

Chapter 2.1

Soil Nutrient Cycling



→ learning objectives

- List and classify sixteen essential plant nutrients.
- Explain the “law of minimum” as it pertains to crop nutrition.
- **Briefly describe three ways plants absorb ions from the soil.**
- **Compare and contrast nutrient availability from different soil nutrient pools.**
- Summarize the processes that occur as part of nutrient cycling in soils.

Important Terms

Table 2.1.1 Key Terms and Definitions

Term	Definition
Adsorption	Is the physical adherence or bonding of ions and molecules onto the surface of another molecule.
Denitrification	The process where soil micro-organisms obtain their oxygen from nitrates and nitrites, resulting in the release of nitrogen or nitrous oxide. This can happen in waterlogged soils when oxygen is limited and anaerobic decomposition occurs.
Eutrophication	The natural 'aging' of aquatic systems caused by the introduction of limiting nutrients.
Fixation (nitrogen)	The conversion of atmospheric nitrogen by soil micro-organisms, such as rhizobia, into organic forms, which can be released into a form plants can use.
Humus	Any organic matter that has reached a point of stability and breaks down very slowly.
Immobilization	The absorption by micro-organisms of nutrients released from organic matter decomposition, preventing these nutrients from being available to plants. The opposite to mineralization.
Labile	Nutrients or organic material that is constantly changing or susceptible to rapid changes.
Leaching	The downward movement of substances, such as nutrients, in water through soil pores.
Macronutrient	An essential chemical element, such as nitrogen or phosphorus that is needed by plants in large quantities for it to function normally.
Micronutrient	An essential chemical element, such as boron or zinc that is needed by plants in small quantities for it to function normally.
Mineralization	In biology, this is the process where an organic substance is converted to an inorganic substance.
Nitrification	The biological addition of oxygen to (oxidation of) ammonia creating nitrite that can be further oxidized into nitrate.
Precipitation	In chemistry, this is the condensation to a solid from a solution during a chemical reaction.
Salinity	The accumulation of free salts in the soil solution.
Sorption	The action of either absorption or adsorption. It is the effect of gasses or liquids being incorporated into material of a different state and adhering to the surface of another molecule.
Stomata	Is a pore or opening in plant leaves (plural term for stoma). Guard cells close and open the stoma, controlling the loss of water vapour and other gasses from the plant.
Transpiration	The process of evaporation of water from above ground parts of plants.
Volatilization	Gaseous loss to the atmosphere. In a nutrient management context, it is the loss of ammonia gas to the atmosphere.

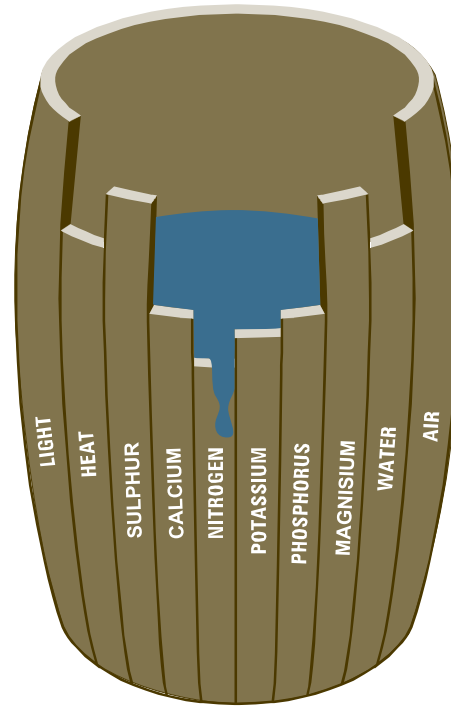
Sixteen mineral and non-mineral nutrients are essential for plant growth. The non-mineral nutrients—carbon (C), hydrogen (H) and oxygen (O)—account for approximately 96% of dry plant weight, mostly in the form of carbohydrates. The sources of C, H, and O in plant materials are carbon dioxide (CO_2) in air and water (H_2O). The energy that drives their conversion into plant material is derived from sunlight.

Mineral nutrients, classified as macro- or micronutrients, are usually obtained from the soil. The macronutrients—nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg)—account for approximately 3.5% of dry plant weight. Accounting for about 0.04% of dry plant weight are the micronutrients—chlorine (Cl), iron (Fe), manganese (Mn), zinc (Zn), boron (B), copper (Cu) and molybdenum (Mo). While this is widely regarded as the traditional list of essential micronutrients, some experts argue that elements such as nickel (Ni), silicon (Si) and cobalt (Co) should be included.

For the majority of prairie soils, N is typically the most deficient (e.g., first limiting) nutrient, followed by P, K, and S. Micronutrient deficiencies in western Canadian soils are rare compared to the size, extent and financial importance of N, P, K, and S deficiencies.

The Principle of the First-Limiting Nutrient

Plant growth will take place normally until it is restricted by the supply of an essential nutrient. A deficiency of any essential nutrient cannot be corrected by the addition of other crop inputs. This forms the basis of Liebig's "Law of the Minimum", which says that the level of crop production is limited by the nutrient in shortest supply.



Adapted from Brady and Weil, 2002

Figure 2.1.1 Conceptual Illustration of the Law of the Minimum, Showing Nitrogen as the Most Limiting Nutrient for Crop Growth

Crop yield is determined by the supply of individual nutrients relative to their required levels for optimal yield. In Figure 2.1.1, the capacity of the barrel represents crop yield, which is limited by the height of the shortest stave of the barrel (e.g., the first limiting nutrient, which is N in this example).

Ion Absorption by Plant Roots

Generally, plants absorb essential nutrients from the soil in soluble, inorganic forms. Nutrients in organic form must be converted to inorganic forms prior to plant

uptake. Exceptions to this generality include some metal elements that can be absorbed as organic complexes.

In order for ions to be absorbed by plant roots, they must come into contact with the root surface. This happens through three main mechanisms: root interception, mass flow, and diffusion.

Root Interception

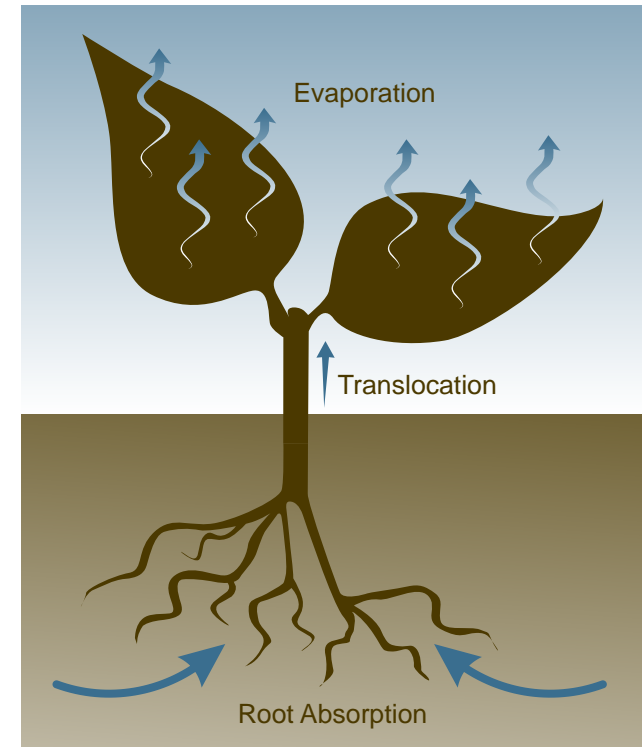
Root interception is the uptake of nutrients by plant roots as they grow through the soil and incidentally come into contact with nutrients. Nutrient uptake by root interception is directly related to the volume of the root system, which in most cases is less than 1% of the total soil volume. Consequently, root interception makes a small contribution to total nutrient uptake.

Mycorrhiza and Plants— An Infectious Partnership

Plant-mycorrhizal associations increase functional root volume. Mycorrhizal fungi infect plant roots and produce their own root-like structures called hyphae, which act as extensions of the plant's root system. Nutrient absorption is enhanced since the hyphae can increase the absorptive surface area of root systems by up to ten times compared to non-infected root systems.

Mass Flow

In mass flow, dissolved nutrients move with water towards root surfaces where they are absorbed. Mass flow is a significant mechanism for the uptake of some nutrients, such as nitrogen. Nutrient uptake by mass flow is reduced in dry conditions and at lower temperatures because the rate of transpirational water uptake is reduced (Figure 2.1.2).



Created by Len Kryzanowski

Figure 2.1.2 Transpirational Movement of Water Through a Plant

While mass flow helps the plant meet its requirements for essential nutrients, it frequently results in excess uptake of several soluble nutrients including K^+ , Ca^{2+} , and Mg^{2+} . This luxury uptake is not essential for crop growth, but can contribute to better feed or food quality of the harvested crop.

Diffusion

Diffusion is the process by which nutrients spread from areas of high concentration to areas of low concentration. When roots absorb nutrients from soil solution the concentration of nutrients surrounding the root drops. As a result, nutrients in areas of higher concentration in soil solution migrate toward the root. Diffusion is an important process in crop uptake of P and K.

Table 2.1.2 Relative Contributions of Root Interception, Mass Flow, and Diffusion in Nutrient Transport to Corn Roots

Relative percentage of nutrients absorbed from the soil by a 12 t/ha (200 bu/ac) corn crop through root interception, mass flow, and diffusion			
Nutrient	Root Interception	Mass Flow	Diffusion
N	1	99	0
P	2	4	94
K	2	20	78
Ca	120	440	0
Mg	27	280	0
S	4	94	2

Adapted from Havlin et al. 2005

Nitrogen

Nitrogen is a key component of soil organic matter and is required by plants in large quantities. It is often the first limiting nutrient in prairie cropping systems.

Nitrogen forms a part of every living cell. It is an essential component of amino acids — the building blocks for proteins. The amount of N supplied to plants influences the production of plant proteins such as enzymes, mitochondria and carrier, storage and structural proteins.

Chlorophyll is the N-based plant component responsible for photosynthesis. The amount of chlorophyll in a plant is reflected by the shade of green in plant leaves. Therefore, plant leaves can provide a visual clue to the N status of a crop (e.g., lighter shades of green in plant leaves could suggest an inadequate N supply).

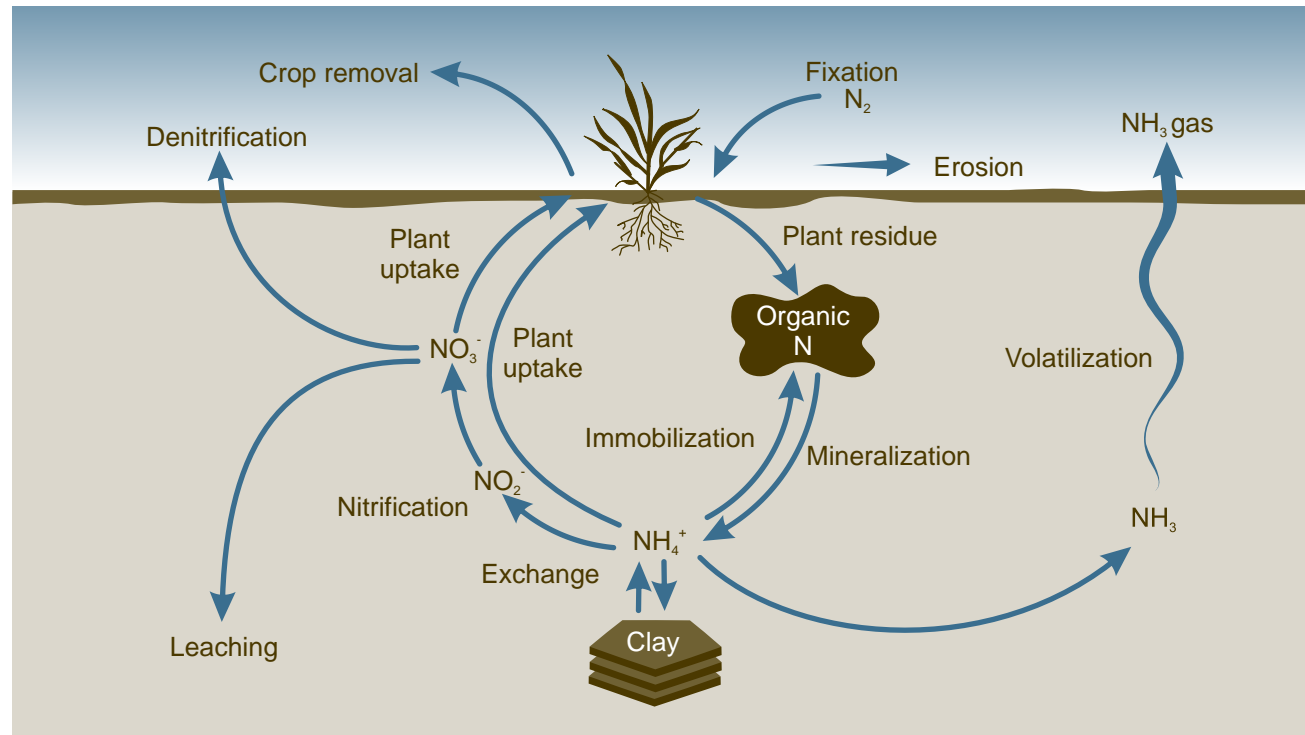
N Cycling in Soils

Nitrogen forms present in soil are constantly undergoing change. Nitrogen cycling is a relationship involving gains, losses and transformations of N among pools in the soil (Figure 2.1.3).



sidebar

Commercial N fertilizers are produced through industrial N fixation. Atmospheric N_2 is reacted with hydrogen gas (produced from the steam treatment of natural gas) under high pressure and heated to form NH_3 , which can be used directly as a fertilizer (i.e., anhydrous ammonia) or can undergo additional processing to produce other forms of N fertilizer.



Adapted from Jones and Jacobsen 2001a

Figure 2.1.3 The Agricultural Nitrogen Cycle

Seven forms of N are involved in the N cycle: atmospheric N gas (N_2), ammonium (NH_4^+), ammonia (NH_3), nitrate (NO_3^-), nitrite (NO_2^-), nitrogen oxide gases (NO , N_2O) and organic N. Each form of N exists in a pool. For example, organic N is part of the organic pool, NO_3^- exists in the soil solution pool and NH_4^+ can be present in the soil solution or exchangeable pool. Plants can only directly use inorganic N (NH_4^+ and NO_3^-) to meet their N requirements.

Atmospheric N_2 makes up 78% of the gases in the atmosphere. While N frequently limits crop production, thousands of tonnes are present in the air. For crops to access this pool of N it must be converted to a plant-available form. Legumes (e.g., alfalfa, clover, peas, beans) are able to access atmospheric N_2 through a symbiotic relationship with Rhizobium bacteria (Figure 2.1.4). In exchange for energy, Rhizobium convert atmospheric N_2 to plant-available forms in a process called fixation.

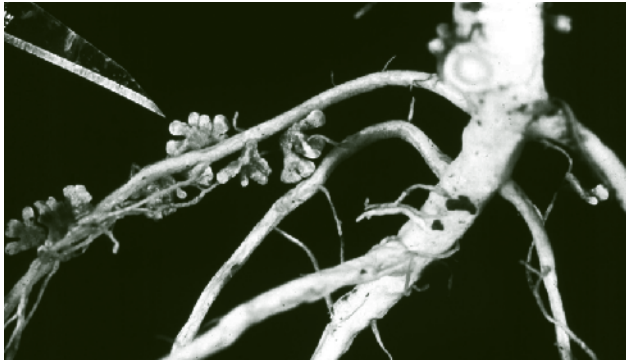


Photo courtesy Surya Acharya, AAFC

Figure 2.1.4 Root Nodules on a Legume Inhabited by Rhizobium Bacteria

Organic N compounds are an important source of N for crops. These compounds, which are part of soil organic matter, must undergo decomposition before the N they contain is plant available. Soil organisms (e.g., insects, small animals, and microorganisms) gradually break down complex N compounds into simpler forms in a process called mineralization. In the process of N mineralization, organic N compounds are converted to NH_4^+ , which can be taken up by plants from the soil. However, NH_4^+ is usually converted quickly to NO_3^- by bacteria in the soil through a process called nitrification.

Ammonium has a positive charge and can be temporarily held by negative charges on soil particles. This type of reaction is called cation exchange and will be discussed further in Chapter 2.2. It is important to know that exchange reactions are critical to the nutrient holding capacity of the soil and the ability of the soil to replenish nutrient concentrations in the soil solution. Adsorbed NH_4^+ makes up a portion of the exchangeable pool of N, but as adsorbed NH_4^+ it is unavailable for plant uptake until released into soil solution.

Nitrogen in the soil can also be temporarily tied up by the microbial biomass, in a process referred to as immobilization. Soil microbes require N to decompose crop residues and can get this either from the residue or soil solution. Residues with higher carbon to nitrogen ratios and more lignin, like cereal straw, decompose more slowly, immobilizing N for longer periods. Eventually decomposition will slow and microbial biomass will release the N, increasing plant available N.

Nitrogen can be lost from the soil in four alternative ways depending on the chemical form. NH_4^+ can be converted to NH_3 gas and lost to the atmosphere through volatilization. Situations that favour NH_3 volatilization include alkaline soil pH, low buffering capacity (directly related to cation exchange capacity) and warm moist (but drying) soil conditions. NO_3^- can be lost from soil through denitrification – the conversion to N_2O or N_2 gas through microbial activity when soil oxygen levels are low. Soils that experience anaerobic (low oxygen) conditions (e.g., water logging) are more subject to denitrification.

Nitrogen is also lost from soil systems through leaching and runoff. Nitrate is one of the most mobile nutrients in the soil system and readily moves with soil water. Leaching losses of NO_3^- in Alberta are limited because of the semi-arid prairie climate, although exceptions do exist. Leaching can occur in years of abnormally high rainfall, under irrigation and on fallowed fields, especially when these conditions occur on coarse-textured soils.

Another mode of N loss from soil is through surface runoff carrying dissolved nutrients or sediments. This can then enter surface water ecosystems, contributing to eutrophication.





Phosphorus

Less than 20% of the total P content of surface soils (0 to 15 cm) is plant-available. Consequently, P is regarded as the second most limiting nutrient in western Canadian soils.

One of the main roles of P in plants is the storage and transfer of energy. The high-energy phosphate bonds in molecules such as adenosine triphosphate (ATP) and adenosine diphosphate (ADP) drive virtually every biochemical reaction in plants (Figure 2.1.5). Phosphorus is also part of important structural components of plants, such as nucleic acids, phospholipids and coenzymes.

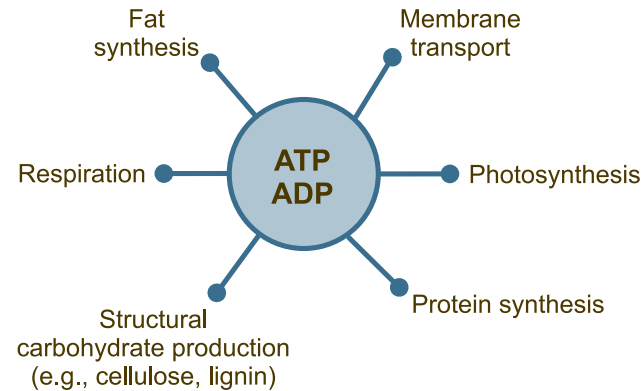


Figure 2.1.5 Summary of Processes and Functions Driven by High-Energy Phosphate Bonds in ATP and ADP

Why Fertilizer P and K Content is Expressed as Percent P_2O_5 and K_2O

Years ago, geochemists described mineral contents as the oxide forms of elements that form upon heating of a substance. When laws governing fertilizer usage were being developed, this standard was adopted (although these are not the actual forms that are in commercial fertilizers).

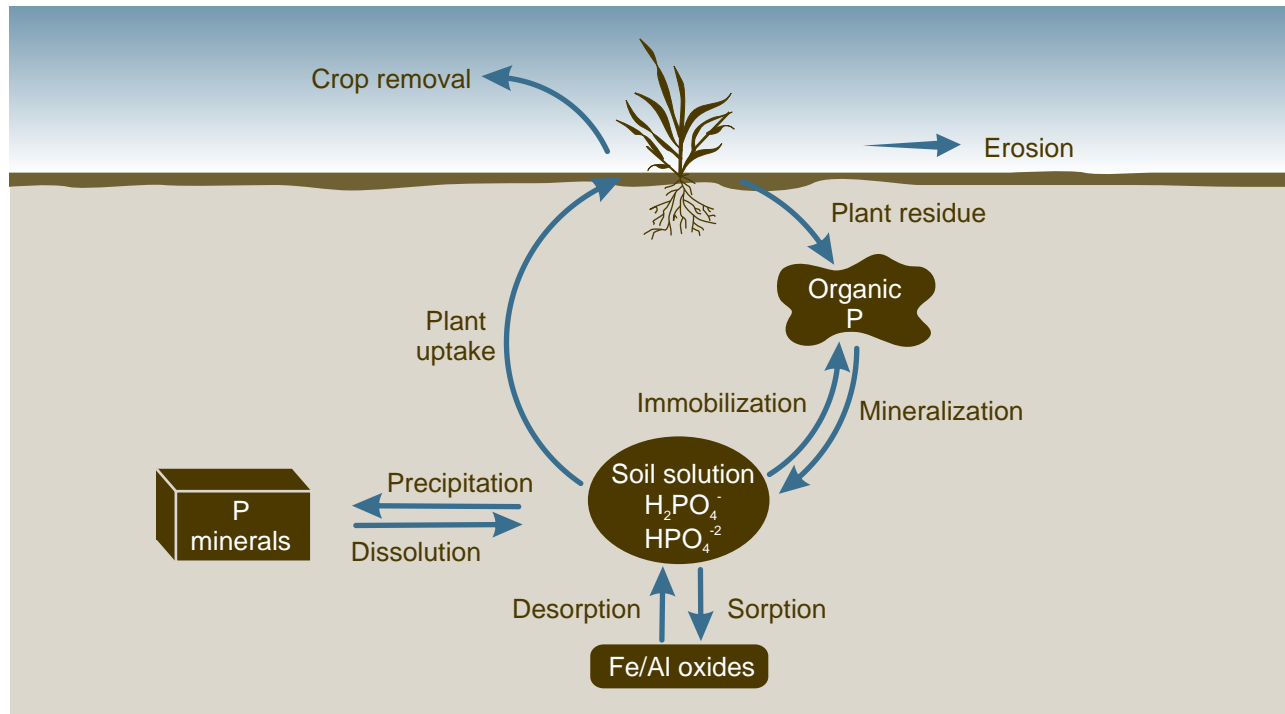
To convert between P_2O_5 and K_2O and their elemental P and K forms, the conversion factors below can be used:

$$\% P_2O_5 \times 0.44 = \% P$$

$$\% P \times 2.29 = \% P_2O_5$$

$$\% K_2O \times 0.83 = \% K$$

$$\% K \times 1.2 = \% K_2O$$



Adapted from Jones and Jacobsen 2002a

Figure 2.1.6 The Agricultural Phosphorus Cycle

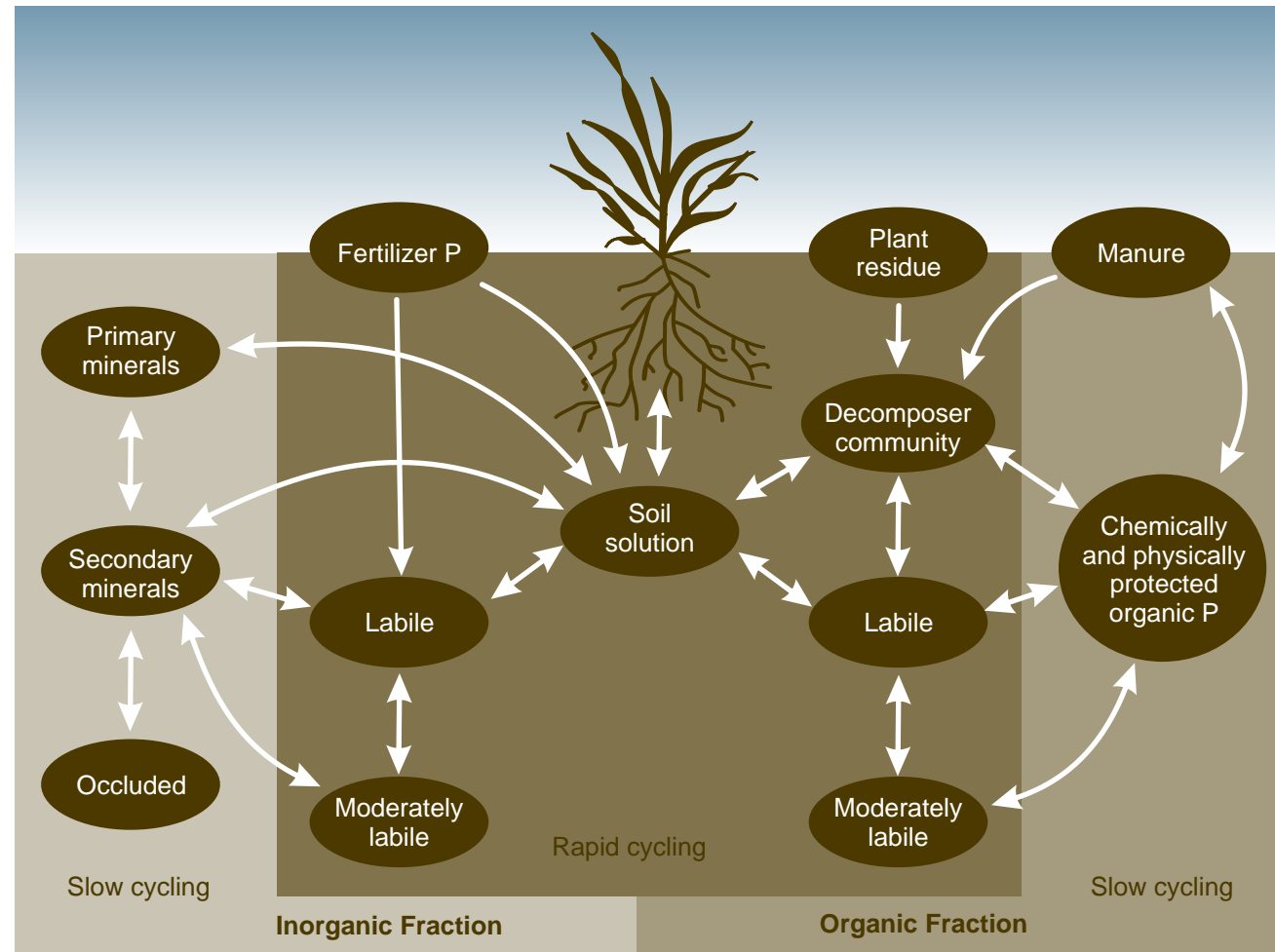
P Cycling in Soils

Phosphorus exists in different pools in the soil. The P cycle, Figure 2.1.6, illustrates these pools and the pathways by which P may be taken up by plants or lost from the soil.

Phosphorus in soil exists in combination with other elements such as O and H. Plant roots absorb P mainly as orthophosphate (H_2PO_4^- or HPO_4^{2-}). The primary orthophosphate form (H_2PO_4^-) dominates in soils below pH 7.2, and the secondary form (HPO_4^{2-}) is prevalent in soils above pH 7.2. Plants are able to absorb the primary form more rapidly than the secondary form.

In soils, P occurs in three pools: soil solution, mineral and organic. Plants can only use P from the soil solution pool. The mineral and organic pools have stable components that change little with time (e.g., humus) and labile portions that gradually release P to the soil solution.

Phosphorus does not always “flow” toward the soil solution pool from the labile pool. It can move from the soil solution to the labile pools or even directly into stable soil components. Similarly, labile P can be tied up in non-labile organic and mineral compounds (Figure 2.1.7).



Created by Len Kryzanowski

Figure 2.1.7 Conceptual Relationship and Interactions Between Soil Phosphorus Pools

The amount of P in soil solution at any given time is usually low. Consequently, to meet crop requirements the P in soil solution is constantly replenished from the labile pools. The rate at which labile P is converted to soluble P is more important than the total P content of the soil. Fertile soils can rapidly replenish P in soil solution, ensuring good crop growth.

The organic P pool comes from microbial, plant and animal residues deposited on or in the soil. Most of the organic pool is found in the top layers of soil and nearly half of this is in the form of phytic acid (Figure 2.1.8). Each molecule of phytic acid has the potential to release six molecules of orthophosphate (H_2PO_4^- or HPO_4^{2-}) to the soil solution.

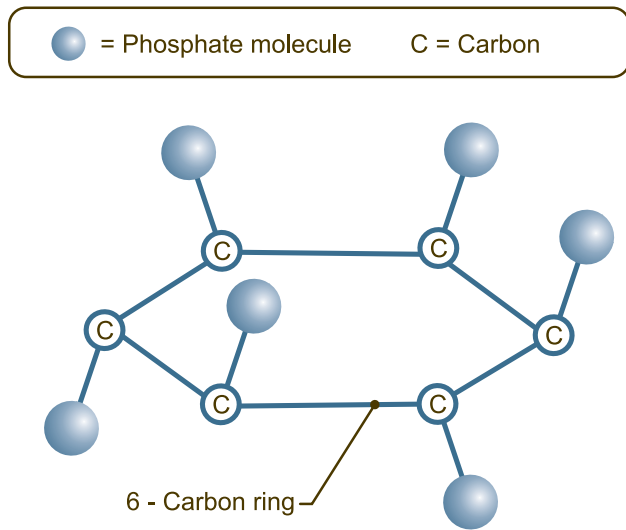


Figure 2.1.8 Phytic Acid

Phosphorus availability for plant uptake can be affected in a number of ways. For example, dissolved P in soil solution will react with soil constituents to form less soluble compounds. Sorption, or the retention of P on soil particles, makes P unavailable to plants for uptake. Sorption is thought to be the major mechanism responsible for decreases in soluble P. Desorption refers to P leaving soil particle surfaces and going back into solution.

Soil pH can also influence P availability. At high pH values (alkaline soils) Ca and Mg phosphates develop and at low pH values (acidic soils) aluminum and iron phosphates develop. These low-solubility products remove P from the soil solution since they are hundreds to millions of times less soluble than P fertilizers.

Water or wind erosion of topsoil is a major route of P loss. Soluble P can also be lost in surface runoff or through deep leaching under some circumstances. For example, when the P fixation capacity of the soil is exceeded and precipitation is greater than soil water

holding capacity, the result is a downward movement or surface runoff of orthophosphate and soluble organic P. Unlike N, there is no mechanism for gaseous P loss from soils.

Potassium

A small percentage of the total arable land on the prairies is K deficient. The highest proportion of these soils is in Alberta. Typically, the most severe deficiencies exist on the coarse textured (sandier) soils located within the Black, Dark Gray and Gray Luvisolic soil zones. The highest levels of plant-available K exist in the Brown and Dark Brown soil zones.

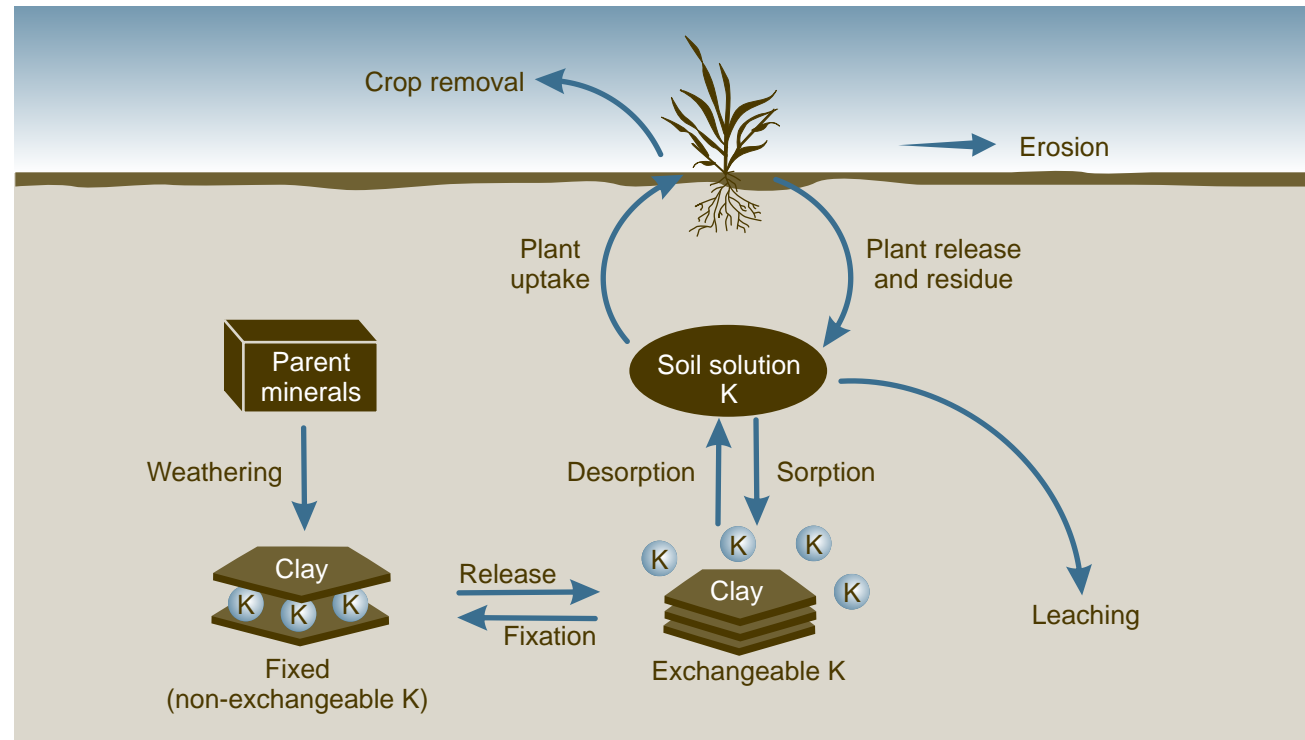
Unlike most essential nutrients, K is not an integral part of any plant structural component. However, it does play a role in many processes vital to plant growth. Among the functions of K in plants are enzyme activation, transport of sugars, plant water balance and regulation of stomata.

Potassium “activates” many different enzymes involved in plant growth. For example, photosynthesis as well as starch and protein synthesis are key pathways that rely on K-influenced enzyme systems.

The transport of sugars produced during photosynthesis also depends on K. Inadequate K can result in a build-up of photosynthetic products in the leaves, which can adversely affect the rate of photosynthesis and plant growth.

Potassium, along with sugars and other inorganic ions, influences the water balance within plants and helps to maintain an inward concentration gradient between roots and the soil solution. Potassium also influences the transpiration rate by controlling the size of the stomatal openings in response to environmental and internal plant conditions.





Adapted from Jones and Jacobsen 2002b

Figure 2.1.9 The Agricultural Potassium Cycle

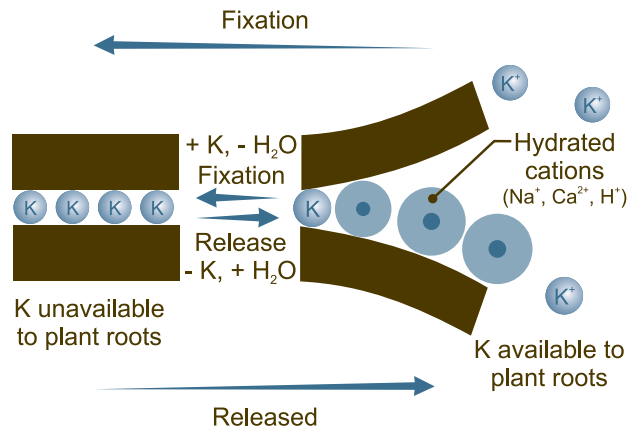
K Cycling in Soils

The main pathways for K in the soil are shown in Figure 2.1.9. Potassium, much like P, exists in pools with differing abilities to replenish crop available K. In soil, K occurs in four pools: soil solution, exchangeable, fixed and parent minerals.

The soil solution and exchangeable pools of K are in equilibrium with each other. Plants absorb K exclusively as the K^+ ion, which is the only form that exists in soil solution. Exchangeable K refers to ions adsorbed to exchange sites on soil particles. It accounts for 1 to 2% of soil K. When K is removed from soil solution by

plant uptake it is replenished by K released from the exchangeable pool. Likewise, if the concentration of K in soil solution exceeds that in the exchangeable pool, K will adsorb to the exchange sites. This equilibrium ensures a steady pool of available K.

Potassium fixation is the entrapment of the K^+ ion in the structure of clay minerals. Fixation accounts for 1 to 2% of soil K (Figure 2.1.10). The fixed pool is not able to release K at rates sufficient to meet the demands of growing crops. However, a portion of this pool will become available as the exchangeable and soil solution K supplies are depleted.



Adapted from Jones and Jacobsen 2002b

Figure 2.1.10 Release and Fixation of Potassium from Micas and Layered Clays

Greater than 90 % of the total K in prairie soils exists as part of the parent minerals: mica and feldspar. Release of K from these parent minerals occurs at a rate far too slow to meet the needs of growing plants.

There are two ways K can be lost from the system: leaching and erosion. Potassium leaching can occur on coarse textured soils that receive above average precipitation. In Alberta, however, K leaching losses are usually low because of the high cation exchange capacity of most soils and the dry climate. Erosion is a more important route of K loss.

Sulphur

Soil S levels can vary considerably within regions and even within fields. The switch to longer or continuous cropping rotations, particularly those that include canola (a high S user), has increased the occurrence of S deficiencies in Alberta.

Sulphur is essential for the conversion of NO_3^- to NH_4^+ in plants, and the synthesis of plant proteins. Sulphur is an integral part of plant processes, including N fixation in legumes, synthesis and functioning of chlorophyll, and oil formation in canola.

Sulphur requirements of crops remain high from germination through to grain filling because it is required to support vegetative growth and grain formation.

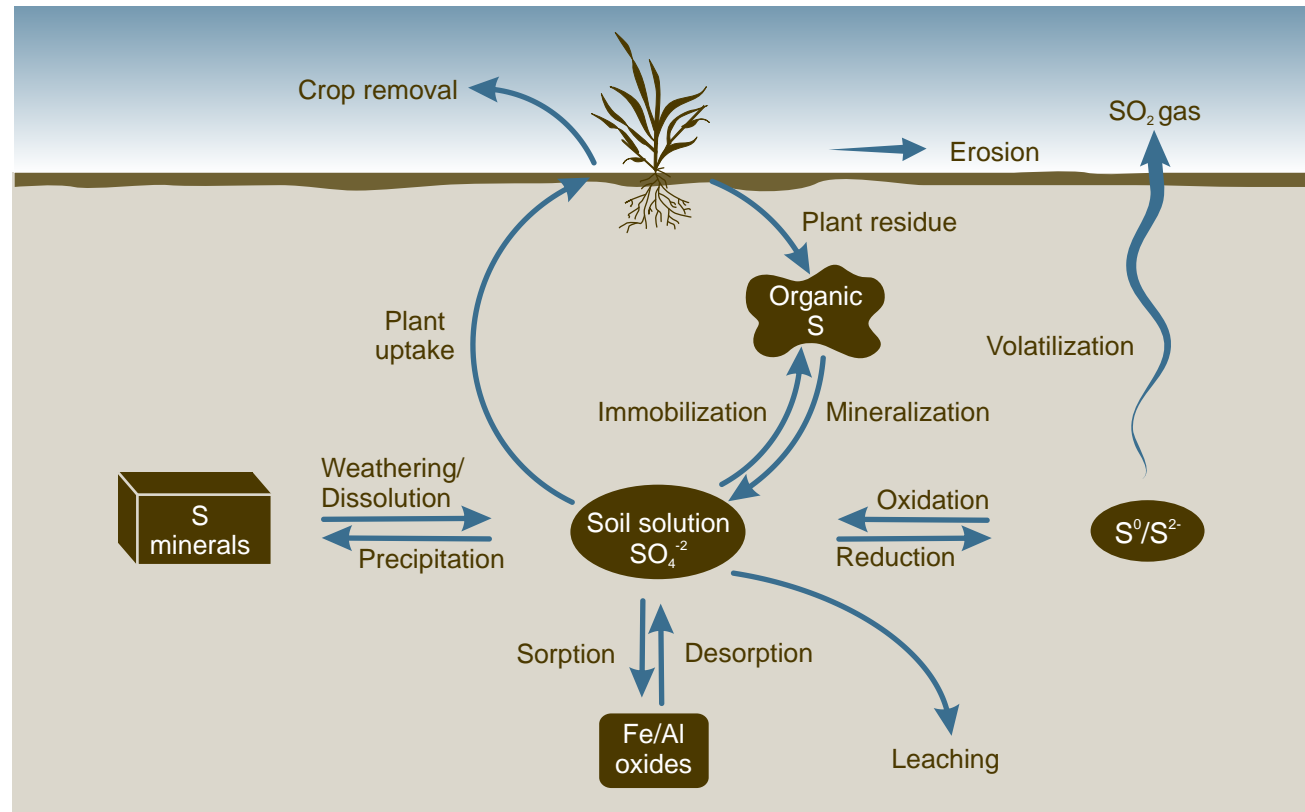
sidebar

In Alberta, salinity problems are often caused by sulphate salt accumulation (gypsum and epsom salts).



sidebar

N and S are closely related in soils worldwide with the ratio of N to S typically between 6:1 and 8:1.



Adapted from Korb and Jacobsen 2002

Figure 2.1.11 The Agricultural Sulphur Cycle

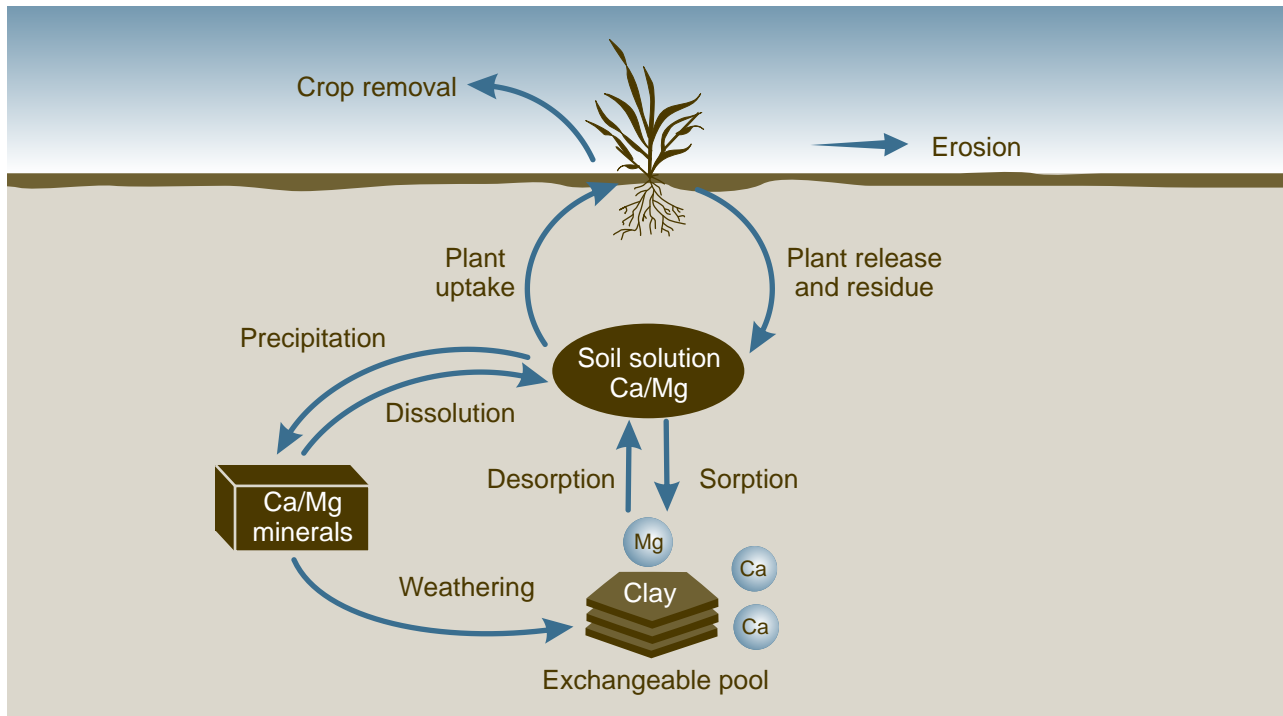
S Cycling in Soils

Figure 2.1.11 represents the basic processes involving S in soils. Only 1 to 3% of the soil total S is in the plant-available form (SO_4^{2-}). The bulk of soil S (200 to 1100 kg/ha) is in soil organic matter. Mineralization of organic S compounds is an important source of S for growing plants.

The weathering of S-containing minerals such as gypsum (CaSO_4) can be a source of crop available S particularly in dry regions where the amount of precipitation is too low to leach it from the soil profile. Other primary and

secondary minerals will release elemental S (S^0/S^{2-}), which is converted to SO_4^{2-} when exposed to moisture, oxygen and microbial processes.

Crop available S (sulphate-sulphur) can become temporarily lost from soil solution through precipitation with magnesium or calcium (typical for Alberta) or adsorption to aluminum or iron oxides on clay particles. Sulphate-sulphur is soluble and mobile in soils and will move with groundwater. Leaching losses of S are possible, especially in coarse textured soils, but with average rainfall this type of loss will be low for most



Adapted from Korb and Jacobsen 2002

Figure 2.1.12 Calcium and Magnesium Cycling

of Alberta. Volatile S losses can sometimes occur, but for most agricultural soils these losses are thought to be insignificant.

Calcium and Magnesium

Ca and Mg are essential for plant and animal growth. Most soils in Alberta have adequate supplies of Ca and Mg because the parent materials from which Alberta soils were developed are rich in these nutrients.

Calcium is a vital structural component of cell walls and influences membrane permeability. It also plays a role in N metabolism as it enhances plant uptake of NO_3^- . Other important functions of Ca include the movement

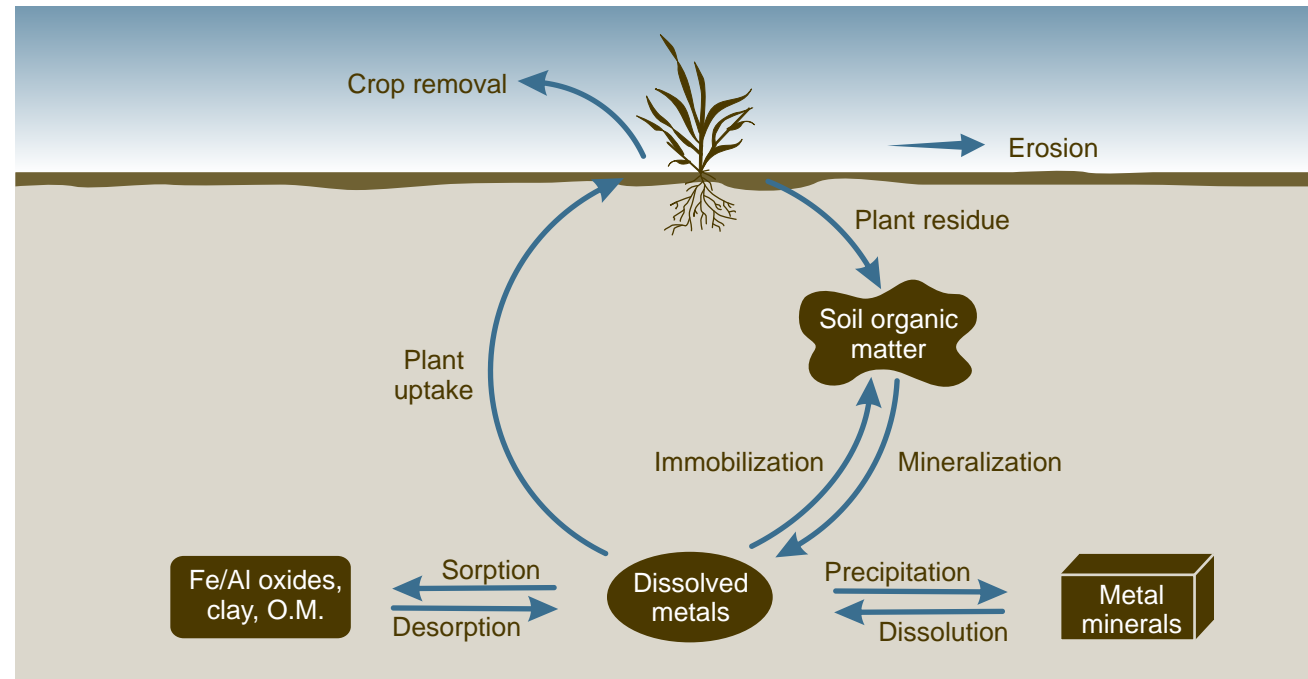
of carbohydrates and other nutrients within the plant and cell elongation and division.

Magnesium is a critical component of chlorophyll, and therefore essential for photosynthesis in the plant. It acts as a catalyst and co-factor for many important enzyme systems within plants and also appears to play a role in the production of oils and fats.

Ca and Mg Cycling in Soils

Figure 2.1.12 represents the basic processes involving Ca and Mg in soils. Plants absorb Ca and Mg as positively charged ions from the soil solution and they are replenished from the exchangeable pool. Weathering of Ca and Mg minerals with time results in crop available





Adapted from Jones and Jacobsen 2003b

Figure 2.1.13 General Pattern of Micronutrient Cycles in Soils

Ca and Mg entering the exchangeable pool. Generally, there is less Mg in the soil solution than Ca. Even though plants require Mg in smaller amounts it is more likely to be deficient than Ca. This is partly because Mg binding to cation exchange sites is weaker than competing cations such as K^+ , Ca^{2+} , and NH_4^+ . Consequently, plants growing on soils with excesses of any of these cations are more likely to show symptoms of Mg deficiency. Erosion is the main route of Mg and Ca loss from the soil.

Micronutrients

Although micronutrients (Cl, Fe, Mn, Zn, B, Cu, and Mo) are required in “micro” quantities, they are significant in terms of their contribution to plant growth.

Soil characteristics can influence micronutrient availability. Clay soils are less likely to be deficient in micronutrients than sandy soils. Soils with low (i.e., less than 1 to 2%) or very high organic matter content (i.e., greater than 30%) often have low levels of micronutrient availability. As soil pH increases, availability of micronutrients tends to decrease. The exception is molybdenum whose availability increases with soil pH. Most soil micronutrient cycles follow much the same general pattern as in Figure 2.1.13.

Inorganic micronutrients occur naturally in mineral soils. As parent minerals break down during soil formation, micronutrients slowly become available to plants. Organic matter is also an important source of micronutrients. Microbial decomposition helps to release micronutrients into plant-available forms.

Table 2.1.3 summarizes key characteristics of each of the essential micronutrients.

Table 2.1.3 Summary of Plant Micronutrient Characteristics

Micronutrient	Form Taken up by Plant	Function in Plants	Comments
Chlorine (Cl)	Cl ⁻ ion	Associated with the suppression of leaf and root diseases.	Added to soil when potash (KCl) is applied.
Iron (Fe)	Fe ²⁺ /Fe ³⁺ ion	A vital constituent of chlorophyll. Important for oxygen transfer within the plant system. Important for the formation/activity of respiratory enzymes.	Deficiency not observed in Alberta field crops, but common in trees, shrubs and ornamentals in southern Alberta.
Manganese (Mn)	Mn ²⁺ and as a component of organic complexes	Seems to play a role in the uptake of other nutrients and the activation of a number of enzyme systems.	Mn toxicity more common than deficiency.
Zinc (Zn)	Zn ²⁺ and as a component of organic complexes	Plays a role in the formation of growth promoting compounds, carbohydrate transformations, regulation of sugar consumption, and is a constituent of several enzyme systems.	Deficiencies are most likely on calcareous, light textured, high pH soils that are high in P content.
Boron (B)	Primarily boric acid (H ₃ BO ₃)	Maintains plant cell wall integrity.	Deficiencies suspected in some canola crops grown in Alberta.
Copper (Cu)	Cu ²⁺ and as a component of organic complexes	Essential for production of Fe-containing compounds. Facilitates synthesis of chlorophyll. Influences several metabolic reactions.	Coarse-textured black soils are often associated with deficiency.
Molybdenum (Mo)	MoO ₄ ²⁻	Enhance plant uptake of N, K, and Ca required by legumes for fixation of atmospheric N by nodular bacteria. Assists in making Fe plant available.	Minimal evidence of confirmed Mo deficiencies in western Canadian field crops.



→ summary

- There are sixteen mineral and non-mineral nutrients essential for plant growth. The non-mineral nutrients—carbon, hydrogen and oxygen—are taken up from air and water. The mineral nutrients are taken up from the soil and are classified as macro- or micronutrients: nitrogen, phosphorus, potassium, sulphur, calcium, magnesium (macronutrients), chlorine, iron, manganese, zinc, boron, copper and molybdenum (micronutrients).
- The law of the minimum states that crop productivity will be limited by the nutrient that is in shortest supply relative to its requirement.
- Plants absorb ions from the soil through root interception, mass flow, and diffusion. Of these processes, mass flow is responsible for the majority of nutrient uptake.
- Nutrients exist in several pools. The crop available and exchangeable pools are most critical for meeting short-term crop needs.
- In most nutrient cycles the basic processes occurring are mineralization, immobilization, sorption, precipitation, weathering and losses.