of chelates and inorganic products being compared.

Natural Organic Complexes

These complexes are made by reacting metallic salts with some organic by-products of the wood pulp industry or related industries. Several types of these complexes are the lignosulfonates, polyflavonoids and phenols. The types of chemical bonding of the metals to the organic components are not well understood. Some bonds may be coordinate as in the chelates, but other types of chemical bonds also may be present. While natural organic complexes are less costly per unit of micronutrient, they usually are less effective than synthetic chelates. They also are more readily decomposed by microorganisms in soil. These sources are more suitable for foliar sprays and mixing with fluid fertilizers.

Frits

Fritted glassy products (frits) in which solubility is controlled by particle size and changes in matrix composition. Micronutrient concentrations vary from 2 to 25 percent, and more than one micronutrient may be included in a fritted product. Fritted micronutrients generally are used only on sandy soils in regions of high rainfall were leaching occurs. This class of materials is more appropriate for maintenance programs than for correcting severe micronutrient deficiencies. Therefore, frits only have a small share of the micronutrient market.

Application with Mixed Fertilizers

The most common method of micronutrient application for crops is soil application. Recommended application rates usually are less than 10 lb/acre (on an elemental basis), so uniform application of micronutrient sources separately in the field is difficult. Therefore, both granular and fluid NPK fertilizers are commonly used as carriers of micronutrients. Including micronutrients with mixed fertilizers is a convenient method of application and allows more uniform distribution with conventional application equipment. Costs also are reduced by eliminating a separate application. Four methods of applying micronutrients with mixed fertilizers are:

- Incorporation during manufacture
- Bulk blending with granular fertilizers
- Coating onto granular fertilizers
- Mixing with fluid fertilizers

Incorporation with Granular Fertilizers

Incorporation during manufacture results in uniform distribution of micronutrients throughout granular NPK fertilizers. Because the micronutrient source is in contact with the mixed fertilizer components under conditions of high temperature and moisture, the rate of chemical reactions which may reduce the plant availability of some micronutrients is increased. For example, acid decomposition of ZnEDTA or any synthetic chelate may occur if they are mixed with phosphoric acid before ammoniation during manufacture, which results in reduced plant availability of the micronutrient. Immediate plant availability of applied zinc in granular ammoniated phosphates also decreases with the level of water-soluble zinc in these products.

Bulk Blending with Granular Fertilizers

Bulk blending of micronutrients with granular NPK fertilizers is a common practice in the U. S. The main advantage is that fertilizer grades can be produced which will provide the recommended micronutrient rates for a given field at the usual fertilizer application rates. The main disadvantage is that segregation of nutrients can occur during the blending operation and with subsequent handling. Segregation results in nonuniform application, which is critical with micronutrients since their application rates are quite low.

Segregation can be minimized by properly matching particle sizes of micronutrient sources with those of the NPK components of the blend. Mechanical devices to minimize coning and segregation of the materials during handling and storage are available. Blending of various sized fertilizer particles results in nonuniform application because of segregation in the applicator during transport and spreading operations.

Coating Granular Fertilizers

Coating powdered micronutrients onto granular NPK fertilizers decreases the possibility of segregation, which is the main disadvantage of bulk blending micronutrients with mixed fertilizers. Fertilizer solutions are preferred as binding agents because the fertilizer grade is not decreased so much as with use of water, oils and waxes. Some binding materials are unsatisfactory because they do not maintain the micronutrient coatings during bagging, storage, and handling. This results in segregation of the micronutrient sources from the granular NPK components.

Agronomic effectiveness of micronutrients coated onto soluble granular NPK fertilizers should be similar to that with incorporation during manufacture. This method of micronutrient application is not commonly used because of the extra costs associated with coating.

Fluid Fertilizers

Mixing micronutrients with fluid fertilizers has become a popular method of application, especially in the U. S. Clear liquids are commonly used as starter fertilizers for row crops and some micronutrients, especially zinc sources, are easily applied with these fluids. Solubility of some micronutrient sources is higher in polyphosphate fertilizers such as 10-34-0 than in orthophosphate clear liquids. Micronutrients also may be applied with nitrogen solutions such as UAN, but solubility of many sources is rather low. Compatibility tests should be made before tank mixing operations of micronutrients with fluid fertilizers are attempted; otherwise, problems could occur when incompatible sources are mixed. Suspension fertilizers also are used as micronutrient carriers. Oxides also can be applied with suspensions since complete solution is not required.

Foliar Sprays

Foliar sprays are widely used to apply micronutrients, especially iron and manganese, for many crops. Soluble inorganic salts generally are as effective as synthetic chelates in foliar sprays, so the inorganic salts usually are chosen because of lower costs. Suspected micronutrient deficiencies may be diagnosed with foliar spray trials with one or more micronutrients. Correction of deficiency symptoms usually occurs within the first several days and then the entire field could be sprayed with the appropriate micronutrient source. Inclusion of sticker-spreader agents in the spray is suggested to improve adherence of the micronutrient source to the foliage. Caution should be used because of leaf burn due to high salt concentrations or inclusion of certain compounds in foliar sprays.

Advantages of foliar sprays are: (1) application rates are much lower than for soil application; (2) a uniform application is easily obtained; and (3) response to the applied nutrient is almost immediate so deficiencies can be corrected during the growing season. Low residue foliar sprays of manganese and zinc have been used to correct deficiencies of citrus and other fruit crops, but sprays which will discolor the fruit should be avoided.

Disadvantages of foliar sprays are: (1) leaf burn may result if salt concentrations of the spray are too high; (2) nutrient demand often is high when the plants are small and leaf surface is insufficient for foliar absorption; (3) maximum yields may not be possible if spraying is delayed until deficiency symptoms appear; and (4) there is little residual effect from foliar sprays. Application costs will be higher if more than one spray is needed, unless they can be combined with pesticide spray applications.

Micronutrient Rates and Example Results

Boron

Recommended application rates of boron are rather low (0.5 to 2 lb/acre), but should be carefully followed because the range between boron deficiency and toxicity in most plants is narrow. Uniform application of boron in the field is very important for the above reason. Boronated NPK fertilizers (those containing boron sources incorporated at the factory) will insure a more uniform application than most bulk blended fertilizers. Foliar sprays also insure a rather uniform application, but costs generally are higher.

Table 9.3: Effect of Soil pH on Boron Availability and Cotton Yields

In an experiment in Arkansas, cotton yields were increased by 490 and 584 lb/acre at boron rates of 0.3 and 0.5 lb/acre, respectively. Response of cotton in Tennessee to boron application is shown below. Without applied boron, cotton yields decreased with increasing soil pH. Yields were increased at all soil pH levels when boron was applied at a rate of 0.5 lb/acre.

SOIL pH	0 lb/acre B	0.5 lb/acre B
	---------- yield, lb/acre ----------	
5.7	1,759	2,100
7.3	1,453	1,784
7.5	862	2,062

Soil tests should be included in boron fertilization programs, first to assess the level of available boron and later to determine possible residual effects (buildup). The most common soil test for boron is the hot-water-soluble test. This test is more difficult to conduct than most other micronutrient soil tests, but most boron response data have been correlated with it.

Copper

Recommended copper rates range from 3 to 10 lb/acre as $CuSO_4$ or finely ground CuO. Residual effects of applied copper are very marked, with responses being noted up to eight years after application. Because of these residual effects, soil tests are essential to monitor possible copper accumulations to toxic levels in soils where copper fertilizers are being applied. Plant analyses also can be used to monitor copper levels in plant tissues. Copper applications should be decreased or discontinued when available levels increase beyond the deficiency range.

Iron

Soil applications of most iron sources generally are not effective for crops, so foliar sprays are the recommended application method. Spray applications of a 3 to 4% FeSO4 solution at 20 to 40 gallons/acre are used to correct iron deficiencies. The application rate should be high enough to wet the foliage. More than one foliar application may be required for correction of iron chlorosis. Inclusion of a sticker-spreader agent in the spray is suggested to improve adherence of the spray to the plant foliage for increased iron absorption by the plant.

Manganese

Recommended application rates range from 2 to 20 lb/acre of manganese, generally as $MnSO_4$. Application rates of MnO would be similar if applied as a fine powder or in NPK fertilizers. Band application of manganese sources with acid-forming fertilizers results in a more efficient use of applied manganese because the rate of oxidation of applied manganese to the unavailable tetravalent form (as in MnO_2) is decreased. There are no residual effects of applied manganese for the same reason, so annual applications are needed. Foliar spray applications of $MnSO_4$ also are used and require lower rates than soil applications.

Table 9.4: Soybean Response to Manganese

Results given below show that soybean yields were more than doubled when 10 lb of manganese/acre was applied as $MnSO_4$ to a poorly drained sandy soil in Georgia.

lb/acre Mn	yield, bu/acre
0	13
2.5	24
5.0	26
10.0	33

Cotton also responded to applied Manganese in Georgia, as shown below.

Table 9.5: Cotton Response to Manganese

lb/acre Mn	yield, lb/acre	increase, lb/acre
0	2,657	----
2.5	2,857	200

Molybdenum

Recommended molybdenum rates are much lower than those for the other micronutrients, and uniform application is very important. Broadcast application of molybdenized phosphate fertilizers prior to planting or to pastures has been used to correct molybdenum deficiencies. Soluble

molybdenum sources also can be sprayed on the soil surface before tillage to obtain a uniform application.

Table 9.6: Soybean Response to Molybdenum

	Mo applied, oz/acre	
soil pH	0	1
	--- yield, bu/acre ---	
5.3	25.7	45.0
5.7	34.3	45.0
6.3	41.8	46.1

Seed treatment is the most common method of molybdenum application. Molybdenum sources are coated onto the seed with a sticking agent and/or conditioner. This method insures a uniform application and sufficient amounts of molybdenum can be seed coated to provide sufficient molybdenum. Data in the following table show the effectiveness for soybean in Georgia of seed-coated molybdenum at a rate of one ounce of molybdenum/acre. Soybean yields without applied molybdenum increased with increases in soil pH, but not as high as those with seed-applied molybdenum at each soil pH level.

Zinc

Recommended rates of zinc generally range from 1 to 10 lb/acre. Band or broadcast applications are used, but foliar applications also are effective. Band applications of zinc sources with starter fertilizers is a common practice for row crops. Foliar sprays of a 0.5% $ZnSO_4$ solution applied at a rate of 20 to 30 gallons/acre also will supply sufficient zinc, but several applications may be necessary. As with copper, residual effects of applied zinc are substantial, with responses found at least 5 years after application. Because of these residual effects, soil test levels of available zinc generally increase after several applications. Many states have reduced their recommended zinc application rates because of these residual effects.

Crop response to several zinc sources each banded with a 10-34-0 starter fertilizer at zinc rates up to 3 lb/acre for corn in Nebraska is shown below. Results show that ZnEDTA was much more effective at the lower zinc rates, but all zinc sources were about equally effective at the highest zinc rate.

Table 9.7: Corn Response to Zinc

	Zn Applied, lb/acre				
Zn Source	0	0.1	0.3	1.0	3.0
	-------- Grain Yield, bu/acre --------				
$ZnSO_4$	62	132	141	131	144
ZnO		124	124	134	144
$ZnSO_4$-NH_3 complex		118	138	134	140
ZnEDTA		138	139	155	141

Summary

Micronutrients are as important as the primary and secondary nutrients in plant nutrition. However, the amounts of micronutrients required for optimum nutrition are much lower. Micronutrient deficiencies are widespread because of increased nutrient demands from the more intensive cropping practices. Soil tests and plant analyses are excellent diagnostic tools to monitor the micronutrient status of soils and crops. Visual deficiency symptoms of these nutrients also are well recognized in most economic crops. Micronutrient recommendations are based on soil and plant tissue analyses, the type of crop and expected yield, management level, and research results.

Numerous micronutrient fertilizers are on the market. These sources are classified as inorganic, synthetic chelates, natural organic complexes, and fritted glasses. Some industrial by-products are used as micronutrient fertilizers because of their lower cost. Micronutrient sources vary considerably in physical form, chemical reactivity, cost, and relative availability to plants. While most micronutrient fertilizers are applied to soils, foliar sprays also are used on tree crops and some vegetables. Because recommended rates usually are low, most micronutrients are applied with NPK fertilizers by incorporation during manufacture or bulk blending with granular fertilizers, or by mixing with fluid fertilizers just before application to soil. Choice of micronutrient source depends on the method of application, compatibility with the NPK fertilizer, convenience of application, and the relative agronomic effectiveness and cost per unit of micronutrient.

Links to other sections of the EFFICIENT FERTILIZER USE MANUAL
History • MEY • Soil • pH • Nitrogen • Phosphorus • Potassium • Secondary • Micronutrients • Fluid-Dry • Sampling • Testing • Site-Specific • Tillage • Environment • Appendices • Authors