A PLANT NUTRITION PRIMER

LESSON 1: ESSENTIAL ELEMENTS--FORM AND FUNCTION

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There are sixteen elements essential for plant growth.

Major elements have concentration requirements from 10 to 5,000 times that of minor elements, also referred to as micronutrients.

The photosynthetic process is influenced by light, temperature, CO_2 concentration and the water and nutritional status of the plant.

We often see plenty of articles on fertilization and nutrient deficiencies with clever equations for fertilizer calculations and tables to help us interpret our soil tests. However, little print is devoted to providing a basic knowledge of plant nutrition. Growers' most common problems are often related to plant nutrition. These problems may be avoided if we had a better understanding of plant nutrition. We are not talking about fertilizer recommendations but how the essential elements are taken up, function and interact in the soil and in the plant. Once we obtain this basic knowledge, we are better able to prevent nutritional problems in our crops.

This is a first in a series of articles on plant nutrition. I hope to provide an easy to understand information on the key elements (pun intended) of plant nutrition that will help growers understand how and why nutritional problems occur and how they can be avoided.

There are sixteen elements essential for plant growth. They are often divided into two categories: major elements and minor elements (Table 1). The distinction between major and minor elements is based on their concentration requirement for sufficiency. Major elements have concentration requirements from 10 to 5,000 times that of minor elements, also referred to as micronutrients (Jones et al., 1991).

Table 1. *Elements essential for plant growth.*

Major Elements	Minor Elements
Carbon (C)	Boron (B)
Hydrogen (H)	Chlorine (Cl)
Oxygen (O)	Copper (Cu)
	Iron (Fe)
Calcium (Ca)	Manganese (Mn)
Magnesium (Mg)	Molybdenum (Mo)
Nitrogen (N)	Zinc (Zn)
Phosphorus (P)	
Potassium (K)	
Sulfur (S)	

What determines whether or not an element is considered essential? Well, an element must meet all three of the following criteria (Arnon and Stout, 1939):

1. Omission of the element in question must result in abnormal growth, failure to complete the life cycle or premature death of the plant.

2. The element must be specific and not replaced by another.

3. The element must exert its effect directly on growth or metabolism and not by some indirect effect such as by antagonizing another element present at a toxic level.

The first three major elements, carbon, hydrogen and oxygen are combined in the process of photosynthesis to form carbohydrate, the plant's source of energy. Hydrogen is taken up by the plant in the form of H_2O through the root system. The carbon source, CO_2, (carbon dioxide) is taken up through the stomata of the leaves. These are combined to form the carbohydrate as shown in the following equation:

$$nCO_2 + nH_2O + light \rightarrow (CH_2O)_n + nO_2$$

The photosynthetic process is influenced by light, temperature, CO_2 concentration and the water and nutritional status of the plant.

Hydrogen and oxygen are readily supplied by sound irrigation practices and are not a concern in the development of a fertilization program. Carbon is readily available as CO_2 in the atmosphere. For this reason CO_2 enrichment of the atmosphere for improved plant growth is often viewed as separate from a mineral nutrition program.

The remaining thirteen essential elements are primarily taken up by the plant through the root system as ions present in the soil water. Atmospheric nitrogen can be fixed by symbiotic

Table 2. *The essential elements, their form for uptake and function in the plant (Mengel and Kirkby, 1987).*

Essential Element	Form for Uptake	Functions in the Plant
C,H,O,N,S	ions in solution (HCO_3^-, NO_3^-, NH_4^+, SO_4^{-2}) or gases in the atmosphere (O_2, CO_2, N_2, SO_2).	Major constituents of organic substances.
P, B	ions in solution (PO_4^{-3}, BO_3^{-3}).	Energy transfer reactions and carbohydrate movement.
K, Mg, Ca, Cl	ions in solution (K^+, Mg^{+2}, Ca^{+2}, Cl^-).	Non-specific functions, or specific components of organic compounds or maintaining ionic balance.
Cu, Fe, Mn, Mo, Zn	ions or chelates in solution (Cu^{+2}, Fe^{+2}, Mn^{+2}, MoO^-, Zn^{+2}).	Enable electron transport and catalysts for enzymes.

Knowledge of the form and function of each element is important in understanding nutritional problems encountered by growers--their cause and how to avoid or correct these problems.

bacteria in roots of legumes and provide some or all of the plants nitrogen needs. Currently, these thirteen elements are supplied by the application of fertilizers in granular, water soluble or slow release forms during crop production. Knowledge of the form and function of each element (Table 2) is important in understanding nutritional problems encountered by growers--their cause and how to avoid or correct these problems.

Several other elements affect plant growth and development but do not meet the criteria for being an essential element. These *beneficial elements* have a positive effect on plant growth when present and share some important functions with the essential elements. This category includes sodium (Na), cobalt (Co), silicon (Si), nickel (Ni), aluminum (Al) and selenium (Se) (Marschner 1986).

Several other elements affect plant growth and development but do not meet the criteria for being an essential element.

The essential elements are discussed briefly in the following section of this article.

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Jones, J.B., Wolf, B. and H.A. Mills. 1991. Plant analysis handbook. Macro-Micro Publishing, Inc., Athens Georgia.

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Carbon Hydrogen Oxygen

Components of:	Carbohydrates	C, H, O (mono-, oligo-, and poly saccharides) +P
	Lipids	C, H, O
	Amino acids	C, H, O + N
	Proteins	C, H, O + various elements
	Enzymes	C, H, O + many other elements
	Vitamins	C, H, O + many other elements

Sources: Carbon: CO_2 in the atmosphere (0.03% by volume or 0.05% by weight)
decomposition of organic matter in the soil
burning of fossil fuels, mammals

Hydrogen: water

Oxygen: atmosphere (21% by volume), water, plants

Basic Reactions:

$$6\,CO_2 + 6H_2O + \text{Light energy} \underset{\text{respiration}}{\overset{\text{photosynthesis}}{\rightleftharpoons}} C_6H_{12}O_6 + 6\,O_2$$

Nitrogen (N)

Mobility: Very immobile

Component of: amino acids, proteins, vitamins, enzymes and alkaloids

Source: 80% of atmosphere is N but plants cannot take it up directly from the air.

N sources in the soil: Nitrate and ammonium forms

Nitrate nutrition requires more Mo; excess nitrate can cause Mo deficiency symptoms.

Ammonium nutrition requires more oxygen, Mn, Cu; excess ammonium increases amino N.

Nitrogen uptake: Nitrate--optimum between pH 4.5 to 7 (highest at pH 5, at pH 7 only 1/2 that at pH 5). Ammonium uptake--optimum at pH 7 (at pH 4 only 1/2 that at pH 7)

Deficiency symptoms:

Stunted growth, smaller leaves, oldest (physiological age) leaves turn evenly yellowish from the base up, color depends on crop, premature leaf drop, leaf cuticle thicker, more stomata per area unit, earlier flowering, small fruits with better keeping quality, high carbohydrate content.

Excess symptoms:

Dark green color, heavy, succulent growth, large leaves, increase chlorophyll synthesis, soft fruit, plants more prone to insect and disease damage, lodging, poor resistance to drought and cold. Nitrate toxicity symptoms--brownish leaf edges under some conditions.

Boron (B)

Mobility: Immobile

Function: Very important in reproduction process (pollen germination, pollen tube growth, fruit set.
Associated with water relations in plants and carbohydrate transport.
In cell division and protein formation.
Building element.

Source: Soil, organic matter.

Uptake:
1. As the anion, borate.
2. Heavy liming reduces B availability.
3. It is suggested that a sugar borate complex is formed which is ionized - effect on uptake is not known.
4. B requirement can vary greatly from crop to crop.

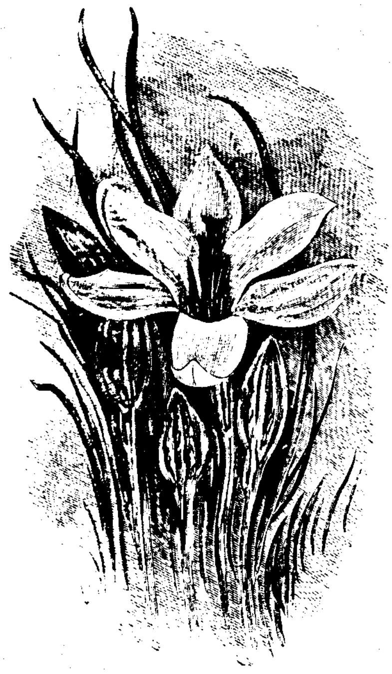
Deficiency symptoms:

Vary from species to species. Breakdown of terminals and collapse of cells. Water soaked spots on veins. Chlorosis, stunted growth and die back.

Excess symptoms:

Chlorotic to scorched leaves. Breakdown of heart leaves in vegetables.

Possible interactions: Ca, N (need less if N is deficient), Mo.



Molybdenum (Mo)

Mobility: Immobile

Component of: Reductase (nitrogen fixation - reduction). Other enzymes.
Catalase and peroxidase activity reduced when deficient.
Acid phosphatase activity reduced when excess.

Source: Soil in molybdate form, availability to plant increases with pH. Liming of soil improves availability.

Uptake: Poor in soils with high ion exchange capacity and low pH.
High in alkaline soils, may be due to toxicity problems.

Deficiency symptoms:

Chlorosis, variations from similar to N deficiency to yellow patches, mottling, scorch and necrosis.

Excess symptoms:

Yellow to reddish yellow shoots.

Possible interactions: Cu, Mn, P, S. May neutralize boron toxicity.

Copper (Cu)

Mobility: Immobile.

Function: As coenzyme and chelating agent.
In cytoplasm and chloroplast (70% of total Cu).
In copper enzymes which are mostly terminal aerobic oxidases producing water (polyphenol oxidase, tyrosinase laccase and ascorbic oxidase).

Source: Soil--mainly in divalent form as Cu^{++}. Availability of Cu depends on total content, organic matter, pH and weather conditions.

Uptake:
1. As Cu^{++} in very small quantities.
2. Sensitivity to Cu depends on species.

Deficiency symptoms:

Chlorotic - golden - colorless terminals. Sometimes interveinal chlorosis. Stunted or bushy growth, twisted leaves. Tip burn, die back (yellow tip). Reduced flowering and fruit set, poor yield. Poor color. More susceptible to chilling or frost damage.

Excess symptoms:

Sometimes due to use of Bordeaux sprays or other copper based fungicides. Stunted root systems (brownish-black roots). Lesions on roots. Root die back.

Possible interactions: Fe.

Iron (Fe)

Mobility: Immobile (80 -90% of Fe in plant is tied to organic structures, only a very small part (13%) of total Fe in plant is in water soluble form).

Function: Catalytic and chelating agent.
Activates a number of enzymes (prostetic group) involving molecular oxygen (oxidases and catalases), metalloproteins, metalloporphyrin.
Active in chlorophyll formation, but not in the chlorophyll molecule, also necessary for carotenoid formation.
In mitochondria, chloroplast and nucleus.

Source: Soil.

Uptake:

1. As Fe^{++}, Fe^{+++} and as an iron complex from soil.
2. In acid soils Fe^{++} predominate with increasing soil pH and oxygen Fe^{++} changes to Fe^{+++} (only Fe^{++} and Fe^{+++} seem to be physiologically active).
3. Fe uptake by plant depends on concentration of "usable Fe" in medium.
4. Capability to take up and translocate Fe varies with species and cultivar.
5. Some plants have the ability to take up and are relatively much higher in Fe when grown in soil or media low in Fe.
6. pH influences Fe uptake: Lower pH, higher uptake. High pH can restrict uptake to the extent that deficiency symptoms occur even though adequate levels of Fe are present.
7. High phosphorus can be a problem in Fe is low, if pH is also high--low P and high pH will be less problematic.
8. Chlorotic plants may be higher in Fe than healthy looking plants, however Fe might be tied up in roots or stems.
9. Fe deficiency results in higher nitrate and sulfate levels in plants.
10. Lime induced chlorosis is the result of an imbalance between mono- and divalent cations (inactivation of Fe).

Deficiency symptoms:

Yellow chlorotic color and interveinal chlorosis. Veins remain green resulting in a characteristic fishnet appearance on leaves. Normally symptoms first appear in terminal portion of the plant.

Excess symptoms:

Seldom seen, may induce Mg, P or Mn deficiency.

Possible interactions: Mg?, P and Mn.

Sulfur (S)

Mobility: Immobile

Component of: Structure and respiratory metabolism of plant.
Constituent of some amino acids
Glutathionine, coenzyme A, Lipoic acid (photosynthesis), thiamine and biotin. Glucosides such as mustard oil.

Source: Soil (0.06% of soil is S). Small amount from atmosphere.

Uptake: as SO_4 by root and reduced in leaf. Excess remains unchanged in plant.
as SO_2 through leaves if gas is in very low concentration. Sulfur dioxide is not as effective as sulfate because it is fixed in the leaf and is not moved to other plant parts.

Deficiency symptoms:

General chlorosis of new (physiologically youngest) leaves, sometimes have reddish-purple spots, small plants with short slender stalks.

Excess symptoms:

Generally not seen. Can have damage to leaves from high sulfur dioxide levels in atmosphere.

Possible interactions: N and Mo. S and N seem to be synergistic.

Manganese (Mn)

Mobility: Immobile.

Function: Integral part of some enzyme systems in other cases acts as an enzyme activator (phosphorylation, N-reductase).
Direct role in photosynthesis--oxygen evolution.
Protein and sugar formation, also increase in vitamin C content.

Source: Soil.

Uptake:

1. As Mn^{++} from soil solution.
2. Immobile in phloem.
3. Mn content of plants varies with location, physiological age of plant and family, species or cultivar.

Deficiency symptoms:

Fish bone like appearance of leaf having green main veins and interveinal chlorosis. Often confused with Fe deficiency. Small cell volume. Basal part of leaf exhibits gray streaks of dots, poor leaf turgor.

Excess symptoms:

Chlorosis, tip burn and necrotic leaf spot, brownish-black roots. Terminals affected.

Possible interactions: Fe.

Magnesium (Mg)

Mobility: Mobile

Component of: Chlorophyll (not more the 20% of total Mg in plant and only metallic element in chlorophyll.
Phytin, cell wall pectin, magnesium oxalate.
Enzymes
Very important activator of enzyme systems (peptidases, phosphorases and tricarboxylic acid cycle).

Source: Soil.

Uptake:
1. As Mg^{++}, translocated acropetally with transpiration stream.
2. In case of stress Mg is translocated from oldest to younger leaves.
3. Depends on soil pH, as well as Ca level, K and NH_4 content (antagonism).
4. Mg content highest in oldest plant part.
5. Mg content in plants varies with families, species and varieties.

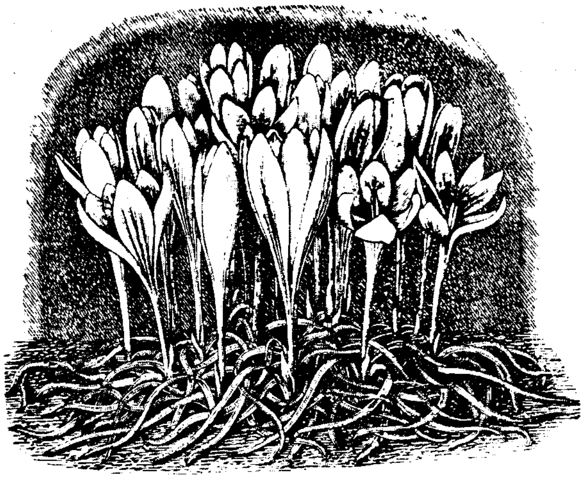
Deficiency symptoms:

Interveinal chlorosis - necrosis on oldest leaves. At beginning leaf margins remain green, only at very advanced stages do they become chlorotic. Leaf pigments generally decreased. Poor root system, decreased drought tolerance.

Excess symptoms:

Rare. May affect other elements (K).

Possible interactions: K, Ca and N.



Phosphorus (P)

Mobility: Mobile

Component of: Storage and structural compounds such as phytin, nucleoproteins and phospholipids.

Source: Soil. 1. Product of weathering of P bearing minerals (inorganic P).
2. Part of organic matter - ratio of organic N to P in field soil is 10:1.

Uptake:

1. Only in inorganic form, mainly as $H_2PO_4^-$, to a lesser degree as HPO_4^{-2} or PO_4^{-3} (very little). Depends of soil pH. Most available at pH 6 - 7. Site of uptake is on roots 1 - 2 cm behind root cap.

2. The plant through its own enzymes acting on the surface of the root can split the phosphate group from organic matter.

3. Plants with mycorrhiza associated with their roots take up phosphorous quicker.

4. Absorption site is very selective for P since other anions (Cl^-, $SO4^{-2}$ and $NO3^-$) cannot replace it.

5. Depends on solubility of P in soil or medium and the amount of other elements present (Interaction with Mg, Fe and Zn).

6. Most critical periods for P are just after germination and before ripening of fruit.

7. If P is applied as a foliar spray, H_3PO_4 is taken up more readily than other forms. Young leaves react much quicker than old ones. P is translocated in the phloem.

8. P taken into roots (inorganic) first spread throughout the root system and then is translocated in organic form to other plant parts. It is thought that P is incorporated into organic compounds in the roots prior to translocation.

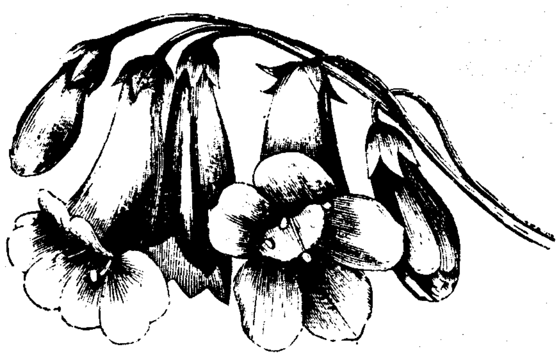
Deficiency symptoms:

Purpling of plant parts. Stiff, thin stems, straight, upright plants, overall dark bluish green leaf color; however oldest leaves can turn from reddish yellow to bronze depending on the crop, early leaf drop. Usually do not see deficiency systems on vegetable crops, just restricted growth.

Excess symptoms:

Not a serious problem. Chlorosis in the terminals of plants similar to Fe and Zn deficiency.

Possible interactions: Mg, Fe and Zn.



Zinc (Zn)

Mobility: Immobile.

Function: Somewhat similar to Mg and Mn cations in activation of the enzyme, Enolase.
Activator of various dehydrases and carbonic hydrase.
Responsible for metabolism of vitamins, purines and amino acids.
Associated with tryptophane synthesis (IAA).
Chelating agent.

Source: Soil--similar to copper. Zinc fixed in organic matter or rock is not available to the plant.

Uptake:

1. As Zn^{++}.
2. More available at lower pH.
3. High soil P results in high degree of Zn fixation in soil. Ties up Zn.
4. Liming may induce Zn deficiency.
5. N fertilization may increase the severity of Zn deficiency, sodium nitrate may decrease Zn uptake, while ammonium nitrate and ammonium sulfate may increase Zn uptake (due to acidifying affect of these compounds on the soil).

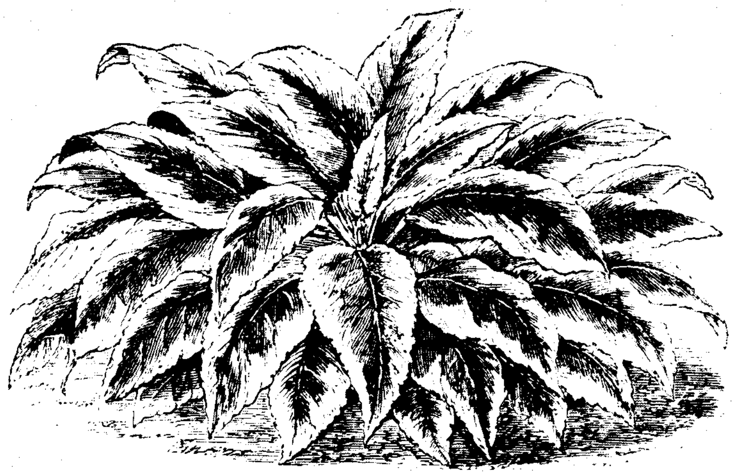
Deficiency symptoms:

Light green, yellow or white interveinal chlorosis and necrosis. Short stem or short internodes, bushy, broom like appearance, rosetting of leaves. Malformation of leaves. Die back and early leaf drop. Very small leaves on new growth ("Little leaf").

Excess symptoms:

Chlorosis (Fe)

Possible interactions: P and some forms of N.



Calcium (Ca)

Mobility: Immobile

Component of: Cell wall and vacuole as calcium phosphate, calcium carbonate, calcium oxalate or calcium sulfate.
Middle lamella: calcium pectate (permeability)
Genes: holds nucleic acid in place
Plasma membrane

Source: Soil.

Uptake:

1. As Ca ion.

2. Moves acropetally with the transpiration stream.

3. There is no transport from leaves to other organs. Thus, physiologically old tissue has high levels of Ca.

4. The relationship between Ca and K, Mg, Na and NH_4 in the soil affects Ca content of the plant. Ca in soil may affect B and Mo in plant.

5. Certain calcium compounds in the plant are characteristic for some species or families.

Deficiency symptoms:

Root die back--blackening. Die back of meristematic tissue. Distorted and chlorotic terminal leaves (youngest), old leaves stay green. Pitting of bark on stems. Development of shoots from axillary buds which die back.

Excess symptoms:

Are not caused by Ca excess but are due to interactions with other elements. See B or Mg deficiency symptoms.

Possible interactions: K, Mg, Na, B and NH_4.

Potassium (K)

Mobility: Mobile

Function: K is present in all living cells as an ion but is not a specific component of any organic compound in the cell.

Is found in the vacuole and cytoplasm but not in the nucleus or plastids.

Serves as a coenzyme for some enzymatic reactions (carbohydrate synthesis) and acts as a regulator. (Enzyme activation)

Influences stomatal behavior, hence, CO_2 assimilation.

Seems to regulate water economy of the plant.

Source: Soil (approximately 3% of the earth is K).

Uptake:

1. Speed of uptake: comparatively: N>K>Mg>Ca.
2. As K ion in ionic form in plant.
3. Water soluble part completely taken up, exchangeable part less, fixed K very little.
4. Distributed in xylem - translocated to bark. (Acro- and basipetally)
5. In the autumn, K is translocated from leaves of deciduous trees and shrubs into twigs and stems. NOT translocated in evergreens (i.e. *Hedera helix*) since they remain green.
6. K content is highest when plants are young. Meristematic tissue and young leaves are highest in K (especially in tissue with active cell division such as, root tips, cambium and pericycle.
7. K will leach out of plants.
8. In general monocots have a higher K content than dicots.
9. Anions are of importance for K uptake (Cl^-, NO_3^-, SO_4^{-2}).

Deficiency symptoms:

Marginal chlorosis to necrosis, blue-green to bronzing of leaves. Retarded growth. Wilting.

Excess symptoms:

In general one does not speak of K toxicity but rather of very high levels since there are no specific K toxicity symptoms. Very high K levels may be expressed as Mg, Ca, Mn, Zn or Fe deficiencies due to either antagonisms or indirect effects.

Possible interactions: Mg, Ca, Mn, Zn, Fe or other cations.

Chlorine (Cl)

Mobility: Mobile.

Function: Not well characterized.
Suggested that it is needed in oxidation of cytochrome C.
Influences O_2 uptake by roots.
Improves growth of plant meristems (Shoot and root tips).

Source: Soil and air

Uptake:
1. As Cl^- by all plant parts and translocated basi- and acropetally. During vegetative growth a considerable amount of Cl is translocated to the roots.
2. Uptake depends on plants (halophytes) and species.

Deficiency symptoms:

VERY RARE, IF EVER. Wilting, cupping of leaves, chlorosis and marginal scorch. Heavy root branching and stubby roots.

Excess symptoms:

Scorched leaf margins and tip burn. Reduced leaf size. Reduced growth and yield. Looks like ozone damage.

Possible interactions: Not known.

MEDIA TEST REVIEW

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Crop	pH	SS	NO_3	NH_4	P	K	Ca	Mg	Na	Fe	Mn	Zn	B
Cineraria	6.5	38	12	<1	11	17	82	44	13	.28	.08	.10	.04

This media test is typical of a test early in production of a crop. The pH is in the recommended range, and if it can be maintained, will be ideal for this crop if you can maintain the pH of your water. Maintaining a pH in a soilless mix is not difficult.

This media test is typical of a test early in production of a crop.

Macro nutrient levels are low, therefore, increase fertilization. Also, the N:K ratio is about 1:1 and should be closer to 3:1. Using postassium nitrate will help to increase this. The Ca:Mg ratio is currently 2:1 and it should be about 3:1. The use of calcium nitrate in the fertilizer mix will help bring that ratio closer to the recommended level.

The level of the micronutrients is acceptable. Currently an addition of micros would probably not be beneficial, however, a little later in the crop a 1/2 strength application of trace elements may be beneficial.