Nutri-Facts
IPNI
Agronomic fact sheets on crop nutrients
NO. 1

# Nitrogen

**North American Edition**

Did you know that about 80 percent of the air we breathe is nitrogen gas ($N_2$)? In fact, every acre of land in the world is covered by about 75 million pounds of N...37,000 tons in the atmosphere. Crop plants can use virtually none of that atmospheric $N_2$ until it is changed by natural processes or by commercial fertilizer N production.

Through various biological or industrial processes of fixation, gaseous atmospheric $N_2$ is changed to plant-usable forms: either ammonium or nitrate. Small amounts can be fixed by lightning and carried to the Earth's surface in rain or snow. It can be fixed by certain organisms in the soil and in nodules on legume roots. Industrial fixation supplies the millions of tons of commercially produced N fertilizers required to grow crops around the world.

Nitrogen is an essential nutrient because it is a part of the makeup of all plant and animal proteins. The nutritive value of the food we eat is largely dependent on having an adequate supply of N.

IPNI PHOTO-SHARMA AND KUMAR

**Nitrogen deficient corn leaf.**

## Nitrogen in Plants

Nitrogen is required in greater quantities by crops than any of the other essential nutrients, except potassium (K). Some crops take up more K than N. **Table 1** shows how much N is required by a number of common crops. Inorganic nitrate and ammonium are the major forms of N taken up by plant roots.

## Nitrogen in Soils

Although the amount of N stored in soil organic matter is large (often more than 1,000 lbs/A), the amount released and available for plant uptake is relatively small. Often, that release is not synchronized with plant demand. Very little N is found in rocks and minerals. Organic matter releases N slowly, the rate being controlled by soil microbial activity (influenced by temperature, moisture, pH and texture).

In general, about 20 to 30 lb N/A are released annually for each 1 percent organic matter contained in the upper 6 to 7 inches of soil. One of the products of organic decomposition (mineralization) is ammonium, which can be held by the soil, taken up by crop plants or converted to nitrate. The nitrate is used by plants, leached out of the root zone or converted to gaseous N and lost back into the atmosphere. The conceptual relationship between plant unavailable N (organic matter) and plant-available N (ammonium and nitrate), and soil temperature effects are illustrated in **Figures 1** and **2**.

**Table 1.** Crops are big users of nitrogen.

| Crop | Yield level | N uptake | N removal |
|---|---|---|---|
| | | ----- lb ----- | |
| Alfalfa† (DM) | 8 tons | 432 | 408 |
| Coastal bermudagrass | 8 tons | 368 | 368 |
| Corn | 160 bu | 160 | 107 |
| Cotton | 1,500 lb lint | 180 | 96 |
| Grain Sorghum | 130 bu | 143 | 86 |
| Peanuts | 4,000 lb | 252 | 140 |
| Potato | 500 cwt | 245 | 150 |
| Rice | 7,000 lb | 110 | 89 |
| Soybeans | 60 bu | 294 | 195 |
| Tomatoes | 40 tons | 224 | 100 |
| Wheat, spring | 60 bu | 132 | 89 |
| Wheat, winter | 60 bu | 114 | 70 |

†Legumes get most of their N from air.
DM = dry matter (0% moisture) basis
For more crops, visit http://ipni.info/nutrientremoval

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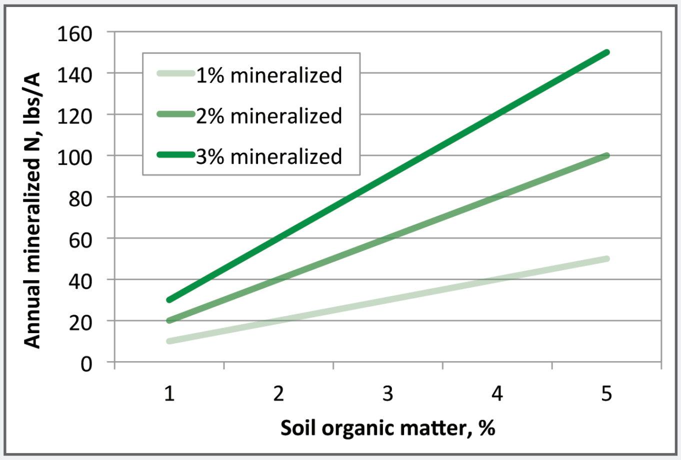


**Figure 1.** Conceptual example of the amount of inorganic N released (mineralized) from soil organic matter at three rates of microbial activity.

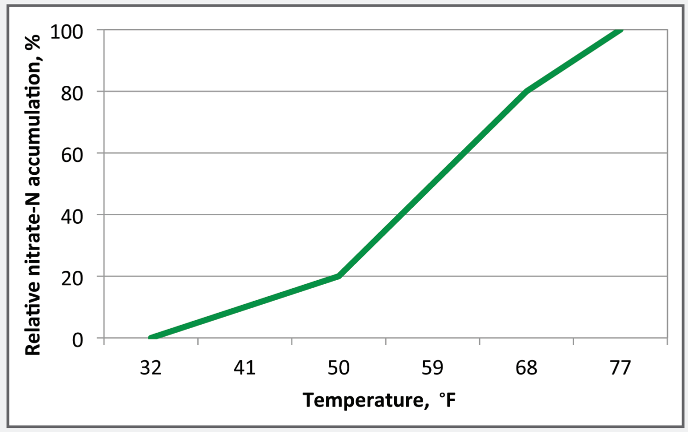


**Figure 2.** Example of the effect of soil temperature on the rate of nitrate accumulation (nitrification) in soil in Illinois.[2]

## Choosing a Nitrogen Fertilizer Source

Since most soils cannot provide sufficient quantities of N to support economically optimum crop growth and quality, commercial fertilizers are widely used to supplement crop needs. Manure, sewage sludge and other waste sources of N are acceptable as well, when they are available. However, those non-fertilizer sources can be difficult to manage and cannot be economically transported long distances. Choosing the correct N source should be based on several factors, including; availability, price, crop being fertilized, timing and methods of application, tillage systems, and risks and pathways for off-site losses. For plant nutrition, a unit of soluble N is the same, regardless of whether it came from fertilizer or organic matter. All N sources require careful stewardship to use them to their potential. Further, all N sources, if not properly managed, can pose a potential source for environmental losses, including nitrate accumulation in groundwater and surface water.

## Nitrogen Deficiency Symptoms

An adequate supply of N is usually seen in most plants as a dark green color in leaves, caused by a high level of chlorophyll. A deficiency results in a yellowing (chlorosis) of the leaves because of inadequate chlorophyll. Deficiency symptoms appear first on older leaves, and then develop on younger ones as the condition becomes more severe. Other symptoms of N deficiency may include:

- Stunted, spindly plants
- Less tillering in small grains
- Low protein content...in seed and vegetative parts
- Fewer leaves
- Higher susceptibility to stress from weather, pests, and diseases

## Crop Response to Nitrogen

The need for N fertilization is more common than for any other essential nutrient. **Table 2** shows how corn yields and nitrogen use efficiency were increased with added N fertilizer and higher plant populations. Nitrogen fertilization is more profitable and environmentally friendly when used with other appropriate best management practices (BMPs).

Because crops are so responsive to additions of N, the optimum rate of N fertilization is changed relatively little by changes in either crop or fertilizer price. This is true as long as the crop exhibits responsiveness. The concept is illustrated in **Table 3**.

Appropriate N management—based on the 4R principles of using the right source at the right rate, right time, and right place—can optimize crop yields and returns, while reducing the risks of potential negative effects on the environment.

## References

1. Ciampitti A. and T. Vyn. 2011. Field Crops Research 121:2-18.

2. University of Illinois. 2012. Illinois Agronomy Handbook. College of Agricultural, Consumer and Environmental Sciences.

**Table 2.** Higher corn population and nitrogen interact to increase yield and nitrogen use efficiency, averaged over two locations and four hybrids in Indiana[1].

| Population, plants/A | Grain yield (bu/A) at different N rates, lb/A | | | Grain yield response to highest N rate, bu/A |
|---|---|---|---|---|
| | 0 | 150 | 300 | |
| 22,000 | 100 | 120 | 127 | 27 |
| 32,000 | 127 (31)† | 152 (38) | 169 (49) | 42 |
| 42,000 | 129 (21) | 161 (47) | 180 (30) | 51 |
| Response to highest population, bu/A | 29 | 41 | 53 | |

†N use efficiency (shown in parentheses) calculated as percent apparent fertilizer N recovery efficiency: [(N uptake with N minus N uptake at zero N rate)/applied N rate] x 100.

**Table 3.** Economically optimum nitrogen rates change little with corn and fertilizer price changes.

| Corn price, $/bu | Price of N, cents/lb | | | |
|---|---|---|---|---|
| | 20 | 40 | 60 | 80 |
| | Optimum N rates on corn, lb/A | | | |
| 2.80 | 162 | 153 | 145 | 136 |
| 3.92 | 164 | 158 | 151 | 145 |
| 5.04 | 165 | 160 | 155 | 150 |

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# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Phosphorus

NO. 2

**NORTH AMERICAN EDITION**

Phosphorus (P) is present in every living cell, both plant and animal. No other nutrient can be substituted for it when it is lacking. Phosphorus is one of the 17 essential nutrients that plants need for growth and reproduction. Phosphorus is considered one of the three major nutrients along with nitrogen (N) and potassium (K). They are termed major nutrients because of the relatively large amounts utilized by plants (**Table 1**) and the frequency with which their deficiencies limit plant growth.

**Table 1.** Phosphorus uptake and removal by crops.

| Crop | Yield level per A | $P_2O_5$ uptake | $P_2O_5$ removal |
|---|---|---|---|
| | | ----- lb ----- | |
| Alfalfa (DM) | 8 tons | 96 | 96 |
| Coastal bermudagrass | 8 tons | 96 | 96 |
| Corn | 160 bu | 90 | 56 |
| Cotton | 1,500 lb lint | 63 | 42 |
| Grain sorghum | 130 bu | 84 | 51 |
| Peanuts | 4,000 lb | 46 | 22 |
| Potato | 500 cwt | 105 | 75 |
| Rice | 7,000 lb | 59 | 47 |
| Soybeans | 60 bu | 66 | 44 |
| Tomatoes | 40 tons | 104 | 37 |
| Wheat, spring | 60 bu | 46 | 34 |
| Wheat, winter | 60 bu | 41 | 29 |

**Note:** To convert $P_2O_5$ to P, multiply by 0.4364
DM = dry matter (0% moisture) basis
For more crops, visit http://ipni.info/nutrientremoval

Phosphorus must be added to the soil when the native supply is too low to support healthy crop growth. Maintaining an adequate supply of P is essential for plant health and high yields.

IPNI PHOTO-SRINIVASAN

**Phosphorus-deficient corn plants.**

## Phosphorus in Plants

Phosphorus is a vital component in the process of plants converting the sun's energy into food, fiber and oil. Phosphorus plays a key role in photosynthesis, the metabolism of sugars, energy storage and transfer, cell division, cell enlargement and transfer of genetic information.

Phosphorus promotes healthy root growth, promotes early shoot growth, speeds ground cover for erosion protection, enhances the quality of fruit, vegetable and grain crops, and is vital to seed formation. Adequate P increases plant water use efficiency, improves the efficiency of other nutrients such as N, contributes to disease resistance in some plants, helps plants cope with cold temperatures and moisture stress, hastens plant maturity and protects the environment through better plant growth.

## Phosphorus in Soils

Plant roots can only acquire P from the soil when it is dissolved in soil water. Since only very low concentrations of P are present in the soil water, P must be continually replenished from soil minerals and organic matter to replace the P taken up by plants. Plant roots generally absorb P as inorganic orthophosphate ions

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($HPO_4^{2-}$ or $H_2PO_4^-$). Phosphorus present in soil organic matter is not available for plant uptake until soil microbes convert the organic compounds into simple inorganic phosphate.

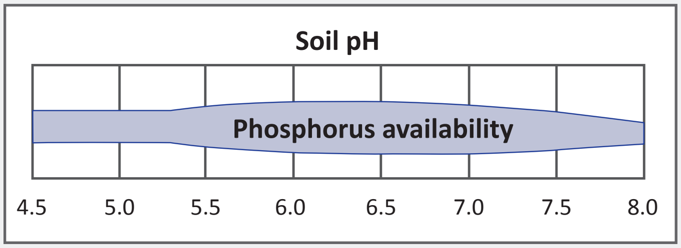


**Figure 1.** Effects of soil pH on P availability for plants.

Many soil factors affect P availability to plants, including the type and amount of clay minerals, P concentration, factors affecting root activity (such as aeration and compaction), soil moisture content, temperature, adequate supply of other essential plant nutrients, and the root properties of the crop. Additionally, soil pH (acid or alkaline) greatly influences the availability of P to plants (**Figure 1**).

The presence of mycorrhizal fungi growing in association with plant roots can enhance P uptake in many situations. The fungi do not provide any additional P to the soil, but can sometimes assist in P recovery.

## Fertilizing Soils with Phosphorus

Very few soils contain an adequate supply of all of the mineral nutrients required for unrestricted crop growth. Soil and plant analysis can be used to assess if the need exists for supplemental P fertilizer.

Extensive research has established the relationship between P concentrations in the soil and the need for additional P fertilizer to achieve optimal growth. Similarly, research has identified the concentration of P required in plant tissue to sustain healthy plant growth. Both soil and plant diagnostic tests can be used as guides for fertilizer decisions.

In cropping systems where more P is removed from the soil during harvest than is being replaced, soil P concentrations will gradually decline over time. On the other hand, if more P is added than is removed, it will accumulate and soil P concentrations will increase.

Careful nutrient management should accompany the use of all plant nutrients, including P. Without proper management, excessively high P concentrations can sometimes lead to unwanted nutrient loss to surface water, where stimulated algae growth may occur. Minimizing P loss from farmland involves consideration of P in the field (source) and transport (such as runoff and erosion loss).

Phosphorus is added to the soil in many forms, including commercial fertilizers, animal wastes, biosolids, crop residues or other by-products. Phosphorus recycling from wastes has been practiced for centuries, but current demands for P in modern food production far outstrip these organic resources.

The P fertilizer industry was developed in the 19th century to better meet crop nutritional needs and to provide readily available forms of P that can be easily transported and applied to soil. Rock phosphate is mined from geologic deposits around the world and processed into many types of solid and fluid fertilizer. As with all earth minerals, P must be managed carefully to avoid waste and promote long-term resource stewardship.

In earlier times, fertilizer P was expressed as $P_2O_5$ and this notation has been maintained. Since $P_2O_5$ contains only 44% P, this notation sometimes can cause confusion.

Added P fertilizer chemically reacts with soil minerals, gradually reducing its solubility. Applying P fairly close to the time of crop utilization can improve P recovery by plants. When P fertilizer is applied beneath the soil surface in concentrated bands, these reactions are slowed. Environmental stress conditions that depress P availability to plants (such as cold soils), can be countered by placement of P close to the seed of crop plants (called starter or pop-up fertilization), even when adequate P is available for growth later in the season.

## Phosphorus Deficiency Symptoms

The first indication of a P shortage is often a stunted plant, which is difficult to diagnose. Leaf shapes may be distorted. With severe deficiency, dead areas may develop on leaves, fruit and stems. Older leaves are affected before younger ones because of P redistribution within the plant. Some plants, such as corn, may display a purple or reddish color on the lower leaves and stems when P is low. This condition is associated with accumulation of sugars in P-deficient plants, especially during times of low temperature. A shortage of P can serve to reduce crop yields, quality, value and profitability.

## Crop Response to Phosphorus

Phosphorus fertilization increases yields and farmer profits in many soils around the world. Data in **Table 2** illustrate the importance of P for increasing crop yields, improving N use efficiency, lowering production costs per unit and increasing crop profitability.

### References

1. Havlin, J.L., and A.D. Halvorson. 1990. MEY Wheat Management Conference. Denver, CO. pp. 82-95.

### Further Reading

Shen, J. et al. 2011. Plant Physiol. 156:997-1005.

Syers, K. 2008. FAO Fertilizer and Plant Nutrition Bulletin 18.

**Table 2.** Adequate P increases wheat yields, improves N use efficiency, lowers production costs per bushel, and improves crop profits[1].

| Fertilizer N, lb/A | Fertilizer $P_2O_5$, lb/A | Yield, bu/A | N use efficiency, bu/lb N | Fertilizer cost, $/bu | Net profit, $/A |
|---|---|---|---|---|---|
| 75 | 0 | 35 | 0.47 | 1.29 | 200 |
| 75 | 20 | 51 | 0.68 | 1.12 | 300 |
| 75 | 30 | 58 | 0.77 | 1.09 | 343 |
| 75 | 40 | 69 | 0.92 | 1.00 | 414 |
| 75 | 50 | 67 | 0.89 | 1.12 | 394 |

Soil test P was low; Cost of fertilizer $P_2O_5$ = \$0.60/lb; N = \$0.60/lb; Wheat grain price = \$7.00/bu.

# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Potassium

NO. 3

North American Edition

Potassium (K) is an essential plant macronutrient taken up in large quantities, like nitrogen. In plants, K does not become part of complex organic molecules. It moves as a free ion and performs many functions.

## Potassium in Plants

In plants, K is involved in many essential functions. It serves to:

- regulate water pressure in plant cells, affecting cell extension, gas exchange, and movement of leaves in response to light;
- activate enzymes that help chemical reactions take place;
- synthesize proteins;
- adjust pH within plant cells;
- increase carbon dioxide fixation during photosynthesis;
- transport chemical compounds; and
- balance electrical charges in various parts of cells.

Harvesting crops removes K from the soil. The quantity removed varies with the quantity of biomass and K content of the plant organs harvested (**Table 1**).

**Table 1.** Potassium uptake and removal rates for selected crops.

| Crop | Yield level per A | $K_2O$ uptake | $K_2O$ removal |
|---|---|---|---|
| | | --------------- lb | ----------- |
| Alfalfa (DM) | 8 ton | 400 | 392 |
| Corn | 160 bu | 224 | 40 |
| Corn silage (67% water) | 25 ton | 183 | 183 |
| Cotton | 1,500 lb lint | 186 | 57 |
| Grain Sorghum | 130 bu | 221 | 35 |
| Potato | 500 cwt | 590 | 325 |
| Rice | 7,000 lb | 171 | 25 |
| Soybean | 60 bu | 138 | 71 |
| Switchgrass (DM) | 6 ton | 348 | 348 |
| Wheat, spring | 60 bu | 90 | 20 |
| Wheat, winter | 60 bu | 120 | 17 |

**Note:** To convert $K_2O$ to K, multiply by 0.8301
DM = dry matter (0% moisture) basis
For more crops, visit http://ipni.info/nutrientremoval

Plants that are supplied with adequate K are better able to withstand stress, insect damage, and many plant diseases compared with plants low in K.

As plants age, rainfall leaches K from plant leaves, depositing K at the soil surface. Plants therefore redistribute K from lower depths to the soil surface, a process termed "uplift." Uplift contributes to nutrient stratification in no-till and reduced tillage systems and affects how soil tests change in response to K additions and crop removal.

## Potassium in Soils

Plants can only access K when it is dissolved in the soil solution. Contributors to potentially plant-available K are:

- K redistributed from other areas, including: irrigation water, precipitation, commercial fertilizer, manure, biosolids, and sediment deposition;
- weathering of K-containing primary minerals like micas and some feldspars;
- K released from the interlayers of the layer silicate minerals illite, vermiculite, and smectite; and
- K desorption from surfaces and edges of layer silicate minerals, termed "exchangeable K."

Exchangeable K is measured by soil tests and is considered readily available for plants. Layer silicate minerals that release

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**Table 2.** Commercial sources of potassium fertilizer.

| Fertilizer name | Chemical formula | Typical nutrient concentration, % | | | | |
|---|---|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ | Mg | S |
| Monopotassium phosphate | $KH_2PO_4$ | | 52 | 34 | | |
| Potassium chloride (Muriate of potash) | KCl | | | 60-62 | | |
| Potassium hydroxide solution | KOH | | | 45 | | |
| Potassium nitrate | $KNO_3$ | 13 | | 44 | | |
| Potassium thiosulfate | $K_2S_2O_3$ | | | 25 | | 17 |
| Potassium sulfate (Sulfate of potash) | $K_2SO_4$ | | | 50 | | 17 |
| Potassium magnesium sulfate (Sulfate of potash magnesia) | $K_2SO_4 \bullet 2Mg\ SO_4$ | | | 22 | 11 | 22 |

K can also "fix" K, or bond K in interlayer positions, thereby removing it from the soil solution. Fixation and release of K by these minerals is dynamic throughout the year.

## Fertilizing Soils with Potassium

Potassium minerals are extracted from geologic sources located throughout the world. Impurities are removed from the ore and the remaining K is transformed into a variety of modern fertilizers. The K content is historically expressed as $K_2O$, even though fertilizers do not actually contain $K_2O$.

### Right Source

The most commonly used K fertilizer source is potassium chloride (KCl), also referred to as muriate of potash (**Table 2**). Chloride-free sources of K fertilizer are sometimes preferred for applications made to chloride-sensitive crops. Compound fertilizers containing chloride, sulfur and/or magnesium are appropriate when soil supplies of these other nutrients are limiting. Liquid products or solid products that are highly soluble in water are used for fertigation.

### Right Rate

Recommended rates of K application are based on both soil testing and crop removal. "Maintenance rates" are those equal to the quantities of K removed and are used to maintain soil fertility.

### Right Time

If chloride-sensitive crops are part of a rotation, chloride forms may be applied to non-sensitive crops grown earlier in the rotation, leaving time for chloride to move out of the root zone. For situations when additional nutrients in a compound fertilizer are needed and the forms of those nutrients are mobile in soils, like chloride and sulfate, applications should be made near or during the cropping season.

### Right Place

Potassium sources vary widely in their effect on the soil solution (salt index). Potassium fertilizer sources with a lower salt index may be used at higher rates when placed near or in direct contact with seed. Subsurface bands of K can provide benefits over broadcast applications when subsoil fertility is lower and when drier growing conditions exist.

## Potassium Deficiency Symptoms

Potassium deficiency slows the growth rate of plants. In corn, for example, K deficiency leads to delayed pollination and maturity. Leaf margins yellow and eventually die, and leaves may not develop fully. The resulting reduction in leaf area reduces crop yields. Stalks are also weakened, increasing the risk of lodging. Plants have a lower resistance to some diseases and to moisture stress. Reduced cell extension shortens internodes, producing stunted plants that may result in greater harvest losses.

IPNI PHOTO-EBELHAR

**Potassium-deficient corn.**

## Crop Response to Potassium

When soils do not supply adequate K, fertilization has a high chance of providing profitable crop responses. **Table 3** shows that larger, less frequent fertilizer K applications can be just as effective as smaller, annual applications.

Harvest removes different amounts of K for various crops. Replacement of this K is necessary to avoid long-term depletion of soil nutrient reserves. There are many excellent fertilizer materials available for maintaining the K supply for healthy crop growth.

## References


1. Mallarino, A. et al., 1991. J. Prod. Agric. 4:562-466.


**Table 3.** Corn and soybean responses and agronomic efficiency of ten annual applications of K compared to the residual effects of a high rate of K rate applied by the initiation of the experiment[1].

| Fertilizer rate | Total K applied after 10 years, lb $K_2O$/A | Cumulative corn response | Cumulative soybean response | Total response | AE, bu/lb $K_2O$ |
|---|---|---|---|---|---|
| | | --------------- bu/A ----------- | | | |
| Annual applications of 48 to 72 lb $K_2O$/A | 600 | 83 | 28.6 | 111.6 | 0.19 |
| Residual effects of 600 lb $K_2O$/A | 600 | 89 | 17.6 | 106.6 | 0.18 |

# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Sulfur

NO. 4

NORTH AMERICAN EDITION

IPNI PHOTO-SHARMA AND KUMAR

**Sulfur deficiency in corn.**

In crop production, sulfur (S) is used by plants in sufficient quantities that it is considered the fourth most needed fertilizer nutrient after the three macronutrients nitrogen (N), phosphorus (P) and potassium (K). Sulfur occurs naturally in deposits nears volcanoes and in various sulfide ore deposits around the world. The main industrial source comes from removal of hydrogen sulfide gas ($H_2S$) from fossil fuel during its processing.

Sulfur fertilization is increasingly common because higher yielding crops are taking up and removing more S from soil as harvested products. Due to a decrease in S emissions from industrial and transportation sources, S deposition from the atmosphere is much lower than a few decades ago. Maintaining an adequate supply of S is essential for sustaining high-yielding crops, as well as for animal and human nutrition.

## Sulfur in Plants

Soluble sulfate ($SO_4^{2-}$) is the primary source of S nutrition for plants. Within the plant, S is required for protein synthesis. It aids in seed production and producing the chlorophyll necessary for plants to carry out photosynthesis. It is a necessary component of three amino acids (cysteine, methionine, and cystine) needed for protein synthesis. It is also required for nodule formation on root hairs of legume crops. Wheat grown in soils with low levels of available S result in lower quality of grain protein, making the flour less suitable for bread making.

Since both S and N are needed for protein formation, these two nutrients are closely linked. Crops have varied requirements for S compared with N, and have a wide N:S ratio in the harvested product (**Table 1**). For example wheat has a relatively low requirement of S, with N:S ratio in grain of 16:1. Canola has a high S requirement, with a N:S ratio of 6:1 in the seed.

Sulfur is involved in a number of secondary plant compounds. For example, the characteristic flavor and smell of onions and garlic is associated with volatile S compounds.

**Table 1.** Total removal of sulfur in the harvested portion of selected field crops compared to N, $P_2O_5$ and $K_2O$ (lb/A).

| Crop | Yield/A | N | $P_2O_5$ | $K_2O$ | S | N:S ratio |
|---|---|---|---|---|---|---|
| Corn | 200 bu | 134 | 70 | 50 | 16 | 8:1 |
| Soybeans | 60 bu | 195* | 44 | 72 | 11 | 18:1 |
| Wheat | 60 bu | 89 | 34 | 20 | 6 | 16:1 |
| Alfalfa | 5 ton | 255* | 60 | 245 | 27 | 9:1 |
| Bermudagrass | 5 ton | 230 | 60 | 250 | 20 | 12:1 |
| Bromegrass | 3 ton | 96 | 30 | 138 | 15 | 6:1 |
| Canola | 50 bu | 80 | 40 | 20 | 12.5 | 6:1 |

*Primarily, symbiotically fixed N by *Rhizobia* bacteria in root nodules.


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**Sulfur-deficient wheat. Inset image shows deficient leaf on left; normal leaf on right.**

## Sulfur in Soils

The majority of S in soil is usually found in organic matter and crop residues. It is present in a variety of organic compounds that are not available for plant uptake until they are converted to soluble sulfate. The speed at which soil microorganisms convert these organic S compounds is governed by temperature, moisture, and other environmental factors.

Only a small fraction of the total S in soil is found as sulfate. Sulfate is generally soluble and readily moves with soil water to roots, or it can move below the root zone in high rainfall areas or with excessive irrigation.

## Fertilizing Soils with Sulfur

There are numerous sources of S fertilizer available for use. Fertilizers containing soluble sulfate provide an immediately available source of plant nutrition. Fertilizers that contain insoluble elemental S require a conversion to sulfate before plant roots take it up. Common soil bacteria (e.g. *Thiobaccilus* species) are responsible for converting elemental S to sulfate, but this process can take from weeks to years. Favorable conditions of soil temperature, moisture, pH, and aeration will speed this conversion to sulfate. Similarly, a small particle size of elemental S will enhance the rate of conversion.

## Sulfur Deficiency Symptoms

Plants do not mobilize S from older tissues to supply the S needs of younger growing points. Once sulfate is assimilated into organic compounds, it does not move again within the plant. For this reason, S deficiency symptoms of chlorosis (yellowing) are first observed in the young tissues of leaves, stocks, and flower buds.

## Crop Response to Sulfur

Crops frequently respond well to S fertilization, especially under conditions of low sulfate availability in soil. Applied S often results in both yield and crop quality improvements (**Table 2**). This is especially important for crops with a high S requirement such as oil seeds (soybean and canola) and forage crops. It is possible to prevent yield losses if S deficiency is diagnosed early in a growing season and is promptly topdressed with a sulfate form of fertilizer. Attention to S fertilization is becoming more important in many areas around the world.

## References


1. Sawyer, J., B. Lang, and D. Barker. 2011. Better Crops 95(2):6-7.


## Further Reading


Norton, R., R. Mikkelsen, and T. Jensen. 2013. Better Crops 97(2):10-12.

Mikkelsen, R., and R. Norton. 2013. Better Crops 97(2):7-9


**Table 2.** Sulfur fertilization increases the yield and the S tissue concentration of alfalfa[1].

| Location | | Wadena, Iowa | | Waucoma, Iowa | |
|---|---|---|---|---|---|
| | | Yield, ton/A | Alfalfa Hay before 2nd Cut, % S | Yield, ton/A | Alfalfa Hay before 2nd Cut, % S |
| S application rate, lb S/A | 0 | 1.32 | 0.14 | 1.85 | 0.21 |
| | 15 | 2.59* | 0.20 | 3.06* | 0.30 |
| | 30 | 3.14* | 0.30 | 3.14* | 0.43 |
| Soil test $SO_4^{2-}$–S, ppm | | 7 | | 3 | |
| Soil Organic Matter, % | | 3.1 | | 2.1 | |
| Soil Type | | Fayette Silt Loam | | Wapsie Loam | |

*Significant difference at p = 0.10 from 0 S rate.

# Nutri-Facts

Agronomic fact sheets on crop nutrients

## Calcium

NO. 5

NORTH AMERICAN EDITION

Calcium (Ca) nutrition plays a vital role in the production of high-quality crops. It also has an important function as a valuable soil amendment in many situations.

### Calcium in Plants

Calcium is classified as a "secondary nutrient" that is needed in relatively large amounts by plants in the form of $Ca^{2+}$. In some species, the requirement for Ca is greater than for the macronutrient phosphorus (P). The critical Ca concentration in plants varies widely, ranging from about 0.2% in grasses, 1.0 to 1.25% in fruit crop foliage, to 2.0% in cotton leaves[1]. The amount of Ca taken up by various crops is listed in **Table 1**.

Calcium plays a key role in cell wall structure and membrane integrity. In addition to plant stability, strong cell walls help prevent invasion by numerous fungi and bacteria. Calcium also promotes proper plant cell elongation, participates in enzymatic and hormonal processes, and plays a role in the uptake processes of other nutrients.

### Calcium in Soils

The total amount of Ca in soils normally ranges from 0.7 to 1.5% in non-calcareous, temperate soils. Highly weathered tropical soils typically have a lower Ca content, ranging from 0.1 to 0.3%, while calcareous soils may contain as much as 25% Ca. Although there may be tens of thousands of pounds of total Ca/A in the root zone, it is common to have less than 100 lb of Ca actually soluble at any one time. The solubility of Ca depends on several soil factors, including:

- Soil pH – soils with higher pH typically contain more available Ca on cation exchange sites
- Cation exchange capacity (CEC) – available Ca is affected by both the soil cation exchange capacity and the Ca saturation on the soil cation exchange sites
- Presence of other soil cations – Ca is preferentially adsorbed on cation exchange sites. Its solubility and plant availability are influenced by other cations in the soil.

**Table 1.** Calcium uptake in the harvested portion of various crops[2].

| Crop | Yield level | Ca uptake, lb |
|---|---|---|
| Alfalfa | 8 tons | 175 |
| Bermudagrass | 8 tons | 52 |
| Corn | 200 bu | 49 |
| Cotton | 1,000 lb lint | 14 |
| Grain Sorghum | 140 bu | 60 |
| Oranges | 540 cwt | 80 |
| Peanuts | 4,000 lb | 20 |
| Rice | 7,000 lb | 20 |
| Soybean | 60 bu | 26 |
| Tomato | 40 tons | 30 |
| Wheat | 60 bu | 16 |

Calcium has an important influence on soil properties, especially as it prevents dispersion of clay. An abundant supply of Ca can help reduce soil crusting and compaction, leading to improved water percolation, and reduced runoff.

### Fertilizing with Calcium

Calcium is not typically formulated into fertilizer sources specifically to meet plant Ca requirements, but rather as a component of other materials. The most common Ca sources are liming materials, mainly $CaCO_3$. Most acidic soils that have been limed to the proper pH will not have Ca nutritional problems. Calcium is often supplied as gypsum as an amendment to improve soil chemical or physical properties.

Clays can disperse in soils with high sodium (Na) content, resulting in poor soil structure and reduced water permeability. Added Ca replaces the $Na^+$ on the cation exchange sites and corrects clay dispersion problems. Calcium is a component of several common nitrogen (N) and P fertilizer materials (**Table 2**).

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IPNI2011GSU03-1369/M.K. SHARMA AND P. KUMAR

**Blossom end rot** in tomato and peppers can develop when inadequate calcium moves with transpiration stream to the end of the fruit.

**Bitter pit** develops in apple fruit when supplied with inadequate calcium.

**Tip burn** in romaine lettuce is associated with inadequate calcium uptake.

**Stunted development** of the growing point of corn is caused by calcium deficiency.

**Table 2.** Common calcium fertilizer sources.

| Source | Ca content, % |
|---|---|
| Calcitic limestone ($CaCO_3$) | 32 |
| Gypsum ($CaSO_4 \cdot 2H_2O$) | 22 |
| Triple superphosphate ($Ca(H_2PO_4)_2 \cdot H_2O$) | 15 |
| Calcium nitrate ($Ca(NO_3)_2$) | 19 |
| Calcium ammonium nitrate solution | 8 |
| Chelated calcium (various formulations) | 2 to 5 |
| Calcium chloride ($CaCl_2$) | 36 |
| Calcium thiosulfate ($CaS_2O_3$) | 6 |

Calcium fertilizers are most often applied directly to the soil, but foliar applications are also common for fruits and vegetables. Foliar applications are made during the growing season to correct deficiencies and improve crop quality. Soluble Ca fertilizers are sometimes applied through the irrigation system

## Calcium Deficiency Symptoms

Calcium deficiencies are not common in most crops, but may occur in acidic soils. Deficiencies occur with some horticultural crops where Ca is not adequately supplied to developing plant cells due to restricted uptake or movement within the plant. Calcium is not moved from older plant tissue or redistributed, so young tissues rely on the continual supply of Ca in the transpiration stream. Since transpiration is low in young leaves, in fruit, and in enclosed tissues, various Ca-related disorders can occur.

Deficiencies of Ca typically occur:

1. In young expanding leaves (such as tip burn in lettuce)
2. In enclosed tissues (such as black heart in celery)
3. In plant tissues fed primarily by phloem (such as blossom-end rot in tomato, pepper, water melon; bitter pit in apples; empty pod in peanuts)

Other symptoms associated with Ca deficiency may include:

1. Abnormal development of growing points (terminal buds)
2. Abnormally dark green foliage
3. Premature shedding of blossoms and buds
4. Weakened stems

## Crop Response to Added Calcium

As with all essential nutrients, when soluble Ca concentrations fall below a critical level, crops are likely to respond favorably to fertilizer application. Calcium uptake occurs primarily at the root tip, so conditions that damage root health will also impair Ca uptake.Since most soils have Ca present, favorable crop responses are generally due to enhancing the Ca supply to developing leaves and fruit (**Table 3**), or as a result of improving the physical condition of the soil (**Figure 1**). Local recommendations should be obtained before adopting techniques to boost the Ca concentrations in plant leaves and fruits that may be lacking an adequate supply.

**Table 3.** Increase in apple fruit Ca concentration from foliar or soil applied treatments compared with untreated control apples.[3]

| Treatment | Increase in fruit calcium concentration, ppm |
|---|---|
| 8 foliar sprays (22 lb Ca/A) | 45 |
| 5 foliar sprays (12 lb Ca/A) | 25 |
| 2 foliar sprays (5 lb Ca/A) | 10 |
| Gypsum on soil (440 lb Ca/A) | 12 |

All foliar sprays were made with $CaCl_2$ diluted to 300 gal/A. Apples with low Ca concentrations can be susceptible to cork spot and bitter pit, resulting in nonmarketable fruit.

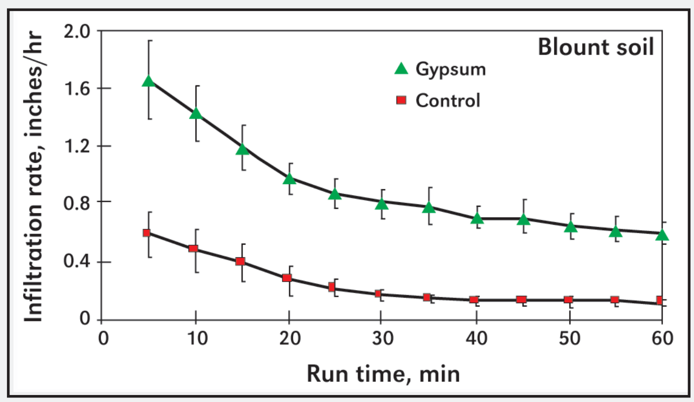


**Figure 1.** Calcium sulfate (gypsum) can improve soil physical properties by enhancing water infiltration and percolation in some soils.[4]

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# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Magnesium

NO. 6

NORTH AMERICAN EDITION

Magnesium (Mg) is one of nine macronutrients and is taken up by plants in quantities similar to that of phosphorus (P).

## Magnesium in Plants

In plants, Mg is essential for many functions. It:

- sets in motion (catalyzes) the production of chlorophyll and serves as the central atom in the chlorophyll molecule;
- serves as a building block of ribosomes, the "factories" that synthesize proteins in cells;
- stabilizes certain structures of nucleic acids, the molecules that transfer genetic information when new cells are formed;
- activates or promotes the activity of enzymes, which are molecules that have specific shapes needed to set in motion certain chemical reactions necessary for proper growth and development of plants;
- serves as an essential element to create adenosine triphosphate (ATP), the "battery" that stores energy in the plant;
- ensures carbohydrates created in leaves are exported to other plant organs. Carbohydrates are used in plants for energy and for structure.

## Magnesium in Soils

Plants can only access Mg in the soil solution. Contributors to this Mg are:

- redistribution from other areas, including: irrigation water, commercial fertilizer, manure, biosolids, and sediment deposition;
- weathering of Mg-containing primary and secondary minerals like certain types of amphiboles, biotite, chlorites, dolomite, garnets, olivine, magnesite, phlogopite, some pyroxenes, serpentines, talc, and tourmaline;
- release from the interlayers of the layer silicate minerals chlorite, smectites, and vermiculite; and
- release (desorption) from surfaces and edges of layer silicate minerals, termed "exchangeable Mg."

Exchangeable Mg and Mg in the soil solution are the Mg forms measured by soil tests and are considered readily available to plants.

Minerals containing Mg are more soluble in acid soils (below pH 7). In sandy soils with low numbers of exchange sites (low cation exchange capacity), dissolved Mg can move below the root zone because there are not enough edges and surfaces of layer silicate minerals to retain it in the upper levels of the soil. Therefore, levels of exchangeable Mg in acid, sandy soils can be too low to meet plant nutritional needs.

When plant roots take up water, more water from farther away moves to the roots to replace that which was taken up. Magnesium that is dissolved in the soil solution moves with this water. This process, termed mass flow, is responsible for keeping the plant supplied with dissolved Mg.

**Table 1.** Commercial sources of magnesium fertilizer[1].

| Fertilizer name | Chemical formula | Typical Mg concentration, % |
|---|---|---|
| Dolomite | $MgCO_3 \cdot CaCO_3$ | 6 - 20 |
| Hydrated dolomite | $MgO \cdot CaO/MgO \cdot Ca(OH)_2$ | 18 - 20 |
| Kainite | $MgSO_4 \cdot KCl \cdot 3H_2O$ | 9 |
| Kieserite | $MgSO_4 \cdot H_2O$ | 17 |
| Langbeinite | $2MgSO_4 \cdot K_2SO_4$ | 11 |
| Magnesium chloride | $MgCl_2$ | 25 |
| Magnesium nitrate | $Mg(NO_3)_2 \cdot 6H_2O$ | 9 |
| Magnesium oxide | $MgO$ | 56 |
| Magnesium sulfate | $MgSO_4 \cdot 7H_2O$ | 9 |
| Schoenite | $K_2SO_4 \cdot MgSO_4 \cdot 6H_2O$ | 6 |
| Struvite | $MgNH_4PO_4 \cdot 6H_2O$ | 10 |

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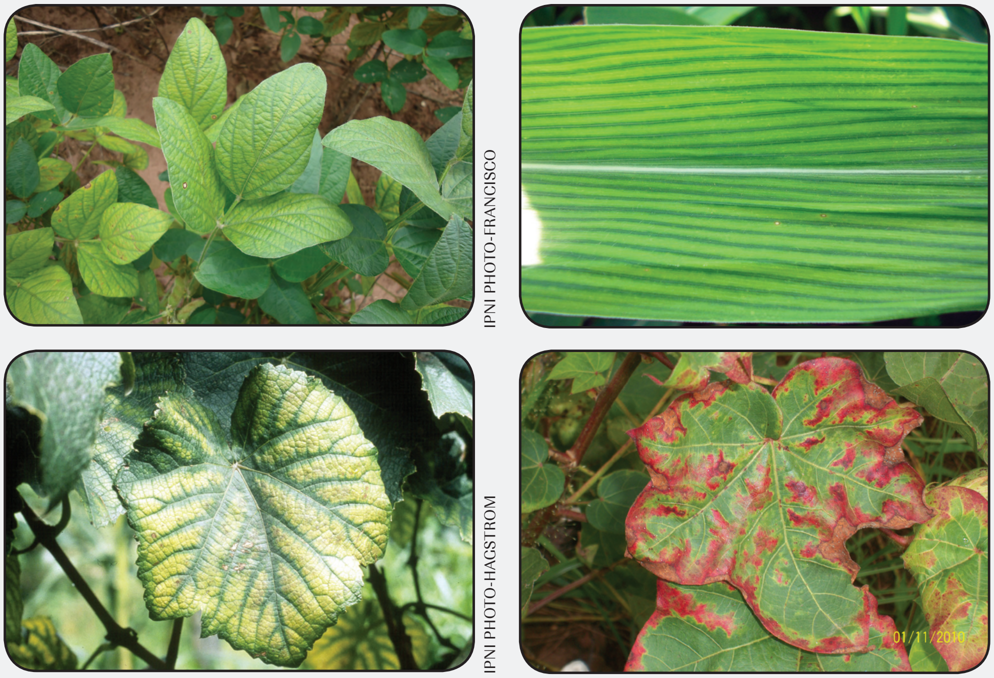

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**Magnesium deficiency** (clockwise order starting top left) in soybean, corn, grape, and cotton. It commonly starts as interveinal chlorosis on leaf margins, spreading towards the center of the leaf as conditions worsen. Tissue become bright yellow between the veins, and finally can become reddish-purple from the outside leaf edges inward.

## Fertilizing Soils with Magnesium

Fertilizing soils with Mg is necessary when the soil alone cannot supply enough to meet crop needs. Soil testing is used to assess soil Mg supplies that are available to plants.

Many other nutrients can compete with Mg for crop uptake (termed antagonism). In acid soils, aluminum (Al), the hydronium ion ($H^+$), and manganese (Mn) can reduce Mg uptake by plants. In basic soils, calcium (Ca) and sodium (Na) compete for Mg uptake. Where higher rates of ammonium ($NH_4^+$) forms of nitrogen have been applied, either with fertilizers or manures, Mg levels in plants can be lower. The same effect occurs where higher rates of potassium (K) have been applied or where soils are naturally high in K, such as in arid regions of the U.S. These antagonisms are most likely to occur where soil Mg levels are marginal.

Many fertilizer sources of Mg are available. **Table 1** lists these sources and their average Mg concentrations, which range from 6 to 56%. Dolomite and hydrated dolomite are used most commonly to correct Mg deficiencies while simultaneously raising soil pH levels in acid soils.

Either soil or foliar applications of Mg may be recommended, depending on the crop to be grown and the growth stage when Mg deficiency is diagnosed. Foliar applications are sometimes recommended for forage crops where Mg concentrations in plant tissues are too low for animal nutrition, which can lead to grass tetany, or hypomagnesemia. Foliar applications must usually be repeated since Mg is taken up in large quantities.

## Magnesium Deficiency Symptoms

When plants don't have enough Mg, an important process gets inhibited. During photosynthesis, carbohydrates are produced. The plant uses these carbohydrates for energy and also for structure. When Mg is deficient, the movement of carbohydrates from the leaves to other parts of the plant is slowed. This results in reduced growth of other plant organs like roots and the reproductive parts that are harvested. Reduced root growth can inhibit the uptake of other nutrients that the plant needs, causing a cascade of nutritional problems. Additionally, the buildup of carbohydrates in the leaves signals the plant to slow down photosynthesis and produce fewer carbohydrates—just the opposite of what a growing plant needs. Stunted plants and smaller root systems are the result. The inhibition of photosynthesis produces an interveinal yellow appearance to leaves, usually most prominent on the older leaves on the plant.

## Crop Response to Magnesium

When plants are deficient in Mg, adding more results in increased Mg concentrations in plant tissues and can also lead to increased growth and yield. The ratio of Mg to K and Ca in plant tissues can be an important issue for forages. **Table 2** provides an example of a crop response to Mg fertilization. Grain sorghum was grown on an acid, sandy loam soil that was low in Mg. Adding Mg increased sorghum grain yield 15 to 29%, depending on the rate applied. The numbers in the table are averages over three different hybrids and three study years. This study reinforces that Mg is an essential nutrient and is required for proper plant growth.

**Table 2.** Sorghum grain yield response to magnesium fertilization[2].

| Mg rate, lb/A | Average grain yield, bu/A | Percent yield increase, % |
|---|---|---|
| 0 | 75 | -- |
| 15 | 86 | 15 |
| 30 | 86 | 15 |
| 45 | 94 | 25 |
| 60 | 97 | 29 |

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# Nutri-Facts

IPNI

Agronomic fact sheets on crop nutrients

# Boron

NO. 7

NORTH AMERICAN EDITION

Over the past 80 years, hundreds of reports have documented a role for boron (B) in agricultural crops around the world. Responses to fertilization have been documented in almost every state and province in the U.S. and Canada. Alfalfa frequently responds, and so do a large number of fruit, vegetable and field crops.

## Boron in Plants

Essentiality for higher plants was recognized by 1923. It has also been found essential for ferns and some algae.

The primary role of B is in the cell walls, providing cross links between polysaccharides to give structure to cell walls. Boron also plays roles in formation of sugar complexes for translocation within plants, and in the formation of proteins. Cell membrane function, nodule formation, flowering, and development of seed and fruit all depend on adequate B. Deficiency can reduce both yield and quality of crops. Flower initiation and pollen development also require adequate B.

## Boron in Soils

Agricultural soils range from 1 to 467 mg/kg in total B concentration. The available forms, $B(OH)_3$ and $B(OH)_4^-$, are usually mobile in the soil solution, but can be adsorbed to the common constituents of soil, including hydroxides of iron (Fe) and alumimum (Al), clay particles, and organic matter. There are several factors that influence B availability in the soil:

**Organic matter** is the most important soil reservoir of B. In hot, dry weather, decomposition slows down in the soil surface horizon where most of the organic matter is found. This can lead to a B deficiency. In cold weather, organic matter decomposition also slows, and low B release affects many cole crops (Brussels sprouts, radishes) and other early planted species.

**Weather conditions:** Dry and cold weather restricts root activity in the surface soil and can cause temporary B shortages. Deficiency symptoms may disappear as soon as the surface soil receives rainfall. Root growth resumes, but yield potential is often cut during the B shortage.

**Soil pH:** Plant availability of B is greatest between pH 5.0 and 7.5. At higher pH values, B uptake is reduced. Liming acid soils can lower B solubility and enhance response to B fertilizers. An experiment on an acidic soil in the southern U.S. coastal plain showed a positive yield response to applied B only when lime was also applied (**Figure 1**). The applied lime raised the soil pH in the top 2 inches from 6.0 to 6.4. Adding lime to raise soil pH may also protect against B toxicity where soil B levels are high.

**Soil texture:** Coarse-textured sandy soils, which are composed largely of quartz, are typically low in minerals that contain B. Plants growing on such soils commonly show B deficiencies.

**Leaching:** Plant available B is mobile in the soil and is subject to leaching. Leaching of B from the root zone is of greater concern on sandy soils and/or in areas of high rainfall.

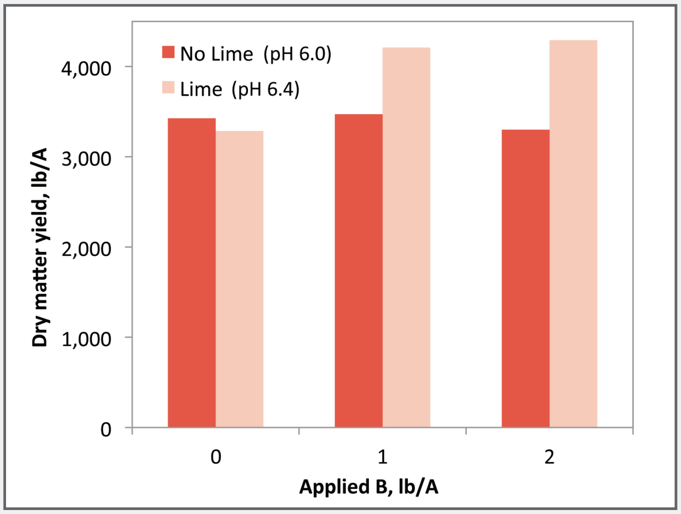


**Figure 1.** Rose clover response to boron depends on applying lime to raise soil pH.[1]

## Fertilizing with Boron

It is important that B fertilizers be properly applied because of the narrow range between deficiency and toxicity. Diagnosing the need for B fertilization needs to consider the factors


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IPNI PHOTO-MILES

**Boron deficiency in alfalfa** is often seen in drought conditions.

listed above controlling soil availability. Plant analysis and visual symptoms are often more useful as diagnostic tools than soil testing.

Boron fertilizer can be broadcast or band applied to soil, or applied as a liquid foliar treatment. Broadcast application requires higher rates than band or foliar. Soil application rates for responsive crops may be as high as 3 lb B/A, and for low and medium responsive crops, 0.5 to 1.0 lb/A (**Table 1**). Common forms of fertilizer are shown in **Table 2**. Soluble forms are usually preferred, except in sandy soils where less soluble forms are less susceptible to leaching.

**Table 1.** Responsiveness of crops to Boron.

| Most response | Medium response | Least response | |
|---|---|---|---|
| Alfalfa | Carrot | Asparagus | Pepper |
| Apple | Clover | Barley | Peppermint |
| Broccoli | Cotton | Bean | Potato |
| Brussels sprout | Cherry | Blueberry | Raspberry |
| Cabbage | Lettuce | Cereals | Rye |
| Cauliflower | Parsnip | Citrus | Snapbean |
| Celery | Pear | Corn | Sorghum |
| Peanut | Radish | Cucumber | Soybean |
| Sunflower | Spinach | Flax | Spearmint |
| Table beet | Sugar beet | Grass | Strawberry |
| Turnip | Sweet corn | Oats | Sudangrass |
| | Sweet potato | Onion | Wheat |
| | Tomato | Pea | |

## Boron Deficiency Symptoms

Although B is mobile in the soil, its mobility within the plant varies among species. Nutrient deficiencies tend to appear on the youngest leaves or growing points. In certain species (such as apples and almonds), B is mobile and moves throughout the plant.

**Table 2.** Common Boron fertilizers.

| Source | Formula | B, % | Water solubility |
|---|---|---|---|
| Borax | $Na_2B_4O_7{\cdot}10H_2O$ | 11 | Soluble |
| Boric acid | $B(OH)_3$ | 17 | Soluble |
| Sodium pentaborate | $Na_2B_{10}O_{16}{\cdot}10H_2O$ | 18 | Soluble |
| Sodium tetraborate | $Na_2B_4O_7{\cdot}5H_2O$ | 14-15 | Soluble |
| Solubor® | $Na_2B_8O_{13}{\cdot}4H_2O$ | 20-21 | Soluble |
| Boron frits | Boric oxide glass | 2-11 | Very slightly soluble |

**Solubor®** is a registered trademark of U.S. Borax Inc.

The following B deficiency symptoms occur in specific crops:

**Alfalfa:** short internodes and stems, younger leaves turn red or yellow, death of terminal bud.
**Almond:** new shoots do not develop. Brown and gummy nuts.
**Apple:** small, flattened or misshaped fruit, internal corking, cracking and russetting, dead terminal buds, brittle leaves, blossom blast.
**Celery:** crooked stem
**Corn:** narrow white to transparent lengthwise streaks on leaves, multiple but small and abnormal ears with very short silk, small tassels with some branches emerging dead, and small, shrivelled anthers devoid of pollen.
**Cotton:** ringed or banded leaf petioles with dieback of terminal buds, causing rosetting effect at the top of the plant. Ruptured squares and thick, green leaves that stay green until frost and are difficult to defoliate.
**Peanut:** hollow heart
**Sugar beet and Table beet:** black heart (heart rot)

## Boron Toxicity Symptoms

Toxic accumulation of B occur in many arid regions. Addition of extra irrigation water will leach soluble B below the root zone. Boron toxicity symptoms appear first on the edges and tips of older leaves.

## Crop Response to Boron

Crops vary significantly in their responsiveness (**Tables 1 and 3**). Most legumes, as well as several fruits and vegetables, are highly responsive to B. Other vegetables show somewhat less response. Grains and grasses are generally less responsive to B. Crops vary in sensitivity to excess B, and those with high requirements do not always have high tolerance. For example, alfalfa and cabbage are only semi tolerant to high boron levels.

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**Table 3.** Examples of crop yield response to application of Boron fertilizer.

| Crop | Source | Rate | Time | Place | Yield response | Reference |
|---|---|---|---|---|---|---|
| Soybean | $Na_2B_8O_{13}{\cdot}4H_2O$ | 0.25 - 1.0 lb/A | V2 or R2 | Foliar | 0 - 130% | 2 |
| Alfalfa seed | $Na_2B_8O_{13}{\cdot}4H_2O$ | 0.4 - 1.1 lb/A | After 1st cut | Foliar | 37% | 3 |
| Alfalfa forage | $Na_2B_4O_7{\cdot}5H_2O$ | 3 - 4 lb/A | Annual | Soil | 46 - 62% | 4 |
| Sour cherry | $Na_2B_8O_{13}{\cdot}4H_2O$ | 500 mg/L | Sept - Oct | Foliar | 0 - 100% | 5 |

# Nutri-Facts

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Agronomic fact sheets on crop nutrients

# Zinc

NO. 8

**North American Edition**

Although Zinc (Zn) is a trace element and only required in very small amounts in the plant, Zn deficiency in crops is widespread around the world. Low Zn content in food crops contributes to Zn deficiency in approximately 30% of human diets. With the world population continuing to expand, it is critical that attention be paid to Zn nutrition in food crop production.

## Zinc in Plants

Zinc is needed in very small amounts by plants. The normal concentration of Zn in most plants is between 20 to 100 ppm. Removal in the harvested portion of most crops is less than 0.5 lb Zn/A. However, this small amount of Zn plays a key role in plants as an enzyme co-factor and a structural component in proteins. Important biochemical pathways affected by Zn in plants include protein synthesis, hormone regulation and energy production.

## Zinc in Soils

The total amount of Zn in soils averages about 50 ppm, ranging from 10 to 300 ppm depending on the geochemical composition and weathering of the parent material. Zinc, like all plant nutrients, must be dissolved in water before it can be taken up by roots. Soil solution Zn concentrations are very low, ranging from 2 to 70 ppb. Zinc exists in the soil solution as the divalent cation $Zn^{2+}$ and its availability for uptake depends on several factors, including the following:

**Soil pH** – Zn becomes less soluble as soil pH increases due to increased adsorptive capacity by clay minerals, aluminum (Al) and iron (Fe) oxides, and calcium carbonates. Zinc availability can also be reduced under low pH conditions, particularly in coarse-textured, highly weathered soils.

**Soil organic matter** – Rapidly decomposable organic matter such as manure can increase available Zn by forming soluble organic Zn complexes. Other organic materials found in peat and muck soils can form insoluble complexes resulting in lower Zn concentrations. Generally, low soil organic matter levels are indicative of low Zn availability. Cultural practices such as land leveling or tilling, as well as erosion can also lead to lower Zn availability by exposing subsoils low in organic matter.

IPNI PHOTO-ESPINOSA

Zinc deficiency in corn.

IPNI PHOTO-SHARMA AND KUMAR

Zinc deficiency in barley.

**Climatic conditions** – Diffusion is the primary mechanism for transporting Zn to plant roots, so any factor that inhibits root development will impair Zn uptake. Climatic factors resulting in reduced Zn uptake include cold, wet soils particularly early in the growing season. Plants may outgrow this early-season deficiency; however, some yield loss may have already occurred. Waterlogged soils can also have lower available Zn levels due to the reduced conditions and subsequent precipitation of insoluble Zn compounds.

**Interaction with other nutrients** – The antagonistic effect of other metal cations, especially copper ($Cu^{2+}$) and $Fe^{2+}$, can inhibit Zn uptake. High phosphorus (P) can also decrease

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concentration uptake of Zn. This interaction is most common in soils that are marginally deficient in Zn. The addition of fertilizer P to soils adequate in Zn will not induce a Zn deficiency. Plant physiological factors may also contribute to the onset of Zn deficiency associated with high P levels.

## Fertilizing with Zinc

Considering the many soil factors that affect Zn availability to plants, soil testing is the best tool for predicting the need for additional Zn. Visual inspection and plant tissue analysis are also useful diagnostic tools to determine Zn fertilizer needs, but they often only are used after a deficiency has already occured.

Three basic types of compounds used as Zn fertilizers include inorganic mineral compounds, synthetic chelates and natural organic materials. Water solubility is the primary factor governing the performance of Zn fertilizers, common sources of Zn fertilizers are listed in **Table 1**.

**Table 1.** Common zinc fertilizer sources.

| Source | Zn content, % |
|---|---|
| Zinc sulfates (hydrated) | 22-36 |
| Zinc sulfate (basic) | 55 |
| Zinc oxide | 50-80 |
| Ammoniated zinc complexes | 10 |
| Zinc chelates | 6-14 |
| Other organics (polyflavonoids) | 5-10 |

Zinc fertilizer rate recommendations vary regionally and by crop. In general, broadcast applications (typically of zinc sulfate) that raise soil Zn levels to adequate amounts are expected to be effective for 3 to 5 years. Some regions recommend a lower rate if the Zn is to be applied in a concentrated band in the soil. However, these reduced rates are usually anticipated to be added annually as part of a starter blend during planting.

Foliar Zn applications of 0.5 to 1 lb Zn/A, typically in chelated forms, have been shown to be effective as an in-season fertilization strategy. However, this approach is best utilized as a rescue treatment or as a compliment to a sound soil-based fertility program.

## Zinc Deficiency Symptoms

Zinc deficiencies occur in a wide variety of plants when the leaf level drops below 15 ppm. Zinc, like most micronutrients, is mostly immobile in the plant and deficiency symptoms appear first in the newly emerging leaves.

Frequent symptoms associated with Zn deficiency include:
- Stunted plants
- Light green areas between the veins of new leaves
- Smaller leaves (little leaf)
- Shortened internodes (rosetting)
- Broad white bands on each side of the midrib in corn and grain sorghum (white bud)

Zinc deficiency symptoms are similar to those of manganese (Mn) and Fe in some crops and a tissue test should be used to confirm the nutrient deficiency.

## Crop Response to Zinc

Crops vary in their responsiveness to Zn (**Table 2**). When needed for production of a responsive crop, Zn fertilizer application can result in substantial increases in crop yield (**Tables 3 and 4**).

**Table 2.** Responsiveness of crops to zinc.

| Most response | Medium response | Least response |
|---|---|---|
| Beans | Barley | Asparagus |
| Corn | Potatoes | Carrots |
| Onions | Soybean | Grass |
| Sorghum | Sudangrass | Oats |
| Sweet Corn | Sugarbeets | Peas |
| Citrus | Table Beets | Rye |
| Rice | Tomatoes | Rye |
| Peaches | Alfalfa | Celery |
| Pecans | Clover | Lettuce |
| Flax | Cotton | Grapes |

**Table 3.** Response of corn to application of zinc in a fertilizer band at planting[1].

| Zn applied*, lb/A | Corn yield, bu/A |
|---|---|
| 0 | 62 |
| 0.3 | 137 |
| 1.0 | 140 |
| 3.0 | 142 |

*Applied in an 8-20-0 suspension; DTPA-extractable Zn in the soil was 0.3 ppm.

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**Table 4.** Response of rice to broadcast and incorporated Zn fertilizer applications[2].

| | Site year 1 | | Site year 2 | | Site year 3 | | Site year 4 | |
|---|---|---|---|---|---|---|---|---|
| | 0 Zn | 12 lb Zn/A | 0 Zn | 12 lb Zn/A | 0 Zn | 12 lb Zn/A | 0 Zn | 12 lb Zn/A |
| Grain yield, t/A | 3.2 | 3.8 | 3.2 | 3.6 | 2.3 | 2.7 | 1.3 | 3.1 |
| Dry matter, lb/A | 248 | 419 | 693 | 920 | 178 | 527 | 349 | 782 |
| Tissue Zn, ppm | 15.1 | 21.0 | 15.6 | 23.5 | 13.9 | 21.5 | 12.4 | 17.9 |

Data are averaged over four Zn sources including a sulfate, ligosulfate, and two oxy-sulfates.

# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Manganese

NO. 9

NORTH AMERICAN EDITION

Manganese (Mn) is one of the 17 elements essential for plant growth and reproduction. It is needed in only small quantities by plants, but like other micronutrients Mn is ultimately as critical to plant growth as are the major nutrients.

## Manganese in Plants

The normal concentration range of Mn in plants is typically from 20 to 300 ppm. When the Mn concentration falls below 15 to 20 ppm, deficiency often occurs (**Table 1**).

**Table 1.** Manganese sufficiency ranges for some crops and crop responsiveness to applied Mn fertilizer.

| Crop | Mn sufficiency range, ppm | Responsiveness |
|---|---|---|
| Corn | 30-150 | Medium |
| Soybeans | 20-100 | High |
| Alfalfa | 30-100 | Medium |
| Wheat | 20-200 | High |
| Sugar beets | 30-150 | High |
| Sorghum | 18-190 | High |
| Cotton | 25-350 | Low |
| Potatoes | 30-200 | Medium |

Manganese is taken up by plants in the $Mn^{2+}$ form, and in organically complexed forms. Plant roots release exudates such as low molecular weight organic acids that aid in Mn uptake from the soil. Within plants Mn functions mostly as an activator in enzyme systems, but it is also a constituent of certain enzymes. It is essential to photosynthesis reactions, and is involved in the evolution of oxygen in photosynthesis. The synthesis of lignin, which adds strength and stiffness to cell walls, is dependent on Mn. Manganese is also essential for root growth.

## Manganese in Soils

The earth's crust is about 0.11% Mn. Total Mn in soils generally ranges from about 20 to 3,000 ppm (0.002 to 0.30%), but only a fraction of this total is plant available. The most common form of Mn in soil solution is $Mn^{2+}$, which is often complexed by organic compounds.

The concentration of $Mn^{2+}$ in soil solution is highly pH dependent, with levels decreasing by about 100x with each unit of pH increase. Thus, plant available Mn increases as soil pH decreases, so deficiencies are more likely to occur in alkaline soils. On the other extreme, if soil pH is too low (<5) Mn can be toxic to sensitive crops.

Crop deficiencies of Mn occur most often on high pH (alkaline) soils, and on soils that are simply naturally low in Mn. Deficiencies may also be problematic in high organic matter soils such as peats and mucks that favor the formation of unavailable Mn chelates. It should be noted too that high levels of copper (Cu), iron (Fe), or zinc (Zn) may reduce $Mn^{2+}$ uptake. The most common extractant used in soil analysis for Mn is the chelating agent DTPA. The critical level for DTPA extracted Mn is usually set at 1 ppm, but this varies depending on local calibration research.

## Manganese Deficiency Symptoms

Manganese, like many other micronutrients, is immobile in plants. This is an important point because it means that deficiency symptoms will first appear on younger leaves since the plant cannot easily scavenge Mn from older tissue. Some crops are more susceptible than others to Mn deficiency. Sensitive crops include soybeans, small grains, peanuts, cucurbits, onions, peas, radishes, and beans. Symptom descriptions for selected crops are given below.

**Soybeans:** Upper leaves first become chlorotic between the veins while veins remain green. Newer leaves become pale green first and then pale yellow. As the deficiency becomes more severe, brown, dead areas appear. Some, but not all

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research has indicated that glyphosate-ready soybeans may be more responsive to Mn addition than conventional varieties.

**Corn:** Deficient plants appear stunted with short, thin stems and pale green to yellow leaves. If deficiency becomes severe, leaves turn pale yellow and white flecks appear in interveinal chlorotic areas. Symptoms appear on younger leaves first.

IPNI PHOTO-SHARMA/KUMAR

**Mn-deficient corn.**

**Cotton:** The younger leaves are affected first. They become cupped and yellowish-grey or reddish-grey in color with green veins. Excessive soil Mn can be toxic at low soil pH. This condition is referred to as crinkle leaf.

**Small grains:** Oats are the most susceptible among this class. A Mn deficiency in oats is sometimes called "gray speck" and usually starts as a gray oval shaped spot on the edge of the new leaf at the 3 to 4 leaf stage. The speck may gradually spread across the entire leaf, or many spots may develop. In wheat and barley, plants develop yellow parallel streaks on the younger leaves that run the length of the leaf. It is always a good idea where possible to confirm field symptoms with plant tissue analysis.

**Onion:** One of the vegetable crops most susceptible to Mn deficiency. Outer leaves show striped interveinal chlorosis and develop tip burn with progressive necrosis. Stunted plants and delayed bulbing are also symptoms.

## Fertilizing with Manganese

IPNI PHOTO-SADANA

**Manganese-deficient wheat.**

Manganese sulfate ($MnSO_4$) is the most common of the Mn fertilizer sources. It is highly water soluble and suited for soil or foliar application. There are several other Mn fertilizer sources including chelates, chlorides, oxides, and oxysulfates (**Table 2**).

Manganese fertilizer can be broadcast, banded in soil or applied as a foliar spray. Rates of Mn application are highly dependent on method of application. Soil-applied broadcast rates generally range from about 10 to 15 lb Mn/A, banded near the crop row ranges from about 3 to 5 lb Mn/A, and foliar application usually ranges from about 1 to 2 lb Mn/A.

Banded or foliar applications are preferable over broadcast in high pH soils since Mn is rather quickly rendered insoluble in alkaline conditions. In these soils, band application minimizes soil-to-Mn contact and thus delays soil-Mn reactions. Also, applying Mn in a band with acid forming fertilizers (e.g., elemental S and ammonium-N) may help prolong availability in alkaline soil conditions.

**Table 2.** Manganese fertilizer sources, formulas and Mn content.

| Source | Chemical formula | Mn content, % |
|---|---|---|
| Manganese Sulfate | $MnSO_4 \cdot 3H_2O$ | 26-28 |
| Manganese Chloride | $MnCl_2$ | 17 |
| Manganese Carbonate | $MnCO_3$ | 31 |
| Manganese Oxide | $MnO_2$ | 63 |
| Manganous Oxide | MnO | 41-68 |
| Manganese Chelate | MnEDTA | 12 |
| Manganese Frits | - | 10-25 |

Water-soluble Mn fertilizers are good sources of Mn when applied to either soil or foliage, but limited solubility Mn sources (like oxides or oxysulfates) should only be used for soil applications and when finely ground to particle sizes less than 0.1 to 0.15 mm. With application of Mn chelates to soil, it should be noted that the chelation feature may be short-lived since the chelating agent may quickly form more stable iron ($Fe^{3+}$) chelates in the soil. It is for this reason that some suggest the use of $MnSO_4$ for soil application.

Foliar applications should be made immediately if deficiency symptoms appear and again if symptoms reappear. Mixing of Mn fertilizers with glyphosate should be avoided since the two will form undesirable complexes.

## Crop Response to Manganese

A soybean trial in Indiana compared a zero Mn control to foliar applications of chelated Mn and $MnSO_4$, as well as various soil applications. Soil applications of Mn included broadcast, in-furrow, and placement with an acid-forming starter fertilizer. A treatment with starter only (no Mn) was also included. Foliar application of $MnSO_4$ was consistently the most effective means of correcting Mn deficiency in soybeans in this experiment.

**Table 3.** Soybean yield response to Mn treatments in Indiana[1].

| Mn Treatment | Mn Rate/A | Yield, bu/A |
|---|---|---|
| Control | 0 | 44.3 |
| Starter alone† | 0 | 47.1* |
| Soil $MnSO_4$ | | |
| Broadcast | 10 lb | 43.4 |
| In-furrow | 6 lb | 43.8 |
| W/ Starter† | 1 qt. Mn complex | 46.5 |
| Foliar $MnSO_4$ | | |
| 1 application | 1 lb | 48.0* |
| 2 applications | 2 lb | 46.9* |
| Foliar EDTA | | |
| 1 application | 16 oz. | 46.4 |

† Acid forming starter fertilizer source was 3-10-10 in 1990 and 10-34-0 in 1991.
* Indicates that the yield was significantly higher than the control yield.

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# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Copper

NO. 10

NORTH AMERICAN EDITION

Copper (Cu) is one of eight essential plant micronutrients. When Cu is deficient, common crop responses to its application include reduced disease, increased crop growth and improved quality. Commonly applied Cu sources include fertilizer, animal manures, biosolids, and pesticides.

## Copper in Plants

Copper has an essential function in human health and for plant growth. Its essential status for plant nutrition was not recognized until 1931. Normal Cu concentrations in plants range from 5 to 20 ppm.

Plant roots absorb the divalent form ($Cu^{2+}$; cupric) and can readily reduce it to the monovalent form ($Cu^{+}$; cuprous). The ease of converting Cu back and forth between the cupric and cuprous forms gives Cu unique functions in the plant. Copper plays roles in photosynthesis and respiration, including the final transfer of electrons to oxygen. Copper helps form lignin in cell walls, which provide support to hold plants upright. It is particularly important to the formation of viable pollen, seed set and stress resistance.

## Copper in Soils

Total Cu in soils commonly ranges between 1 to 40 ppm, but the Cu concentration dissolved in the soil solution is much lower. The availability of Cu in soils for plant uptake is affected by the following characteristics:

- **Organic matter.** Copper is more tightly bound to organic matter than any other micronutrient. Plant Cu deficiencies often occur in crops growing on peats, mucks, and soils with more than 8% organic matter. Critical concentrations of soil test Cu (DTPA-extractable Cu) are much higher in these soils than in mineral soils.
- **Texture.** Plants growing in sandy-textured soils are more likely to be deficient than those growing in loams and clays. Clay-textured soils generally hold more Cu in exchangeable form, available to crops. Other soil components, such as oxides and carbonates, can further reduce Cu availability.
- **Soil pH.** Copper solubility decreases as pH increases to 7 and above. Higher pH increases the strength by which Cu is held by soil clays and organic matter, thus making it less available to crops.
- **Nutrient balance.** High concentrations of zinc (Zn), phosphorus (P), aluminum (Al), and iron (Fe) in soils can depress Cu absorption by roots and aggravate Cu deficiency. Risks of Cu deficiency also increase with higher rates of nitrogen (N) application.

## Fertilizing Soils with Copper

**Source:** When additional Cu is required, the most common fertilizer source is copper sulfate, although many other excellent materials are available (**Table 1**). Additional sources of Cu include livestock and poultry manures, and municipal wastes or biosolids. Some animal manures contain elevated concentrations of Cu due to its addition to animal feed, or its use in foot baths to prevent foot rot.

**Rate:** Where crop deficiencies have been identified, the right rate depends on the specific Cu source. Copper fertilizers vary in their Cu content and solubility in soil. For example, rates of 3 to 14 lb/A of Cu as copper sulfate or around 0.5 lb/A of Cu as chelate are used for soil application, with lower rates for foliar application.

**Time:** Since Cu is tightly retained in soil, the timing of soil applications is flexible and Cu availability can be improved for several years following a single application. Foliar applications are usually limited to emergency situations where the deficiency is identified after planting, or as part of a maintenance foliar fertilization program.

**Place:** Effectiveness of Cu delivery is increased by thoroughly mixing fertilizers into the root zone or by band application near the seed row. The risk of root injury increases when a high rate of Cu is band applied near the seed.

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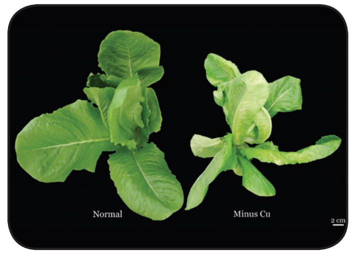
IPNI2010PPI05-2460

**Healthy to severely Cu deficient** wheat heads, showing signs of melanosis.

IPNI2010PPI06-1766

**"Pig-tailing" of wheat leaves** is a common **copper deficiency** symptom.




D. PITCHAY

**Copper deficiency** in lettuce compared with normal growth (left).

IPNI2010PPI05-2302

**Copper deficiency** in citrus.

**Table 1.** Common Cu Sources[1,9].

| Source | Formula | Cu, % |
|---|---|---|
| Copper sulfate | $CuSO_4 \cdot 5H_2O$ | 25 |
| Copper chelate EDTA | $Na_2Cu$ EDTA | 13 |
| Copper sulfate monohydrate | $CuSO_4 \cdot H_2O$ | 35 |
| Copper acetate | $Cu(CH_3COO)_2 \cdot H_2O$ | 32 |
| Copper ammonium phosphate | $CuNH_4PO_4 \cdot H_2O$ | 32 |
| Cupric oxide | CuO | 75 |
| Cuprous oxide | $Cu_2O$ | 89 |
| Animal manures[2] | - | 0.002 - 0.07 |
| Biosolids[3] | - | <0.43; mean 0.074 |

## Copper Deficiency Symptoms

Copper deficiency symptoms vary with the crop. Mild or moderate deficiency may reduce yield or plant growth without clear signs. Copper does not move in the plant, so symptoms appear first in younger growth.

In corn and small grains, young leaves become yellow and stunted; early symptoms may be confused with those of frost or drought. In advanced stages, leaves may brown at the margins similar to potassium (K) deficiency symptoms. In small grains, ergot infection, stem melanosis, take-all root rot, and Fusarium head blight can increase when Cu is deficient. Browning of the head and bending of the stem at maturity are common signs of Cu deficiency in wheat and barley. The heads are often empty and contain shriveled grain.

In many vegetable crops, leaves may look wilted, turn a bluish-greenish cast before turning yellow and curling, and flower production fails.

## Copper Toxicity Symptoms

Copper toxicities can occur after repeated applications of manures, biosolids or pesticides that are high in Cu. Symptoms of toxicity include reduced shoot vigor, poorly developed root systems, discolored roots, and leaf chlorosis (yellowing). They can be confused with symptoms of Fe deficiency. Crop species differ markedly in tolerance; for example, bean tolerates Cu toxicity much better than corn does. Regulatory limits exist in some states to control the application of Cu-rich manures to land.

## Crop Response to Copper

Crop species and cultivars vary considerably in their sensitivity to Cu deficiency and in their response to Cu application (**Table 2**). Sensitivity to Cu toxicity does not necessarily follow the reverse order.

A set of 115 field trials on spring wheat in the Prairie Provinces of Canada found an 87% frequency of grain yield response to applied Cu where the DTPA-extractable Cu in the soil was less than 0.4 ppm[5]. Grain yield response to added Cu at these concentrations averaged 47%, and at soil test levels between 0.4 and 0.8 ppm, the yield boost averaged 10%. While the soil test was effective at identifying deficiencies, the frequency of profitable response to applied Cu ranged from 19 to 77% (depending on wheat price and required rate of return) for soils testing below 0.4 ppm, and was very rare at higher Cu concentrations.

In North Dakota USA, a concentration below 0.4 ppm of the DTPA-extractable Cu correctly identified 4 of 10 sites where Cu application reduced Fusarium head blight in spring wheat.[6] Reducing this disease may have great economic value in some years. The soil test did not correlate well to predicting yield increases to added Cu. In Australia, critical DTPA-extractable Cu concentration is around 0.12 ppm, but this test has moderate to poor reliability. When tissue concentrations of Cu in the youngest expanded leaf blade in wheat are <1.5 ppm, a yield benefit is expected from Cu fertilization.[7,8]

**Table 2.** Crop sensitivity to Cu deficiency.[1,4]

| Most response | Medium response | Least response |
|---|---|---|
| Alfalfa | Apples | Asparagus |
| Beet, table | Barley | Bean |
| Canary seed | Beet, sugar | Canola |
| Carrot | Blueberry | Grass (forage) |
| Citrus | Broccoli | Grape |
| Flax | Cabbage | Lupine |
| Lettuce | Cauliflower | Pea |
| Oat | Celery | Peppermint |
| Onion | Clover | Pine |
| Rice | Corn | Potato |
| Spinach | Cucumber | Rapeseed |
| Sudan grass | Parsnip | Rye |
| Wheat | Pineapple | Soybean |
| | Radish | Spearmint |
| | Sorghum | Turfgrass |
| | Strawberry | |
| | Timothy | |
| | Tomato | |
| | Turnip | |

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# Nutri-Facts

Agronomic fact sheets on crop nutrients

# Chloride

NO. 11

North American Edition

Chloride is commonly found in nature—from seas, to soils, to the air—it's everywhere. It is a monovalent anion, having a single negative charge ($Cl^-$). Plants take up the element chlorine in this anionic form. Under standard conditions chlorine (Cl) is an unstable, yellow-green gas. Unlike $Cl^-$ , free Cl rarely occurs in nature.

Chloride was first generally recognized as a plant nutrient in the mid 1950s. However its value as a fertilizer supplement was not appreciated until the 1970s when work in the northwestern U.S. and elsewhere showed that some crops may indeed respond to $Cl^-$ fertilizer application. Since that time there has been a great deal of work investigating crop response to the addition of $Cl^-$, and determining optimal management practices for $Cl^-$ fertilization.

## Chloride in Plants

Chloride fulfills many important functions in plants. Some of the roles of $Cl^-$ in plants are:

- Photosynthesis and enzyme activation. Some of the enzymes activated are involved in starch utilization which affects germination and energy transfer.
- Transport of other nutrients. Chloride aids in the transport of nutrients such as potassium ($K^+$), calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) since it acts as a counterion to maintain electrical balance.
- Water movement in cells. Cellular $Cl^-$ helps water move into cells and also aids in water retention in cells, thereby impacting cell hydration and turgor.
- Stomatal activity. Both K and $Cl^-$ are involved in the movement of guard cells that control the opening and closing of leaf pores or stomata.
- Accelerated plant development. Adequate $Cl^-$ in small grain production results in earlier head formation and emergence than where $Cl^-$ is deficient. In winter wheat production maturity advances of 5 to 7 days have been observed.
- Reduced lodging. Chloride strengthens stems, helping to reduce lodging later in the season.

Among the most notable impacts of $Cl^-$ is its role in reducing the effects of numerous plant diseases. This effect may be related to its function in osmotic regulation. In wheat, $Cl^-$ has been shown to suppress take-all root rot, tan spot, stripe rust, leaf rust, and Septoria, while in corn and grain sorghum it has been shown to suppress stalk rot.

## Chloride in Soils

Nearly all $Cl^-$ in soils exists in soil solution. Chloride, like nitrate ($NO_3^-$), is mobile in soils and moves freely with soil water. Thus, under certain conditions it can be readily leached from the root zone. There are several potential sources of $Cl^-$ in crop production systems, including rainfall, marine aerosols, volcanic emissions, irrigation water, and fertilizer. Some irrigation water contains substantial amounts of $Cl^-$—often enough to meet or exceed crop needs. Atmospheric deposition can be particularly high in coastal areas. But regions further inland, such as the Great Plains of the U.S., have much lower atmospheric deposition of $Cl^-$ making the likelihood of response to $Cl^-$ fertilizer higher. Where there is a history of $Cl^-$–containing fertilizer application (such as muriate of potash; also known as MOP, potassium chloride, or KCl) it is not likely that $Cl^-$ will be limiting for crops.

## Fertilizing with Chloride

There are several fertilizer sources of $Cl^-$, but the most common and readily available is KCl (**Table 1**). All sources perform similarly—one is not superior to another when strictly considering $Cl^-$. Since $Cl^-$ is soluble and moves readily with soil water, placement is not as great an issue as with more immobile

**Table 1.** Chloride fertilizer sources and percent of nutrient.

| Fertilizer name | Formula | % $Cl^-$ |
|---|---|---|
| Potassium chloride | KCl | 47 |
| Magnesium chloride | $MgCl_2$ | 74 (dry)<br>22 (liq.) |
| Ammonium chloride | $NH_4Cl$ | 66 |
| Calcium chloride | $CaCl_2$ | 65 |

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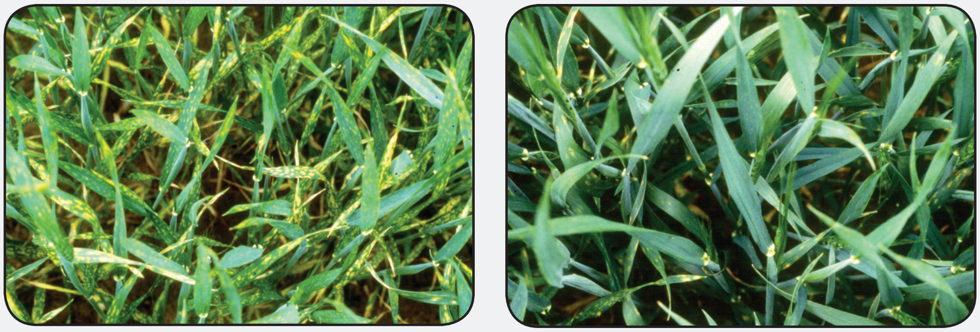



**Chloride deficiency** observed as physiological leaf spot in winter wheat (left). Photo on the right shows wheat that received $Cl^-$ fertilizer application.

nutrients like phosphorus (P). Surface-applied $Cl^-$ will move into the root zone with a timely rainfall event.

Some laboratories make fertilizer recommendations for $Cl^-$ based on soil and/or tissue analysis. It is usually recommended that soil samples be taken from a depth of 0 to 24 inches since $Cl^-$ is mobile. The Kansas State University soil testing lab recommends application of 20 lb $Cl^-$/A to corn, wheat and grain sorghum when soil test level in the upper 24 inches is less than 30 lb $Cl^-$/A[1].

## Chloride Deficiency Symptoms

Chloride deficiency symptoms have been observed and characterized in several crops and can vary, but the two most common symptoms are chlorosis in the younger leaves and an overall wilting. Necrosis of some parts of the plant, leaf bronzing, and reduction in root and leaf growth may also occur. Increased susceptibility to infection of various diseases may result from $Cl^-$ deficiency as well.

In the early 1990s, physiological leaf spot syndrome was first observed in certain winter wheat varieties in Montana. These symptoms are similar in appearance to tan spot and Septoria leaf blotch diseases, but are not associated with pathogens. Research has shown that this spotting is the result of $Cl^-$ deficiency.

## Crop Response to Chloride

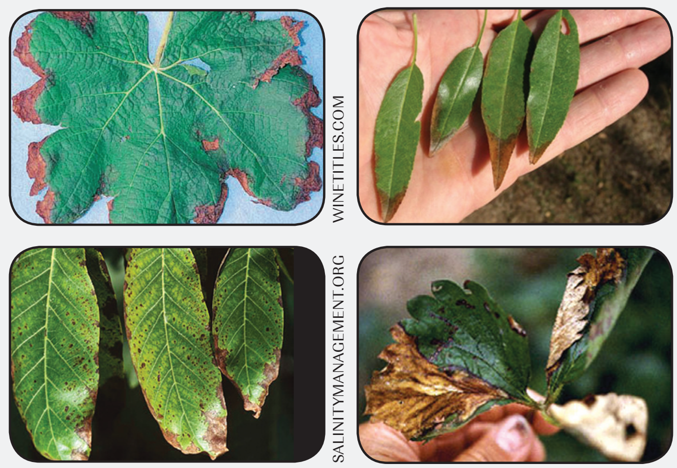
There has been a great deal of research done on $Cl^-$ nutrition of crops on the Great Plains, mostly with winter wheat but some on other crops as well. **Table 2** shows grain yields and tissue $Cl^-$ concentrations from multiple site years for dryland winter wheat, corn and grain sorghum receiving $Cl^-$ in Kansas.

In a recent meta-analysis of $Cl^-$ response data with winter wheat collected from 1990 to 2006 at 53 locations across Kansas it was concluded that application of $Cl^-$ fertilizer generated an average yield increase of approximately 8%, and that application rates greater than about 20 lb $Cl^-$/A would seldom result in further yield increases[2].

Circumstances that favor response to $Cl^-$-containing fertilizer are low soil and/or plant tissue levels, high foliar and or root fungal disease pressure, responsive cultivar, and where KCl fertilization is minimal in non-coastal areas.

## Chloride Sensitivity

Plants growing in salt-affected soils or irrigated with high-$Cl^-$ water can be negatively impacted by additional $Cl^-$ fertilization. Leaf damage can also result from excessive $Cl^-$ deposited on foliage during irrigation. Careful fertilizer and water management is needed to manage $Cl^-$ in these situations. Some crops are reported to be sensitive to elevated $Cl^-$ (e.g., tobacco, potato, a number of fruit, berry, and vegetables, some tree crops, and some soybean varieties) although this sensitivity varies depending on the growing conditions.




**Some plants are sensitive** to high $Cl^-$ concentrations. Symptoms of excessive $Cl^-$ (clock-wise starting top-left: grape, almond, walnut, strawberry) usually appear first at the tips and edges of older leaves.

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**Table 2.** Yield and tissue response to 20 lb $Cl^-$/A for wheat, corn and grain sorghum in Kansas[3].

| Crop | Grain Yield, bu/A | | | Leaf $Cl^-$, % | | Site years |
|---|---|---|---|---|---|---|
| | Control | 20 lb $Cl^-$/A | Response | Control | 20 lb $Cl^-$/A | |
| Winter wheat | 48.4 | 52.5 | 4.1 | 0.29 | 0.43 | 34 |
| Corn | 104.4 | 108.9 | 4.5 | 0.17 | 0.27 | 11 |
| Grain Sorghum | 98.5 | 108.2 | 9.7 | 0.10 | 0.24 | 20 |

Plant tissue for wheat and grain sorghum sampled at boot, corn taken at tassel.

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# Iron

NO. 12

North American Edition

Iron (Fe) is a nutrient required by all organisms, including microbes, plants, animals, and humans. It was first recognized as a necessary plant nutrient in the mid 19th century when Fe-deficient grapes were successfully treated with foliar applications of Fe salts. Iron is a component of many vital plant enzymes and is required for a wide range of biological functions. It is common in the earth's crust and as a result, most soils contain abundant Fe, but in forms that are low in solubility and sometimes not readily available for plant uptake.

## Iron in Soils

Iron is abundant in many rocks and minerals and as soils develop there can be either enrichment or depletion of Fe. Depletion commonly leads to deficiency and enrichment can cause toxicity in unique conditions. The main source of Fe in soils for use by plants comes from secondary oxide minerals that are adsorbed or precipitated onto soil mineral particles and organic matter. Although Fe is very abundant, it's availability for plant uptake is quite low.

## Iron in Plants

Plant roots absorb Fe from the soil solution most readily as (ferrous) $Fe^{2+}$ but in some cases also as (ferric) $Fe^{3+}$ ions. The chemical nature of Fe allows it to play an essential role in oxidation and reduction reactions, respiration, photosynthesis, and enzyme reactions. For example, Fe is an important component of the enzymes used by nitrogen-fixing bacteria.

The Fe concentration in plant leaf tissues varies between plant species, but is generally between 50 and 250 ppm (dry weight basis). If the Fe concentration is less than 50 ppm there are usually signs of deficiency, and toxic effects may be observed when the concentration exceeds 500 ppm.

The solubility of Fe oxide minerals in soil is very low, so plant roots have two general ways to access the $Fe^{2+}$ or $Fe^{3+}$ ions. The first strategy occurs in dicot species, and non-grass monocot species where $Fe^{3+}$ ions are reduced to $Fe^{2+}$ ions before moving into the root across selective membranes. This process involves the root excreting a variety of organic compounds and acids into the soil. In the second strategy, roots of grass species acquire Fe by excreting an organic chelate (siderophore) that solubilizes Fe from the soil, allowing enhanced uptake.


**Iron deficiency** in soybean (left), sorghum (middle), and wheat (right).

## Soil Factors and Iron Deficiency

Most soils contain adequate Fe for plant nutrition, but chemical and environmental factors restrict plant uptake. Iron deficiencies are commonly observed in soils with elevated pH (>7.5), especially where there is abundant calcium carbonate (lime). Iron solubility is greatly increased as soil pH drops into the acidic range.

Soils containing abundant calcium carbonate can form bicarbonate ions ($HCO_3^-$) if the soils become overly wet, and bicarbonate interferes with Fe uptake by plants. This inhibition is usually only temporary and Fe deficiency symptoms disappear when the soil drains and warms up.

When soils become saturated, $Fe^{3+}$ becomes converted to $Fe^{2+}$ by microbial action. The $Fe^{2+}$ form is much more soluble and can even result in toxicity for some rice varieties in flooded soils under strongly acid conditions.

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Plants growing in soils with low organic matter content are generally more susceptible to Fe deficiency than with abundant organic matter. Humus compounds are effective at binding and releasing Fe ions into soil solution. Portions of a field that are eroded (low soil organic matter) tend to be more susceptible to Fe deficiency.

Since many soil and environmental factors combine to regulate the Fe supply to plants, there is no widely accepted method of testing soils to predict the need for supplemental fertilization.

## Deficiency and Toxicity Symptoms

Iron deficiency symptoms are universal among plant species, with general stunting and yellowing of younger leaves. Young Fe-deficient leaves develop chlorosis (yellowing) between the leaf veins, while the veins initially remain green. As the deficiency becomes more severe, the younger leaves become pale yellow to white in color. The young tissue is impacted first because Fe is poorly mobile within plants and does not readily translocate from older to younger tissues.

Iron toxicity is relatively rare, but the symptoms include bronzed and striped leaves. These effects are the result of excess Fe-hydroxyl radicals disrupting cellular functions. Due to the importance of maintaining Fe concentrations within safe ranges in plant tissues, the whole process of Fe uptake into roots (i.e., the movement from roots to shoots, and storage and release within plant cells) is highly regulated.

Tissue analysis for Fe can be complicated since any dust that may be present on the leaf surface will also contain Fe. Rinsing or washing plant leaves is recommended prior to Fe analysis. Most tissue analyses rely on sampling the young leaves, since they are generally the first to show deficiency symptoms.

## Fertilizing for Iron Deficiency

When inorganic Fe fertilizers are added to soil (e.g., ferric sulfate, ferrous sulfate, ferrous ammonium phosphate, ferrous ammonium sulfate, and oxides of Fe), they are rapidly converted to insoluble forms and provide minimal benefit for plant nutrition. Iron fertilizers protected with an organic chelate can be effectively applied to soils to correct plant deficiencies. For example, chelated fertilizers such as Fe-EDDHA and Fe-EDTA have been used with reasonable effectiveness (**Table 1**), but their cost is often prohibitive for large-scale application. Foliar sprays containing Fe salts or chelates are effective at correcting plant Fe deficiencies during the growing season, but they may require repeated applications to prevent reoccurrence of deficiency.

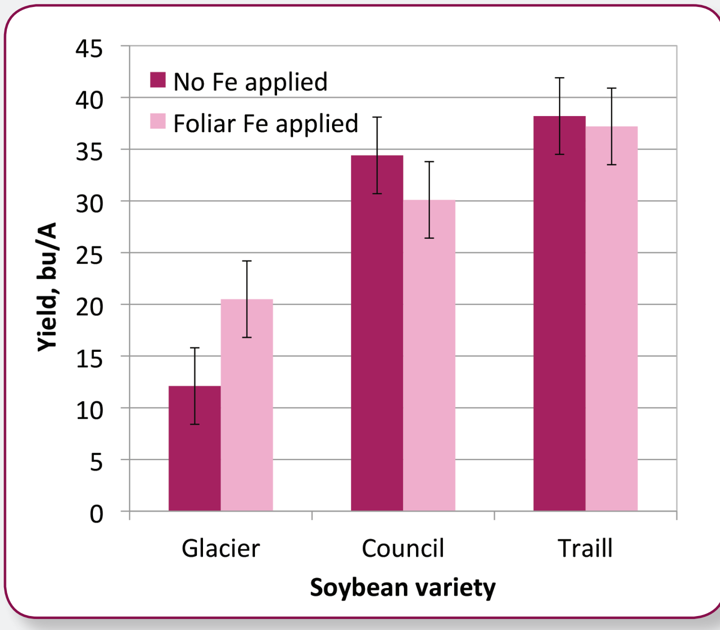


**Figure 1.** Grain yield of three soybean varieties grown in calcareous soil. The Glacier variety, susceptible to Fe deficiency, responded to foliar Fe application while no yield response was observed for more tolerant Council and Traill varieties[1]. Error bars denote an LSD (0.05).

## Crop Response

Several remedies are used to compensate for plant Fe deficiency. Depending on local conditions, some of these solutions may be more practical than others.

- Grow plant varieties and cultivars specifically adapted to the local conditions that are tolerant of low-Fe conditions. Large genetic differences exist among cultivars and a variety change is often effective for dealing with challenging soil conditions. (**Figure 1**).
- Apply a Fe-containing fertilizer in the form of an inorganic salt or a chelated material to the soil.
- Spray a Fe-containing solution onto plant leaves to prevent or correct deficiencies. This does not correct any underlying soil problems preventing uptake of adequate Fe, but it can assist with eliminating growth limitations from Fe deficiency.
- Add an acidifying material to soils with elevated pH to improve the solubility of Fe. This acidification can be done for the entire field or spot treatment of a portion of the root zone is often sufficient to improve Fe availability.
- Improve Fe availability by growing two plant species together. The ability of one crop to solubilize and acquire Fe sometimes results in sharing with a companion crop that has lesser capacity to extract Fe (**Table 1**).

**Table 1.** Relative grain yield of two soybean varieties, one susceptible and one tolerant to Fe deficiency, compared with the tolerant variety grown on a Fe-sufficient site (100%)[2].

| Oat companion crop | Fe-chelate fertilizer | Fe chlorosis susceptible variety | Fe chlorosis tolerant variety |
|---|---|---|---|
| | | Relative yield, % | |
| No | No | 48 e | 82 c |
| No | Yes | 71 d | 87 bc |
| Yes | No | 73 d | 76 cd |
| Yes | Yes | 87 bc | 93 ab |

Treatments include addition of a Fe-chelate fertilizer, or the presence of an oat companion crop on severely Fe-deficient soils. Letters following relative yields indicate significance at $p \leq$ to 0.10 for both varieties.

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Nutri-Facts
Agronomic fact sheets on crop nutrients

# Molybdenum

NO. 13
North American Edition

Molybdenum (Mo) is a trace element required in very small amounts for the growth of both plants and animals. Crop deficiencies of Mo are fairly uncommon, but there are a variety of soil and foliar fertilizers that can be used to correct this condition when it occurs.

## Molybdenum in Plants

All plants require very small amounts of Mo for normal growth and development. However, among the plant micronutrients, Mo and nickel (Ni) are required in the lowest concentrations.

Within the plant, Mo is primarily used in the production of "molybdoenzymes" that regulate various plant functions. The most well known of these Mo-containing enzymes regulate nitrogen (N) nutrition. In non-legumes, Mo-enzymes regulate the conversion of nitrate into proteins (nitrate reductase). In legume crops, another Mo-enzyme (nitrogenase) is needed by the root nodule bacteria for N fixation. The Mo requirement of legumes is greater than that of grasses and other crops.

Molybdenum toxicity in plants is rare under most agricultural conditions. However, sheep and cattle feeding on plants with a high Mo concentration may suffer from molybdenosis. This condition is a result of high Mo concentrations suppressing the availability of dietary copper (Cu) in these animals.

## Molybdenum in Soils

Plant-available Mo is in the anion form of $MoO_4^{2-}$; or molybdate. It is released from solid minerals through normal weathering processes and then undergoes various reactions in the soil. Once it is dissolved, $MoO_4^{2-}$ anions are subject to adsorption processes on clays, metal oxides of iron (Fe), aluminum (Al), and manganese (Mn) as well as organic compounds, and carbonates.

IPNI PHOTO/SNYDER

**Soybeans showing Mo deficiency in the foreground.**

The solubility of $MoO_4^{2-}$ is greatly influenced by soil pH, similar to the chemically analogous nutrient phosphate ($PO_4^{3-}$). Molybdenum is the only micronutrient that has increased plant availability as the soil pH rises. Molybdate solubility increases approximately 100 times for every unit increase in soil pH. Therefore, the use of lime to increase the pH of acid soils is an important management tool to improve Mo availability. In soils with a pH of 6 or greater, it is uncommon to encounter Mo deficiencies.

Addition of sulfate ($SO_4^{2-}$) fertilizer tends to decrease $MoO_4^{2-}$ uptake, as they both compete for root uptake sites. For example, one study showed that the plant Mo concentration of peanuts was decreased by more than 70% following fertilization with $SO_4^{2-}$-containing single superphosphate (SSP), but Mo concentrations increased by 20% following fertilization with triple superphosphate (TSP) fertilizer that contains no sulfate[1]. The addition of phosphate often results in the release of Mo that is adsorbed on soil solids, leading to greater Mo uptake and accumulation in plants.

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## Fertilizing with Molybdenum

In many soils, application of a liming material to increase pH will release Mo from insoluble forms. For example, a study showed that addition of lime alone resulted in the same soybean yield as when Mo fertilizer was added to unlimed soil[2]. However, the chemical release of soluble Mo following lime application may take weeks or months to occur.

If lime is not required for crop growth or when the Mo concentration of the soil is low, it may be useful to fertilize with additional Mo in the following ways:

**Soil:** Molybdenum fertilizers can be banded or broadcast on the soil. It is commonly added in small amounts, ranging from 0.5 to 2 lb/A. It is often mixed with other fertilizer materials to help with uniform application or it may be dissolved in water and sprayed on the soil before planting. Molybdenum trioxide ($MoO_3$) is only suitable for soil application due to its low solubility.

**Foliar:** Soluble Mo sources, such as sodium or ammonium molybdate, are used for foliar application to plants. Foliar application of dilute solutions of Mo is generally most effective when applied at earlier stages of plant development. Foliar applications are beneficial for immediate correction of Mo deficiency symptoms, compared with soil applications, which have a longer residual benefit.

**Seed:** Treatment of seed with small amounts of Mo fertilizer is common in regions where deficiency occurs. This technique ensures that each seed is uniformly provided a small, but adequate amount of Mo for healthy growth. *Rhizobia* inoculants for legume crops are sometimes amended with small amounts of Mo to promote vigorous N fixation. Excessively high application rates can lower seed germination or cause Mo accumulation to concentrations that may be harmful for grazing animals.

The selection of a specific Mo fertilizer depends largely on how the material will be applied. Some common fertilizer products containing Mo are given in **Table 1**.

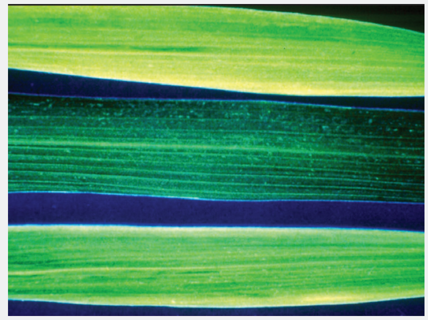
**Table 1.** Some common fertilizer products containing Molybdenum (Mo).

| Name | Chemical formula | Mo content | Solubility |
|---|---|---|---|
| Sodium Molybdate | $Na_2MoO_4 \cdot 2H_2O$ | 39% | 653 g/L |
| Ammonium Molybdate | $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ | 54% | 400 g/L |
| Molybdenum Trioxide | $MoO_3$ | 66% | 3 g/L |

## Molybdenum Deficiency Symptoms

Molybdenum is mobile within plants and deficiency symptoms can appear on the entire plant.

**Non-legumes:** Since adequate Mo is essential for proper N metabolism, deficiencies commonly appear as stunted plants and failure of leaves to develop a dark green color. In more severe deficiencies, the leaves may develop a pale green or yellow area around the edges and between the veins.



IPNI PHOTO/YAMADA

**Varying degrees of Mo deficiency on rice leaves.**

Advanced symptoms of insufficient Mo may appear as burning (necrosis) around the leaf edges and between the veins, because the plant cannot assimilate the nitrate and convert it to protein.

A well-known Mo deficiency symptom has been described for cauliflower, which develops a "whiptail" when the leaf tissue fails to develop surrounding the mid-leaf vein.

**Legumes:** These plants have an additional requirement for Mo, since it is required for N fixation by the root nodule bacteria, in addition to the internal utilization of nitrate. The symptoms of insufficient Mo include a general stunting and yellowing, typically seen as a result of insufficient N supply.

## Crop Response to Molybdenum

The benefit of supplying adequate Mo most commonly relates to boosting the ability of plants to utilize N. Plant Mo deficiencies may not always require supplemental fertilization, especially in acid soils where application of lime will increase Mo availability to plants. Similarly, addition of P fertilizer releases Mo into solution after it exchanges with $MoO_4^{2-}$ on soil adsorption sites.

Where adequate Mo is lacking, supplemental fertilization has resulted in large increases in plant growth and yield. One study demonstrated large yield increases in legumes from both Mo application and additions of lime[3] (**Figure 1**). Another study found that melon yields increased from 19 melons in plots with unfertilized soil to over 250 melons following a foliar spray of Mo[4].

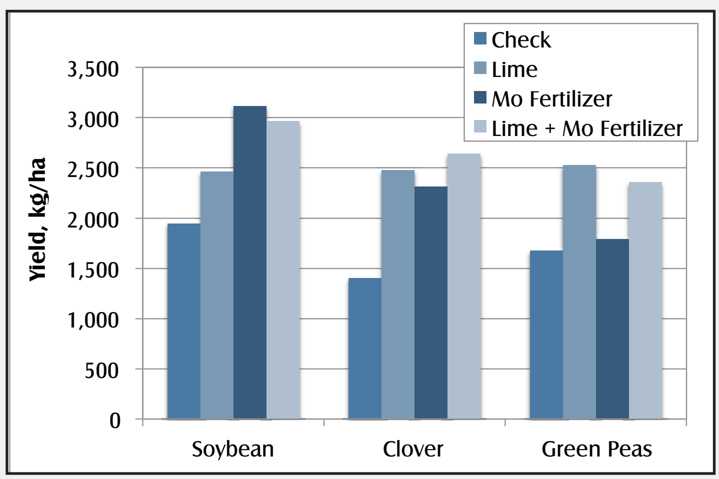



**Figure 1.** Effect of lime and fertilizer Molybdenum (Mo) application on yields of three crops[3].

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# Nutri-Facts

IPNI

Agronomic fact sheets on crop nutrients

## Silicon

NO. 14

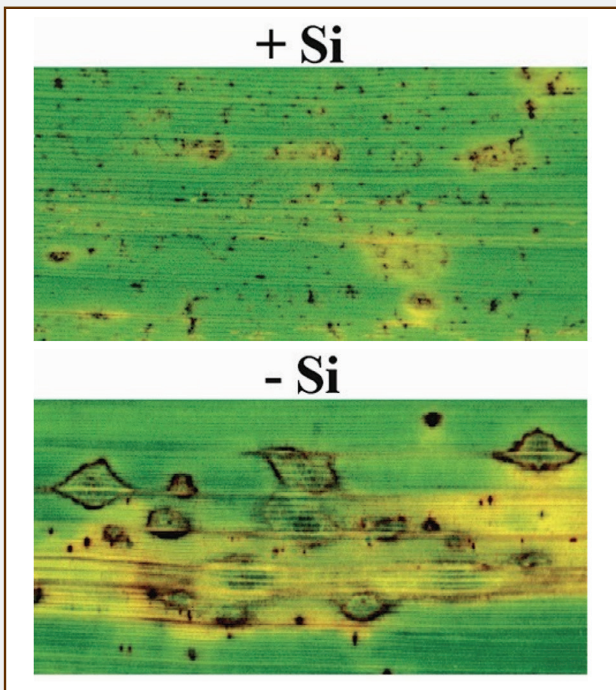
NORTH AMERICAN EDITION

Silicon (Si) is generally not considered an essential element for plant growth. However, due to its important role in plant nutrition, particularly under stressful conditions, it is now recognized as a "beneficial substance" or "quasi-essential."

### Silicon in Plants

Silicon refers to the chemical element, while silica or silicon dioxide ($SiO_2$) are solid, glass-like compounds containing both Si and oxygen. Plants roots take up soluble Si from the soil in the form of silicic acid [$Si(OH)_4$]. It is translocated through the plant until it is deposited and precipitated in the intercellular spaces of the plant[1].

When Si forms solid structures in the plant tissue (called phytoliths), it provides important strength to cell walls, without a direct role in plant metabolism. Many plants, especially grasses, accumulate large amounts of Si, which contributes to stalk strength and helps keep them upright. Accumulation of silica in sugarcane leaves provides protection from over-exposure to ultraviolet light, preventing leaf freckling. These small solid particles of silica located in leaves and stems also help protect some plants from a variety of environmental stresses, insect attacks, and disease[2].

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**Development of leaf blast symptoms in rice** with (top) or without (bottom) additional silicon.

Silicon deposition between cells also provides benefits beyond mechanical strength, although less is known about these contributions to plant growth. For example, Si is beneficial in stimulating natural plant defenses against fungal pathogens by activating various organic compounds and enzymes.

The quantity of Si taken up and accumulated by plants varies according to the species, but it can be significant. Higher plants are divided into three main groups according to their ability to accumulate Si. The highest concentrations of Si (up to 10%) are found in sedges (such as horsetail) and some wetland grasses. Dryland grasses, such as sugarcane, most cereals, and a few dicots will typically contain 1 to 3% Si. The lowest Si concentrations (<0.5%) are found in most dicots, especially legumes. Plants with Si concentrations >1% are classified as "accumulators", <0.5% are "excluders", and plants with Si concentrations between these levels are known as "intermediates".

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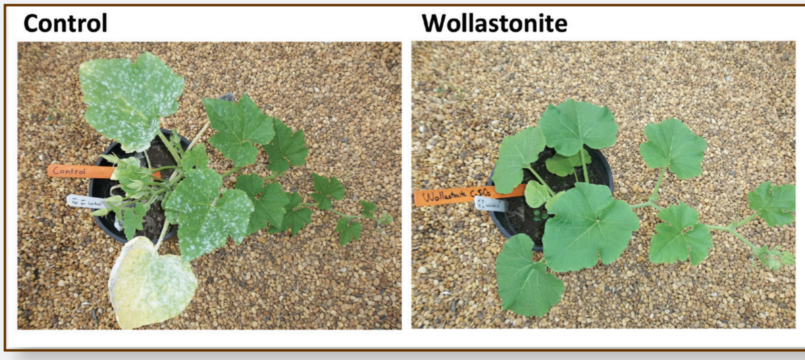


J. HECKMAN

**Figure 1.** Powdery mildew disease suppression in pumpkin plants following calcium silicate (Wollastonite) application[2].

M.K. SCHON

**Figure 2.** Leaf freckling is a symptom of low Si in sugarcane receiving direct sunlight. Silicon is thought to act as a filter for harmful UV radiation.

**Table 1.** Silicon concentration in the shoots of various crops[3].

| Crop | % dry weight |
|---|---|
| Rice | 4.2 |
| Wheat | 2.5 |
| Barley | 1.8 |
| Sugarcane | 1.5 |
| Soybean | 1.4 |
| Corn | 0.8 |
| Cassava | 0.5 |
| Potato | 0.4 |

Examples of Si concentrations of several crops are reported in **Table 1**.

## Silicon in Soils

Silicon is second only to oxygen in the amount present in the earth's crust. Soils commonly contain as much as 30% Si, almost all of which is found in minerals and rocks. A lack of Si in soil is not common, but the concentration of soluble silicic acid can be too low to meet plant needs. Soluble Si concentrations typically range between 3.5 and 40 mg Si/L, averaging about 14 to 20 mg/L across most agricultural soils.

Soil texture has been considered one of the most important factors affecting Si concentration in the soil solution. Although sand is mostly composed of $SiO_2$, it is not very soluble. The low water-holding capacity of sandy soils also prevents Si accumulation. Highly weathered tropical soils tend to have a lower Si content, as do soils containing very high organic matter, such as peats and muck soils.

## Fertilizing with Silicon

Since the requirement for Si in plants is not clearly determined, it is difficult to predict Si fertilizer needs. When needed, the typical approach is to apply Si in combination with other essential nutrients. The most commonly applied Si fertilizer source is calcium silicate ($CaSiO_3$). Calcium silicate is abundant in steel mill slag by-products and also occurs naturally as the mineral wollastonite. Calcium silicate can be used as a liming agent in low pH soils. Other Si fertilizer sources include potassium silicate ($K_2SiO_3$) and sodium silicate ($Na_2SiO_3$), which can be applied to high-value horticultural crops through drip irrigation systems.

**Table 2.** Response of rice grain yield to Si fertilization[4].

| Application rate, kg $Na_2SiO_3$/ha | t/ha |
|---|---|
| 0 | 7.0 |
| 75 | 7.9 |
| 105 | 8.2 |
| 135 | 8.2 |

## Silicon Deficiency Symptoms

Visual symptoms of Si deficiency in plants are generally not directly observed. Because of its natural abundance in soil and water (even highly purified water contains trace concentrations of Si), leaves of accumulator plants in a "no silicon" experiment may contain 1 to 4 mg $SiO_2$/g leaf dry weight, which contributes to the difficulty in determining the essentiality of Si for plant growth.

More commonly observed symptoms of Si deficiency are secondary effects such as an increase in disease or pest damage in plants not receiving adequate Si **(Figure 1)**, a lack of stem strength, or abiotic stress symptoms like leaf freckling in sugarcane **(Figure 2)**.

**Table 3.** Response of sugarcane yield to Si fertilization[5].

| Location | Si source | Rate, t/ha | Cane yield, t/ha |
|---|---|---|---|
| Mauritius | Electric furnace slag | 0 | 267 |
| | | 6.2 | 314 |
| Hawaii | TVA slag | 0 | 253 |
| | | 4.5 | 327 |
| Hawaii | Calcium silicate | 0 | 131 |
| | | 1.7 | 166 |
| Florida | Calcium silicate slag | 0 | 126 |
| | | 6.7 | 156 |

## Crop Response to Silicon

Several crops including corn, wheat, oats, pumpkin, cucumber, and various species of ornamentals have been shown to respond favorably to additions of Si under certain conditions. The most frequently observed positive results have been reported in rice **(Table 2)** and sugarcane **(Table 3)**.

Without adequate soil tests or tissue testing guidelines, there are no routine recommendations to predict when responses to additional Si will be beneficial. There are a growing number of examples of positive responses to Si fertilization, but there is still much to learn about this potentially beneficial nutrient.

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# Nutri-Facts

IPNI

Agronomic fact sheets on crop nutrients

## Cobalt

NO. 15

NORTH AMERICAN EDITION

Cobalt (Co) fertilization is occasionally reported to benefit crop growth, but the need for supplemental Co is rather rare. Cobalt has only recently been recognized as a potentially essential nutrient for plants. Cobalt is necessary for nitrogen (N) fixation occurring within the nodules of legume plants.

Cobalt is a metallic element located in the same row of the chemical periodic table as many other micronutrients. This group of metals is vitally important for biochemical reactions in most organisms, especially for reactions involving enzymes. Cobalt has been long known as essential for animals. However, the understanding of the essential role of Co in plant enzyme reactions is still incomplete.

| 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|
| **Mn** | **Fe** | **Co** | **Ni** | **Cu** | **Zn** |
| 54.93 | 55.84 | 58.93 | 58.69 | 63.54 | 65.40 |
| Manganese | Iron | Cobalt | Nickel | Copper | Zinc |

**Cobalt in relation to other nearby transition metals** that are essential micronutrients in plants.

The best-known function of Co in plants is for N-fixing microorganisms, such as *Rhizobia*, which live symbiotically with legume plants. In N-fixing bacteria, Co is a vital component needed to synthesize vitamin $B_{12}$, which is necessary to form hemoglobin. The hemoglobin content in legume root nodules is directly related to successful N fixation.

### Cobalt in Plants

Some plants appear to benefit from trace amounts of Co, but the concentration of beneficial Co for plants is not known. Cobalt concentrations in forage dry matter typically range from 0.01 to 0.5 parts per million (ppm). Forage mixtures ideally contain at least 0.1 ppm Co to meet animal nutritional requirements. There is greater Co uptake by broadleaf plants (i.e., legumes and bush species) than in grass species. Even if a soil is comparatively low in Co, having legumes in the mix of forage species along with grasses often improves the Co supply to grazing livestock.

Recent research on Co has shown it to be an essential component of several enzymes and co-enzymes that can affect the growth and metabolism of plants. In some low-Co conditions, a small increase in Co stimulates growth for both simple algae and higher plants. However, high Co concentrations can become toxic to plants.

Cobalt is actively absorbed by roots as $Co^{2+}$, and it can be moderately mobile within plants by complexing with organic compounds. However, inorganic $Co^{2+}$ movement from roots to stems and leaves is limited, and it is considered poorly mobile in plants.

There is insufficient understanding of the role of Co in plant nutrition. Some observed beneficial effects of Co include retardation of leaf senescence, increase in drought resistance in seeds, regulation of alkaloid accumulation in medicinal plants[1], and blocking ethylene formation[2], a plant stress hormone. Cobalt is not found at the active site of any respiratory chain enzymes, but is involved in mitochondrial respiration[1].

Cobalt is essential in animal nutrition for the synthesis of vitamin $B_{12}$. Where animal Co deficiencies occur, mineral supplements can be provided to animals, or crop fertilization with Co can be useful. Cobalt deficiencies were first identified in grazing cattle and sheep in New Zealand and Australia consuming low-Co feed. Since Co is essential for animals, low concentrations in plant forages can cause poor health of grazing animals. Most research on plant Co was conducted to define critical concentrations needed in forages to support grazing livestock.

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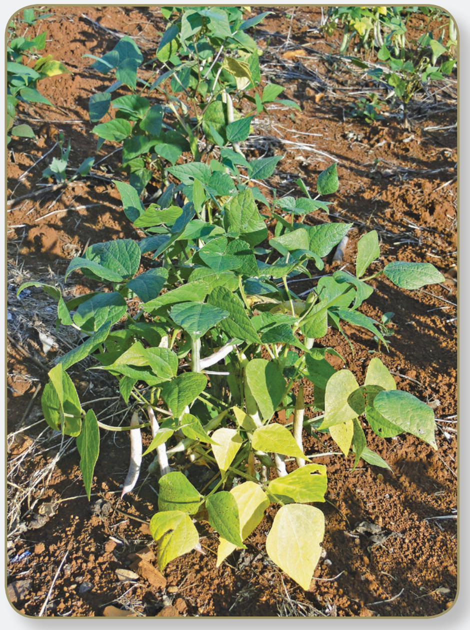
## Cobalt in Soils

Cobalt is found in medium abundance in the earth's crust and in low concentrations in most soils, depending on the parent material. Soils developed from minerals such as olivine and pyroxene have ample Co that can be acquired by plants and grazing animals. Cobalt is largely present as $Co^{2+}$ and participates in soil cation exchange reactions. Soils low in Co are generally weathered, coarse-textured soils, where the Co has been transported deep into the soil profile. Finer-textured soils, and soils containing higher levels of organic matter tend to have greater Co concentrations.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**Common bean** showing N deficiency symptom.

## Fertilizing with Cobalt

Cobalt deficiency in grazing animals (due to low Co concentrations in plants) has been corrected by mixing Co-containing salts with a fertilizer or sand carrier and spreading over grazed pastures[3]. Application rates of Co required to improve legume growth are very low, e.g., 0.04 to 0.13 lb Co/A[4]. Other methods to boost plant Co concentrations include seed treatment or foliar sprays. Providing mineral supplements directly to grazing animals can also alleviate deficiencies.

## Deficiency Symptoms

Adequate Co is required for N fixation, and leguminous plants growing in Co-deficient soil will develop N deficiency symptoms due to inadequate vitamin $B_{12}$ synthesis. Non-legume plant species (i.e., grasses) can grow on soils lower in Co availability compared to legume plant species, but animals grazing on the forage may develop Co deficiency symptoms. There are no known visual Co deficiency symptoms for non-legume plants.

## Crop Response

The most obvious plant response to Co deficiency is yellowing and stunting in legume crops. Cobalt fertilization of peanuts greatly increased the concentration of N, phosphorus (P), potassium (K), manganese (Mn), and zinc (Zn), and also allowed peanuts to more effectively use supplemental N fertilizer[5]. The growth of peanuts was improved 34% when 8 ppm Co was dissolved in the irrigation water, compared with peanuts without Co fertilization. This positive growth response was attributed to improved N-fixation.

There are reports of enhanced crop growth from non-legume crop species following seed treatment with dilute Co solutions (**Table 1**). For example, summer squash responded to Co seed treatment with increased dry matter growth, female flowers, and fruit yields, while oats responded to supplemental Co with increased panicle length, seeds per panicle, and grain yield[6]. Symptoms of excessively high Co accumulation appear as interveinal chlorosis in new leaves, followed later by white leaf margins and tips.

Research into Co nutrition of plants has shown that it is not only an essential nutrient for N-fixing bacteria, but is also beneficial, and possibly essential to numerous non-legume plants. However, the critical concentration of Co needed in soils to meet the plant requirement varies between crop species. Rates of supplemental Co applied to crops, as soil-applied fertilizer, seed treatment, and or foliar applications are very low, and there needs to be additional research to improve the understanding of Co behavior.


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**Table 1.** Influence of cobalt seed treatments on crop yields in noted crops[6].

| Source | Solution Concentration | Crop Species | Yield Increase, % |
|---|---|---|---|
| $Co(NO_3)_2$ | 1 mg Co/L | Common bean | 53 |
| $CoSO_4$ | 10 mg Co/L | Oat | 11 |
| $CoSO_4$ | 0.5 mg Co/L | Summer squash | 41 |

Nutri-Facts

Agronomic fact sheets on crop nutrients

# Nickel

NO. 16

North American Edition

Nickel (Ni) is the most recent element to be added to the list of essential plant nutrients. While it was identified as a component of the urease enzyme as early as 1975, it was not formally recognized as an essential nutrient until 1987[1]. Prior to this, chloride ($Cl^-$) was the most recently discovered plant nutrient (1954). Relatively little is known about Ni nutrition in plants compared with other plant nutrients. More detailed information about the role of Ni in plant nutrition can be found in the comprehensive chapter by Wood, 2015[2].

Nickel makes up only about 0.009% of the earth's crust, with most Ni concentrated in the planet's core. Nickel is widely used in the production of stainless steel and metal alloys. It is used to produce items such as rechargeable batteries, coinage, plating, and catalysts.

## Nickel in Plants

Plants take up Ni in the form of soluble $Ni^{2+}$. It is readily mobile within plants and is preferentially translocated to developing seeds in some species. The Ni concentration in most plant leaf material normally ranges from about 0.1 to 5 ppm (in dry weight), but can be highly variable depending on its availability in soils, plant species, plant part, and the season. Tissue Ni concentrations greater than 10 ppm are considered toxic in sensitive crop species. Nickel becomes toxic in moderately tolerant species at concentrations greater than 50 ppm. Some species can tolerate Ni concentrations in plant tissue as high as 50,000 ppm. There are some 350 species of these "hyperaccumulators", which are defined as plants that can accumulate at least 1,000 ppm Ni without phytotoxicity.

Pecan is a species that has a relatively high Ni requirement due to its unique physiology. For pecan, deficiency symptoms occur when Ni concentrations in the tissue fall below 1 ppm. Toxicity occurs when concentrations exceed 100 ppm. The adequate range of tissue Ni in pecan is between 2.5 to 30 ppm, however, these Ni threshold values depend on concentrations of competing cations such as zinc ($Zn^{2+}$), copper ($Cu^{2+}$), and iron ($Fe^{2+}$).

Although there are still many unknowns regarding the functions of Ni in plants, it is known to be an irreplaceable constituent of the urease enzyme. Urease—whether produced by plants, microbes, or animals—contains Ni at the core. The urease enzyme is essential in converting urea to ammonium ($NH_4^+$). Thus Ni is required in the nitrogen (N) nutrition of plants[3]. Under certain conditions where Ni is insufficient and urea is the major source of N, urea can accumulate in leaves to the point of plant toxicity. This urea toxicity manifested as necrosis of leaf tips, is actually a symptom of Ni deficiency.

Nickel has been shown to play a role in protecting against some plant diseases. It is involved in the synthesis of chemicals (phytoalexins) that the plant produces to defend against pathogens. Nickel deficiency has been associated with diminished lignin production, which is a component of cell walls that strengthens plants and contributes to disease resistance.

## Nickel in Soils

Nickel is present in nearly all agricultural soils, which commonly have Ni concentrations of 20 to 30 ppm and seldom exceed 50 ppm. Nickel in soils comes from geologic parent material and by human activity. Soil Ni concentration can exceed 10,000 ppm where they are formed from parent materials high in Ni. Nickel concentrations can also be elevated as a result of atmospheric deposition near metal refineries and from soil application of biosolids and sewage sludge.

The most important soil factor affecting Ni availability and solubility is pH. The plant availability of Ni decreases as soil pH increases. Thus, plants grown in high pH soils may be more vulnerable to Ni deficiency. Other factors reducing Ni uptake by plants include cool and/or dry soil conditions in the early spring, and nematode damage to feeder roots. Also, high soil concentrations of other metal cations such as $Zn^{2+}$, $Cu^{2+}$, $Fe^{2+}$ and cobalt ($Co^{2+}$) can inhibit uptake of Ni in soils.

Soil testing for Ni as a plant nutrient is not an established practice since there has been little research in the area of Ni nutrition

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**Examples of Ni deficiency** in pecan showing (Clockwise starting top left) blunt and disorted leaf tip; cupping and leaf tip necrosis; rosetting at growing points; normal (left side) versus Ni deficient leaves (right side). **Courtesy B.W. Wood, USDA-ARS.**

and fertilization of most crops. However, established soil testing methodology exists to identify "environmentally available" Ni. This procedure involves a very strong acid digestion, and is not suitable for making fertilizer recommendations.

## Fertilizing with Nickel

Soil application of Ni is rarely needed since most plants are adequately supplied. Also, trace amounts of Ni are contained in some commonly applied fertilizers. Where Ni fertilizer is needed to address a crop deficiency, it is most often applied as a foliar spray. Nickel salts (e.g., sulfates and nitrate) and organic Ni ligands (e.g., lignosulfonates, heptogluconates) are effective foliar fertilizers. The Ni-lignosulfonate form is preferred for field use due to potential safety concerns for field workers with other foliarly applied sources.

## Nickel Deficiency Symptoms

The occurrence of Ni deficiency symptoms on plant leaves is not nearly as common as it is with micronutrients such as Zn and Fe, but there are conditions where Ni deficiency symptoms are observed. As more is learned about the role of Ni in plants, it is likely that a better understanding of symptomology and diagnosis will also develop. Nickel deficiency, while rare, is most likely to occur in high organic matter soilless potting mixes, in solution culture, in high pH soils, where roots have been damaged by nematodes, or where excessive amounts of Fe, Zn or Cu have been applied.

One common Ni deficiency symptom across plant species is the necrosis of leaf tips due to the accumulation of urea to toxic concentrations. For non-woody plants, deficiency symptoms can also include chlorosis of young leaves, reduced leaf size, and less upright leaf growth.

For woody perennials, chlorosis similar to that of Fe or sulfur (S) deficiency has been noted as an early indicator of Ni deficiency. Other more severe symptoms that have been observed in pecan trees include a rounding or blunting of the leaflet tips, and dwarfing of foliage to produce what has been termed "mouse ear" or "little leaf". This rounding of leaf tips is associated with buildup of urea to toxic levels[4]. With severe Ni deficiency, leaf deformation is often most prominent at the top of the tree canopy. Affected foliage is thicker, less pliable, and tends to be brittle, and may exhibit cupping or wrinkling. Severe Ni deficiency results in plant stunting and abnormal growth patterns.

Nickel toxicity most commonly occurs with non-hyperaccumulating species near mining or industrial sites, where waste materials have been applied, or on serpentine soils. Toxicity symptoms vary, but in most cases they have the appearance of Fe deficiency, since Ni competes with Fe within plants.

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# Nutri-Facts

IPNI

Agronomic fact sheets on crop nutrients


# Selenium


NO. 17

NORTH AMERICAN EDITION


Selenium (Se) is not essential for plants, but is required for many physiological functions in humans and animals. Since Se is obtained primarily from food, it's accumulation by plants impacts human health.

## Selenium in Plants

Selenium is not involved in any essential functions for plants and is not classified as an essential element for growth. However, it is essential in more than 20 human proteins, where it is involved in diverse roles such as cancer protection, anti-oxidants, maintaining defenses against infection, and regulating proper growth and development[1].

Selenium behaves very similarly to sulfur (S) and plants do not distinguish between these two elements. Selenium can be substituted for S in many plant proteins and enzymes. Plant species that have a high S requirement also have a tendency to accumulate larger amounts of Se. At very high Se concentrations, this substitution causes metabolic problems for plants. However, there are no reports of naturally occurring Se causing damage to agricultural plants in the field.

**High Se-accumulating crops** include those within the *Brassica* genus. Other high-Se foods include Brazil nuts, whole grains, and edible seeds.

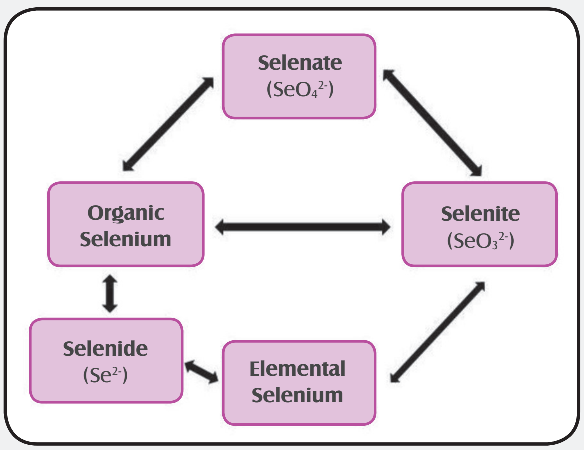


**Figure 1.** Selenium cycle in soil.

A number of non-agricultural plants are able to accumulate Se to concentrations where it is toxic when consumed by livestock. Accumulator plants may accumulate up to 3,000 parts per million (ppm) Se, compared to less than 1 ppm in most food crops.

## Selenium in Soils

Selenium is found in both organic and inorganic forms in soil (**Figure 1**). However, plants only utilize Se from the soil in the inorganic form. Soil organic matter is an important reserve of Se that will become available for plant uptake over time.

The inorganic forms of Se include:

**Selenate** ($Se^{6+}$): This form ($SeO_4^{2-}$) is most readily taken up by plants. It is very soluble and behaves quite similar to sulfate ($SO_4^{2-}$). Selenate is most likely to be found in well-aerated, neutral pH soils. Selenate is translocated directly from the roots to the leaves and stored in the cell chloroplasts before being converted to organic compounds such as selenomethionine. An abundance of $SO_4^{2-}$ in the soil inhibits the uptake of $SeO_4^{2-}$ since they both compete for uptake at the same transport sites of roots.

**Selenite** ($Se^{4+}$): This form ($SeO_3^{2-}$) is more typically found in aerated soils with acid to neutral pH. Selenite is much more reactive with various soil minerals than selenate, making it less soluble in the soil solution. When plants take up selenite, much of it is converted to organic compounds (such as selenomethionine) before being translocated in the xylem.


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**High Se-accumulating crops include those within the Brassica genus. Other high-Se foods include Brazil nuts, whole grains, and edible seeds.** A useful resource to determine the nutrient content of food (including selenium) can be found at http://ndb.nal.usda.gov/ndb/nutrients/index

**Elemental Selenium** ($Se^{o}$): Metallic, insoluble, and not available for plant uptake.

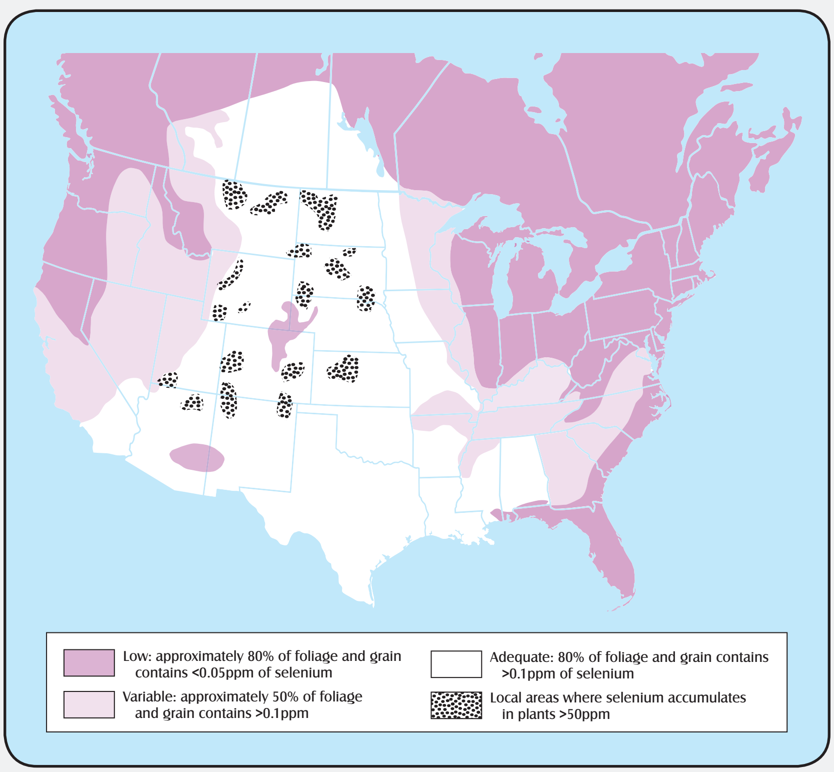
**Selenide** ($Se^{2-}$): This form is primarily found in flooded soils. It may be present in combination with a variety of minerals and organic compounds. It is mostly unavailable for plant uptake.

## Fertilizing Soils with Selenium

Plants are never fertilized with Se to boost yields, but to supplement the Se concentration in the harvested or grazed crop[2]. Some soils support crops that contain Se at concentrations too low to meet human and animal nutritional requirements. This can only be determined through chemical analysis, since there are no plant Se deficiency symptoms. In these locations (such as in Finland and New Zealand), efforts have been made to increase plant Se concentrations through fertilization. Because of the high uptake of selenate and the risk of toxicity to humans from excessively high Se concentrations, many farmers prefer to use the less soluble selenite fertilizer where supplementation is needed.

Selenate fertilizer is the most readily available form of Se for plant uptake. Selenite is not as soluble in soil and less available for plant uptake. Selenate sources of fertilizer increase plant Se concentrations 20 to 50 times more than selenite sources. Elemental Se requires microbial oxidation before becoming available for plant uptake and is not used as a fertilizer source.

Soil properties influence plant uptake of Se from soil. Selenium uptake generally decreases with increasing amounts of clay, iron oxide and organic matter in the soil. To avoid soil factors that make Se supplementation difficult, foliar and seed applications of supplemental Se are successfully used to boost plant Se concentrations.




**Selenium availability to plants varies** across the US and Canada. Even if your area is considered low or adequate, pockets of high-selenium soils may exist.[3, 4]

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