Plants' essential chemical elements

Every garden center and hardware store sells fertilizer guaranteed to "feed" plants. In a strict sense, we can't feed plants. Food contains an energy source. Green plants capture solar energy and make their own food through photosynthesis! Photosynthesis and other metabolic processes require chemical elements in appropriate doses for plants to survive and thrive. We can help, directly or indirectly, to provide plants these essential chemical elements.

Back in 325 B.C., Aristotle taught that all earthly things were composed of four elements: earth, air, fire, and water. That remained the dominant view for many centuries. In the 1830s and 1840s, scientists -- such as the pioneering agricultural chemist J. von Liebig -- hotly debated the question of "What do plants need to grow?" Soil, mild temperatures, sunlight, and water were easy answers that roughly corresponded to Aristotle's elements. But why did manure and compost increase growth? Was there some vital force in organic matter that nurtured plants?

This concept of vitalism was discredited by the new agricultural chemists. They determined that inorganic mineral elements were essential for plant life. Their arguments were so convincing that the concept of a vital life force became a discredited superstition. Plant nutrition could be reduced to a recipe of sterile elements.

Origin of elements. What is an element? Chemically, an element is a pure substance composed of atoms that all have the same number of protons in the nucleus. That number is the "atomic number" and specifies the element's position in the periodic table. The atomic nucleus also contains neutrons. For each element, the sum of the numbers of protons and neutrons is the approximate atomic weight. Depending on the definition, 16 out of the 94 naturally occurring elements are generally considered essential for the growth of plants. Where do these elements really come from, before they are bagged and boxed for sale?

Approximate composition of elements necessary for plant growth

Element	Symbol	Atomic number	Approximate atomic weight	Percent composition	Relative number of atoms
Hydrogen	H	1	1	6	57,600,000
Carbon	C	6	12	45	30,857,143
Oxygen	O	8	16	45	27,000,000
Nitrogen	N	7	14	2	1,028,571
Potassium	K	19	39	1	246,154
Calcium	Ca	20	40	<1	120,000
Magnesium	Mg	12	24	<1	80,000
Phosphorus	P	15	31	<1	61,935
Sulfur	S	16	32	<1	30,000
Chlorine	Cl	17	35	<1	2,743
Boron	B	5	11	<<1	1,745
Iron	Fe	26	56	<<1	1,714
Manganese	Mn	25	55	<<1	873
Zinc	Zn	30	65	<<1	295
Copper	Cu	29	64	<<1	90
Molybdenum	Mo	42	96	<<1	1

Astrophysics tells us that virtually all chemical elements were formed in the aftermath of the Big Bang or in the thermonuclear heat of stars as they burn or explode. The essential elements can vary widely in the quantities required to support survival and growth. The relative amounts that are needed can be compared by weight or by the number of atoms (table, above).

Essential elements for growth. The elements in greatest abundance in plants are the raw materials for photosynthesis. Photosynthesis uses light energy to split apart the oxygen and hydrogen of water and to split apart the carbon and oxygen from carbon dioxide taken from the atmosphere. Photosynthesis then releases the oxygen from carbon dioxide back into the atmosphere and recombines the remaining elements to form sugar. Sugar is the starting material for all processes in plants that require energy. Also, the bulk of a plant is made of sugar polymers (e.g. cellulose and starch) or compounds derived from sugar (e.g. lignin). Soil organic matter is largely cellulose and lignin which is critically important for soil moisture retention, aeration, mineral element storage, and to fuel the communities of soil organisms that provide natural fertility.

However, the carbon contained in organic matter is not directly taken up by plants. Through the 1880s, the scientist A.B. Frank described the critical role of mycorrhizae in plant nutrition, especially for trees. Mycorrhizae (Greek for "fungus-roots") are symbiotic organs containing plant roots and one or more species from a broad array of fungi. The plant feeds sugar to the fungus while the fungus enhances the uptake of essential elements -- particularly P and N. These beneficial infections may also increase resistance to drought and some plant diseases.

This nutritional role of mycorrhizae and of free-living communities of fungi, bacteria, and other microorganisms is sometimes hidden, largely due to disruption of the natural soil environment and through inhibition due to heavy applications of chemical fertilizer -- particularly of P and N. These non-target consequences of common cultural practices in plant care are just beginning to get the depth and breadth of attention that they warrant. Ongoing research seeks to identify what we can do to restore and maintain these important relationships.

Products and treatments continue to be developed to restore these communities of microorganisms that benefit plants. Although the treatment thresholds are not always known, the target should be clear. Practices that increase the natural ability of soil to cycle elements in a form available to plants should be encouraged and situations or practices that disturb or diminish the processes such as low organic matter, heavy fertilization, soil compaction, and improper drainage should be discouraged.

What do essential elements do for the plant? Nitrogen is the element that is most associated with enhanced plant growth and is a key component of all proteins. Many proteins function as enzymes or biological catalysts, making plant metabolism possible. Plants have very efficient pumps to take N from the soil, usually in the form of nitrate, and to bind it to sugar fragments to form amino acids, the building blocks of proteins. Deficiency in N decreases production of chlorophyll and enzymes, resulting in decreased photosynthesis, decreased growth, and premature senescence.

Potassium is also critical for photosynthesis, cell expansion, and to regulate the opening and closing of stomates. Deficiency of K leads to chlorosis and scorching of the leaf margins.

Calcium interacts with pectin to crosslink plant cell walls and to act as a messenger to regulate growth hormones. Woody stems contain an even greater proportion of Ca than is shown in the table, which is drawn from herbaceous plants. Calcium deficiency reduces elongation of internodes and overall growth.

A magnesium atom lies in the center of the chlorophyll molecule and also increases the effectiveness of some enzymes. Magnesium deficiency often appears as chlorosis and scorching between leaf veins and premature leaf shedding.

Phosphorous is part of the "backbone" of nucleic acids that carry genetic information. Phosphorous is also a key element in ATP, the primary molecule for the transfer of biological energy. Deficiency in P causes severe stunting and reduced flowering and fruiting.

Sulfur is a constituent of two essential amino acids as well as plant vitamins and enzyme cofactors. Deficiency of S causes on overall yellowing of younger leaves, and chlorosis and necrosis in older leaves as well as rosetting of lateral shoots.

Chlorine is required for photosynthesis, but in such low quantities that deficiencies rarely occur.

Although present in plants in even smaller quantities, boron deficiencies do occur, resulting in marginal scorch of leaves, dead shoot tips, and deformation of fruits.

Iron has a key role in the synthesis of chloroplasts, the site of photosynthesis within cells, as well as several critical respiratory enzymes. Deficiency of Fe is extremely common in alkaline soils due to impaired availability at high pH, causing interveinal chlorosis and shoot dieback.

Manganese is also required for chlorophyll synthesis and the release of oxygen during photosynthesis. Deficiency of Mn causes chlorosis, necrosis, and deformation of leaves.

Zinc is a structural part of some enzymes and a cofactor for others. Deficiency in Zn can reduce internodal elongation and discolor the lower leaf surface to produce "bronzing".

Copper is a constituent of several enzymes. Deficiencies of Cu can cause interveinal chlorosis, defoliation, leaf mottling, and shoot dieback.

Although molybdenum is the essential element in the lowest concentration in plants, Mo is still essential for the conversion of nitrate into amino acids in living cells.

Plants as part of natural systems. In nature, plant nutrition is far from the simple view of roots immersed in a solution of inorganic chemicals. The importance of the living web of plant nutrition is especially clear with trees and other perennial woody species that involve long-term relationships with communities of soil organisms including fungi, bacteria, and protozoa. All of these organisms, directly or indirectly, require organic matter in the soil to fuel their metabolism. As with living roots, these organisms require the proper combination of air and water in the soil for their own respiration. Soil compaction and adverse changes in soil chemistry and drainage reduce the effectiveness of the microbial communities to support plant growth. The 19^{th} century vitalists held a germ of truth in the midst of their misunderstanding of plant nutrition. The life force in manure was exactly that. Life in diverse, interacting

Healthy, forest-grown oak seedling is showing extensive connections between roots and soil organic matter that support soil microorganism diversity

communities of microorganisms sustains living communities of green plants and especially trees. As plant parts are shed and individuals die, the breakdown of organic matter as well as exudates from living plants fuel communities of beneficial microorganisms.

Plant nutrition links the astrophysics of chemical elements to the utilization of solar energy of plants, the capture of carbon from and the release of oxygen to the atmosphere, and the rich diversity of soil microorganisms. Of course, urban and community landscapes and the nurseries that serve them may feel the need to compromise part of the natural system to support short-term management needs. Still, plants did not develop in sterile laboratories, but in living soil.

(Written by Dr. Kevin T. Smith, US Forest Service and originally published in American Nurseryman 206 (10): 10-11, 2007).