

# Strategic Analysis Paper

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## The Chemical Fertility of Soils: Soil Nutrients and Plant Nutrition

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### Key Points

- There are a number of element nutrients that are essential for plant growth.
- Carbon, hydrogen and oxygen, three of the essential plant nutrients, are taken up from the atmosphere and from water. The other essential nutrients come from the soil.
- The major nutrients, or macronutrients, supplied by the soil are nitrogen, phosphorus, potassium, sulphur, magnesium and calcium.
- The minor nutrients, also referred to as micronutrients or trace elements, supplied by the soil are molybdenum, copper, zinc, manganese, iron, nickel, boron and chlorine.
- A deficiency in any one of these essential nutrients will reduce growth, as plant yield is dependent on the amount of the most limited nutrient, whichever it may be.
- Soil fertility is comprised of a complex interaction between the three fertility components: chemical fertility, structural fertility and biological fertility. They are strongly influenced by the presence of carbon and water.
- Our understanding of how the soil fertility components interact is incomplete and requires further research in order to adequately advise agricultural producers.

## Summary

Plant growth, vigour and yield are dependent upon the availability of a number of essential element nutrients. Detailed lists of these elements vary slightly but most sources identify three essential, non-mineral elements: carbon, oxygen and hydrogen; six major or macro-nutrients: nitrogen, phosphorous, potassium, sulphur, calcium and magnesium; and a range of micronutrients which include, molybdenum, copper, boron, manganese, iron, nickel, chlorine and zinc. In addition to these elements there are also nutrients that are either essential to some but not all plants or beneficial but not essential. Plant uptake of all nutrients is limited by the single, scarcest element and not by the availability of an individual element.

Many of the soil types found in Australia are deficient in some of the essential nutrients and the solution is not as simple as just adding fertiliser. A plant's ability to take up nutrients, even when they are abundantly available, is strongly influenced by the availability of water, the presence of soil organic matter, soil structure and microbiology.

## Analysis

### *Introduction*

Over 150 years ago, science determined that some chemical elements were absolutely essential to plant life. Today, depending upon the research source, science recognises 16 or 17 elements as essential to all plants. Additional elements have also been identified that are either essential to some plants or beneficial but not essential for plant growth. Minor differences in source opinion notwithstanding, it is a firmly established principle that soils must provide plants with a significant number of chemical element nutrients for the plant to complete its lifecycle.

In natural, healthy ecosystems soil nutrient levels are maintained by the nutrient cycle and are relatively stable. Agricultural soils, however, can become nutrient deficient as agricultural ecosystems are not closed and nutrients will permanently exit the system as plant or animal products. Even with the best possible agricultural practices, an open system such as this cannot be sustained indefinitely. Plant nutrient access, uptake, replacement and supplementation are not as simple as identifying and adding chemicals. Uptake mechanisms are varied and can be complex. Scientific research continues to improve our understanding of how to best maintain soil chemical fertility.

### *Definition of Nutrients*

The definition of a plant nutrient is deceptively simple; it is a chemical element that is necessary or beneficial for plant growth or some other life-cycle process such as reproduction. For a nutrient to be classed as **essential**, it must either be necessary for the plant to complete its life-cycle or it must be part of an essential plant component such as cell structures or a metabolic process, the chemical processes that occur within living organisms,

such as photosynthesis. In other words, an essential element is necessary for the plant to grow and reproduce (Koch's postulate).

### ***The Essential Nutrient Elements***

Of the 17 essential nutrients, **carbon**, **oxygen** and **hydrogen** are classed as non-mineral elements. They are accessed from air and water and are therefore not considered soil nutrients. Carbon forms the backbone of many plant biological molecules, including proteins, starches and cellulose. It is fixed by photosynthesis (the process by which green plants use sunlight and chlorophyll to construct foods from carbon dioxide and water) from carbon dioxide and is a part of the sugars and starches that store energy in the plant. Hydrogen is obtained almost entirely from water. It is a critical element in photosynthesis and for respiration, the process of generating energy through the consumption of foods made by photosynthesis. Oxygen is gained from the air as oxygen gas or in the molecules of water or carbon dioxide. It is also necessary for plant respiration (the process by which the plant accesses energy from sugars and starches in the presence of oxygen). The remaining 14 elements are all classed as soil nutrients. They are divided into two categories: the macronutrients and the micronutrients.

The macronutrients, as the name suggests, are required in relatively large quantities. They are necessary for the basic, day-to-day plant biological functions such as growth, photosynthesis and respiration. The macronutrients are:

- **Nitrogen** is needed for all plant growth processes.
- **Phosphorus** is an essential component in many vital plant processes.
- **Potassium** is also needed for a wide range of important processes within the plant.
- **Sulphur** is required for the formation of several amino acids, proteins and vitamins and for chlorophyll production.
- **Calcium** is involved in the proper functioning of growing points, especially root tips.
- **Magnesium** is an essential component of chlorophyll and is, therefore, vital for photosynthesis.

The micronutrients, while equally important as the macronutrients, are only required in small quantities. Deficiencies in micronutrients are more common in highly leached sands, organic soils and in highly alkaline soils. Deficiencies can also develop in intensely cropped soil. The micronutrients can be harmful or detrimental to plant growth if they are present in large quantities. The CSIRO publication, *Australian Soils and Landscapes; An Illustrated Compendium*, notes that the agricultural development of large areas of Australia was only possible when micronutrient deficiencies were recognised and remedied. The current recognised essential micronutrients are:

- **Molybdenum**, which is directly involved in nitrogen metabolism.
- **Copper** that is required for the formation of enzymes for chlorophyll production.

- **Boron** is necessary for the movement of sugars throughout the plant and the metabolism of nitrogen.
- **Manganese, Iron and Zinc** are essential for plant growth process.
- **Nickel** is the most recently identified essential plant nutrient. It is a key component of processes involved in nitrogen metabolism and the biological fixing of nitrogen.
- **Chlorine** is required for carbohydrate metabolism and chlorophyll production. It should be noted that chlorine can be defined as a macronutrient. Due to its usual abundance in the environment it is very rarely deficient and is, therefore, often grouped with the micronutrients.

In addition to the essential nutrients, there are a number of elements that do not fully meet the strict definition of essential but which are, nevertheless, important. These elements are either essential to some, but not all, plant species or they are highly beneficial to plant growth. It is important to note that as our scientific knowledge of plant nutrition grows so does this list of elements. Some of the nutrients in this category are:

- **Sodium** which, at proper levels, plays major beneficial roles in plant metabolism. It is essential to a small group of plants that grow in high-salt environments, known as halophytes. It is also beneficial as a partial substitute for potassium in some species.
- **Cobalt** has proven to be essential for effective fixation of atmospheric nitrogen in the root nodules of legumes (beans, lentils and other pulse).
- **Silicon** is deposited as silica in the plant cell walls, improving cell wall structural rigidity and strength.
- **Selenium** can increase the tolerance of plants to ultraviolet light-induced stress, delay biological ageing and growth promotion.

### ***Liebig's Law of the Minimum***

While the available quantities of each of the essential nutritional elements are important, plant nutrient uptake is not individually independent. A deficiency of one component can influence total plant nutrient uptake. In publications released in 1840 and 1855, the German biological chemist Justus von Liebig popularised a finding named the Law of the Minimum, often shortened to Liebig's Law. This Law states that plant growth is controlled not by the total amount of nutrients or resources available, but by the availability of the scarcest resource. A plant's development is limited by the one essential mineral that is in the relatively shortest supply. This principle is used for determining the application of fertiliser in modern agriculture. The key being the identification and application of the correct nutrient as application of the wrong one will provide little or no yield return.

### ***Plant Nutrient Uptake***

There are a number of ways mineral nutrients are transferred from the soil and other sources to the plant. Some plants, such as those that feed off other plants or those that trap

insects, have specialised mechanisms to access nutrients. For the majority of plants, however, nutrients are absorbed by the plant through roots, and the root hairs in particular. The plant accepts the dissolved, nutrient elements through the cell wall.

In addition to the direct uptake of nutrients through the roots, many plants engage in mutually beneficial relationships with microorganisms. Some plants, legumes for example, utilise bacteria such as rhizobia, to carry out biological nitrogen fixation where-by atmospheric nitrogen, which is not directly available to the plant, is converted into ammonium nitrate, a form of nitrogen which is available. A second example is the relationship many plants form with mycorrhiza fungi. This association provides the fungus with relatively constant and direct access to energy sources, such as sugars and starches, from the plant. In return, the long thread-like structures of the fungi act as an extension of the plant's root system and increase the plant's access to some of the essential nutrients. This relationship gives the plant far greater access to nutrients than would otherwise be available. In some situations, essential macronutrients such as phosphorus are only available to the plant in quantities needed to sustain healthy growth through this association.

### ***Improving Soil Fertility***

So far our discussion has focused upon soil nutrients or chemical fertility of the soil but this is only one fertility component. Physical fertility refers to the physical properties of the soil, its structure, texture and water holding properties, the way water flows to plant roots and how those roots penetrate the soil. Biological fertility refers to the organisms that live in the soil and their ability to perform essential roles. These three components strongly interrelate and even optimal nutrient levels may be of little value if the soil structure and biology are not conducive to plant health.

The makeup of a soil, its acidity or alkalinity, and its ambient temperature are just a sample of the many factors that will determine the extent to which nutrients are available to plants. The relative importance of these factors depends upon the nutrient, the plant and the soil. Most importantly, soil composition affects how well nutrients and water are retained in the soil. Clays and soils containing organic matter hold nutrients and water much better than sandy soils. As water drains from sandy soils, it often carries nutrients along with it. This condition is called leaching. When nutrients leach from the top-soil, they are not available for plants to use. The soil structure will also strongly influence the microbiology of the soil. Plants that rely on bacteria or fungal populations for nutrient uptake will not grow if the soil does not allow these populations to thrive.

Some Australian soils, particularly in Western Australia, are old and weathered and some are considered the oldest soils in the world. Over long periods of time the soil nutrients have been leached, resulting in soils of low chemical fertility. For example, these old Australian soils have phosphorus levels that are 40% lower than soils in the United Kingdom and up to 50% lower than some North American soils. It is important to note, however, that this comparison does not apply to the richer agricultural soils of eastern Australia. Until recently the most widely used remedy for nutrient deficiency was the application of fertiliser. The difficulty with fertiliser application, however, is the identification of which nutrients are genuinely in need of supplementation and by how much. Timing is also important as plant

nutrient requirements vary over the plant life cycle. The influence of Liebig's Law can mask the identity of truly deficient nutrients as deficiency symptoms may not directly identify the correct scarce nutrient. The plant uptake mechanisms, while simply described above, can also be complex. When the necessary structural and biological conditions are not present, additional fertiliser will be of little or no assistance. Improved plant vitality will depend on improving soil structural and biological fertility. Inappropriate fertiliser application is at best a waste of time and money but it can also have dire environmental consequences.

The scientific body of knowledge, readily and economically available to the Australian agricultural producer for accurate analysis and interpretation of soil fertility, is varied. The ability to test and analyse soil nutrient levels is well established and its use is financially sustainable and widely accepted by producers. Much effort has been devoted to mapping, describing and classifying Australian soils over many years, particularly in agricultural areas. Soil testing is available to individual farmers to analyse their soils to determine nutrient deficiencies and toxicities. Soil tests can be augmented by plant analysis which is far more reliable than diagnosis of visual symptoms described above. The ability to provide the same depth of analysis into soil structural and biological fertility is, however, more recent and, as yet, does not have the same level of utility in many regions. Analysis can be expensive and is currently less widely embraced by the agricultural community. The ultimate goal of a comprehensive understanding of all three soil fertility components combined with an equally comprehensive understanding of how these components interrelate with each other and with water and carbon in agricultural ecosystems, is likely to remain a worthy aspiration for the foreseeable future.

### ***Conclusion***

The deceptive simplicity of the concept that plants need nutrients in order to grow and thrive has perhaps lead to an underestimation of the underlying complexity of the metabolic process involved in the transfer of essential chemical elements from the soil into plant tissue. We are all aware, to some degree, of the need for forms of life, including ourselves, to gain nourishment from the environment to live, grow and reproduce. This simplicity notwithstanding, the essential mineral nutrients plants gain from the soil are just one interrelated component in a dauntingly complex system of relationships and cycles. The challenge to improve our understanding of these relationships and to draw practical and sustainable agricultural practices from it, may well underpin our capacity to sustain agricultural production in the future.

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