



Effects of Manure and Fertilizer on Soil Fertility and Soil Quality

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Learning Objectives

After completing this review, you should be able to explain and/or describe:

1. The overall behaviour of N, P, K, S and micronutrients in agricultural soils
2. How soil properties and environmental conditions affect nutrient availability and movement in the soil
3. How the environment and management practices affect the utilization of manure nutrients by crops in terms of agronomic benefits and environmental risks
4. Sources and loadings of trace elements in manures and potential long term implications
5. The effect of manure on soil properties such as salinity, sodicity, pH, organic matter content, and microbial and enzyme activity

Overview

The Effects of Manure and Fertilizer on Soil Fertility and Soil Quality focuses primarily on the behaviour of nitrogen (N) and phosphorus (P) in soil because these two nutrients are the main nutrients that limit crop yields in Manitoba and they are also the nutrients of particular concern for environmental quality. In addition, potassium (K), sulphur (S), macronutrients and other trace elements, salts and sodium, soil pH and organic matter and microbial activity are covered.



Nutrients in Crop Production

Nutrients are essential for crop production. All plants require nutrients to grow and a significant portion of these nutrients are removed and exported when a crop is harvested. Sustainable crop production requires the nutrients that are removed to be replaced with synthetic fertilizers, manures, municipal wastes or, in a few cases, the atmosphere.

Generally, plant nutrients are divided into two groups, according to the amount of each nutrient required for plant growth: **macronutrients** which are required in large amounts (generally measured in several or many pounds per acre) and **micronutrients** which are required in relatively small amounts (generally less than 1 lb per acre). This definition, based on requirement, does not always match up with the quantities actually found in soils or plants. For example, iron (Fe) is the most abundant mineral nutrient present in soil and chlorine (Cl) is often found in large quantities in plant tissue. However, the plant's true nutritional requirements for Fe and Cl are very small, so both of these elements are regarded as micronutrients.

Macronutrients that are generally derived from carbon dioxide (CO₂) in the atmosphere and water (H₂O) from soil, and are therefore not generally regarded as limiting for crop production, include:

- C** Carbon
- H** Hydrogen
- O** Oxygen

Macronutrients that are derived mainly from soil, and are therefore often referred to as "mineral" nutrients that might be limiting for crop production, include:

- N** Nitrogen (some N is also derived from the atmosphere)
- P** Phosphorus
- K** Potassium
- S** Sulphur (some S is also derived from the atmosphere)
- Ca** Calcium
- Mg** Magnesium

Micronutrients essential for plant growth that are derived mainly from soil include:

- Mo** Molybdenum
- B** Boron
- Cl** Chlorine (some Cl is also derived from the atmosphere)
- Cu** Copper
- Zn** Zinc
- Mn** Manganese
- Fe** Iron

There are also several additional elements that may be regarded as essential nutrients but which have little, if any, practical importance for crop nutrient management in the Canadian Prairies. These include nickel (Ni), sodium (Na), silicon (Si), vanadium (V), fluorine (F), iodine (I), strontium (Sr), barium (Ba), aluminium (Al), and cobalt (Co) which are sufficient in Manitoba soils for Manitoba crops.

Elements that are not essential for plant growth but are essential for animal nutrition, such as selenium (Se), are often added to livestock feeds in Manitoba.

Regardless of whether the nutrient is required in large or small quantities, if the plant does not have a sufficient supply, the growth of the plant will be limited by that nutrient. This principle is commonly referred to as Liebig's Law, which states that the level of plant growth can be no greater than that allowed by the most limiting of all essential plant growth factors (Figure 1).

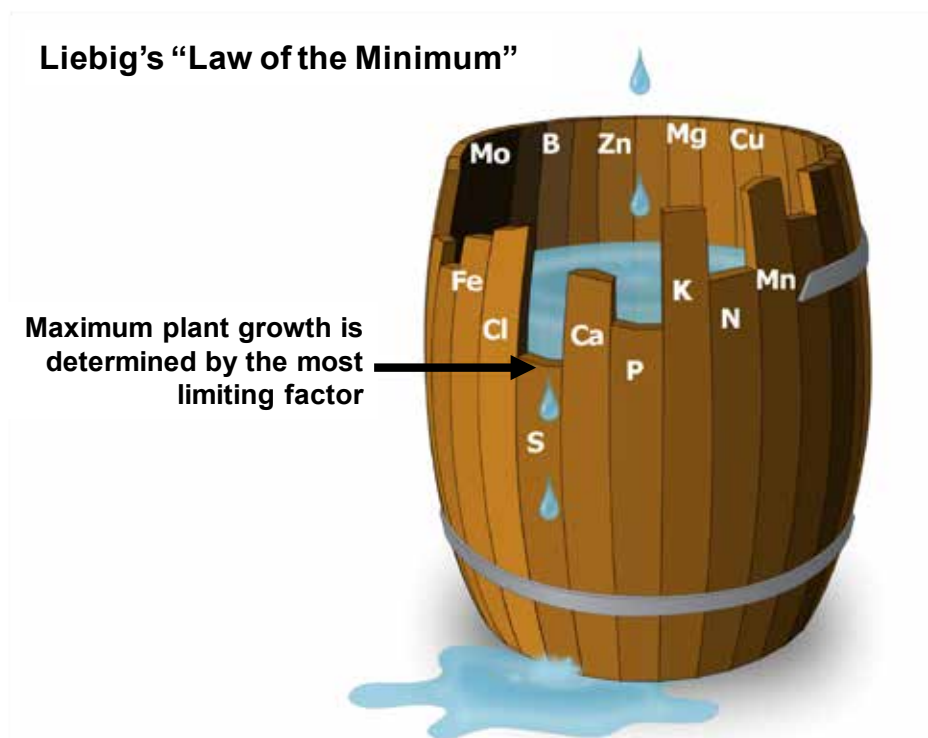


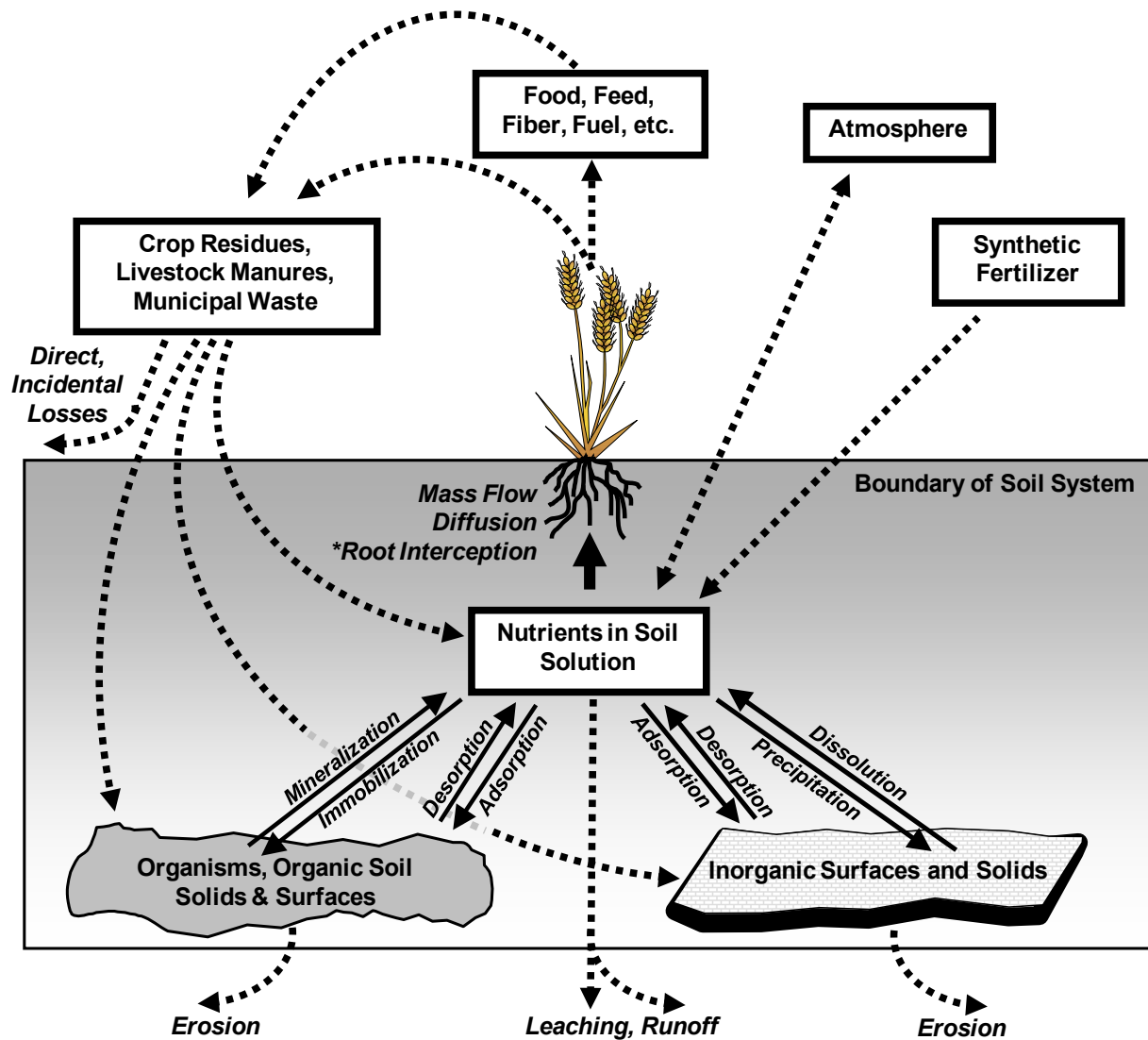
Figure 1 | Liebig's "Law of the Minimum" for crop growth can be illustrated by a barrel. In this case, sulphur (S) is the most limiting nutrient (*figure adapted from Saskatchewan Ministry of Agriculture*)

If nutrients are supplied to crops at rates below crop requirements, yields will be reduced and the long term productivity of the land will decline. However, if nutrients are applied in excess of crop requirements and removal, they increase the risk of agronomic problems such as crop lodging (in the case of N), nutrient imbalances or toxicities and environmental problems such as nitrate leaching to groundwater, P runoff to surface water and release of greenhouse gases to the atmosphere.

The main challenge for managing nutrients in crop production systems is to provide sufficient nutrients for optimum plant growth without causing unacceptable risk to the environment. In order to meet this challenge successfully, nutrient management planners must understand the processes that control nutrient availability to crops and the environment and employ beneficial management practices accordingly.

The Nutrient Cycle

From an agricultural perspective, the nutrient cycle can be thought of in terms of gains, removals, internal transformations and losses (Figure 2). Within the soil portion of the nutrient cycle, nutrient fate is controlled by interactions between nutrients in soil solution and plant roots, soil solids and soil surfaces (Figures 2 and 3). These complex interactions result in a relatively small proportion of the soil's nutrients (often only 1-2 per cent or less) being immediately available to plants.



*Root interception of nutrients directly from soil surfaces and solids is generally negligible for most nutrients

Figure 2 | The nutrient cycle. Dashed lines represent nutrient gains or losses in the soil system; solid lines represent internal transformations within the soil system.

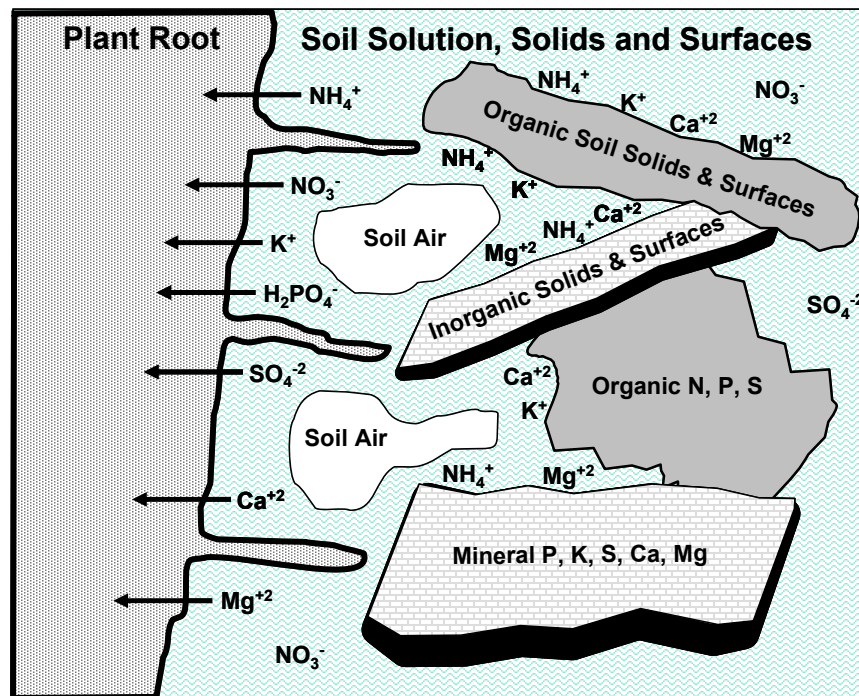


Figure 3 | Soil portion of the nutrient cycle. Nutrient ions move from soil solution into plant roots and are replenished from reserves in soil solids and on soil surfaces.

Nutrients in soil solution – At the heart of the nutrient cycle (Figure 2) are the nutrients in soil solution which are in the form of free ions (ex: cations such as NH_4^+ and anions such as NO_3^-) or in other soluble forms, such as chelates.

Chelates – Some nutrients bond with soluble organic compounds in soil to form ring complexes called chelates. Chelation increases the solubility of nutrients, preventing the formation of insoluble precipitates and decreases the toxicity of some micronutrients. Although chelated nutrients may not be immediately available, they are mobile and can quickly convert to plant available forms near the root surface.

Gains of Nutrients to Soil

Atmospheric deposition – Atmospheric deposition refers to nutrients that are deposited on land or water from the air.

Biological fixation – Biological nitrogen (N) fixation is the conversion of biologically unavailable atmospheric N to plant available ammonium (NH_4) by rhizobial bacteria.

Application of synthetic fertilizers – Synthetic fertilizers are applied to agricultural soils to increase crop yields and quality in Manitoba. Synthetic fertilizers can be formulated to provide more than one nutrient. A variety of fertilizers are available with nutrients in varying proportions. Fertilizers are most commonly granular but can also be in a liquid or gaseous state.

Plant residues – Crop residues contain significant quantities of nutrients that are returned to the soil if the residues are not removed from the field at harvest.

Livestock manures – Manure is a by-product of livestock production and an excellent source of nutrients for crop production.

Municipal biosolids, industrial waste and other amendments – Municipal and industrial wastes contain a variety of nutrients that enter the nutrient cycle when applied to soil.

Crop Uptake and Removal of Nutrients from Soil

Crop uptake of nutrients from soil – Almost all of the nutrients used by plants are taken up in soluble, inorganic free ion forms from the soil solution. In these forms nutrients are able to pass from the soil solution through the root surface. These ions may be positively charged cations or negatively charged anions. The quantity of nutrient taken up is a function of crop species and growth.

Cations are positively charged ions such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}). **Anions** are negatively charged ions such as nitrate (NO_3^-), phosphates (HPO_4^{2-} and H_2PO_4^-) and sulphate (SO_4^{2-}).

Crop removal of nutrients at harvest – Nutrients are removed from the soil in harvested materials that leave the field. The quantity of nutrient removed is less than total uptake and varies significantly with crop species, yield, where the nutrient is stored in the plant and the portion of the crop that is removed.

For example, approximately 156 lb of N and 64 lb of P_2O_5 are removed from the soil when a high yielding (5 dry ton/acre) silage corn crop is harvested. However, if only the grain is harvested from a high-yielding corn crop (100 bu/ac), only about 97 lb of N and 44 lb of P_2O_5 will be removed.



Movement of Nutrients to Plant Roots

Nutrients move from the soil to the plant root by three processes (Figure 2): mass flow, diffusion and root interception.

Mass flow occurs as dissolved nutrients in the soil solution flow towards roots as the plant takes up water. The amount of nutrient taken up by this process is determined by the amount of available water in the soil, the concentration of nutrient in soil solution and the volume of water consumed by the plant (ex: mass flow is less in dry soil and during cool weather). This process is most significant for nutrients that are relatively soluble in water such as $\text{NO}_3\text{-N}$ and $\text{SO}_4\text{-S}$.

Diffusion is driven by micro-scale differences in the soil solution's nutrient concentrations and a variety of environmental factors that influence nutrient movement. This process is important for nutrients such as P and K that are strongly retained by soil and therefore are present at very low concentrations in soil solution. During diffusion, random movement of ions in soil solution slowly and steadily moves nutrients from areas of relatively high concentration (on or near soil particles) to areas of relatively low concentration (on or near the root). Plants take advantage of this process by depleting the concentration of nutrients near the root surface to levels that are below that of the bulk soil solution. Given the micro-scale nature of this process, diffusion distances are very short (much less than 1 mm) and high densities of roots are required for significant uptake.

Factors that affect the rate of diffusion towards the root surface include:

- **Temperature** – Warm temperatures increase random ionic movement and the rate of diffusion in the soil solution.
- **Soil moisture** – Moist soils increase the rate of diffusion because soil water is the pathway for ion movement and the thickness of water films determines the ease of nutrient movement to the root.
- **Nutrient concentration** – Greater concentrations of nutrients in soil increase the rate of diffusion.
- **Soil texture** – Coarser soils (ex: sands and loams) have higher rates of diffusion since the pores are larger and pathways are not as convoluted as for fine textured soils (ex: clays).
- **Nutrient retention** – Diffusion is greater in soils with low nutrient retention (ex: less adsorption and precipitation).

Root interception is the process whereby nutrients are taken up as a result of direct contact between roots and soil particles. This type of uptake is not very efficient because roots have direct contact with less than 1 per cent of soil volume and less than 5 per cent of available nutrients. Therefore, this process accounts for negligible uptake for most nutrients in most situations.

Internal Transformations of Nutrients in Soil

Soil organic matter and inorganic minerals are the foundation of nutrient availability because they release and retain nutrients through internal transformations in soil (Figure 2). Nutrients are released and retained by six processes: mineralization, immobilization, precipitation, dissolution, adsorption and desorption.

Mineralization – Mineralization is the microbial process of converting organic nutrients into inorganic forms making them available to plants. Mineralization occurs when soil microorganisms feed on organic matter that contains concentrations of nutrients that are greater than their own immediate requirements. Since the organic matter contains more nutrients than the organisms require, they release the unneeded nutrients to the soil solution. Organic materials with a low carbon (C) to nutrient ratio are likely to cause mineralization during their decomposition.

Immobilization – Immobilization is the opposite of mineralization and occurs when soil microorganisms incorporate inorganic, plant available forms of nutrients into their body tissues making the nutrients unavailable to plants. Immobilization occurs when soil microorganisms feed on organic materials that contain concentrations of nutrients that are lower than their own immediate requirements. Since the organic materials do not contain sufficient nutrients, the organisms consume nutrients in the soil solution to make up the shortfall. Therefore, organic materials with a high ratio of C to nutrient are likely to cause immobilization during their decomposition. However, immobilization does not render these nutrients permanently unavailable. In fact, a large proportion of the nutrients that are immobilized are eventually mineralized as the process of decomposition proceeds.

Mineralization-immobilization turnover – Mineralization and immobilization occur simultaneously in soil. However, the net balance between the two varies with environmental conditions and the characteristics of the organic material available for decomposition. Both mineralization and immobilization are accelerated by conditions favourable for microbial growth such as moist soil, warm temperatures, good aeration, easily degradable organic substrate material (ex: low C:N ratio), physical mixing of soil via tillage and alkaline soil pH.

Precipitation – Precipitation occurs when water soluble forms of nutrients consolidate and separate from the soil solution to form a solid, inorganic mineral. Precipitation decreases the supply of nutrients that is immediately available to plants.

Dissolution – Dissolution is the opposite of precipitation and occurs when inorganic minerals release water soluble nutrients from their bulk solid reserves into solution where they become available for plant uptake. Dissolution can occur quickly, for example, when highly water soluble forms of granular fertilizer such as urea dissolve in moist soil. Dissolution can also occur slowly, such as when soil clay particles are weathered by natural physical and chemical processes, releasing potassium (K) into soil solution.

Adsorption – Adsorption is the process by which nutrients, in their ionic forms, become attached to the charged surfaces of soil organic matter and some inorganic minerals. There are two types of adsorption: exchangeable and non-exchangeable.

Exchangeable adsorption of cations – Soil organic matter and clay particles have negatively charged surfaces which attract cations. In most of these cases, the cations are adsorbed weakly by electrostatic attraction and are, therefore, regarded as “exchangeable” with other cations. Exchangeable adsorption is a beneficial process for soil fertility because the nutrients remain available to plants but are protected from losses due to leaching, runoff and volatilization.

Non-exchangeable adsorption of cations – Ammonium (NH_4^+) and potassium (K^+) ions are small relative to other cations and sometimes become trapped in small pockets on some types of soil surfaces or in between layers of some types of clay-sized minerals (ex: vermiculite and illite). This type of adsorption, also called NH_4 and K “fixation”, is strong and is difficult to reverse, so these ions are not easily exchanged with other ions and are no longer immediately available to plants. In addition, soil organic matter and oxides can strongly adsorb cations in a non-exchangeable manner, substantially reducing the availability of these nutrients to plants.

Adsorption of anions – Manitoba soils are generally negatively charged and do not adsorb anions such as nitrate (NO_3^-) and sulphate (SO_4^{2-}). However, some anions such as phosphate (HPO_4^{2-} , H_2PO_4^-) are adsorbed in a non-exchangeable, relatively strong manner regardless of the soil’s charge.

Desorption – Desorption is the opposite of adsorption and occurs when adsorbed nutrients are released from the surface of soil organic matter and inorganic minerals.

The balance between adsorption and desorption depends on the nature and strength of attraction between the soil surface and the nutrient.

Soil characteristics that play a large role in the internal transformations of nutrients include:

- **Cation exchange capacity (CEC)** – The total number of exchangeable cations that a soil can hold depends on the number of exchange sites and is called cation exchange capacity (CEC). The CEC of a soil is primarily dependent on the amount and type of clay, organic matter, as well as the amount of Fe, Al and Mn oxides. Each of these soil components has different retention properties, but generally the higher the CEC the greater the capacity of the soil surfaces to adsorb cations without potential deleterious effects on plants and/or soil biological functions. Soil organic matter and clay particles have large surface areas and have a large number of exchange sites. Most Prairie soils have reasonably high CEC due to sufficient concentrations of clay and organic matter, combined with neutral to alkaline pH (see **Soil pH** below). Sand particles have a much smaller surface area and fewer exchange sites; therefore, sandy soils have a lower CEC. These soils are more vulnerable to leaching of nutrient cations.

- **Soil organic matter** – In addition to its role in retaining cations in exchangeable forms, soil organic matter also has the capacity to adsorb some cations very strongly in non-exchangeable forms that are relatively stable and unavailable for uptake by plants or movement with water. Micronutrients such as Cu and Mn are held especially strongly by soil organic matter and their low availability in high organic matter soils (ex: peat soils) may cause Cu and Mn deficiencies in crops. Conversely, Zn is not held strongly by organic matter, so availability of Zn increases in the presence of organic matter.

Organic matter enhances the formation of chelates and other soluble organic complexes, helping to dissolve and mobilize some micronutrients and trace metals. These soluble organic complexes allow some micronutrients to move more readily to plant roots for uptake by crops. However, these soluble complexes also enable these micronutrients to run off more easily into surface water or leach more easily into ground water, especially in sandy soils.

- **Soil pH** – Soil pH is a measure of soil acidity ($\text{pH} < 7$) or alkalinity ($\text{pH} > 7$). Acidic (low pH) soils have a high concentration of hydrogen ions (H^+) in soil solution while alkaline or basic (high pH) soils have a low concentration of hydrogen ions in soil solution. Since hydrogen ions affect the charge on soil surfaces and the forms of nutrients in solution, pH plays an important role in determining the amount and strength of adsorption of nutrients to soil surfaces. Hydrogen ions also participate in many precipitation and dissolution reactions, therefore, pH also plays an important role in the solubility of nutrients in soil. Soil pHs that are slightly acidic to neutral (pH 6.0-7.5) are often the best for overall availability of nutrients (Figure 4).

- **Aeration** – Aeration directly affects the availability of N, S, Mn, and Fe and indirectly affects the availability of many other nutrients. In a well-aerated soil, the supply of oxygen is sufficient to maintain normal, aerobic respiration by soil microbes. However, if soil is poorly aerated due to excess water or compaction, some of the soil microbes will switch to anaerobic respiration and use alternatives to oxygen (O_2) to breathe. Some of these alternatives to O_2 include plant available nitrate (NO_3^-) and sulphate (SO_4^{2-}) that are converted to gases and lost to the atmosphere. In addition, during anaerobic respiration, some microbes will convert unavailable forms of Fe and Mn oxides into soluble, plant available forms.

Furthermore, anaerobic respiration tends to lower the pH of alkaline soils and raise the pH of acid soils, which then affects the solubility and adsorption of nutrients described in the previous paragraph.

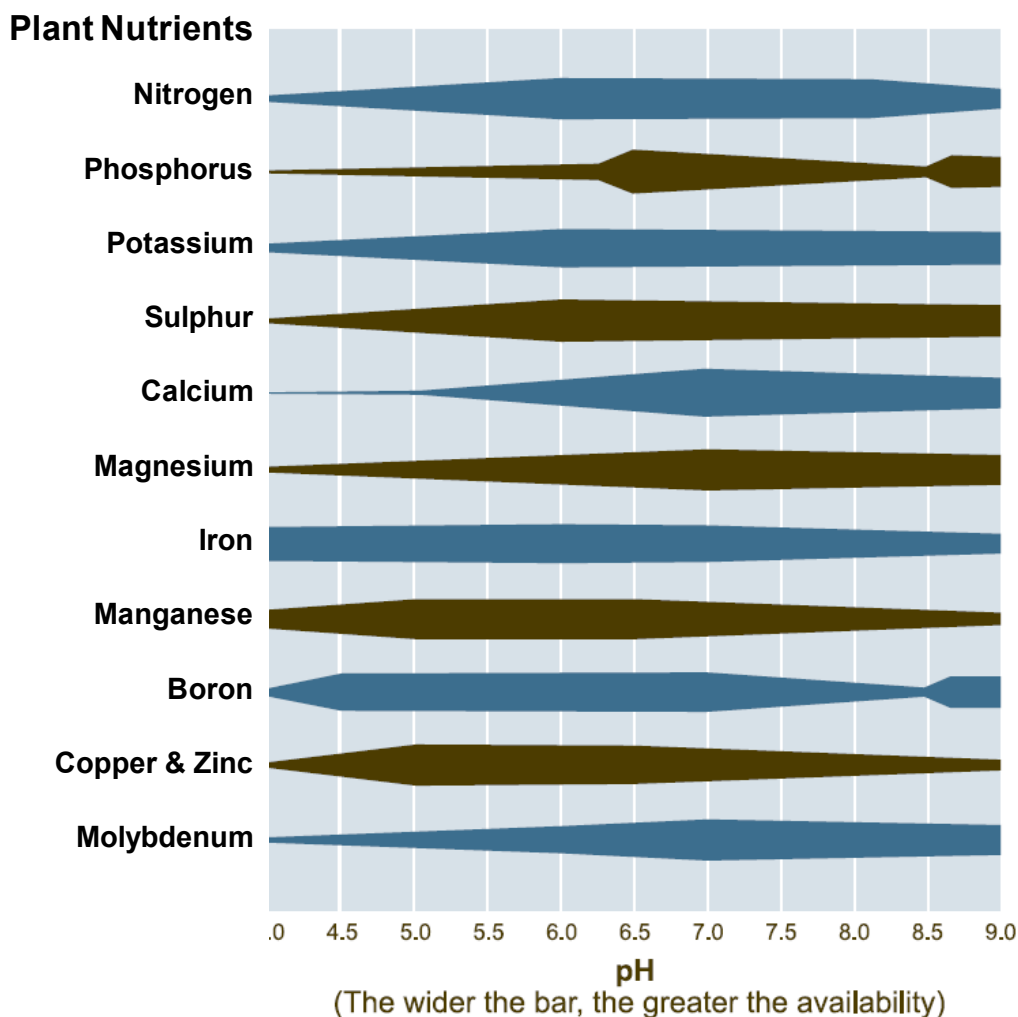


Figure 4 | Effect of soil pH on availability of nutrients to crops. The wider the bar, the greater the availability. (Source: Alberta Agriculture and Food. 2008 Nutrient Management Planning Guide.)

Losses of Nutrients from Soil

Atmospheric losses – Nutrients can be lost to the atmosphere through chemical and biological processes. Volatile nutrients can be easily lost as gases when exposed to the atmosphere. As well, during anaerobic microbial respiration some nutrients are converted to gases and lost to the atmosphere.

Leaching – Leaching is the downward movement of water and soluble substances in soil below the root zone. It is an environmental concern when it contributes to groundwater contamination. Leaching occurs during periods of wet weather, at certain times of year (most likely early spring and late fall) and in certain places in the landscape, especially in sandy soils. Depressions in the landscape where groundwater recharge occurs are more susceptible to leaching because they collect water from surrounding areas, particularly during heavy rainfall events or during snowmelt runoff over frozen soils, which then moves downward to groundwater.

Groundwater Recharge areas occur where the net movement of water is downward. In these areas infiltration exceeds the storage capacity of the soil and moves downward to the zone of saturation (groundwater). The surface and subsoil are usually non calcareous and non-saline.

Groundwater Discharge areas occur where the net movement of water is upward. In these areas, the zone of saturation is at or near the surface and the net movement of water is towards the ground surface. Discharge may be focused in areas such as springs, weeping embankments and baseflow discharge, or it may be diffuse over larger areas of the landscape. These areas may be characterized by soils that are calcareous and often have a build-up of salts.

Runoff – Runoff occurs when rainfall or snowmelt exceeds the infiltration rate of the soil. Runoff carries away dissolved nutrients.

Soil erosion – Soil erosion is the movement and loss of soil by water, wind or tillage. Soil erosion carries away nutrients that are associated with the soil particles.

Soil erosion by water – Water erosion is the detachment, movement and removal of soil from the land surface in runoff. Soil erosion by water carries away the dissolved nutrients in the runoff as well as the nutrients that are associated with the soil particles.

Factors that affect the risk of nutrient loss in runoff and water erosion include:

- **Infiltration rate** – Runoff and/or erosion losses are greatest in soils with slow or restricted water infiltration. Infiltration rate may be impeded due to:
 - **Soil texture** – Fine textured soils have smaller pores and, therefore, slower infiltration rates than coarse textured soils.
 - **Frozen soil** – Frozen soil near the surface impedes infiltration.
 - **Compaction** – Intensive tillage (plow pans), heavy equipment or livestock can cause soil compaction.
 - **Surface crusting** – Soil crusts are created when the soil structure at the surface is destroyed by water and then dries leaving a thin, dense, somewhat continuous seal.
- **Slope** – Areas with steep and/or long slopes are most susceptible to water erosion.
- **Inundation and ponding** – Surface soil that has been in extensive contact with water, such as in flooded and depressional areas, is at increased risk of losing nutrients when the water runs off the surface.
- **Connectivity to surface water** – Agricultural soils that are connected to ditches or streams provide a direct pathway for contaminated runoff to enter surface water bodies.
- **Climate** – In Manitoba, most of the runoff occurs during the spring when large amounts of snow melt rapidly over frozen, impermeable soils. The degree of erosion during snowmelt is highly variable, depending on the extent that the surface soil has thawed during the runoff event.

Agricultural areas of Manitoba with a long term history of less evaporation, less transpiration and/or more precipitation (ex: eastern Manitoba) are generally more susceptible to runoff than drier areas (ex: western Manitoba).

- **Weather** – Wet weather increases the risk of runoff and erosion, especially when the wet weather occurs during periods of low water use by crops. The risk of runoff and erosion is most significant during intense and/or prolonged rainfall.
- **Tillage** – Water erosion losses are greater under intensive tillage and annual crop production than under conservation tillage and perennial forage production.



- **Rate of application** – The risk of nutrient loss in runoff and erosion increases if excessive rates of nutrients are applied.
- **Method and season of nutrient application** – Surface application of nutrients in the fall without incorporation increases the risk of nutrient loss in runoff during spring snowmelt. Nutrient losses in runoff are reduced if manure or fertilizer is properly covered by soil with injection, incorporation or banding.
- **Crop type** – Land under perennial forage is less likely than annual crop land to have substantial runoff and erosion losses because the perennial forage uses more water and the crop canopy protects the soil throughout the year. The risk of runoff and erosion losses from long season annual crops is less than from short season annual crops for the same reasons. Row cropping increases the susceptibility of the soil to erosion compared to solid-seeding as the soil between plant rows is not protected.
- **Summerfallow** – Summerfallow leaves the soil very vulnerable to nutrient loss from runoff and erosion.
- **Artificial drainage** – Improved surface drainage generally increases the risk of runoff and erosion losses. However, subsurface drainage (ex: tile drainage) may reduce the risk of runoff and erosion losses by reducing water flow over the soil surface.

Soil erosion by wind – Wind erosion is the detachment, movement and removal of soil from the land surface by wind. Soil erosion by wind carries away nutrients that are associated with the soil particles.

Soil erosion by tillage – Tillage erosion is the progressive downslope movement of soil by tillage causing loss of soil on hilltops and the accumulation of soil at the base of slopes. Soil erosion by tillage carries away nutrients that are associated with the soil particles. It can result in significant redistribution of nutrients in the field.

Direct loss – Direct or “incidental” loss is the loss of fertilizer or manure to water before interacting significantly with soil. It can result from over-application, heavy rainfall immediately following application or application directly into a waterway (including ditches). Direct losses of manure can also be substantial if manure is applied onto frozen soils or snow in the winter, where the manure can be directly transported to surface water during snowmelt runoff.

Nitrogen (N)

Nitrogen (N) is a macronutrient that is required by crops in large amounts and is frequently deficient in agricultural soils, limiting crop production. Therefore, applications of N frequently increase yield and quality of crops in Manitoba.

When fertilizer N and manure are applied to the soil, the N enters the soil N cycle. Similar to the nutrient cycle, the N cycle can be thought of in terms of gains, removals, internal transformations and losses of N in soil (Figure 5).

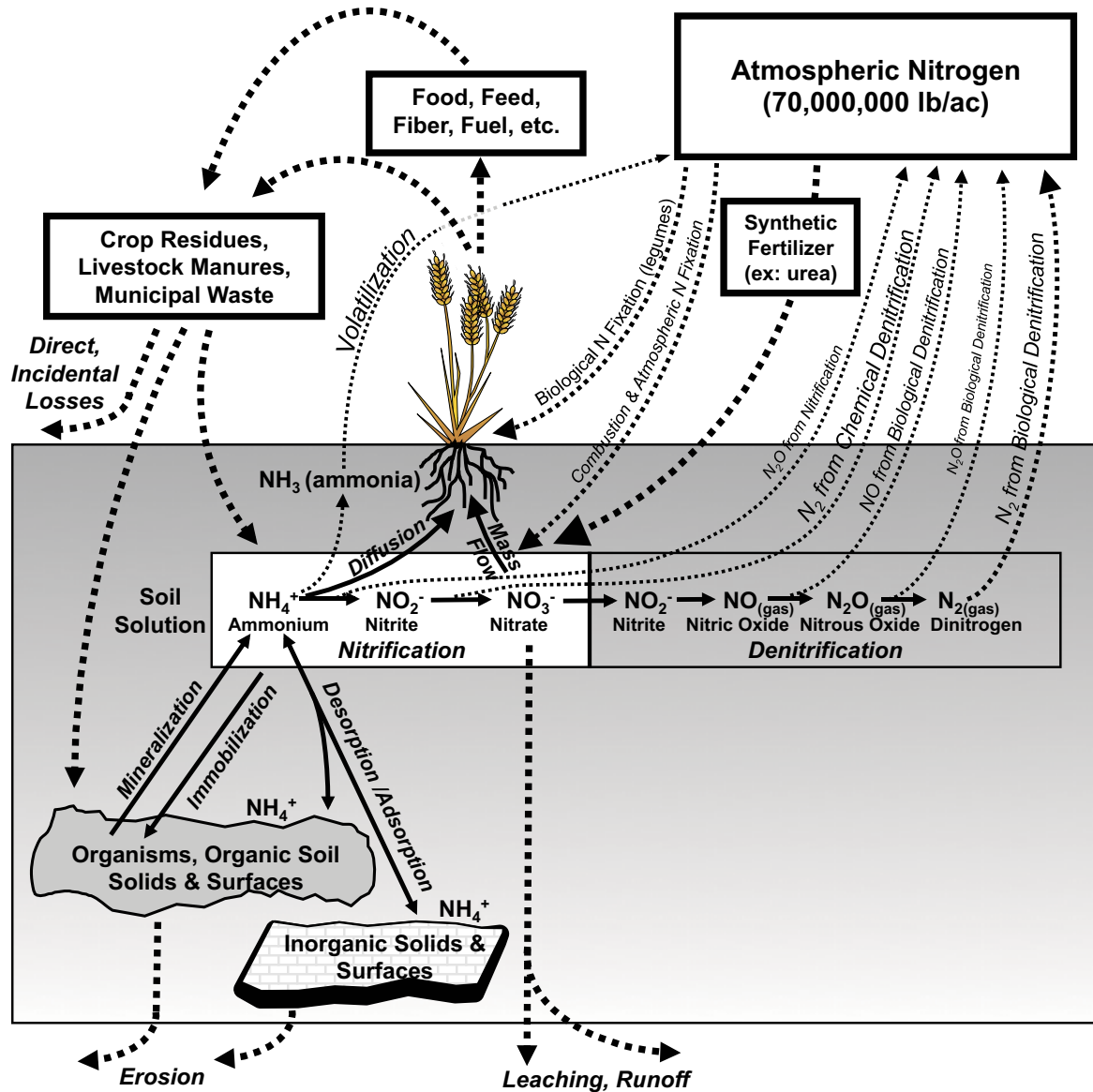


Figure 5 | The N cycle. Nitrogen behaviour in soil is complex and dynamic, with many forms, transformations and potential losses. Dashed lines represent N gains or losses in the soil system; solid lines represent internal transformations within the soil system.

The amount of N in soil is very small, compared to the huge reservoir in the atmosphere, which is 78 per cent N₂.

Gains of N to Soil

Atmospheric fixation and deposition – Reactions between atmospheric N and lightning or sunlight generate small quantities of plant available ammonium (NH₄) and nitrate (NO₃) that is deposited onto soil.

Combustion fixation and deposition – During the combustion process, diesel and gasoline engines convert small quantities of atmospheric N into plant available N that is eventually deposited onto the soil.

Biological N fixation – Most of the biological fixation of N in agricultural soils is by Rhizobium bacteria in the nodules of legume crops such as alfalfa, beans, peas and lentils. In the case of green manures, legume crops are grown to fix N for the subsequent crop.

Application of synthetic N fertilizers – Synthetic N fertilizers are applied to agricultural soils to increase crop yields and quality. A variety of N fertilizers are available with the N in specific proportions. Nitrogen fertilizer can be in a granular, liquid or gaseous state. Specialty products are also available that slow the release of N.

Virtually all of the world's synthetic N fertilizer is manufactured using the "Haber-Bosch" process to make ammonia from natural gas and atmospheric N, under high pressures and temperatures (industrial fixation). The ammonia from this process is then either applied directly into soil as anhydrous ammonia (82-0-0) or converted into other N fertilizers such as urea (46-0-0) or urea-ammonium nitrate solution (28-0-0).

Plant residues – Nitrogen that is contained in unharvested plant residue eventually returns to the soil N cycle. The amount of N that is returned to the soil depends on how much residue is left behind and the concentration of N in the residue.

Livestock manures – Livestock manure is an excellent source of organic and inorganic N. Unlike synthetic fertilizer, manure is a heterogeneous mix of micro and macro nutrients and organic matter making it more challenging to manage well. In Manitoba, livestock manure must be land applied as a fertilizer for crop production. Manure application rates are most often applied to meet the N requirements of the crop.

Municipal biosolids, industrial waste and other amendments – Municipal biosolids, solid municipal waste and some industrial wastes contain N in a variety of organic and inorganic forms.

Crop Uptake and Removal of N from Soil

Crop uptake of N from soil – Plants take up large quantities of N from the soil, primarily as NO₃ but also NH₄. The amount of N taken up by Manitoba crops varies widely by crop species and yield (Table 1). Plants use N to form nucleic and amino acids, proteins and enzymes that are necessary for growth.

Table 1 | Typical rates of crop uptake and removal for nitrogen (N).¹

Crop	Uptake per Unit of Crop ²	Removal per Unit of Crop ³	Example Manitoba Target Yields ⁴	N removed from a field (lb/ac) ³
Alfalfa	N/A	58.0 lb/ton	5 tons/ac	290
Barley – Grain	1.39 lb/bu	0.97 lb/bu	80 bu/ac	78
Barley – Silage	N/A	34.4 lb/ton	4.5 tons/ac	155
Canola	3.19 lb/bu	1.93 lb/bu	35 bu/ac	68
Corn – Grain	1.53 lb/bu	0.97 lb/bu	100 bu/ac	97
Corn – Silage	N/A	31.2 lb/ton	5 dry tons/ac	156
Dry edible beans	N/A	4.17 lb/cwt	18 cwt/ac	75
Fababeans	8.4 lb/cwt	5.02 lb/cwt	34 cwt/ac	171
Flax	2.88 lb/bu	2.13 lb/bu	24 bu/ac	51
Grass hay	N/A	34.2 lb/ton	3 tons/ac	103
Lentils	5.08 lb/cwt	3.39 lb/cwt	18 cwt/ac	61
Oats	1.07 lb/bu	0.62 lb/bu	100 bu/ac	62
Peas	3.06 lb/bu	2.34 lb/bu	50 bu/ac	117
Potatoes	0.57 lb/cwt	0.32 lb/cwt	400 cwt/ac	128
Rye	1.67 lb/bu	1.06 lb/bu	55 bu/ac	58
Soybeans	5.2 lb/bu	3.87 lb/bu	35 bu/ac	135
Sunflowers ⁵	N/A	2.80 lb/cwt	22 cwt/ac	62
Wheat – Spring	2.11 lb/bu	1.5 lb/bu	40 bu/ac	60
Wheat – Winter	1.35 lb/bu	1.04 lb/bu	75 bu/ac	78

¹ Nutrient uptakes and removals for all crops except sunflowers were adapted from Nutrient Uptake and Removal by Field Crops, 2001. Compiled by the Canadian Fertilizer Institute. http://www.cfi.ca/files/publications/archive/d161_NU_W_01.pdf

² Total nutrient taken up by the crop

³ Nutrient removed in the harvested portion of the crop.

⁴ Example target yields for Manitoba. Actual yields for any parcel of land should be used to calculate field specific nutrient removal values. Actual yields depend on the agricultural capability of the land, climate and the producer's management practices.

⁵ Nutrient uptake and removal for sunflowers were adapted from "Nutrients Removed in Harvested Portion of Crop" compiled by the International Plant Nutrition Institute. [http://www.ipni.net/ppiweb/ppibase.nsf/\\$webindex/article=FC18933385256A00006BF1AD5F8663ED](http://www.ipni.net/ppiweb/ppibase.nsf/$webindex/article=FC18933385256A00006BF1AD5F8663ED)

Crop removal of N at harvest – The quantity of N removed when a crop is harvested is less than total uptake and varies substantially with crop species, yield, and portion of the crop that is removed (Table 1).

Movement of N to Plant Roots

The main processes for movement of N to plant roots are mass flow and diffusion.

Mass flow of NO₃ to roots – Nitrate travels to roots via mass flow because it is highly soluble, negatively charged and is not adsorbed onto soil particle surfaces. Therefore, NO₃ from the entire root zone is accessible to the plant as it can be taken up with the water that is consumed to meet the crop's normal requirements for transpiration.

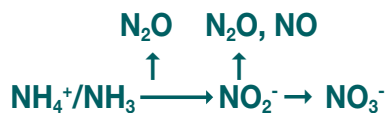
Diffusion of NH₄ to roots – Ammonium is also soluble but its positive charge is attracted to negatively charged surfaces of clay, soil organic matter and oxides. Therefore, NH₄ is not very mobile in soil and can only travel to roots over short distances by diffusion. As with all nutrients that move by diffusion to plant roots, this process is fastest in warm, moist, neutral pH, medium to coarse textured soils, with sufficient supplies of NH₄.

Internal Transformations of N in Soil

The main transformations of N in soil are mineralization, nitrification, immobilization, mineralization-immobilization turnover, NH₄ adsorption and NH₄ desorption.

Mineralization of N – Mineralization is the microbial process of converting organic N to NH₄, increasing the amount of plant available NH₄ in soil. This process occurs when the microbes are feeding on organic material that contains more N than they require for their own growth. For example, during the decomposition of organic material with a low C:N ratio, such as legume crop residues, microorganisms release N that is not required for their own growth, increasing the amount of N available to crops (see C:N ratio below).

Nitrification – Soil bacteria convert NH₄/NH₃ to NO₃ to generate energy for their own benefit. Nitrite (NO₂) is formed as an intermediate step in the process but is usually rapidly oxidized to NO₃ by the bacteria. Although most readily available N in manure is applied as NH₄/NH₃, nitrification of available manure N can create significant quantities of NO₃ in soil. Nitrification is slow below 5°C and above 40°C with optimum temperatures occurring between 15 and 30°C.



Nitrifying bacteria can release nitrous oxide (N₂O) and small amounts of nitric oxide (NO) as by-products of the nitrification process.

Immobilization of N – Immobilization occurs when microbes take up plant available N (NH₄ and NO₃) from the soil solution and retain it in their own biomass, thereby decreasing the amount of plant available N in soil. This process occurs when the microbes are feeding on organic material that contains less N than they require. For example, during the decomposition of organic material with a high C:N ratio, such as straw, microorganisms immobilize soil N that is required for their growth (see C:N ratio below).

Mineralization immobilization turnover – Both mineralization and immobilization occur simultaneously in soil. However, the net balance between the two varies with environmental conditions and the characteristics of the organic material available for decomposition.

Factors that influence mineralization and immobilization of N in soil include:

- **Carbon to nitrogen (C:N) ratio** – During the decomposition of organic material, the microbial population requires a diet with a C:N ratio of approximately 15 to 1 to meet their needs for energy (C) and protein (N), respectively. Therefore, materials with a C:N ratio of approximately 15:1 are likely to have little short term effect on plant available N supply.

Materials with a C:N ratio of less than ~15:1 (ex: legumes, solid poultry manure, liquid pig manure) have more N than the microbes require for their own growth and are likely to provide significant plant available N during their initial decomposition. Materials with a C:N ratio of ~15:1 to ~20:1 (ex: some solid cattle manures) may result in immobilization of plant available N during the initial decomposition of the manure, as the microbes consume inorganic soil N to supplement their diet. Materials with a C:N ratio of more than ~20:1 (ex: cereal straw, flax shives and wood chips) are very likely to result in the immobilization of plant available N during their initial decomposition. Agricultural lands that receive these materials may require supplemental fertilizer N to sustain optimum yields.

Many solid manure systems use bedding materials that have a high C:N ratio. However, the deposition of N-rich feces, urine and wasted feed into the bedding lowers the C:N ratio in the manure that is created. For example, in an Alberta study, the C:N ratios in raw straw and wood chips prior to being used for bedding was approximately 90:1 and 310:1, respectively. However, after being used for bedding by cattle in a feedlot, the C:N ratios in the manures that were created had dropped to 15:1 and 26:1, respectively (Larney et al. 2008a).

There is also a strong relationship between the C:N ratio of manure and its NH_4 content. On the basis of mineralization-immobilization turnover, Beauchamp and Paul (1989) divided manures into 2 groups: either high C:N ratio with low NH_4 content or low C:N ratio with high NH_4 content.

- **Stages of decomposition** – During decomposition of organic material with a high C:N ratio (ex: solid manure with a high proportion of bedding material), microorganisms will shift from immobilization during the early stages of decomposition to mineralization during later stages, followed by a period of stability with little further change in available N supplies.

In the early stages of decomposition of high C:N ratio manures, microbial populations increase. The manure's C is used as a source of cellular material and an energy source for respiration, converting C to CO_2 , which is then lost to the atmosphere (Figure 6). Nitrogen is consumed from the soil for protein synthesis and is temporarily immobilized. As decomposition proceeds, the C:N ratio of the material drops, and the microbes shift from feeding on easily decomposable material in the raw manure to feeding on less decomposable material. As the readily available C supply decreases, microbial populations decline and dead microbial tissue and other decomposition products become another source of food for the microbes. The death of microbial populations also releases plant available N, and towards the end of the decomposition process, concentrations of plant available N rise above their original levels. As the organic material becomes very stable further release of N is minimal. So, even if the initial C:N ratio for a manure is >15:1, the initial period of N immobilization will eventually be followed by a period of N mineralization, as the C:N ratio of the decomposing manure drops below the C:N threshold of 15:1 that separates net immobilization from net mineralization.

The time required for complete mineralization of the organic N in solid manures could be several years. Therefore, repeated annual applications of manure will result in the accumulation of organic N over time. This accumulation increases the N supplying capacity of the soil. Failure to account for this N during the calculation of fertilizer or manure requirements could result in over application.

- **Rate of decomposition** – There are various factors that affect the rate of decomposition which will determine when a particular material will start to release N and the amount of plant available N that will be available over a particular growing season.

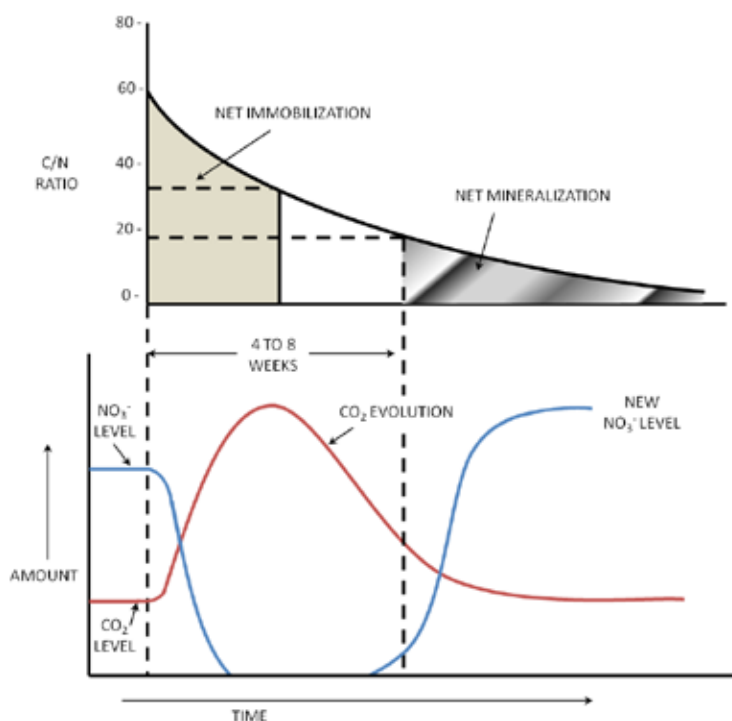


Figure 6 | Effect of decomposition on C/N ratio and NO₃ and CO₂ levels
(Adapted from Sabey, U of Illinois).

Factors that affect the rate of decomposition include:

- **Type of organic material** – Some types of organic materials are more easily decomposed than others. The rate of decomposition of a material depends on its chemical structure. For example, simple sugars decompose rapidly, followed by starches, celluloses, waxes, resins and finally lignins (woody materials). Therefore, even if two materials have similar C:N ratios, the more easily decomposable material will start to break down sooner.
- **Particle size** – Microbial activity is the greatest on the surface of decomposing material. In general, smaller particles decompose more rapidly than large particles because they present larger surface areas for microbial activity.
- **Soil temperature** – Temperature has a dramatic impact on microbial activity and, therefore, rate of decomposition. In soil, there is very little or no microbial activity at or below 0°C. Above 0°C microbial activity increases as temperature rises with a considerable increase in rate at about 10°C. Optimum rates of microbial activity occur between 25 to 35°C although different species of microbes differ in their optimum temperatures. Above 40°C, microbial activity declines.
- **Soil aeration** – Oxygen also has a dramatic impact on microbial activity and rate of decomposition. Air supply is affected by soil moisture and texture. Microbial decomposition tends to be slower in soils with fine texture (high clay content) and in saturated soils due to insufficient soil aeration.
- **Soil moisture** – Microbial decomposition is greatest at moisture contents near field capacity because at field capacity, soils tend to provide a balance of both air and water. By comparison, microbial decomposition is slow in very dry soils because they do not supply enough water, or in saturated soils because they do not supply enough air.
- **Soil pH** – Microbial decomposition is slower in acidic soils compared to neutral to alkaline soils.

Ammonium adsorption and desorption – Ammonium adsorption occurs when positively charged ammonium (NH_4^+) is adsorbed onto the surfaces of negatively charged clay particles, soil organic matter and oxides. Ammonium desorption occurs when adsorbed NH_4 is released from the surfaces of soil particles.

Exchangeable NH_4 adsorption and desorption – If the adsorption is weak, the NH_4 can be easily exchanged for other cations, resulting in the NH_4 being desorbed. Ammonium held and released by this process is regarded as exchangeable NH_4 and available to plants.

Non-exchangeable NH_4 adsorption – Some forms of clay and organic matter adsorb NH_4 very strongly, causing non-exchangeable NH_4 adsorption or “ **NH_4 fixation**” which is not immediately available to plants. Some sandy soils in Manitoba (ex: Almasippi soils on the western edges of the Red River Valley) have minerals such as vermiculite that can adsorb NH_4 strongly in this manner.

Losses of N from Soil

Losses of N from soil include: gaseous losses to the atmosphere due to volatilization, nitrification and denitrification; nitrate leaching to groundwater; and loss to surface water through runoff and erosion.

Ammonia (NH_3) volatilization – Most synthetic fertilizers and livestock manures contain or can form NH_3 gas. This form of N is easily lost if exposed to the atmosphere.

If urea or manure is surface-applied, volatilization can result in a substantial loss of agronomically available and economically valuable N. In addition, subsequent deposition of NH_3 causes environmental problems such as NH_3 toxicity in sensitive plants, plant species shifts in natural areas and eutrophication if deposited on surface water. Ammonia can also combine with other compounds in the atmosphere to form particulate matter in the air that is linked to respiratory problems in humans or can contribute to the formation of haze. Ammonia is also an indirect source of N_2O , a strong greenhouse gas.

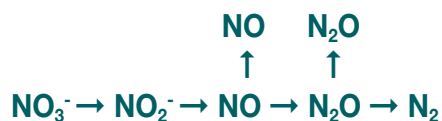
Factors that affect the formation of NH_3 and loss by volatilization include:

- **Soil coverage** – Volatilization of NH_3 is reduced if the manure or NH_4 -based fertilizer is properly covered by soil. Volatilization losses from surface applied manure can be minimized if manure is immediately and well incorporated into soil. Losses are negligible from manure that is injected into soil with proper closure of injection furrows.
- **Soil pH** – Volatilization is greater on high pH (alkaline) soils than on low pH (acidic) soils because the low concentration of H^+ in high pH soils favours the formation of NH_3 instead of NH_4 .
- **Weather** – Warm weather increases the rate of NH_3 formation and the risk of loss. Wind increases the rate of air exchange and the rate of NH_3 loss to the atmosphere. In addition, warm temperatures and wind also encourage drying of moist soil, which concentrates the NH_3 in soil solution and forces it into the air.
- **Soil texture and organic matter** – Sandy soils with low clay and soils with low organic matter contents have low cation exchange capacity, resulting in a low capacity to retain NH_4 and a higher risk of losing NH_3 through volatilization.

Denitrification – Denitrification is the conversion of NO_3 or NO_2 to gaseous forms of N, including dinitrogen gas (N_2), N_2O and NO , which are then lost to the atmosphere. The conversion may be a biological or simply a chemical process.

N_2O is a powerful greenhouse gas with approximately 300 times the warming potential of carbon dioxide (CO_2).

Biological denitrification – Soil microorganisms use NO_3 as a substitute for O_2 during anaerobic respiration. This is a microbial process that is favoured by large supplies of NO_3 and decomposable C, low or no O_2 , (such as in saturated soils or areas of high microbial activity), warm temperatures and neutral to alkaline pH. Biological denitrification shuts down at temperatures below about 5°C .



Emissions of N_2O from biological denitrification are difficult to predict. If conditions are very dry, denitrification will not occur. However, if conditions are very wet and highly favourable for biological denitrification, soil microorganisms fully convert soil NO_3 to N_2 , with very low emissions of N_2O .

Denitrification can cause significant agronomic and economic losses of plant available NO_3 , especially on poorly drained soils, during the early spring thaw and snowmelt period, as well as during wet periods of the growing season.

When manure is applied to soil, microbial activity increases as manure decomposition proceeds. Very high rates of microbial activity due to a source of easily decomposable manure C can result in anaerobic pockets adjacent to aerobic areas where nitrification is increasing NO_3 concentrations. These conditions are ideal for denitrification and may make manure N more susceptible to denitrification and emissions of N_2O than synthetic fertilizer.

Chemodenitrification – Chemodenitrification is a process by which N gases are formed in soils by chemical reactions of NO_2 with organic matter. It is less important than nitrification or biological denitrification as a source of N_2O in most agricultural soils, but may occur when soils are freezing or thawing.

Nitrification – Soil microorganisms convert NH_4/NH_3 to NO_3 to generate energy for their own benefit (see Internal Transformations of N in Soil). Nitrifying bacteria can release nitrous oxide (N_2O) and small amounts of nitric oxide (NO) as by-products of the nitrification process.

Nitrate (NO_3) leaching – Nitrate is highly soluble, negatively charged (NO_3^-) and is not adsorbed onto soil particle surfaces. If there is excess water moving downward through the soil, nitrate will be carried with it and is susceptible to being leached below the root zone, where it can eventually contaminate ground water. Simply, NO_3 leaching occurs when excess NO_3 and excess water occur simultaneously.

The fate of deeply leached NO_3 is uncertain. Nitrate that reaches groundwater may enter drinking water sources, it may be denitrified in the upper layer of the aquifer or it may be discharged into surface water (Figure 7).

Nitrate in drinking water is regarded as a human health risk due to concerns about methemoglobinemia (“blue baby syndrome”) and gastrointestinal cancers.

Factors that affect the risk of NO₃ leaching and contamination of groundwater include:

- **Soil texture** – Sandy soils generally have the highest risk of NO₃ leaching due to their low water holding capacity and rapid rate of water infiltration and percolation.
- **Landscape position** – Depressions in the landscape where groundwater recharge occurs are more susceptible to leaching because they collect water from surrounding areas, especially during heavy rainfall events or during snowmelt runoff over frozen soils, which then moves downward to groundwater.
- **Shallow depth to ground water** – Ground water that is shallow (ex: sandy soils with a high or perched water table) has a higher risk of being contaminated by NO₃ leaching than ground water that is deep.
- **Climate and weather** – The climate in agro-Manitoba is generally semi-arid to sub-humid (i.e. mean annual precipitation is generally less than potential evaporation plus transpiration). As such this region is less susceptible to large amounts of NO₃ leaching compared to wetter regions of the country such as eastern Canada. Similarly, within agro-Manitoba areas with a long term history of less evaporation, less transpiration and/or more precipitation (ex: eastern Manitoba) are generally more susceptible to leaching than drier areas (ex: western Manitoba).

Although climate is an important long term factor to consider, wet weather increases the risk of leaching in the short term, especially when the wet weather occurs during periods of low water use by crops.

- **Season** – In Manitoba, the risk of leaching is lower during the growing season, when evapotranspiration is high relative to precipitation. However, in the fall and early spring periods, the risk of leaching is higher because evapotranspiration is low relative to precipitation. Also, snow accumulates for several months over winter, melts over a relatively short period in the spring, resulting in runoff on frozen soils entering depressional areas, dramatically increasing the water load and risk of leaching in these areas.
- **Residual soil nitrate** – Residual soil NO₃ is the amount of NO₃ in the soil following harvest. Elevated residual soil NO₃ levels increase the risk of nitrate leaching during periods of excess water such as during high rainfall and spring snowmelt. Residual soil NO₃ testing should be used to estimate the amount of N remaining after harvest and to match N application rates to crop N requirements.
- **Rate of N application** – If manure or fertilizer N is applied at rates that exceed crop N requirements, excess NO₃ may be left in the soil after harvest (residual soil NO₃) and the following spring when moisture levels and leaching risk are higher. Conversely, applying insufficient N to meet crop needs can increase NO₃ leaching by limiting crop growth and reducing uptake of water and nutrients (Campbell et al. 1984, 1993).
- **Season of application** – Application of N as close to when the crop can use it reduces the risk of NO₃ leaching. Therefore spring, post-emergence and mid-season applications of N fertilizers and manure are recommended where appropriate. Late fall application of NH₄-based fertilizers is also recommended because nitrification (the conversion of NH₄ by soil microorganisms to NO₃) is slow below 5°C. Nitrification in soil can create significant quantities of NO₃ if NH₄-based fertilizers or manure is applied in the early fall.
- **Water and N use by crops** – Crops that grow over a long period generally consume more water and N than crops that grow over a short period. The risk and quantity of leaching is much less for perennial forages (ex: grass and alfalfa) compared to short season annual crops such as wheat, oats, barley or canola in part because they use more water and N. The leaching risks for fall planted crops (ex: fall rye, winter wheat) and long season crops are also lower than for short season annual crops (Campbell et al. 1984). Cover crops can also take up residual NO₃ and reduce the risk of nitrate leaching.
- **Root density** – Crops with dense or deep rooting systems reduce the risk of leaching over crops with sparse or shallow rooting systems. For example, alfalfa has both a dense and deep rooting system, is a large user of water and N, and presents a low risk of NO₃ leaching.
- **Summerfallow** – With no significant plant growth or transpiration, summerfallow increases the risk of NO₃ leaching even in the relatively dry Prairie climate.

- **Artificial drainage** – Improved surface drainage generally reduces the risk of leaching by reducing ponding and infiltration of water. Subsurface drainage (ex: tile drainage) may also reduce the risk of NO_3 reaching groundwater by intercepting water and NO_3 before or as they enter the water table. However, both of these types of drainage may increase the risk of N loading to surface water.
- **Irrigation** – The effect of irrigation on NO_3 leaching risk is complex. In Manitoba, irrigation provides water that is supplemental to rainfall. Heavy rainfall shortly after irrigation can increase the risk of NO_3 leaching, compared to a dryland situation. However, judicious irrigation can also maintain crop growth and yield potential during critical dry periods of the growing season, thereby increasing the overall capacity for the crop to consume water and NO_3 for the remainder of the growing season.

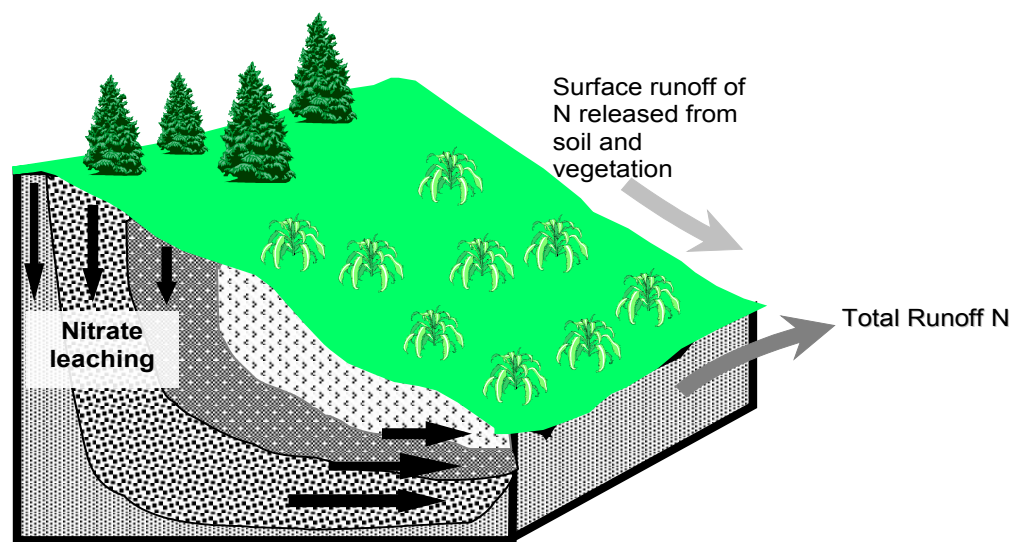


Figure 7 | Nitrogen can be transported to groundwater and surface water along surface and subsurface pathways (Adapted from Sharpley 2007).

Runoff – Runoff occurs when rainfall or snowmelt exceeds the infiltration rate of the soil. Runoff will carry away dissolved N such as NO_3 or NO_2 .

Soil erosion by water – Water erosion is the detachment, movement and removal of soil from the land surface in runoff. Soil erosion by water carries away the dissolved N in the runoff as well as the organic N and NH_4 that are associated with the soil particles.

In Manitoba, surface runoff of the dissolved fraction of N is more likely, as erosion of particulate N is not a common transport pathway for our relatively flat agricultural landscapes and dry, cold climate, where snowmelt over frozen soils is the dominant form of runoff.

Minimizing runoff and erosion losses of manure N helps to maximize the agronomic value of the manure, as well as to protect water quality. Nitrate loading to surface water is generally a minor concern for aquatic health in freshwater systems. Ammonia is a substantial concern because it is toxic to fish at relatively low concentrations.

Factors that affect the risk of N loss in runoff and water erosion include:

- **Infiltration rate** – Runoff and/or erosion losses are greatest in soils with slow or restricted water infiltration. Infiltration rate may be impeded due to:
 - **Soil texture** – Fine textured soils have smaller pores and, therefore, slower infiltration rates than coarse textured soils.
 - **Frozen soil** – Frozen soil near the surface impedes infiltration.
 - **Compaction** – Intensive tillage, heavy equipment or livestock can cause soil compaction.
 - **Surface crusting** – Soil crusts are created when the soil structure at the surface is destroyed by water and then dries leaving a thin, dense, somewhat continuous seal.
- **Slope** – Areas with steep and/or long slopes are most susceptible to water erosion.
- **Inundation and ponding** – Surface soil that has been in extensive contact with water, such as in flooded and depressional areas, is at increased risk of losing N when the water runs off the surface.
- **Connectivity to surface water** – Agricultural soils that are connected to ditches or streams provide a direct pathway for contaminated runoff to enter surface water bodies.
- **Climate** – In Manitoba, most of the runoff occurs during the spring when large amounts of snow melt rapidly over frozen, impermeable soils. The degree of erosion during snowmelt is highly variable, depending on the extent that the surface soil has thawed during the runoff event.

Agricultural areas of Manitoba with a long term history of less evaporation, less transpiration and/or more precipitation (ex: eastern Manitoba) are generally more susceptible to runoff than drier areas (ex: western Manitoba).

- **Weather** – Wet weather increases the risk of runoff and erosion, especially when the wet weather occurs during periods of low water use by crops. The risk of runoff and erosion is most significant during intense and/or prolonged rainfall.
- **Tillage** – Water erosion losses are greater under intensive tillage and annual crop production than under conservation tillage and perennial forage production. In Manitoba, conventional tillage has been shown to result in higher N and sediment losses than conservation tillage (Tiessen et al. 2010).
- **Rate of N application** – The risk of N loss in runoff and erosion increases if excessive rates of N are applied.
- **Method and season of application** – Surface application of N in the fall without incorporation increases the risk of N loss in runoff during spring snowmelt. Nitrogen losses in runoff are reduced if manure or fertilizer is properly covered by soil with injection, incorporation or banding.
- **Crop type** – Land under perennial forage is less likely than annual crop land to have substantial runoff and erosion losses because the perennial forage uses more water and the crop canopy protects the soil throughout the year. The risk of runoff and erosion losses from long season annual crops is less than from short season annual crops for the same reasons. Row crops increase the susceptibility of the soil to erosion compared to solid-seeded crops as the soil between plant rows is not protected.
- **Summerfallow** – Summerfallow leaves the soil very vulnerable to N loss from runoff and erosion. Manure application to summerfallow is prohibited in Manitoba.
- **Artificial drainage** – Improved surface drainage generally increases the risk of runoff and erosion losses. However, subsurface drainage (ex: tile drainage) may reduce the risk of runoff and erosion losses by reducing water flow over the soil surface.

Soil erosion by wind – Wind erosion is the detachment, movement and removal of soil from the land surface in wind. Soil erosion by wind carries away the N that is associated with the soil particles.

Soil erosion by tillage – Tillage erosion is the progressive downslope movement of soil by tillage causing loss of soil on hilltops and the accumulation of soil at the base of slopes. Soil erosion by tillage carries away the N that is associated with the soil particles. It can result in significant redistribution of nutrients in the field.

Direct loss – Direct or incidental loss is the loss of fertilizer or manure to water before interacting significantly with soil. It can result from over-application, heavy rainfall immediately following application or application directly into a waterway (including ditches). Direct losses of manure can also be substantial if manure is applied onto frozen soils or snow in the winter, where the manure can be directly transported to surface water during snowmelt runoff.

Ammonia is toxic to fish at relatively low concentrations. However, ammonium in surface applied manure volatilizes quite quickly after application. Therefore, the risk to fish is greatest if manure is applied directly into a fish-bearing watercourse or in close proximity to the watercourse and heavy rainfall occurs very shortly after application.





Phosphorus (P)

Similar to N, P is a macronutrient that is required by crops in large amounts and it is frequently deficient in Manitoba's agricultural soils. Therefore, applications of P fertilizer and manure frequently increase yields and quality of crops in Manitoba.

When P fertilizer and manure are applied to the soil, the P enters the soil P cycle. From an agricultural perspective, the P cycle can be thought of in terms of gains, removals, internal transformations and losses (Figure 8).

Gains of P to Soil

Atmospheric deposition – From an agricultural perspective, the small amounts of P deposited by rainfall, snowfall and phosphine gas (0.2 to 0.4 lb/acre) to soil are not significant. However, over the long term, these rates of P addition can be an important source of P loading to lakes and natural areas.

Application of synthetic P fertilizers – Most of the P applied onto agricultural land in Manitoba is applied as synthetic fertilizer such as monoammonium phosphate (11-52-0) or ammonium polyphosphate (10-34-0). These fertilizers contain P in readily soluble, inorganic forms that are immediately or quickly available for uptake by plant roots. By convention, the amount of P in fertilizers is expressed as diphosphorus pentoxide or P_2O_5 , even though this form of P is not found in fertilizers.

Livestock manures – In contrast to synthetic fertilizers, the P concentration in livestock manures is much lower. Therefore, the amounts of manure that must be applied to match crop requirements are much greater than for synthetic fertilizer. Annual manure application rates, however, are most often applied to meet the N requirements of the crop.

Municipal biosolids, industrial waste and other amendments – Municipal biosolids, solid municipal waste and some industrial wastes contain P in a variety of organic and inorganic forms.

Plant residues – Phosphorus that is contained in unharvested plant residue eventually returns to the soil P cycle. The amount of P that is returned to the soil depends on how much residue is left behind and the concentration of P in the residue.

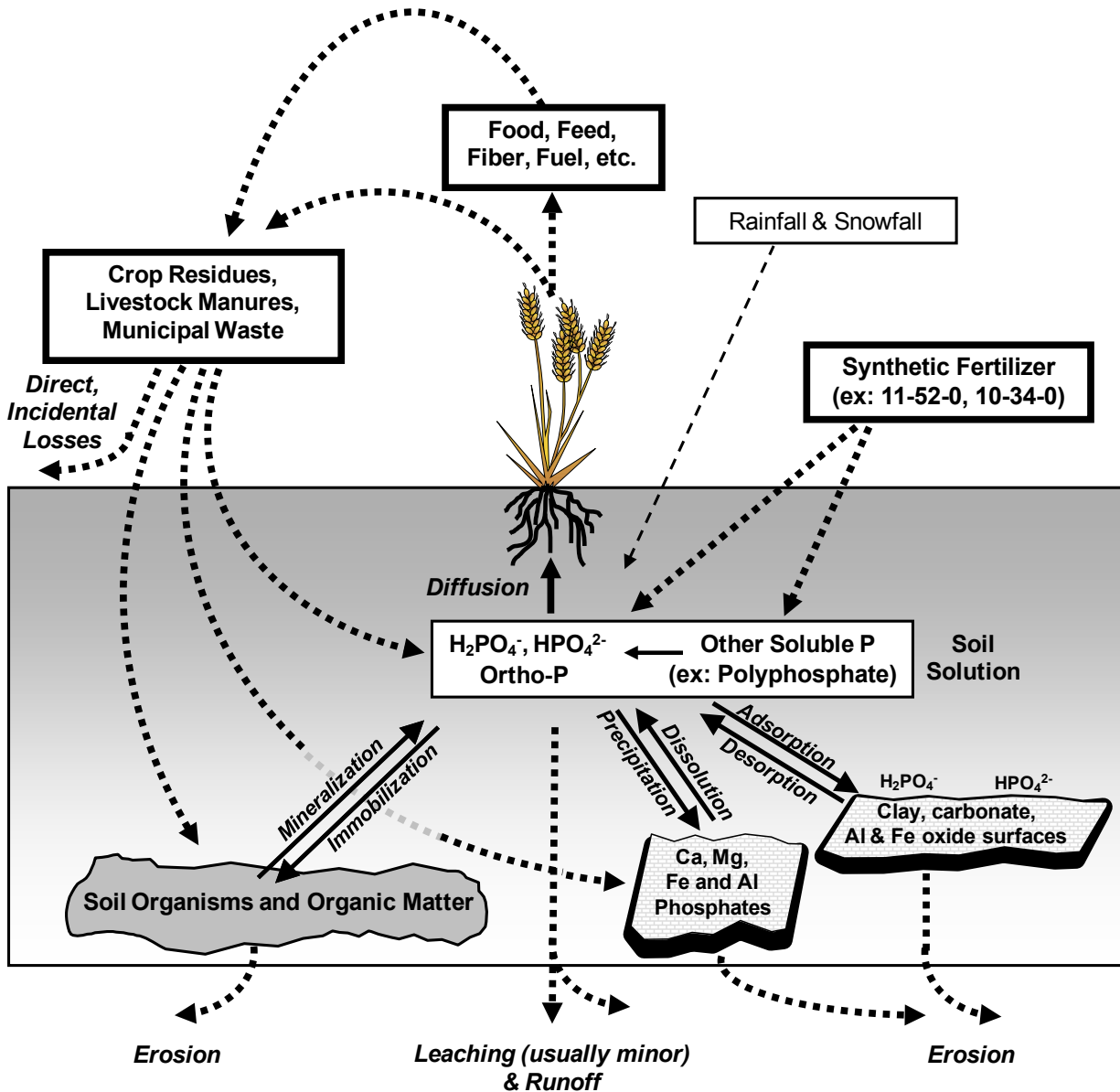


Figure 8 | The P Cycle. Phosphorus is generally held strongly in soil by adsorption, precipitation, and immobilization processes. Dashed lines represent phosphorus gains or losses in the soil system; solid lines represent internal transformations within the soil system.

Crop Uptake and Removal of P from Soil

Plant uptake of available P – Plants take up large quantities of P from the soil (Table 2) for a variety of unique and vital functions within the plant. Plants are able to take up P in the ortho-phosphate form, either as H_2PO_4^- or HPO_4^{2-} , but they are not able to directly absorb organic P or polyphosphate-P (chains of P linked together). The most prevalent form of ortho-phosphate in soil solution is a function of soil pH (Figure 9). Since P is needed for plant growth, early season demand for P is large.

Plants use P for energy transfer (ex: P bonds are used in ADP and ATP to store and release energy for plant growth and survival), structural components (ex: phosphate bonds join the subunits of DNA and RNA together), intermediate compounds in metabolic pathways and overall regulation of plant growth.

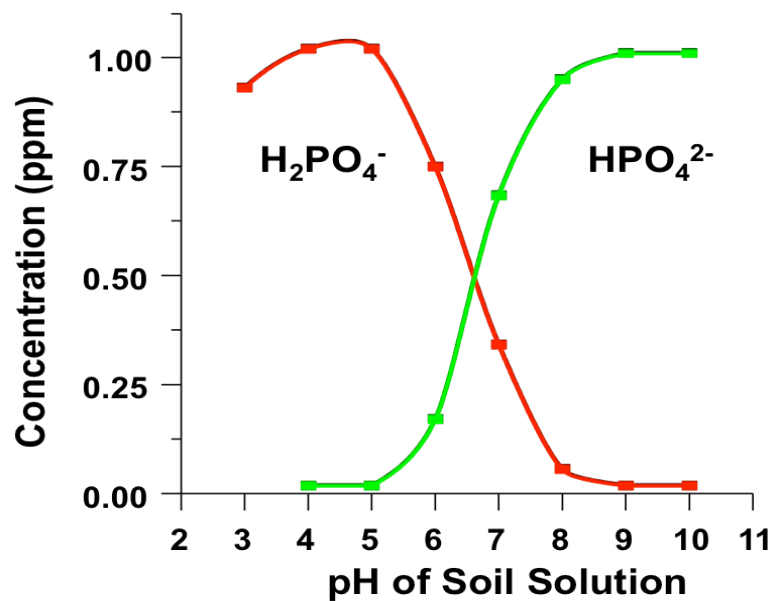


Figure 9 | Ortho-phosphate forms as a function of soil pH.

Crop removal of P at harvest – As with N, the net quantity of P removed when a crop is harvested varies substantially with crop species, yield and portion of the crop that is removed (Table 2). For example, the rate of P removal for a bushel of canola is nearly twice as large as for a bushel of wheat. Also, most of the P taken up by a crop is removed in the grain; however, removal of the whole crop (ex: harvesting the crop for straw, silage or hay) increases the amount of P removed.

Table 2 | Typical rates of crop uptake and removal for phosphorus (P₂O₅).¹

Crop	Uptake per Unit of Crop ²	Removal per Unit of Crop ³	Example Manitoba Target Yields ⁴	P ₂ O ₅ removed from a field (lb/ac) ³
Alfalfa	N/A	13.8 lb/ton	5 tons/ac	69
Barley – Grain	0.56 lb/bu	0.42 lb/bu	80 bu/ac	34
Barley – Silage	N/A	11.8 lb/ton	4.5 tons/ac	53
Canola	1.47 lb/bu	1.04 lb/bu	35 bu/ac	36
Corn – Grain	0.63 lb/bu	0.44 lb/bu	100 bu/ac	44
Corn – Silage	N/A	12.7 lb/ton	5 dry tons/ac	64
Dry edible beans	N/A	1.39 lb/cwt	18 cwt/ac	25
Fababeans	2.90 lb/cwt	1.79 lb/cwt	34 cwt/ac	61
Flax	0.83 lb/bu	0.65 lb/bu	24 bu/ac	16
Grass hay	N/A	10.0 lb/ton	3 tons/ac	30
Lentils	1.37 lb/cwt	1.03 lb/bu	18 cwt/ac	19
Oats	0.41 lb/bu	0.26 lb/bu	100 bu/ac	26
Peas	0.84 lb/bu	0.69 lb/bu	50 bu/ac	35
Potatoes	0.17 lb/cwt	0.09 lb/cwt	400 cwt/ac	36
Rye	0.84 lb/bu	0.45 lb/bu	55 bu/ac	25
Soybeans	0.90 lb/bu	0.84 lb/bu	35 bu/ac	29
Sunflowers ⁵	N/A	1.10 lb/cwt	22 cwt/ac	24
Wheat – Spring	0.8 lb/bu	0.59 lb/bu	40 bu/ac	24
Wheat – Winter	0.61 lb/bu	0.51 lb/bu	75 bu/ac	38

¹ Nutrient uptakes and removals for all crops except sunflowers were adapted from Nutrient Uptake and Removal by Field Crops, 2001. Compiled by the Canadian Fertilizer Institute. http://www.cfi.ca/files/publications/archive/d161_NU_W_01.pdf

² Total nutrient taken up by the crop

³ Nutrient removed in the harvested portion of the crop.

⁴ Example target yields for Manitoba. Actual yields for any parcel of land should be used to calculate field specific nutrient removal values. Actual yields depend on the agricultural capability of the land, climate and the producer's management practices.

⁵ Nutrient uptake and removal for sunflowers were adapted from "Nutrients Removed in Harvested Portion of Crop" compiled by the International Plant Nutrition Institute. [http://www.ipni.net/ppiweb/ppibase.nsf/\\$webindex/article=FC18933385256A00006BF1AD5F8663ED](http://www.ipni.net/ppiweb/ppibase.nsf/$webindex/article=FC18933385256A00006BF1AD5F8663ED)

Movement of P to Plant Roots

The main process for P movement to plant roots is diffusion.

Diffusion of phosphate ions to roots – Due to strong retention of P by the soil, the concentration of ortho-phosphates in soil solution is usually very low. Therefore, plants rely on the process of diffusion to move enough P from the soil into their root system. Diffusion of ortho-phosphates to plant roots results in the slow, short distance movement of P from zones of high concentration (near soil surfaces) to zones of low concentration (near root surfaces).

Diffusion requires large amounts of root growth and surface area. Also, applied P should be placed as close as possible to the seed row, where early season access and root density are greatest.

As with all nutrients that move by diffusion to plant roots, this process is fastest in warm, moist, neutral pH, medium to coarse textured soils with sufficient supplies of soil test P.

Internal Transformations of P in Soil

The main transformations of P in soil are mineralization and immobilization (including mineralization-immobilization turnover), adsorption, desorption, precipitation and dissolution.

In most soils, the majority of the P is held very strongly by precipitation and adsorption reactions. A large amount of P can be retained by a soil that is rich in Ca, Mg, Fe or Al. Much of the soil P is also in stable organic forms. However, a small, but very important fraction of the soil's P reserves is regarded as "**labile P**" because this P can quickly replenish the solution P through the processes of dissolution, desorption, and mineralization. Labile P is the most agronomically and environmentally important fraction of P in the soil, because it quickly becomes available to crops or to water that is running over or through the soil.

Although the P retention capacity in most soils is large, it is never infinite. Therefore, if the rate of P application exceeds the rate of removal by the crop, soil test P levels will increase and the risk of P loss increases. Agronomic soil tests for P are designed to measure a representative portion of labile P, not total P in soil. In other words, soil test P is an index of plant available P in soil, not an absolute measure of either plant available P or total P in soil.

Mineralization of P – Mineralization is the microbial process of converting organic P to plant available inorganic P in soil. This process occurs when the microbes are feeding on organic material that contains more P than they require for their own growth.

Predicting how much and when the organic fraction of manure P will be available for crop uptake following application is difficult. A significant proportion of the organic P in manure is relatively stable and is mineralized slowly (Ajiboye et al. 2004, 2007). Therefore, mineralization of manure P can occur over the course of the growing season, gradually releasing plant available P.

Immobilization of P – Immobilization is the conversion of inorganic, plant available P by soil microorganisms into organic forms that are not immediately available to plants. This process occurs when soil microorganisms feed on organic materials that contain concentrations of P that are lower than their own immediate requirements. Since the organic materials do not contain sufficient nutrients, the organisms consume P in the soil solution to make up the shortfall.

Mineralization Immobilization Turnover – Both mineralization and immobilization occur simultaneously in soils, where diverse populations of microorganisms feed on a variety of food sources. These processes are important for manure because organic P accounts for a substantial portion of P in manure, especially in solid manures. Mineralization and immobilization play important roles in determining the P fertility of a soil.

Factors that influence mineralization and immobilization of P during decomposition of manure:

Theoretically, many of the same substrate characteristics and environmental factors that affect mineralization and immobilization of N should have similar effects on microbial transformations of P. Therefore, factors such as easily decomposable material, warm temperatures, moisture content near field capacity, good aeration, tillage, neutral to alkaline soil pH, and medium to coarse soil textures will generally result in faster rates of mineralization and immobilization.

- **Carbon to phosphorus (C:P) ratio in manure** – Similar to N, mineralization of P requires concentrations of P in the decomposing material that are high enough to meet the needs of the microbial decomposers. For example, Havlin et al. (2005) state that C:P ratios less than 200:1 and P concentrations greater than 0.2 per cent (dry matter basis) in the decomposing material will result in net mineralization or release of plant available P. The ratios of C:P in manure are much less than 200:1 and the manure P concentrations are high enough to favour net mineralization. Therefore, manure P is usually rapidly mineralized in soil (Hedley and McLaughlin 2005). However, Manitoba studies have shown that if the manure contains high concentrations of straw as bedding material, such as in some solid cattle manure, P may be immobilized after manure is applied (Kashem et al. 2004).

Adsorption of P – Adsorption is the process whereby negatively charged phosphates (H_2PO_4^- or HPO_4^{2-}) become attached to soil surfaces. From a theoretical viewpoint, adsorption is a quick, two-dimensional process that occurs when a thin layer of phosphate, only one or two P molecules in thickness, becomes attached to soil surfaces through bonds with calcium (Ca), magnesium (Mg), iron (Fe) or aluminum (Al). However, from a practical perspective, the same elements that cause adsorption of P also cause precipitation, making these two retention processes difficult to separate.

Desorption of P – Desorption is the opposite of adsorption whereby P detaches from positively charged surfaces.

Precipitation of P – Precipitation creates solid forms of P from reactions between dissolved forms of P and other soil constituents. Theoretically, precipitation is a process whereby P reacts with Ca, Mg, Fe or Al in soil solution to form a new solid. Compared to adsorption, it is a slower, three-dimensional process that does not require any surface to initiate the P retention process. However, as mentioned before, these two retention processes occur simultaneously in soil, using similar elements to retain P, so they are very difficult to distinguish from each other from a practical perspective.

Dissolution of P – Dissolution is the opposite of precipitation, creating dissolved forms of P from solid forms.

For example, when highly water soluble, plant available granular P fertilizer such as mono-ammonium phosphate (11-52-0) is added to soil the P fertilizer dissolves and quickly reacts with calcium in Manitoba soils to form a Ca-P precipitate called dicalcium phosphate or “dical.” Dical, which is much less soluble than mono-ammonium phosphate, then slowly dissolves during the growing season to provide P to the current and succeeding crops.

Factors that affect adsorption, desorption, precipitation or dissolution include:

- **Ca and Mg content** – Soils with alkaline (basic) pH, such as most soils in agro-Manitoba, have large concentrations of exchangeable Ca and Mg that can be released and react with P in solution.
- **Fe and Al oxide content** – Acid soils often have significant quantities of soluble Fe and Al that can react with P to form precipitates that are very insoluble. However, soils with alkaline pH predominate in agro-Manitoba.
- **Clay content** – Clay particles have large surface areas with high concentrations of exchangeable Ca and Mg on those surfaces that can be released and react with P.
- **Carbonate content** – Soils with alkaline pH, such as most soils in agro-Manitoba, often contain calcium and magnesium carbonates (CaCO_3 and MgCO_3) that can adsorb P on their surfaces and provide Ca and Mg for precipitation reactions.
- **Soil pH** – Soil pH near neutral (6-7) are often the best for P availability (Figure 4). Soils with pH near neutral often have the smallest capacity to adsorb P, since these soils have lower concentrations of oxides or carbonates than acid soils or alkaline soils, respectively. Soils with a pH near neutral also have the smallest capacity to precipitate P. Phosphorus forms relatively insoluble precipitates with Al and Fe at low (acid) pH and Ca and Mg at high (alkaline) pH.
- **Soil organic matter and microbial activity** – Organic matter competes with P for adsorption sites. Therefore, P from sources such as manure, with large amounts of organic matter, may not be adsorbed as much or as strongly as P from inorganic sources such as synthetic fertilizers. Decomposition of organic matter by soil microorganisms also produces CO_2 which dissolves in water to form carbonic acid, increasing the solubility of Ca-P and Mg-P precipitates in high pH soils.
- **Degree of P saturation** – Soils that already contain large amounts of P relative to their P retention capacity (such as soils that have a history of repeated, high P applications), have the ability to retain less additional P because they have fewer unoccupied adsorption sites than similar soils with small amounts of P. This is one of the reasons why soils with high concentrations of soil test P are likely to lose more P to runoff than soils with low concentrations of soil test P.
- **Soil temperature** – Precipitation and dissolution reactions are slower in cold soils than in warm soils. Therefore, the precipitation of recently added soluble P from manure or fertilizer is slower in cold soils than in warm soils, slowing the conversion of added P to less soluble forms and preserving the P in highly available forms. However, the dissolution of stable forms of soil P is also slower in cold soils, resulting in slow release of P from the soil's reserves. Therefore, during the early spring, when Manitoba soils are cold, our crops are very reliant on P applied near the seed row for early season P uptake and seedling vigour (Grant et al. 2001).

Losses of P from Soil

Three transport mechanisms account for the loss of P from soil: erosion of P on soil particles, runoff of dissolved P and leaching of P to groundwater (Figure 10). In addition to these losses from soil, manure P can also be lost directly, as incidental loss.

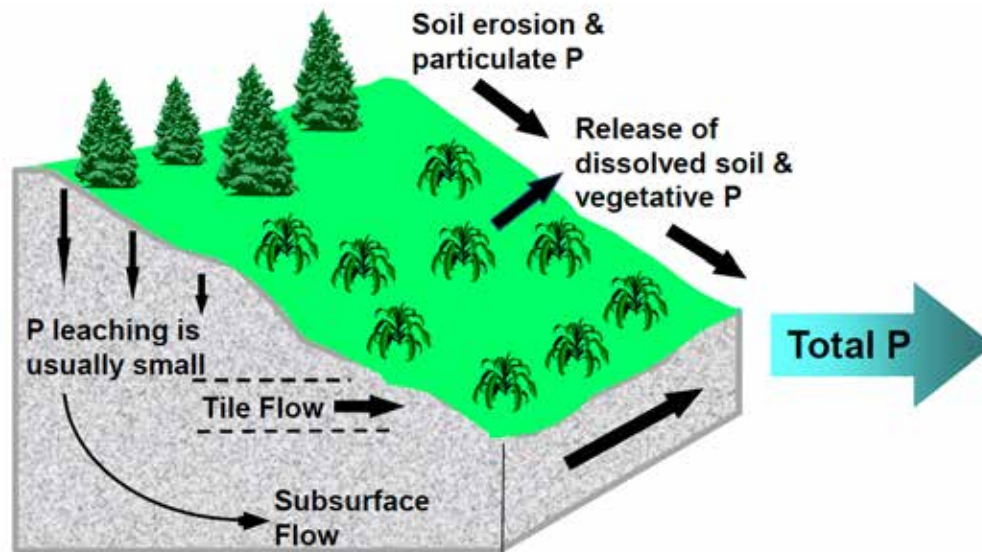


Figure 10 | Phosphorus can be transported in dissolved and particulate forms to surface water along surface or subsurface pathways. (Adapted from Sharpley 2007).

Runoff – Runoff occurs when rainfall or snowmelt exceeds the infiltration rate of the soil. Runoff will carry away dissolved P.

In Manitoba, most of the P lost from agricultural land to surface water is in the dissolved form (Glozier et al. 2006; Sheppard et al. 2006; Tiessen et al. 2010) because the majority of agricultural land is nearly level, the climate is relatively cold and dry and most runoff occurs as a result of snowmelt processes over frozen soil (Salvano et al. 2009, Tiessen et al. 2010). Once dissolved P enters a surface water pathway, it can be transported for long distances and is very difficult to intercept, compared to particulate P.





Soil erosion by water – Water erosion is the detachment, movement and removal of soil from the land surface in runoff. Soil erosion by water carries away the dissolved P in the runoff as well as the organic P and P that is associated with the soil particles (particulate P).

Soil erosion by water is an important pathway for P loss where land is steeply sloped and rainfall is the dominant cause of runoff (ex: in the Eastern and Southern U.S. and most of Europe). Transport distances for particulate forms of P are relatively short and losses of this form of P can be reduced with erosion control beneficial management practices.

Factors that affect the risk of P loss in runoff and water erosion include:

- **Infiltration rate** – Runoff and/or erosion losses are greatest in soils with slow or restricted water infiltration. Infiltration rate may be impeded due to:
 - **Soil texture** – Fine textured soils have smaller pores and, therefore, slower infiltration rates than coarse textured soils.
 - **Frozen soil** – Frozen soil near the surface impedes infiltration.
 - **Compaction** – Intensive tillage, heavy equipment or livestock can cause soil compaction.
 - **Surface crusting** – Soil crusts are created when the soil structure at the surface is destroyed by water and then dries leaving a thin, dense, somewhat continuous seal.
- **Slope** – Areas with steep and/or long slopes are most susceptible to water erosion.
- **Inundation and ponding** – Surface soil that has been in extensive contact with water, such as in flooded and depressional areas, is at increased risk of losing P when the water runs off the surface.
- **Connectivity to surface water** – Agricultural soils that are connected to ditches or streams provide a direct pathway for contaminated runoff to enter surface water bodies.
- **Climate** – In Manitoba, most of the runoff occurs during the spring when large amounts of snow melt rapidly over frozen, impermeable soils. The degree of erosion during snowmelt is highly variable, depending on the extent that the surface soil has thawed during the runoff event.

Agricultural areas of Manitoba with a long term history of less evaporation, less transpiration and/or more precipitation (ex: eastern Manitoba) are generally more susceptible to runoff than drier areas (ex: western Manitoba).

- **Weather** – Wet weather increases the risk of runoff and erosion, especially when the wet weather occurs during periods of low water use by crops. The risk of runoff and erosion is most significant during intense and/or prolonged rainfall.
- **Tillage** – Water erosion losses are greater under intensive tillage and annual crop production than under conservation tillage and perennial forage production. Recent studies near Miami, MB have shown that although conservation tillage may have lower erosion losses of particulate P than conventional tillage, total losses of P are greater with conservation tillage due to substantial increases in losses of dissolved P (Tiessen et al. 2010).
- **Soil test P** – Soils with high concentrations of soil test P are likely to lose more P to runoff than soils with low concentrations of soil test P. In Manitoba soils, the relationship between the concentration of P in runoff and the concentration of soil test extractable P is linear (Figure 11, Sawka 2009).

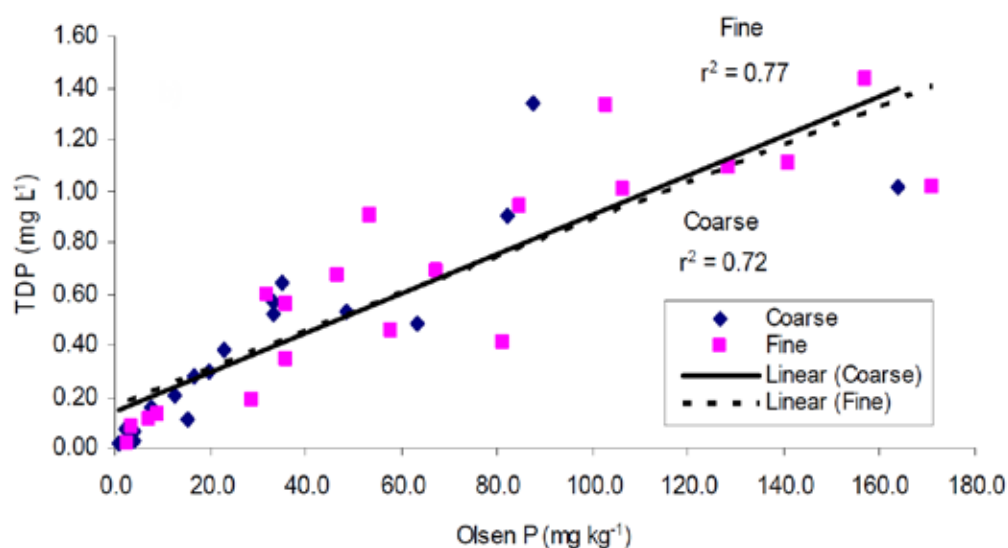


Figure 11 | Olsen soil test P and total dissolved P concentrations in simulated runoff are strongly related for coarse-textured (sandy soils) and fine-textured (loamy or clay) soils in Manitoba (Sawka 2009).

- **Crop type** – Land under perennial forage is less likely than annual crop land to have substantial runoff and erosion losses because the perennial forage uses more water and the crop canopy protects the soil throughout the year. The risk of runoff and erosion losses from long season annual crops is less than from short season annual crops for the same reasons. Row crops increase the susceptibility of the soil to erosion compared to solid-seeded crops as the soil between plant rows is not protected.

The decreased runoff volume from crops that use more water can be offset by increased concentrations of P in runoff if large amounts of P-rich crop residues are left on the surface of the soil during snowmelt.

- **Summerfallow** – Summerfallow leaves the soil very vulnerable to P loss from runoff and erosion. Manure application to summerfallow is prohibited in Manitoba.
- **Artificial drainage** – Improved surface drainage generally increases the risk of runoff and erosion losses. However, subsurface drainage (ex: tile drainage) may reduce the risk of runoff and erosion losses by reducing water flow over the soil surface.

Soil erosion by wind – Wind erosion is the detachment, movement and removal of soil from the land surface in wind. Soil erosion by wind carries away the P that is associated with the soil particles.

Soil erosion by tillage – Tillage erosion is the progressive downslope movement of soil by tillage causing loss of soil on hilltops and the accumulation of soil at the base of slopes. Soil erosion by tillage carries away the N that is associated with the soil particles. It can result in significant redistribution of nutrients in the field.

Direct loss – Direct or incidental loss is the loss of fertilizer or manure to water before interacting significantly with soil. It can result from over-application, heavy rainfall immediately following application or application directly into a waterway (including ditches). Direct losses of manure can also be substantial if manure is applied onto frozen soils or snow in the winter, where the manure can be directly transported to surface water during snowmelt runoff.

The main concern for P loss to surface and ground water is eutrophication of surface water. Eutrophication results in a decline in water quality characterized by increasing growth of algae and surface scums, followed by depleted oxygen concentrations, foul odours, sedimentation, fish kills and release of algal toxins. The P responsible for eutrophication originates from a variety of sources, not only from livestock production and other agricultural activities, but also from natural ecosystems and direct discharge of human and industrial wastewater.

Eutrophication occurs at very low concentrations of P in water. For example, the Canadian Council of Ministers of Environment classifies water bodies as eutrophic if the total P content is within a range of 0.035 – 0.10 ppm (Table 2.7; CCME 2004), which is only 35 to 100 parts per billion. Such small amounts of P loss are not agronomically significant, but are very significant from an environmental perspective. In addition, the environmental impacts of these small losses of P occur many miles from the P source (ex: Lake Winnipeg) and reflect the cumulative impact of all sources.



P leaching – In most soils, the majority of the P is held very strongly by precipitation and adsorption reactions. Although the P retention capacity in most soils is large, it is never infinite. Therefore, if the rate of P application exceeds the rate of removal by the crop, soil test P levels will increase and the risk of P leaching may increase.

In the Prairies, the dry climate and the soils' large capacity for P retention are unlikely to allow significant amounts of P loss by leaching, unless extremely large quantities of excess P are applied. As a result, research with field application of livestock manure in the Prairies usually measures insignificant amounts of manure P leaching (Akinremi 2005; Ominski et al. 2007). However, some leaching of cattle feedlot manure P to a depth of 60 cm was observed in an irrigated trial in Alberta (Olson et al. 2010). Also, Campbell and Racz (1975) observed leaching of manure P under cattle feedlots in Manitoba. In their study, although manure P moved faster than inorganic P, the concentrations of organic P in soil samples from under cattle feedlots were low, caused by a greater mineralization of organic P under manured than non-manured conditions.

Phosphorus in groundwater does not pose an immediate environmental or human health risk. However, a substantial portion of groundwater often eventually flows into surface water bodies, where the discharge of groundwater P can cause eutrophication of surface water over the long term.

Factors that affect the risk of P leaching and contamination of ground water include:

Soils with the greatest risk of leaching include high P soils with a low P retention capacity, such as coarse textured (sandy) soils, or with preferential flow pathways such as cracking clay soils, or fields with earthworm or plant root channels or tile drains. Avoiding excess accumulation of P in areas susceptible to P leaching greatly reduces this risk.

- **Soil texture** – Sandy soils generally have the highest risk of P leaching due to their low water holding capacity and rapid rate of water infiltration and percolation.
- **Preferential flow** – Soils with significant preferential flow pathways such as cracks, earthworm holes and root channels, can increase the risk of groundwater contamination.
 - **Tillage** – Leaching losses may increase where reduced tillage increases preferential flow paths by old root and/or earthworm channels. Therefore, where cracks and channels increase the risk of preferential flow and groundwater contamination, tillage may be recommended prior to nutrient application.
- **Landscape position** – Depressional or low areas of the landscape that are recharge areas are more susceptible to leaching because they collect water from surrounding areas, especially during heavy rainfall events or during snowmelt runoff over frozen soils.
- **Depth to ground water** – The risk of groundwater contamination increases where there is a shallow depth to the water table or a seasonally fluctuating water table.
- **Climate and weather** – Agricultural areas of Manitoba with a long term history of less evaporation, less transpiration and/or more precipitation (ex: eastern Manitoba) are generally more susceptible to leaching than drier areas (ex: western Manitoba).

Although climate is an important long term factor to consider, the short term effects of wet weather periods is also an important factor that increasing leaching losses, especially when the wet weather occurs during periods of low water use by crops.

- **Season** – In Manitoba, the risk of leaching is lower during the growing season, when evapotranspiration is high relative to precipitation. However, in the fall and early spring periods, the risk of leaching is higher because evapotranspiration is low relative to precipitation. Also, snow accumulates for several months over winter, melts over a relatively short period in the spring, resulting in runoff on frozen soils entering depressional areas, dramatically increasing the water load and risk of leaching in these areas.
- **Rates of P application** – Repeated applications of manure at P rates that exceed crop P removal will increase soil test P levels and may increase the risk of P leaching.
- **Water use by crops** – Crops that grow over a long period generally consume more water than crops that grow over a short period. The risk and quantity of leaching is much less for perennial forages (ex: grass and alfalfa) compared to short season annual crops such as wheat, oats, barley or canola in part because they use more water. The leaching risks for fall planted crops (ex: fall rye, winter wheat) and long season crops are also lower than for short season annual crops.
- **Root density** – Crops with dense or deep rooting systems reduce the risk of leaching over crops with sparse or shallow rooting systems. For example, alfalfa has both a dense and deep rooting system, is a large user of water and P, and presents a low risk of P leaching.
- **Summerfallow** – With no significant plant growth or transpiration, summerfallow increases the risk of leaching even in the relatively dry Prairie climate.
- **Artificial drainage** – Improved surface drainage generally reduces the risk of leaching by reducing excess ponding and infiltration of water. Subsurface drainage (ex: tile drainage) may also reduce the risk of P reaching ground water by intercepting water and P before or as they enter the water table. However, both of these types of drainage may increase the risk of P loading to surface water.

Potassium (K)

Similar to N and P, K is a macronutrient that is required by crops in large amounts. Crops require nearly as much K as N. Unlike N and P, K is abundant in most of Manitoba's clay and loam soils. Therefore, crop responses to fertilizer or manure K are unlikely to occur except in sandy or organic (peat) soils.

When K is added to soil, it enters the soil K cycle (Figure 12). The K cycle can be thought of in terms of gains, removals, internal transformations and losses of K in soil.

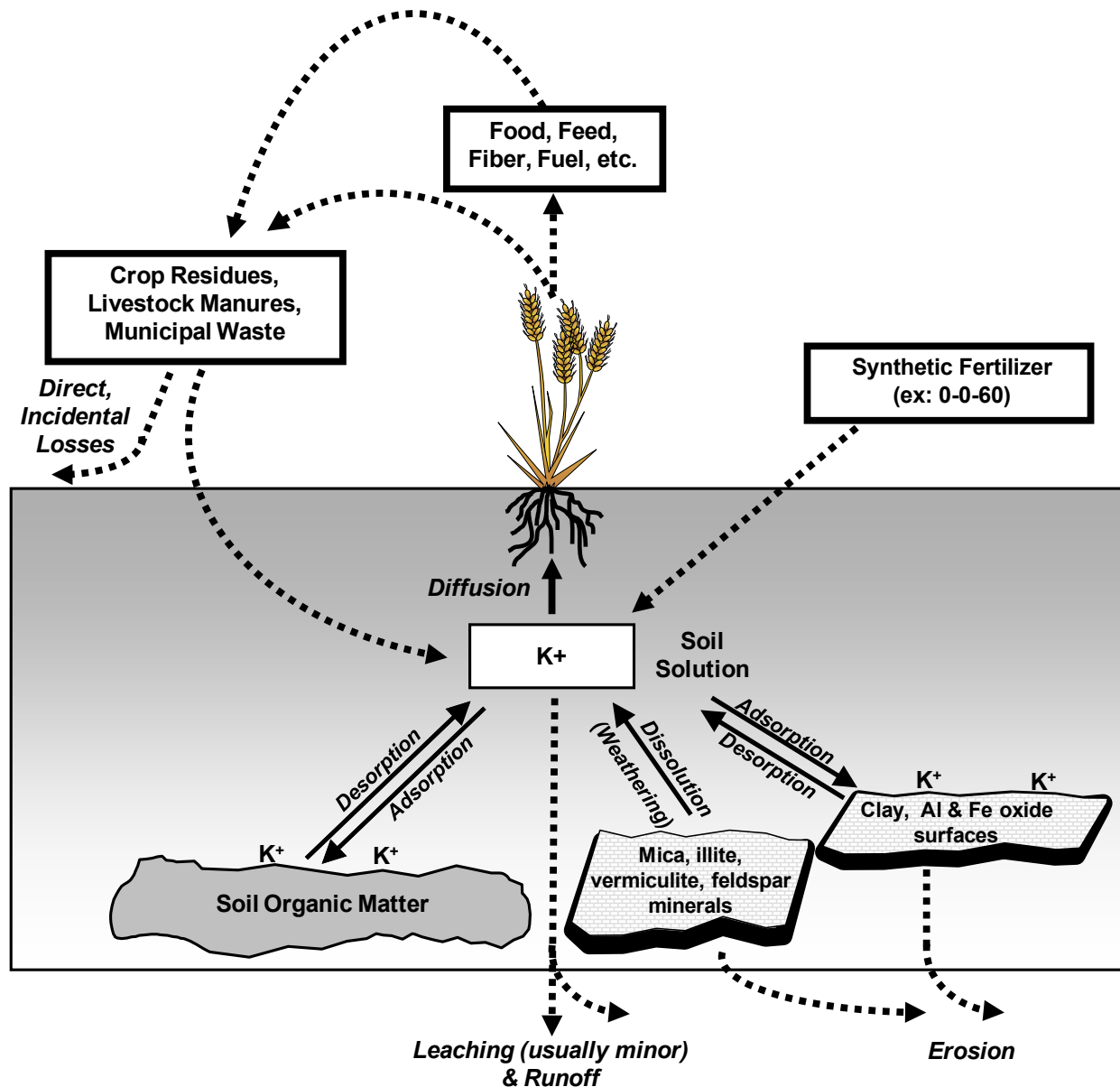


Figure 12 | The K cycle. Dashed lines represent K gains or losses in the soil system; solid lines represent internal transformations within the soil system.

Gains of K to Soil

Synthetic K fertilizer – Potassium is applied to some Manitoba soils as potash fertilizer (0-0-60). However, the amounts of K fertilizer applied in Manitoba are very small, compared to N and P fertilizer because of substantial reserves of K in most clay and loam soils.

Livestock manures – Most manures contain substantial amounts of K. The K in manure is in an inorganic, highly soluble form and is considered to be 90-100 per cent as available to crops as synthetic fertilizer K (Schoenau and Davis 2006).

Repeated applications of livestock manure increase plant available K in soil. High concentrations of plant available K can suppress plant uptake of divalent cations such as Ca^{2+} or Mg^{2+} . Feeding high K forages to cattle or sheep increases the risk of dietary imbalances, such as grass tetany, milk fever and udder oedema. Testing to determine the risk of dietary imbalances should be considered for all feeds grown on heavily manured soils.

Municipal biosolids, industrial waste and other amendments – Municipal biosolids, industrial waste and other amendments are a source of K.

Plant residues – Potassium that is contained in unharvested plant residue returns to the soil K cycle. The amount of K that is returned to the soil depends on how much residue is left behind and the concentration of K in the residue. The K in mature plants is highly soluble; therefore, it leaches readily out of the residue and into soil with rainfall (Lupwayi et al. 2006).

Crop Uptake and Removal of K from Soil

Plant uptake of available K – Plant roots take up K in the free ion form (K^+). The K in soil solution and on the cation exchange sites together make up the total pool of plant available K. Plant available K can be measured in the lab and is commonly referred to as extractable or exchangeable soil K.

In contrast to N and P, K is used almost exclusively as a tool for plant growth, rather than as a structural component. For example, K is used to activate enzymes for photosynthesis, starch formation and protein synthesis. Potassium is also very important as a tool for controlling water balance in the plant, through maintenance of internal salt concentrations in cells and controlling the opening and closing of leaf stomata.

Crop removal of K at harvest – Since K is used mainly as a tool for plant growth, most of the plant's K is found in the vegetative tissue (ex: in straw of cereal crops). As such, the rate of crop K removal is highly dependent on whether only the grain is removed or the whole plant (ex: baling straw or harvesting a crop for hay or silage).

Movement of K to Plant Roots

The main process for K movement to plant roots is diffusion.

Diffusion of K to roots – Potassium is soluble in water but its positive charge is attracted to the negatively charged surfaces of clay, organic matter and oxides. Therefore, K is not very mobile in soil and travels to roots over short distances by diffusion. As with all nutrients that move by diffusion to plant roots, this process is fastest in warm, moist, neutral pH, medium to coarse textured soils (ex: loams to sands) with sufficient supplies of soil test K. Similar to P, applied K should be placed as close as possible to the seed row, where early season access and root density are greatest.

Internal Transformations of K in Soil

The main transformations of K in soil are adsorption, desorption and dissolution. Potassium in plant material is not bonded to carbon materials and does not undergo microbial mineralization or immobilization processes. As well, because K is readily soluble, it is not subject to significant precipitation reactions.

Adsorption of K – Adsorption is the process whereby positively charged potassium ions (K^+) become attached to negatively charged surfaces. Concentrations of K in soil solution are usually very low because most soils have sufficient negative charge or cation exchange capacity (CEC) to hold substantial quantities of K on their surfaces by adsorption. There are two types of adsorption: exchangeable and non-exchangeable.

Exchangeable K adsorption – Most soils adsorb K in a manner that is sufficiently strong to resist leaching losses, but not strong enough to prevent exchange with other cations and uptake by plant roots. When K is applied to soil, it is quickly adsorbed onto the soil's cation exchange sites, increasing exchangeable K concentrations in soil.

Non-exchangeable K – Some soils have minerals that trap K tightly between their layers, resulting in strongly adsorbed K that is released very slowly. This process is sometimes called "K fixation". Some sandy soils in Manitoba (ex: Almasippi soils on the western edges of the Red River Valley) have these types of minerals and can adsorb K strongly in this manner.

Desorption of K – Desorption is the opposite of adsorption whereby K detaches from negatively charged surfaces. The release of K from soil surfaces is affected by competition with other cations. A low concentration of K in the soil solution is maintained because the exchangeable K continuously replenishes the supply of K in solution in response to crop uptake during the growing season.

Dissolution of K during weathering of minerals – The vast majority of K in Prairie soils occurs as structural components within soil minerals such as micas in clay particles and feldspars in sand particles. These minerals slowly break down in soil due to physical and chemical weathering and release plant available K during the process. Once the mineral K is released by weathering, it is highly soluble, does not re-precipitate, and is quickly adsorbed onto negatively charged soil surfaces. Although weathering releases substantial amounts of K from micas in clay or clay loam soils, the rate of release from feldspars in sandy soils is far too slow to match crop uptake and removal. Therefore, sandy soils are often deficient in K and respond positively to application of K. Organic (peat) soils also respond frequently to K because these soils have very low concentrations of K bearing minerals.

Losses of K from Soil

Three transport mechanisms account for the loss of K from soil: leaching of K to groundwater, runoff of dissolved K and erosion of K associated with soil particles. In addition to these losses from soil, manure K can also be lost directly, as incidental loss.

The environmental concerns related to K loss are regarded as minor, compared to N and P losses.

Leaching of K to ground water – Leaching losses of K are generally negligible, except in very sandy soils, and are regarded as being of minor concern from an environmental or human health perspective. Continuous application of high rates of manure K in excess of crop removal, however, can saturate the soil's K retention capacity, resulting in small amounts of downward movement (Olson and Papworth 2006).

Runoff – Runoff occurs when rainfall or snowmelt exceeds the infiltration rate of the soil. Losses of dissolved soil K in runoff are very small, due to adsorption processes that keep K attached to the surfaces of soil particles in most soils. Losses of K from plant residues may be significant during spring runoff.

Soil Erosion by Water – Water erosion is the detachment, movement and removal of soil from the land surface in runoff. Soil erosion by water carries away the dissolved K in the runoff as well as the organic K and K that is associated with the soil particles (particulate K).

In Manitoba, loss of particulate K is not a common transport pathway for our relatively flat agricultural landscapes and dry, cold climate where snowmelt over frozen soils is the dominant form of runoff.

Direct loss – Direct or incidental loss is the loss of fertilizer or manure to water before interacting significantly with soil. It can result from over-application, heavy rainfall immediately following application or application directly into a waterway (including ditches). Direct losses of manure can also be substantial if manure is applied onto frozen soils or snow in the winter, where the manure can be directly transported to surface water during snowmelt runoff.

Sulphur (S)

Sulphur is a macronutrient, however, it is required by crops in much smaller quantities than N and K. Ensuring adequate S nutrition is important, especially for crops with high S demand.

Sulphur is abundant in most of Manitoba’s agricultural soils, mainly due to large reserves of calcium sulphate (gypsum, CaSO_4) in subsoils. However, well drained sandy soils, highly leached soils and some well drained areas of loam soils may be deficient in S. These soils require routine S fertilization, especially for crops that have large S requirements such as canola and alfalfa.

When S is applied to land, it enters the soil S cycle (Figure 13). The soil S cycle can be described in terms of gains, removals, internal transformations and losses.

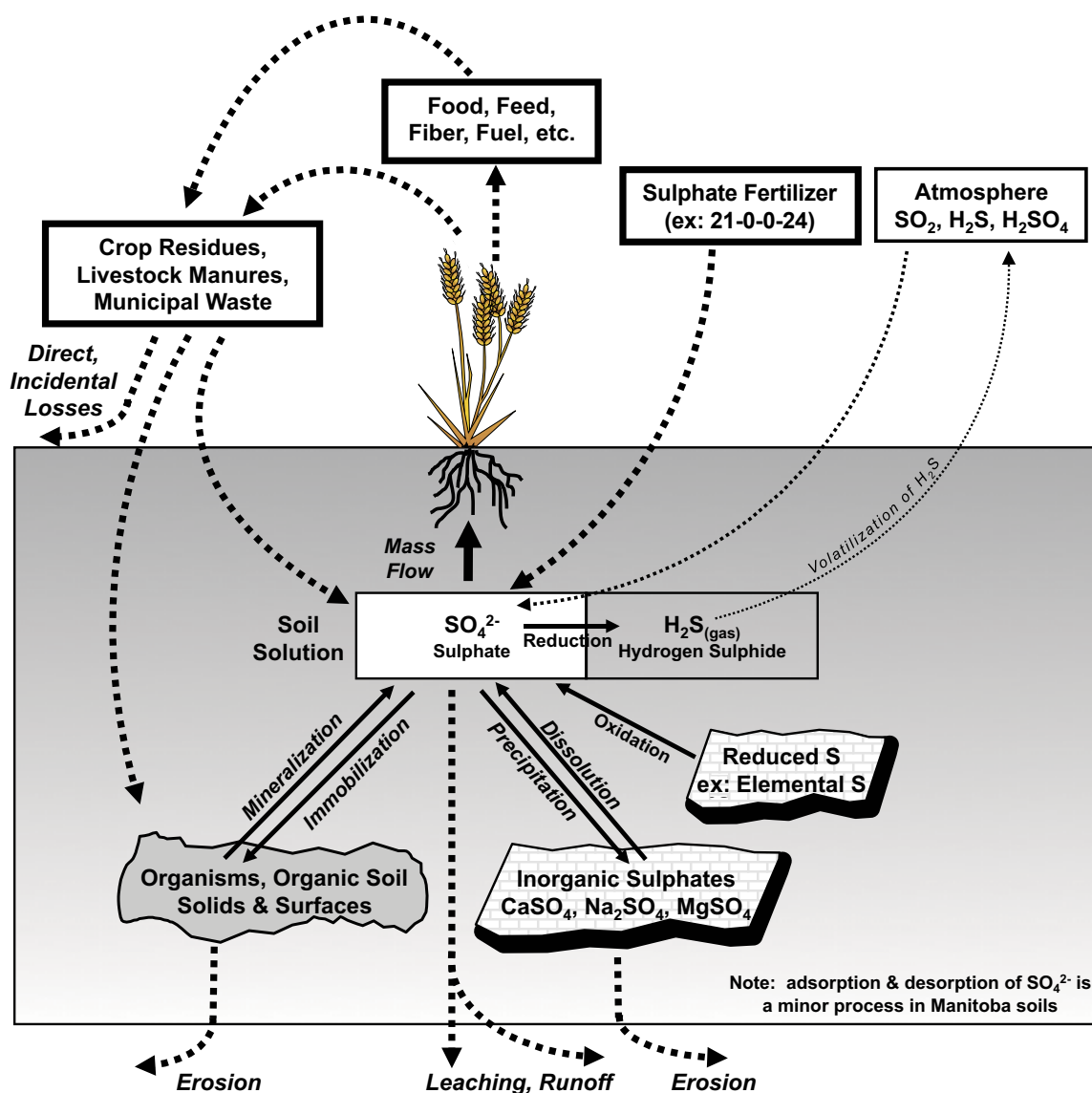


Figure 13 | The S cycle. Dashed lines represent S gains or losses in the soil system; solid lines represent internal transformations within the soil system.

Gains of S to Soil

Atmospheric deposition – Similar to N, significant amounts of S can be deposited onto agricultural land from the atmosphere, especially near industrialized areas where S emissions result in deposition of sulphuric acid (H_2SO_4) as “acid rain.” Atmospheric deposition can be substantial near coal-fired power plants, smelters, etc. However, atmospheric deposition of S in agricultural areas of Manitoba is very small and of little or no agronomic significance.

Synthetic S fertilizers – Sulphur is frequently applied as synthetic fertilizer (ex: ammonium sulphate (21-0-0-24)) to avoid the risk of S deficiency in crops such as canola, which have a large requirement for S. However, most soils in Manitoba contain sufficient amounts of S for most crops. Therefore, responses to S fertilizer are much rarer than responses to N and P on Manitoba soils.

Plant residues – The concentration of S relative to C in crop residues is sufficiently high that decomposition of crop residues releases more S than soil microbes require, resulting in net mineralization of S for the next crop. Therefore, crop residues are an important source of S in annual cropping systems.

Livestock manures – Sulphur is present in livestock manures in both organic and inorganic forms. However, as much as 95 per cent of the total S in manure is not readily available to plants (Eriksen 2009). The concentrations of plant available S in typical livestock manures are often low relative to the concentrations of N, P and K, especially in liquid manures. Therefore, application of manure to meet crop requirements for N may not supply sufficient amounts of S for crops that require large amounts of S (ex: canola and alfalfa). Alberta studies have measured N:S ratios from 7:1 to 17:1 for cattle manure and from 13:1 to 25:1 for pig slurry (Alberta Agriculture 2001). The majority of these N:S ratios are too large to ensure that canola will have sufficient S, since canola requires an N:S ratio of ~7:1.

Saskatchewan studies have shown crop responses to supplemental S fertilizer on manured soils in field trials where S deficiencies exist (Schoenau and Davis 2006). So, although livestock manures can provide S to crops, supplemental fertilizer S on S deficient soils that receive manure may also be required to meet crop needs.

Municipal biosolids, industrial waste and other amendments – Municipal biosolids, industrial waste and other amendments are sources of S.

Crop Uptake and Removal of S from Soil

Plant uptake of S – Sulphur is taken up by plants as sulphate (SO_4^{2-}) which is a readily soluble, oxidized anion. It is essential for the formation of amino acids and proteins and is required for three essential amino acids in particular: cysteine, cystine, and methionine. Sulphur bonds help to shape and stabilize proteins and also enable enzyme function.

Unlike N, plants cannot remobilize vegetative S from old plant tissue to young plant tissue. This lack of S mobility within the plant means that late season deficiencies of S have a disastrous effect on grain formation and crop yield, much more severe than for a nutrient such as N that is remobilized within the plant.

Crop removal of S at harvest – As with other nutrients, the net removal of S at harvest varies substantially with crop species, yield and the portion of the crop that is harvested. Approximately half of the S taken up by the crop is removed in the grain.

Movement of S to Plant Roots

Mass flow of sulphate (SO_4) to plant roots – Plant available SO_4 is not adsorbed in Manitoba soils and is sufficiently soluble that it moves to roots by mass flow, along with the water that is consumed by the plant to meet its normal transpirational needs. As a result of this process, SO_4 from the entire root zone is available for crop uptake.

Internal Transformations of S in Soil

Adsorption and desorption – Adsorption and desorption of SO_4 to and from soil surfaces are of negligible importance in Manitoba due to our soils' negatively charged surfaces that are unable to attract and hold the negatively charged SO_4 anions.

Precipitation and dissolution – Sulphate can react with Ca to form calcium sulphate (CaSO_4 or gypsum), which is only moderately soluble and can accumulate in Prairie subsoils where leaching intensity is often low. The deep reserves of gypsum-S become available to the crop only if crop roots grow into the subsoil. Therefore, if concentrations of plant available SO_4 in the surface soils are low, crops may experience early season S deficiencies. Also, subsoil gypsum-S can vary greatly within a field, depending on the degree of leaching within different locations in the landscape. The large variability of S reserves within a field mean that soil tests that measure adequate supplies of S in a composite soil sample may not account for localized areas of S deficiency.

Sulphate can also react with Mg to form magnesium sulphate (MgSO_4) and Na to form sodium sulphate (Na_2SO_4). However, both of these compounds are readily soluble. High concentrations of MgSO_4 and Na_2SO_4 are the leading cause of soil salinity in Manitoba.

Mineralization and immobilization – Soil organic matter contains large reserves of organic S. Therefore, mineralization and immobilization of S are important processes for the release and retention of plant available S, respectively.

A significant portion of the S in liquid and solid manures is present in organic form. Organic S must be mineralized into inorganic SO_4 by soil microorganisms before it becomes available to crops. The low concentrations of plant available S in manures are probably due, in part, to immobilization of plant available inorganic forms of S into organic forms during storage (Eriksen 2009).

In general, application of organic materials with a C:S ratio less than 200:1 will result in net mineralization, whereas ratios greater than 400:1 will lead to net immobilization. Most livestock manures have ratios of C:S that are less than 300:1; therefore immobilization of S following application of manure is unlikely (Eriksen 2009). However, the rate of mineralization and oxidation of S from manures may not be sufficient to meet the needs of crops with a high demand for S (Eriksen and Mortensen 1999).

Reduction – Microorganisms can use SO_4 as a substitute for O_2 during anaerobic respiration. This process is similar to denitrification, but with the SO_4 being reduced and hydrogen sulphide (H_2S) being generated. Conditions for this to occur must be much more anaerobic than for denitrification. Therefore, this process rarely occurs in Manitoba's cultivated agricultural soils. However, it does occur in the digestive tracts of livestock and in manure storages, especially liquid manure storages, decreasing the concentrations of plant available SO_4 in manure.

Oxidation – Reduced forms of S must be oxidized by soil microorganisms before they will become available for crop uptake. Reduced forms of S are rarely found under natural conditions in Manitoba's agricultural soils, however they may be applied to soil in manure, particularly liquid manure, or synthetic S fertilizers that contain S in the reduced elemental form.

Reduced forms of S include elemental S (S^0) in fertilizer and sulphides such as H_2S in livestock manure. Sulphate (SO_4) is the plant-available, oxidized form of S.

Losses of S from Soil

Losses of S from soil include volatilization, leaching, runoff, erosion and direct loss. Compared to N and P, the environmental risks associated with S losses are regarded as minor.

Volatilization of H_2S – Similar to NH_3 , if liquid manure is surface-applied H_2S can be volatilized. Hydrogen sulphide contributes to the odours generated during manure agitation and application.

Hydrogen sulphide (H_2S) is a colourless gas that smells like rotten eggs. It is extremely poisonous and can be deadly at low concentrations in poorly ventilated spaces.



Leaching – Sulphate S is moderately soluble and is not adsorbed to the surfaces of soil particles in Manitoba's agricultural soils. Therefore, SO_4 is regarded as reasonably mobile in soil and susceptible to leaching. However, SO_4 leaching is of negligible agronomic or environmental concern. For example, concentrations of SO_4 -S at depths below 15 cm were unaffected even after applying very high rates of cattle manure for 5 and 25 consecutive years (Hao and Chang 2003; Olson and Papworth 2006).

Runoff – Runoff occurs when rainfall or snowmelt exceeds the infiltration rate of the soil. The loss of dissolved S in runoff is generally not a concern for water quality, compared to losses of P and N.

Soil Erosion by Water – Water erosion is the detachment, movement and removal of soil from the land surface in runoff. Soil erosion by water carries away the dissolved S in the runoff as well as the organic S that is associated with the soil particles. However, erosion is not a common transport pathway for our relatively flat agricultural landscapes and dry, cold climate, where snowmelt over frozen soils is the dominant form of runoff.

Direct loss – Similar to any other component of manure, direct, incidental losses of manure S can occur if manure is applied onto frozen soils or snow, or immediately prior to heavy rainfall.

Micronutrients and Other Trace Elements

A trace element is a chemical element that is present in minute quantities in the environment or is required by plants or animals in minute quantities to maintain normal function.

Micronutrients are trace elements that are required by plants or animals in small amounts (generally less than 1 lb per acre in the case of crops). Each micronutrient has a range of safe and sufficient intake. Intake in excess of this range may be toxic and intake below this range may cause deficiency problems. The range of optimal intake for each micronutrient is specific to each plant or animal.

Excessive concentrations of trace elements in soil can cause problems for plant, animal and microbial life. For example, sheep are particularly sensitive to copper (Cu). In general, sheep need between 5-25ppm Cu in their total diet depending upon the interaction of Cu with molybdenum (Mo) and sulphur (S) coming from other sources. More than 25 ppm of Cu in total sheep diet can cause toxicity. In contrast to sheep, cattle can tolerate concentrations of Cu 10 times higher in their diet. Pigs and chickens can tolerate even higher levels.

Micronutrients essential for plant growth that are derived mainly from soil include:

Mo	Molybdenum
B	Boron
Cl	Chlorine (some Cl is also derived from the atmosphere)
Cu	Copper
Zn	Zinc
Mn	Manganese
Fe	Iron

Where micronutrient concentrations in soil are deficient, application can improve crop growth. However, repeated or heavy applications of micronutrients can lead to accumulations of these elements in soil that may pose a risk to soil, plant, animal or human health.

There are also several elements that may be regarded as essential but which have little, if any, practical importance for crop nutrient management in the Canadian Prairies. These include nickel (Ni), sodium (Na), silicon (Si), vanadium (V), fluorine (F), iodine (I), strontium (Sr), barium (Ba), aluminum (Al), and cobalt (Co) which are sufficient in Manitoba soils for Manitoba crops.

Elements that are not essential for plant growth but are essential for animal nutrition, such as selenium (Se), are often added to livestock feeds in Manitoba.

Trace elements that are not essential for plant or animal growth have very little or no effect on growth when present at normal or low concentrations. Again however, when the concentration of these elements is high, soil, plant, animal or human health may be adversely affected.

Some potentially toxic trace *metals* such as cadmium (Cd), lead (Pb) and mercury (Hg) have no beneficial role in plants and animals. Application of these metals can have negative effects on crop yield and/or crop quality when added in excess. Consumption of food or feed with a high concentration of metals, particularly over a long period of time, can lead to health problems in animals and humans. In addition, microbial processes and the activity of soil organisms are negatively affected at very high metal concentrations, reducing soil respiration, nutrient cycling, and enzymatic processes. Also, metals at very high concentrations may move to groundwater and or to surface waters thus reducing water quality and limiting use.

When micronutrients and other trace elements are applied to the soil, they enter the soil nutrient cycle which can be thought of in terms of gains, removals, internal transformations and losses (Figure 14).

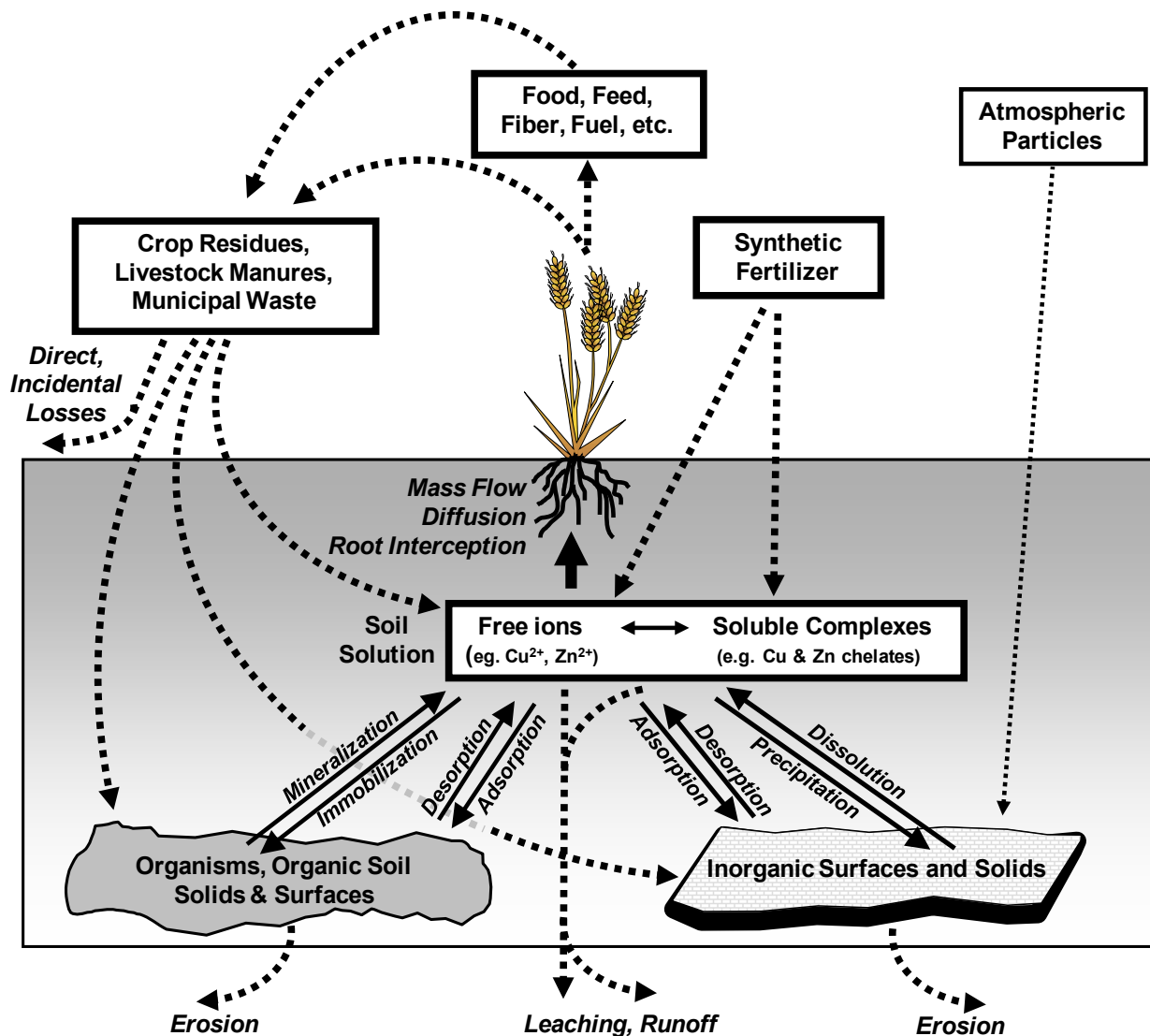


Figure 14 | Behaviour of micronutrients and other trace elements in soil is subject to the same processes of retention and release as for the macronutrients, except that formation of soluble complexes, such as chelates, plays a substantial role in determining their availability and mobility.

Gains of Micronutrients and Other Trace Elements to Soil

Parent Material – In their natural condition, soils contain highly variable concentrations of trace elements. Total concentrations of trace elements depend, in part, on parent material and soil forming processes, particularly weathering of rock fragments. Generally soils with shale parent material (clay soils) have higher trace element content than soils formed from granitic materials. Soils developed on limestone parent material generally have the lowest trace element contents.

Atmospheric Deposition – Atmospheric deposition of micronutrients and other trace elements onto agricultural soils can be from natural sources or pollution.

Natural Sources – Dust from soil and volcanic ash are sources of trace elements.

Combustion Processes – Combustion of coal, gasoline and other oil products results in atmospheric emission and deposition of trace elements.

Industrial Activities – Mining, smelting and some manufacturing processes are significant sources of trace elements.

Synthetic Fertilizers – Where micronutrient concentrations in soil are deficient, application of synthetic fertilizers containing these micronutrients can improve crop growth. Some fertilizers also contain trace elements that are not required by plants or animals including potentially toxic trace metals. Phosphorus fertilizers, for example, often contain Cd. The concentration of Cd in the fertilizer depends on how much Cd was in the rock from which the fertilizer was made. Long term use of fertilizers containing micronutrients and other trace elements may result in increased concentrations of these elements in soil.

Pesticides – Trace elements have been added to land in pesticides. For example, elevated lead and arsenic have been found in orchard soils where lead arsenate was used as a pesticide in the 1960s.

Irrigation Water – Micronutrients and other trace elements may be added to land in irrigation water.

Plant Residues – Micronutrients and other trace elements contained in unharvested plant residue eventually return to the soil nutrient cycle.

Livestock Manures – Livestock manure contains micronutrients and other trace elements. Manures can be excellent sources of essential nutrients on soils marginal or deficient in these elements. Thus, opportunities to recycle micronutrients in manure should be exploited in areas where soils are deficient in these elements.

The concentration of many of the trace elements in manure is generally low. Therefore, the short term risk of excessive accumulations of these micronutrients and trace elements is generally small if manure is applied at recommended rates and frequencies, especially under the new P based manure application regulations. For example, after three to seven consecutive annual applications of solid cattle manure and liquid pig manure at agronomic rates for crop N requirements at various sites in Saskatchewan, accumulations of copper, zinc and cadmium in soil were either not significant or very small (Qian et al. 2003; Lipoth and Schoenau 2007). Over the long term, however, large annual applications of manure may pose some risk (Benke et al. 2008).

Manure from livestock that are fed high levels of micronutrients, however, can contain significantly higher concentrations of those micronutrients. For example, very high concentrations for Cu and Zn were measured in manures from nursery piglets that were fed high rates of Cu and Zn (Sheppard and Sanipelli, 2012). Accumulation of these micronutrients in soil from repeated applications of manure high in these micronutrients was also measured (Sheppard and Sanipelli, 2012).

Municipal Biosolids, Industrial Waste and Other Amendments – Municipal biosolids, solid municipal waste and industrial wastes contain a variety of micronutrients and other trace elements. Various jurisdictions have guidelines for acceptable loadings of trace elements to soil for amendments such as municipal biosolids. These guidelines can be used to determine degree of risk to soil, plants and food or feed.

Crop Uptake and Removal of Micronutrients and Other Trace Elements from Soil

Crop uptake and removal of micronutrients and other trace elements is a function of crop type, soil type and the trace element.

Crop uptake of micronutrients and other trace elements from soil – Plants adsorb trace elements through their roots. Generally, trace elements must be in the free ion form before they can enter the root membrane. However, chelates and other soluble complexes can protect trace elements from precipitation and adsorption reactions (below), increasing the solubility of trace elements, and enhancing transport of trace elements to the root surface.

Chelation – Some trace elements bond with soluble organic compounds in soil to form ring complexes called chelates. Chelation increases the solubility of trace elements, preventing the formation of insoluble precipitates, and decreases the toxicity of some trace elements. Although chelated micronutrients may not be immediately available, they are mobile and can quickly convert to plant available forms near the root surface.

Plants can also absorb trace elements through their leaves and foliar uptake can be a significant route of entry for elements such as cadmium, copper and zinc. For manure application foliar absorption may be of consequence only when manure is applied to perennial forage and/or sprayed onto crops.

Soil and climatic conditions as well as management affect trace element absorption. For example, restricted root growth due to cold, wet soil usually reduces trace element uptake.

Crop removal of micronutrients and other trace elements at harvest – The quantity of micronutrients and other trace elements removed when a crop is harvested is a function of yield and concentration of the element in the plant material that is removed.

Trace elements are not uniformly distributed in plant tissues. The amounts of micronutrients and other trace elements in plant parts is determined by: 1) the concentration and species of the trace element in soil solution, 2) movement of the trace element to the roots, 3) absorption of the trace element from the root surface into the root and 4) translocation of the trace element to the various plant parts. Translocation is a function of element, plant type, age of plant and plant part. In general, Cl, B, Zn, Mo, and Se are easily translocated and others such as Cu, Mn and Fe are not as easily translocated within most crops.

Usually seeds contain lower concentrations of most trace elements than the vegetative parts; therefore, the part of the plant that is harvested is important to consider in soils that have high concentrations of trace elements.

Movement of Micronutrients and Other Trace Elements to Plant Roots

Sufficient supplies of micronutrients move to roots by all three mechanisms of transport: mass flow, diffusion and root interception.

Mass flow occurs as soluble nutrients and nutrient complexes in the soil solution flow towards roots as the plant takes up water. The amount of nutrient moved by this process is determined by the amount of available water in the soil, the concentration of nutrient in soil solution and the volume of water consumed by the plant (ex: mass flow is less in dry soil and during cool weather). Therefore, this process is significant for soluble and chelated micronutrients.

Diffusion is driven by micro-scale differences in the soil solution's nutrient concentrations and a variety of environmental factors that influence nutrient movement. This process is important for micronutrients that are strongly retained by soil and therefore are present at very low concentrations in soil solution. During diffusion, random movement of ions in soil solution slowly and steadily moves nutrients from areas of relatively high concentration (on or near soil particles) to areas of relatively low concentration (on or near the root). Plants take advantage of this process by depleting the concentration of nutrients near the root surface to levels that are below that of the bulk soil solution. Given the micro-scale nature of this process, diffusion distances are very short (much less than 1 mm) and high densities of roots are required.

Root interception is the process whereby nutrients are taken up as a result of direct contact between roots and soil particles. This type of uptake is not very efficient, because roots have direct contact with less than 1 per cent of soil volume and less than 5 per cent of available nutrients.

Internal Transformations of Micronutrients and Other Trace Elements in Soil

Most prairie soils have a large capacity to retain trace elements in highly insoluble and/or adsorbed forms. It should be noted, however, that no soil has an infinite capacity to retain trace elements in insoluble forms. Adsorption and precipitation play important roles in retaining trace elements in soils. The concentration of most trace elements in the soil *solution* is usually very low, due to the soil's capacity to retain trace elements by adsorption and precipitation.

Precipitation occurs when water soluble forms of trace elements consolidate and separate from the soil solution to form a solid, inorganic mineral. Precipitation decreases the supply of trace elements that is immediately available to plants.

Dissolution is the opposite of precipitation and occurs when inorganic minerals release water soluble forms of trace elements from their bulk solid reserves into solution where they become available for plant uptake.

Adsorption is the process by which trace elements become attached to surfaces of soil organic matter and some inorganic minerals.

Exchangeable adsorption of micronutrients and other trace elements occurs when micronutrients and other trace elements are held weakly and remain available to plants.

Non-exchangeable adsorption of micronutrients and other trace elements occurs when micronutrients and other trace elements are held strongly by soil constituents such as soil organic matter or Fe and Al oxides, substantially reducing the plant availability of these elements.

Desorption is the opposite of adsorption and occurs when adsorbed trace elements are released from the surface of soil organic matter and inorganic minerals.

The balance between **adsorption** and **desorption** depends on the nature and strength of attraction between the soil surface and the element.

Mineralization and immobilization of micronutrients and trace elements are not well understood. In cases where the micronutrients are very strongly bonded to the organic matter, mineralization of the organic matter may be necessary before the micronutrient is released into soil solution for plant uptake.

Soil characteristics that play a large role in the internal transformations of micronutrients and other trace elements include:

- **Cation exchange capacity (CEC)** – The total number of exchangeable cations that a soil can hold depends on the number of exchange sites and is called **cation exchange capacity (CEC)**. The CEC of a soil is dependent on the amount and type of clay, organic matter, and amount of Fe, Al and Mn oxides. Each of these soil components has different retention properties, but generally the higher the CEC the greater is the capacity of the soil surfaces to adsorb trace elements without potential deleterious effects on plants and/or soil biological functions. Soil organic matter and clay particles have large surface areas and have a large number of exchange sites. Most Prairie soils have reasonably high CEC due to sufficient concentrations of clay and organic matter, combined with neutral to alkaline pH (see pH below). Sand particles have a much smaller surface area and fewer exchange sites; therefore sandy soils have a lower CEC.
- **Soil Organic Matter** – In addition to its role in retaining some trace elements (such as Zn) in exchangeable forms, soil organic matter also has the capacity to adsorb other trace elements (such as Cu and Mn) very strongly in non-exchangeable forms that are relatively stable and unavailable for uptake by plants or movement with water. Therefore, crops grown on soils that have received heavy applications of solid and semi-solid manure may be susceptible to Cu and Mn deficiencies.

For example, 25 years of annual applications of cattle manure to soil in Southern Alberta increased organic matter concentrations substantially. Soil test extractable Cu concentrations declined significantly whereas extractable Zn concentrations increased (Benke et al. 2008).

Organic matter enhances the formation of chelates and other soluble organic complexes, helping to dissolve and mobilize some trace elements. These soluble organic complexes allow some micronutrients to move more readily to plant roots for uptake by crops. However, these soluble complexes also enable these micronutrients to run off more easily into surface water or leach more easily into ground water, especially in sandy soils.

- **Soil pH** – The capacity and strength of adsorption varies substantially with soil pH, especially for oxide surfaces. Positively charged ions such as Cu^{2+} , Zn^{2+} and Cd^{2+} are adsorbed in greater quantities and with greater strength at high soil pH, as the soil surfaces become more negatively charged. In general, soils with high concentrations of clay, organic matter, and oxides (high cation exchange capacity), plus high pH have the greatest ability to retain positively charged elements such as Zn^{2+} and Cu^{2+} . Conversely, many negatively charged ions such as selenate (SeO_4^{2-}) become more available at high soil pH.

The pH of surface soil of most Manitoba soils is near neutral or alkaline and thus soil pH is not an environmental limitation for manure application in the short term because most of the trace elements added will be adsorbed and not be mobile and/or highly bioavailable. Some caution will need to be exercised with respect to loadings of trace elements such as Zn and Cu on low pH soils (< pH 6.5) particularly if the soil is of sandy texture and low in organic matter. Also long term high loading of elements such as Se to soil of high pH is also of concern.

Soil pH also plays an important role in the solubility of trace elements such as Mn and Fe. For example, the solubility of Fe and Mn oxides decrease by 1000 and 100 times, respectively, for every pH unit increase (Havlin et al. 2005). However, these micronutrients are rarely limiting for crop production in Manitoba soils.

- **Aeration** – Aeration directly affects the availability of Mn, and Fe and indirectly affects the availability of many other nutrients. In a well-aerated soil, the supply of oxygen is sufficient to maintain normal, aerobic respiration by soil microbes. Excess water or compaction in agricultural soils causes anaerobic or reducing conditions because the soil microorganisms quickly consume all the oxygen dissolved in the soil water for respiration. In the absence of oxygen, other substances such as Mn and Fe oxides will be used as oxidizing agents for respiration and become reduced in the process, dramatically increasing their solubility and plant availability.

For example, in experiments in Manitoba with Red River and Lakeland clay soils, the concentrations of Fe in soil solution increased from 0.00 to 1.25 ppm and from 0.10 to 12.20 ppm after 35 days of flooding. Concentrations of Mn increased from 0.00 to 4.00 ppm and from 0.20 to 7.40 ppm, respectively for the Red River and Lakeland soils over the same period (Olomu, 1971).

Anaerobic conditions also affect soil pH, generally lowering the pH of high pH (alkaline) soils and raising the pH of low pH (acid) soils. The pH of a water-logged high pH soils is decreased due to accumulation of CO₂ as carbonic acid. For example, researchers at the University of Manitoba have measured decreases in pH of 1.0 and 0.9 units within two weeks of flooding Red River and Lakeland soils, respectively (Olomu 1971). In low pH soils, the solubilisation of Fe and Mn oxides consumes H⁺ from soil solution, decreasing soil acidity and raising soil pH. These changes in pH then affect the retention of trace elements.

Losses of Micronutrients and Other Trace Elements from Soil

Losses of micronutrients and other trace elements from soil include: volatilization; leaching to groundwater; loss to surface water through runoff and erosion; and direct or incidental loss.

Sheppard et al. (2009) derived trace element removal and loss rates for As, Cd, Pb, Se, Cu and Zn for Canadian soils. Leaching and crop removal were the two dominant soil depletion mechanisms for all elements except for Se, where volatilization was the dominant mechanism. Based on the medians for As, Cd and Se, loss by leaching was more than twice that by crop removal whereas the reverse was noted for Cu.

Crop removal and loss of trace elements from agricultural soils are generally very small and less than the rates at which many trace elements are deposited or applied (Sheppard et al. 2009). Therefore, most soils used in agriculture will increase in trace metal concentration as a result of agricultural activity and other human activities. In general a doubling of trace metal concentration in Canadian soils is likely during the next 100 years (Sheppard et al. 2009). Therefore, trace metal accumulation is a long term concern that should be considered prior to any deleterious effects to crop yield, quality and/or the environment.

Volatilization – Chemical and biochemical reactions induced by soil microorganisms can volatilize As, Hg and Se in soils. Selected plants are also known to absorb Se from soil and volatilize it. Soil conditions, however, are rarely optimal for substantial amounts of As, Hg or Se to be volatilized.

Leaching – The risk of leaching for most trace elements, except for B, Cl and Se, is low and most of the trace elements added are retained in the top layers of soil because these trace elements are tightly bonded to oxides and/or to organic matter and highly insoluble. As well, the formation of soluble complexes such as chelates may increase the risk of leaching micronutrients and other trace elements, particularly in sandy soils.

Despite the retention of most trace elements by soil constituents, downward movement to depths of 120 cm has been noted in fine-textured (clay) soils as a result of preferential flow in soil cracks on soil drying.

Runoff – As with leaching, the formation of soluble complexes such as chelates may increase the risk of micronutrients and other trace elements leaving the field in runoff.

Erosion by water – Erosion of soil rich in trace elements may increase the risk of trace element contamination of surface water. For example, although oxides such as iron oxide strongly retain large amounts of trace elements in an aerobic environment, these oxides can release trace elements when the oxide becomes solubilized in an anaerobic environment such as sediment.

Direct loss – Direct or “incidental” loss is the loss of fertilizer or manure to water before interacting significantly with soil. It can result from over-application, heavy rainfall immediately following application or application directly into a waterway (including ditches). Direct losses of manure can also be substantial if manure is applied onto frozen soils or snow in the winter, where the manure can be directly transported to surface water during snowmelt runoff.

Salts and Sodium

Soil salinity is the soluble salt content of soil. The process of increasing the salt content of a soil is called **salinization**. Salinity develops naturally (from processes such as mineral weathering, groundwater recharge and discharge) and can be modified by human activities on the landscape (such as irrigation and artificial drainage).

Groundwater Recharge areas occur where the net movement of water is downward. In these areas infiltration exceeds the storage capacity of the soil and moves downward to the zone of saturation (groundwater). The surface and subsoil are usually non calcareous and non-saline.

Groundwater Discharge areas occur where the net movement of water is upward. In these areas, the zone of saturation is at or near the surface and the net movement of water is towards the ground surface. Discharge may be focused in areas such as springs, weeping embankments and baseflow discharge, or it may be diffuse over larger areas of the landscape. These areas may be characterized by soils that are calcareous and often have a build-up of salts.

Elevated soil salinity can impede the ability of a growing plant to absorb water from the soil, even in conditions of otherwise adequate soil moisture. Different crops have different tolerances to soil salinity. Therefore, salinization will reduce the types of crops that can be produced on salt-affected land.

Soil salinity can be measured in the laboratory and is expressed as electrical conductivity (EC) in units such as deci-siemens per metre (dS/m), milli-siemens per centimetre (mS/cm), or millimhos per centimetre (mmhos/cm), all of which are equivalent. Generally, soils with EC values less than 2 are regarded as non-saline. Soils with EC values greater than 2 create problems for pulses and vegetables. EC values greater than 4 create problems for other crops.

Soil sodicity is caused by a high proportion of Na on the soil's cation exchange relative to Ca and Mg. It can adversely affect soil structure by making the soil very susceptible to crusting, impeding water infiltration and hindering root growth.

Sodicity is expressed as the soil solution's sodium adsorption ratio (SAR) which is calculated from the measured concentration of Na, Ca and Mg. Soils with SAR values less than 6 are generally regarded as non-sodic and satisfactory for crop production. Soils with SAR values between 6 and 13 are regarded as slightly sodic. Soils with values greater than 13 are regarded as sodic and, therefore, problematic.

Gains of Salts and Sodium to Soil

Saline groundwater – Long term continuous discharge of saline groundwater results in salinization of soils.

Application of synthetic fertilizers – A variety of fertilizers are available with salts in varying proportions. For example, potash is potassium chloride, a salt of K and Cl.

Municipal biosolids, municipal effluents, industrial waste and other amendments – Municipal and industrial wastes and other amendments contain a variety of salts that contribute to soil salinity when applied to land.

Livestock manures – Manure contains the salts of NH_4 , Ca, Mg, K and Na. The salt content of manure is highly variable, depending on the livestock species, diet formulation and salt content of the livestock drinking water. Therefore, when manure is applied to soil, varying quantities of salts are also applied.

In areas of adequate precipitation and drainage, application of manure at agronomic rates does not create a problem for crop production over the short term because the salts are leached through the soil profile. For example, after five to eight years of applying liquid pig manure and solid cattle manure at agronomic rates at various sites in Saskatchewan, Schoenau et al. (2005) reported small, but agronomically insignificant increases in soil salinity and sodicity. In areas with borderline saline soils and low annual precipitation, however, manure additions may cause a salt build-up in excess of crop tolerance, even if applied at agronomic rates.

In an Alberta study, salinization was measured following 25 years of heavy, annual applications of salt-rich cattle manure (Hao and Chang, 2003). The cattle manure was applied at rates of 0, 30, 60 and 90 $\text{T ha}^{-1} \text{ yr}^{-1}$ under non-irrigated and at 0, 60, 120 and 180 $\text{T ha}^{-1} \text{ yr}^{-1}$ under irrigated conditions. The total amounts of soluble salts added to soil over the 25 years were substantial. Soil EC, soluble Na and K, and SAR all increased with rate of application. The authors concluded that applying repeated, heavy rates of cattle manure that is high in salt to soil is not sustainable over the long term because it will lead to soil salinization.

In Manitoba, Fitzgerald and Racz (2001) calculated loadings of several major water soluble elements including Na from pig manures applied rates that supplied 70 kg available N ha^{-1} . Their calculations showed that salts and Na were applied at rates that exceeded crop removals. Therefore, repeated application of pig manure could increase soil salinity in areas of low precipitation and drainage where the salts are not leached through the soil profile or on borderline saline soils.

Losses of Salts and Sodium from Soil

Leaching of salts – Leaching is the downward movement of water and soluble substances in soil below the root zone. Leaching of salts by rainfall or irrigation prevents salinization of soils that receive repeated applications of manure and other amendments that contain salts. However, leaching of salts is an environmental concern when it occurs at rates high enough to contribute to groundwater contamination.

Soil pH

Soil pH is a measure of soil acidity ($\text{pH} < 7$) or alkalinity ($\text{pH} > 7$). Acidic (low pH) soils have a high concentration of hydrogen ions (H^+) in soil solution while alkaline or basic (high pH) soils have a low concentration of H^+ in soil solution. Since hydrogen ions affect the charge on soil surfaces and the forms of nutrients in solution, pH plays an important role in determining the amount and strength of adsorption of nutrients to soil surfaces. Hydrogen ions also participate in many precipitation and dissolution reactions; therefore, pH also plays an important role in the solubility of nutrients in soil.

Very low soil pH (acidic soil) results in high concentrations of aluminum and/or manganese in soil solution which can reduce plant growth and soil microbial processes. Very high soil pH can result in major and minor element deficiencies due to the extreme insolubility of some components in soil. Soil pHs that are slightly acidic to neutral ($\text{pH} 6.0\text{--}7.5$) are often the best for overall availability of nutrients (Figure 4), plant growth and microbial processes.

Effects of manure on soil pH – The ability of manure to influence soil pH depends on the amounts of various constituents in the manure. When manure is applied to soil, nitrification and decomposition produce various acids. Nitrification is the conversion of NH_4 to NO_3 by soil microorganisms. It releases H^+ into soil solution. Organic acids and carbonic acid are produced during the decomposition of the organic fraction of the manure (Chang et al. 1991). Liquid and poultry manures have relatively high concentrations of $\text{NH}_4\text{-N}$ and low concentrations of organic matter; therefore, as is the case with NH_4 -forming synthetic fertilizers, liquid and poultry manures may lower soil pH.

Solid manures contain significantly more organic matter than liquid manures. The organic matter added with manure acts as a pH buffer, releasing H^+ (acidity) in response to the addition of alkaline materials and accepting H^+ in response to the addition of acidic materials. Some solid manures also contain significant concentrations of Ca, Mg and lime (CaCO_3). The organic matter and lime-like materials in solid manure tend to offset the acidity produced when the NH_4 in the manure is converted to NO_3 .

Application of solid cattle manure moves soil pH towards neutrality in acidic (Benke et al. 2009) and alkaline soils (Chang et al. 1990; Hao and Chang 2002), thus improving nutrient availability especially for P and micronutrients (Figure 4). This move towards neutrality is also favourable for plant growth and a variety of beneficial microbial processes. Therefore, solid manure should be regarded not only as a source of nutrients, but also as a beneficial soil conditioner (Schoenau and Davis 2006). The overall effect of manures on the pH of calcareous prairie soils, however, is probably small due to high concentrations of Ca, Mg and Ca/Mg carbonate in these soils.

Soil Organic Matter and Microbial Activity

Soil Organic Matter

Soil organic matter encompasses the vast array of C compounds in soil and includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms and substances synthesized by the soil population. These compounds play a variety of roles in soil nutrient, water and biological cycles.

Soil organic matter improves the following soil properties:

- **Structure, tilth and aeration** – Improving soil structure makes the soil more friable, less compacted, easier to till and improves aeration.
- **Water infiltration rate** – Increasing water infiltration rate reduces runoff and increases the amount of water available to crops. Reducing runoff also decreases sediment and soluble nutrient transfer from soils to surface waters. Walters et al. (2002) showed that applications of composted beef cattle manure to soils decreased runoff and that sediment loss was directly proportional to runoff volume. Increased water infiltration rate and reduced runoff volume may translate to less nutrient loss from fields that receive manure than equivalent applications of N and P as commercial fertilizer due to the addition of organic matter with the manure.
- **Water holding capacity** – Increased water holding capacity is of particular importance in sandy soils and in areas of low precipitation. The organic fraction in very sandy soil is responsible for much of its total water holding as well as available water capacity.
- **Cation exchange capacity (CEC)** – Soil organic matter has a cation exchange capacity of about 200 to 250 cmole_c/kg, or about 2 to 3 times that of the highest cation exchange capacity for clay minerals. Coarse sandy soils, low in organic matter, have cation exchange capacities of 2 to 5 cmole_c/kg. Thus, the concentration of organic matter in soil greatly influences cation exchange capacity, particularly for sandy soils.
- **Buffering pH** – Soil organic matter acts as a pH buffer or stabilizer, releasing H⁺ in response to the addition of alkaline materials and adsorbing H⁺ in response to the addition of acidic materials.
- **Chelation of micronutrients and trace elements** – Some micronutrients and trace elements bond with soluble organic compounds to form chelates and other soluble organic complexes helping to dissolve and mobilize micronutrients and trace metals. Chelation increases the solubility of nutrients, preventing the formation of insoluble precipitates and decreases the toxicity of some micronutrients. Although chelated nutrients may not be immediately available, they are mobile and can quickly convert to plant available forms near the root surface.

Because organic matter contributes to improved soil properties, increasing soil organic matter generally results in increased soil productivity. But on many soils, suitable soil properties occur at relatively low levels of organic matter (2-4 per cent).

The largest source of organic matter added to soil is the residue remaining following crop production. Fertilization indirectly increases soil organic matter levels by boosting crop yields and, consequently, the amount of residues returned to the soil. Soil organic matter cannot be increased quickly, however, because only a small fraction of the crop residues added to soil remain as soil organic matter following decomposition.

Effects of manure on soil organic matter – Manure is an excellent source of nutrients as well as organic matter. Manure indirectly increases soil organic matter because it increases crop yields and the amount of residues returned to the soil. Organic matter is also added directly to the soil with manure application, particularly solid manure.

The organic matter content of manure is highly variable. Solid and semi-solid manures have higher organic matter contents than liquid manure because of added bedding. Long term applications of solid manure can result in very large increases in soil organic matter (Sommerfeldt et al. 1988; Hao et al. 2003). Although liquid manure adds less organic matter to soil than solid manure, these additions are still greater than with synthetic fertilizers. King (2002) found that three annual applications of liquid pig manure to forage increased the light fraction of organic matter in soil, even though total organic C content in soil was not significantly affected over this relatively short period.

The light fraction of organic matter is a highly reactive (labile) pool of organic matter consisting of relatively new, uncomplexed organic residues in various stages of decomposition. The heavy fraction of organic matter, on the other hand, consists of highly decomposed, stable, humic substances that form organo-mineral complexes or are protected within stable soil aggregates.

Soil Microbial Activity

Soil microbial activity is important because microbial processes are responsible for decomposition of crop residues and mineralization of organic nutrients to inorganic forms for plant uptake. It is generally accepted that the larger the soil microbial community and the greater the diversity, the greater the potential for nutrient mineralization.

Application of manure to soil affects microbial communities. Manure additions to soil have beneficial effects on nutrient cycling, soil microbial biomass, soil microbial activity and enzymatic processes, provided that the manures do not contain high concentrations of undesirable constituents (ex: potentially toxic trace metals).

An enzyme is a protein that speeds up a biochemical reaction. The enzymes involved in mineralization exist both inside and outside of microbial cells.

Microbial biomass – Addition of manure increases soil microbial biomass as the organic materials provides an energy source for microbial growth. For example, in Quebec soils, Lalande et al. (2000) showed that microbial biomass carbon was greater in surface soils after 17 applications of hog manure than in untreated soils. In Manitoba soils, Czurak-Dainard (2005) found that fields with longer histories of pig and cattle manure application generally contained higher concentrations of microbial biomass carbon than soils with no manure. Manure amended soils also exhibited higher concentrations of microbial biomass N than soils without manure. Cattle and hog manure had similar effects on soil microbial biomass carbon and N.

Microbial activity – In her study with Manitoba soils, Czurak-Dainard (2005) found highly variable rates of soil respiration in manured and unmanured soils, with no significant differences between these two groups of soils. However, she found that manured soils had significantly greater concentrations of dehydrogenase enzyme, another measure of microbial activity, than unmanured soils. Fields treated with cattle manure had greater concentrations of dehydrogenase than fields treated with hog manure.

Enzyme activity – In addition to increasing dehydrogenase activity, addition of manure to soil increases the activity of a variety of other soil enzymes (Lalande et al., 2000). For example, the activity of urease, the enzyme that converts urea in manure or synthetic fertilizer to ammonium N, increases with application of manure (Czurak-Dainard 2005). Amounts of phosphatase in soils, enzymes that mineralize organic P is often greater in manure-amended than non-amended soils (Lalande et al. 2000). However, in Manitoba soils, Czurak-Dainard (2005) found no significant differences in phosphatase activity between manured and unmanured fields and treatments. In this Manitoba study the effects of manure on the activity of glutaminase, a N mineralizing soil enzyme, were not consistent across sampling periods and varied by type of crop. However, for late summer sampling dates, the average for manure-amended soils was greater than for non-amended soils and for early and late summer sampling dates, soils amended with cattle manure had more glutaminase activity than soils treated with hog manure.

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