CHAPTER 7

PLANT NUTRITION AND NUTRITIONAL DISORDERS

INTRODUCTION

***Fresh plant material is usually made up of between 80 and 95% water** (depending on plant species and turgidity of the plant – and that depends on time of day the sample was taken, the amount of water available to the roots, temperature, wind velocity, etc.).

***Plants require certain elements** (referred to as mineral nutrients) for growth.

***These elements are usually taken up by the roots in their ionic form** (an element or compound that has an electrical charge).

***So far, there are 16 elements that have been found to be essential for plant growth.** Early researchers in plant nutrition established 3 criteria for an "essential element":

1. The plant can not complete its life cycle without the element.
2. Action of the element must be specific – no other element can substitute for it.
3. The element must be directly involved in the nutrition of the plant.
    a) As a structural component or constituent of an essential metabolite.
    b) Required for the action of an essential enzyme.

***The plant uses these 16 elements along with light in the process of "photosynthesis" to create all of the other compounds it needs** including carbohydrates (sugars), proteins (structural, enzymes, etc.), vitamins, fats, etc. NOTE: Animals do not perform photosynthesis and therefore have to ingest all of these, including mineral nutrients.

PLANT MINERAL NUTRIENTS AND THEIR FUNCTIONS

Nutrients absorbed in large amounts from the air, water and soil.

1. **Carbon:** All life on Earth is considered to be "carbon based" – all carbohydrates, proteins and fats are composed of a backbone of carbon atoms. The carbon atoms in all living things initially come from the air in the form of carbon dioxide and are "fixed" into plant carbohydrates through the process of photosynthesis (photo = light, synthesis = to make; or to make compounds using the energy from light).
    Deficiency Symptoms: Not usually a problem with abundant carbon dioxide (CO_2) in the atmosphere. HOWEVER, in a closed greenhouse during winter, or early in the morning before the vents open, plants can use up enough CO_2 such that the reduced level reduces growth. Carbon dioxide enrichment is advised using a CO_2 generator (burns natural gas).

2. **Oxygen:** This element is also a part of all carbohydrates, proteins and fats and is therefore critical. It is also required for the metabolic process of respiration. Both plants and animals take in oxygen from the air, use it to “burn” or metabolize molecules in order to form energy, and then give off carbon dioxide. Plants also take in oxygen as part of water molecules (H_2O) and as part of the ionic forms of the mineral nutrients (e.g., $MgSO_4$). In a hydroponic system, where the roots can be submerged in nutrient solution, this is most important. If the roots are completely submerged, oxygen must be supplied by aeration of the solution.

   Deficiency Symptoms: Respiration will be curtailed and the tissue will die. In roots this appears as browning followed by rotting of the roots.

3. **Hydrogen:** This element is also a part of all carbohydrates, proteins and fats and is therefore critical. It is derived from water molecules (H_2O) and is part of the ionic forms of the mineral nutrients (e.g., KH_2PO_4). This element, in and of itself, should never be limiting.

   Deficiency Symptoms: Usually, not a problem.

MACROELEMENTS: Nutrients required in large amounts and absorbed from the soil or a complete hydroponic nutrient solution.

4. **Nitrogen:** Elemental nitrogen (N_2) in the air can not be utilized by plants. In nature N_2 must first be “fixed” into the nitrate or ammonium forms by certain bacteria that live in association with “legume” plants (the pea and bean family which includes clover, alfalfa, mesquites, etc.). These “fixed” forms of nitrogen can then be absorbed through the roots as part of such molecules as ammonium nitrate (NH_4NO_3), potassium nitrate (KNO_3) and calcium nitrate ($Ca(NO_3)_2$). What we use in hydroponics are chemical fertilizers where the nitrogen is already fixed. Nitrogen is also available to the plant roots over a wide range of pH’s.

   Overall function: This element is a part of every “amino” acid and therefore every protein. It is also a part of nucleic acids (RNA and DNA) and the chlorophyll molecule (necessary for photosynthesis). Nitrogen stimulates above-ground growth (stems and leaves) and helps the plant produce the “healthy green” color. It also stimulates the increase of proteins in fruits and grains and helps in the utilization of other nutrients including phosphorus and potassium.

   Deficiency Symptoms: Nitrogen is highly translocatable, therefore, deficiency symptoms will appear first on the older growth. Growth is restricted. Leaves become light green, then yellow (chlorotic), then die. Stems, petioles and lower leaf surfaces of corn and tomato can turn purple.

   Toxicity Symptoms: Too much nitrogen in the soil or nutrient solution will cause the plant to be dark green with abundant foliage but a restricted root system, few blossoms and a restricted fruit set. There can also be a build up of nitrites in the plant tissue that can cause the plant to be more susceptible to disease BUT can also be harmful to the animals, including humans, who eat the plants.

5. **Phosphorus:** This element, like nitrogen, can not be absorbed by the plant in its elemental form, but first must be combined to form the orthophosphate ion ($H_2PO_4^-$). A typical compound used in hydroponic solutions that contains phosphorus is monopotassium phosphate (KH_2PO_4). In soilless mixes, increasing pH may limit the availability of phosphorus to the plant

    Overall function: Phosphorus is part of the "energy currency" of the cells of all living things (ATP, etc.). It encourages root development, encourages rapid strong growth, hastens the maturity of plants and stimulates blooming. By promoting early cell development it helps the plant build resistance to disease.

    Deficiency Symptoms: Phosphorus is highly translocatable so deficiency symptoms will appear first on older growth. Leaves, and later stems and petioles, turn dark bluish-green changing to purplish in color on the lower surfaces. There may also be a "silvery tinge" on the underside of the leaves and the leaves may curl downward. Plants are slow to develop, flowering may be delayed, the root systems may be poorly developed and plants may be more susceptible to infection.

    Toxicity Symptoms: No direct effects are known. However, excess phosphorus in a hydroponic nutrient solution, if the solution has a pH below 5.5, may be converted into a precipitate that could effect the uptake and translocation of iron, zinc or copper (which could cause deficiencies of these "micro" elements – see below).

6. **Potassium:** This element is found in its ionic form (K^+) in the soil solution or in a hydroponic nutrient solution. This is also the form that the plant can absorb. Changes of pH do not effect the availability of potassium to the plant.

    Overall function: Potassium acts as a catalyst or activator of certain enzymes. It helps encourage healthy root development and has a lot to do with the vigor and health of the overall plant. It may participate in organic salt transport and storage and is critical in controlling the turgor of the guard cells of the stomates (pores through which water leaves the plant (transpiration) and though which gases (oxygen and carbon dioxide) pass (i.e., gas exchange). It also enhances the translocation of magnesium and photosynthates through the phloem.

    Deficiency Symptoms: Potassium is highly translocatable, therefore deficiency symptoms will appear first on older growth. Enzyme reactions are inhibited which leads to poor growth, weak root systems, weak stems and may contribute to a reduced tolerance to drought, frost, fungal attack and/or salinity. In dicot plants chlorotic (yellow) then necrotic (dead) areas appear on the leaves. In monocots the tips and edges of the leaves die first. The stomates do not function properly and may not open in the light resulting in reduced transpiration and gas exchange. In tomatoes low potassium in relation to nitrogen may cause blotchy fruit ripening and/or fruit cracking.

Toxicity Symptoms: Potassium is not usually absorbed in excessive amounts. However, high potassium may cause calcium, magnesium and perhaps manganese, zinc and/or iron deficiencies.

7. **Calcium:** This element is found in its ionic form (Ca^{++}) in the soil solution and in a hydroponic nutrient solution. This is also the form that the plant can absorb. Acidification of the nutrient solution when using soilless mixes can cause a slight reduction in the availability of calcium to the plant.

   Overall function: In the cell, calcium can combine with bicarbonate to form the base, calcium bicarbonate, that is an effective neutralizing agent for acids formed during cellular metabolism. Calcium is also an activator of the enzymes amylase and ATPase. A primary role for calcium is as a cementing or cross-linking agent within the plant cell walls that adds to the general vigor and strength of the plant.

   Deficiency Symptoms: In its role as a cell wall cross-linking agent, calcium is not translocatable. Therefore, deficiency symptoms tend to appear first in the new growth. Apical meristems (shoots and roots) show misshapen, poor or no growth. The “terminal bud” may be “hooked”, the stems weakened and flowers/buds may drop off. Older leaves may be downturned with marginal chlorosis. In tomato fruit calcium deficiency is expressed as “blossom end rot”, a leathery brown patch on the blossom end of the fruit. In lettuce, an increase in tip burn may result. Since calcium is moved up the plant via the water stream in the xylem (a result of “root pressure” and “transpiration”), conditions that slow that water movement (i.e., problems with absorption at the root or low transpiration and/or humid condition surrounding the leaf surfaces) will slow the movement of calcium and cause calcium deficiencies.

   Toxicity Symptoms: None consistent. However, any symptoms are usually associated with high carbonate levels ($CaCO_3$ formation).

8. **Magnesium:** This element is found in its ionic form (Mg^{++}) in the soil solution and in a hydroponic nutrient solution. This is also the form that the plant can use.

   Overall function: Magnesium is the heart of the complex ring molecule called “chlorophyll”, the green pigment used in plants to absorb radiant energy (from a natural (e.g., the sun) or artificial light source) that drives the process of photosynthesis. Magnesium also combines with ATP and ADP and acts as a “metal activator” for enzymes that use these two substrates. Magnesium also activates enzymes needed in photosynthesis, respiration and the formation of DNA and RNA.

   Deficiency Symptoms: This element is easily translocatable and therefore deficiency symptoms appear first in the lower parts of the plant. With less chlorophyll formed the lower leaves show interveinal chlorosis (yellow to white color between the veins) and finally necrosis (death). Leaves are often brittle and tend to curl upward. A reduction in enzyme activity causes reduced growth.

   Toxicity Symptoms: Very little information is available.

9. **Sulfur:** Sulfur must be oxidized (i.e., in the sulfate form – $SO4^{=}$) in order to be absorbed by plants. Absorption does not appear to be effected by solution pH.

Overall function: Sulfur is an integral part of two amino acids, cysteine and methionine. Amino acids are the building blocks of proteins and the sulfur atom serves in the formation of "disulfide bonds" or "sulfur bridges" which aid in the conformation or structure of proteins. These proteins are critical to all metabolic processes of the plant cell.

Deficiency Symptoms: This element is only moderately translocatable and therefore deficiency symptoms occur in younger parts of the plant. Since sulfur is critical to protein synthesis, a deficiency of sulfur will cause a reduction of protein synthesis and all molecules dependent upon them, including chlorophyll. Therefore, middle or younger leaves will show chlorosis. Stems and roots will have smaller diameters but will increase in length and the root system will be more massive and invasive than normal. Stems may also be rigid and brittle.

Toxicity Symptoms: Excesses of sulfur may cause a reduction in growth and leaf size as well as interveinal chlorosis or burning of the leaves.

MICRONUTRIENTS: Elements required in small amounts and absorbed from the soil or a complete hydroponic nutrient solution.

10. **Iron:** This element can be added in several forms: ferrous sulfate, ferric chloride or iron chelate (a "metal" atom bound to an organic compound by two or more bonds forming a ring structure, e.g., Sequestrene). The latter is expensive but the best source of iron. pH is critical for iron availability. A solution that is especially too basic (above about 8) can cause problems in uptake. Also, a solution too acidic or basic (or even neutral - pH 7) can cause the iron and phosphate to combine forming an insoluble iron phosphate precipitate (Fe_2PO_4 – a whitish compound that will settle to the bottom of the tank and no amount of mixing or heating will dissolve it). Best pH: 5.6 - 6.6. Note that iron can also be applied as a foliar spray.

Overall function: Iron is involved in enzyme activation as a catalyst, in redox reactions and electron transfer, and it acts as an oxygen carrier. It is involved as an enzyme activator or cofactor in the synthesis of chlorophyll, and in the functioning of several other enzymes including catalase, peroxidase, ferredoxin and the cytochromes. It is therefore crucial for chlorophyll production, protein synthesis and respiration. In legume plants, iron is important in nitrogen fixation.

Deficiency Symptoms: Since iron is usually bound (chelated) to various compounds in the plant it is fairly immobile. Therefore, symptoms appear first on the young growth in the form of interveinal chlorosis.

Toxicity Symptoms: Not usually seen. However, if foliar applications of iron are used in excess, necrotic (dead spots) on the leaves may appear.

11. Manganese: This element is actively absorbed by plant roots as the manganous ion (Mn^{++}). It can also be applied in a foliar spray as an inorganic ion or in the chelated form. Manganese is best absorbed by plant roots at lower pH's (less than 6.5).

Overall function: Manganese is involved in enzyme activation as a catalyst in carbohydrate reduction, chlorophyll formation, and RNA and DNA synthesis. It is important in energy storage metabolism and directly involved in the production of oxygen during photosynthesis. It also oxidizes excess iron in the plant.

Deficiency Symptoms: Interveinal chlorosis is evident and similar to that for magnesium, except that manganese is relatively immobile, therefore symptoms appear in the younger growth first. Symptoms may also be confused with those for zinc or iron. In advanced cases necrotic spots and leaf shedding may occur, however the veins always remain green. Flower formation is reduced or halted and growth is erratic.

Toxicity Symptoms: Brown spots in the older foliage, sometimes chlorosis and uneven chlorophyll distribution may be evident. High manganese levels may cause iron deficiency. There is usually an overall reduction of growth.

12. Boron: This element is probably taken up in the undissociated boric acid form. It is best taken up from a solution that is below about pH 6.5.

Overall function: Boron seems to be related to the metabolism of calcium and potassium. It is used to regulate carbohydrate metabolism and is involved in RNA synthesis.

Deficiency Symptoms: Boron seems to be very mobile within the leaf but is not translocated back down the phloem to the stem. Therefore, it is not translocatable within the plant and younger growth shows symptoms first. Shoots show abnormal or retarded growth, then blackening, and both shoots and roots tend to die back. Stems and petioles may be brittle and develop cracks. Young leaves may appear thick and curled. Flowering and fruiting are restricted or inhibited. Typical rots of fruits and vegetables may be attributable to boron deficiency.

Toxicity Symptoms: This can be a problem in arid and semi-arid regions where the ground water can have high boron levels (as much as 0.8 ppm). Levels in the final nutrient solution should be around 0.44 ppm. Toxicity symptoms may appear as deficiencies. Also, leaf tip chlorosis may be followed by necrosis starting at the tip or margins and progressing inwards.

13. **Zinc:** Uptake of zinc into the plant appears to be an active process and it may compete with copper, manganese and iron for the same carrier. Zinc uptake is not as pH sensitive as that of manganese or boron. However, it does appear to be related to light availability, more light resulting in more zinc uptake.

Overall function: Zinc is an enzyme activator and involved in protein, hormone (i.e., IAA) and RNA/DNA synthesis and metabolism and in ribosome complex stability.

Deficiency Symptoms: Zinc deficiencies can be induced by high levels of phosphorus, nitrogen, copper or iron. Symptoms can include abnormalities in the roots and shoots with a general stunted appearance. Internode length and leaf size may be reduced. Leaf edges can be puckered or distorted. Since this element is not easily translocatable, apical or younger growth is inhibited. However, both young and older leaves can show interveinal chlorosis (pale green, yellow or even white).

Toxicity Symptoms: There may be a reduction in leaf expansion and root growth with high levels of zinc resulting in iron deficiency symptoms (i.e., interveinal chlorosis).

14. **Copper:** Uptake into the plant in the ionic form (Cu^{++}) appears to be an active process and can be inhibited by zinc. Copper uptake does not appear to be as sensitive to pH changes as does manganese or boron.

Overall function: Copper is involved in chlorophyll synthesis with nearly 70% of all copper in the leaves found in the chloroplasts. It is also a constituent of plastocyanin, a chloroplast protein that is part of the photosynthetic electron transport system. Copper is also a constituent of several oxidases (enzymes that catalyze oxidation-reduction reactions). It may play a role in elemental nitrogen fixation in legumes and in the production of vitamin A. It may also be involved in RNA and DNA synthesis.

Deficiency Symptoms: Since this element is not easily translocatable symptoms appear first in the younger tissue. These can include short stem internodes with resulting death of the tip, stunting and/or twisting of new leaf growth with dark green to bluish-green coloration and necrotic spots, a loss of turgor (firmness) in the leaves and stems, stunted root development and a reduction of flowering and fruiting. Severe copper deficiency may be similar to potassium deficiency. Copper deficiency may also be caused by excesses in phosphorus.

Toxicity Symptoms: High levels of copper can displace iron causing the iron deficiency symptom interveinal chlorosis. Other symptoms include overall reduced growth and stunting as well as thickening and darkening of the roots. Copper tubing and fixtures should be avoided in irrigation systems to reduce the input of unwanted copper.

15. Molybdenum: This element is needed in the smallest amounts of all the mineral elements and is absorbed into the plant in the molybdate form ($MoO_4^{=}$). Uptake can be inhibited by sulfate ions and low pH, but enhanced by phosphate ions. Foliar sprays of 0.5% ammonium molybdate can be used on vegetables.

Overall function: Molybdenum is involved in nitrogen metabolism as a part of the nitrogenase enzyme (nitrogen fixation in legumes) and as an electron carrier for nitrogen reductase (the enzyme responsible for nitrate reduction). It is also involved in carbohydrate metabolism.

Deficiency Symptoms: Since this element is somewhat translocatable within the plant, symptoms usually start with the older growth and progress to younger growth. This includes interveinal chlorosis, similar to nitrogen deficiency, mottling and sometimes marginal scorching or inward cupping of the leaves. Chlorotic areas may turn puffy and severe stunting may occur in advanced stages.

Toxicity Symptoms: This is rarely seen but tomato leaves can turn yellow while cauliflower seedlings will turn bright purple.

16. Chlorine: This element is actively taken up by plant roots in the chloride (Cl^-) form.

Overall function: Though required by plants in small amounts, chloride is now known to have many roles in plant growth. It is an activator for the enzyme that releases oxygen from water during photosynthesis. It also appears to be involved in respiration. Recent preliminary studies indicate that “adequate” levels of chloride in the nutrient solution may reduce the amount of nitrogen required without effecting plant growth or yield. The negatively charged chloride “anion” also acts as a counter ion to the positively charged “cations” in the cell. Chloride is involved in regulating turgor pressure and growth of cells and is important in drought resistance. Chloride may also be beneficial in disease prevention, especially of the roots, by promoting healthy growth of the plant while creating a root zone environment (pH and osmotic properties) detrimental to pathogens (disease causing organisms).

Deficiency Symptoms: Since chloride is mobile within the plant, symptoms appear first on the older growth. Leaves will become chlorotic and finally necrotic with leaf area being reduced. Wilting is common and transpiration can be reduced. There is an overall stunting of the plant and subsequent die back.

Toxicity Symptoms: High amounts of chloride produce typical “salt stress” or salinity effects including leaf tip or edge burning, chlorosis, “bronzing” and premature leaf drop.

NOTE: Tomatoes are highly tolerant of high levels of chloride ion and recent use at almost “macronutrient” concentrations in the nutrient solution are proving beneficial.

OTHER NUTRIENTS: Elements that have been found in plant tissue and are most likely required by some plants in some amounts for growth.

1. **Sodium:** Essential for some C4 plants – may increase PEP carboxylase activity.
2. **Silicon:** May be involved in cellulose formation and carbohydrate metabolism. Seems to protect against insects, diseases and many environmental stresses. Beneficial for C4 and CAM plants.
3. **Cobalt:** Required by nitrogen fixing bacteria in legume plants.
4. **Vanadium:** Essential for a green alga. Toxic in high amounts in water culture.
5. **Iodine:** Stimulates growth at low concentrations, but toxic at high levels.
6. **Bromine:** Can substitute in part for chloride. Toxic to some plants producing salt stress symptoms. Tomato and some others are insensitive to high levels.
7. **Fluorine:** Toxic to most plants. However, some plants accumulate it and the resulting "fixed" form is toxic to animals. Commercial teas have high levels.
8. **Aluminum:** Required for normal growth of the tea bush. There are tolerant species but, in most plants, aluminum is toxic.
9. **Nickel:** May be required by nitrogen fixing plants and others that use urea as a nitrogen source. Toxic to other plants.
10. **Selinium:** Has been seen at high levels in certain milk vetches (*Astragalus*). Resembles sulfur in its chemical properties, but is toxic to most plants.

REFERENCE MATERIAL:

1. **Nutrient Management in Recirculating Hydroponic Culture.** 1995. B. Bugbee. In: Proceedings of the 16th Annual Conference on Hydroponics. Edited by M. Bates. Hydroponic Society of America, 2819 Crow Canyon Road, Suite 218, San Ramon, CA 94583.
2. **Hydroponic Nutrient Management.** 1994. C. Erikson. In: The Best of the Growing Edge. Edited by D. Parker. New Moon Publishing, Inc., 215 SW Second St. #201, P.O. Box 1027, Corvallis, OR 97339. ISBN 0-944557-01-5
3. **Hydroponic Nutrients.** 1993. M.E. Muckle. Growers Press Inc., P.O. Box 189, Princeton, B.C., Canada, V0X 1W0. ISBN 0-921981-33-3
4. **Hydroponic Food Production.** 2001. H.M. Resh. Woodbridge Press Publishing, P.O. Box 209, Santa Barbara, CA, 93160. ISBN 0-88007-222-9
5. **Principles of Plant Nutrition.** 1982. K. Mengel and E.A. Kirkby. International Potash Institute, P.O. Box CH-3048, Worblaufen-Bern/Switzerland.