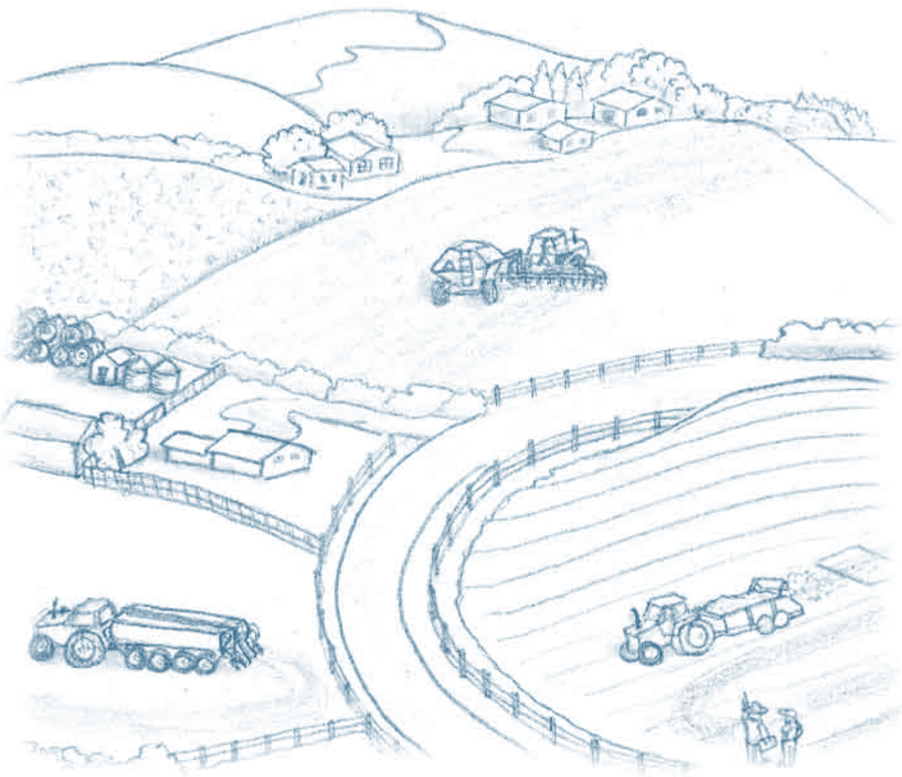
Chapter 2.2

Basic Soil-Plant Interactions



learning objectives

- Describe the process of cation exchange in soils and its implications for crop nutrition.
- Briefly explain the importance of soil organic matter for crop production.
- Describe how acid soil conditions can limit crop growth.
- Explain how salinity can limit crop growth.

This chapter will discuss soil characteristics and processes that influence plant nutrient availability including: ion exchange in soils, organic matter, pH (acidity and alkalinity), and salinity.

Important Terms

Table 2.2.1 Key Terms and Definitions

Term	Definition
Aerobic	The presence of oxygen.
Aggregate	A soil structure unit formed from primary soil mineral particles (sand, silt, clay) and organic matter that are grouped together.
Anaerobic	The absence of oxygen.
Anion	An atom or group of atoms (e.g., a molecule) with a net negative charge.
Base Saturation	Is the percentage of total cation exchange capacity occupied by base cations such as calcium, magnesium, sodium and potassium.
Buffering Capacity	The resistance of a soil to change in pH.
Calcium Carbonate Equivalent	The carbonate content of a liming material that is calculated as if all the carbonate is in the form of calcium carbonate.
Cation	An atom or group of atoms (e.g., a molecule) with a net positive charge.
Cation Exchange Capacity	The capacity of a soil for exchange of positively charged ions between the soil and the soil solution.
Ions	Are atoms or groups of atoms (e.g., a molecule) that carry an electrical charge due to the loss or addition of one or more electrons.
Osmotic Stress	The adverse response of a plant to a high salt concentration in the soil relative to the plant.
Saline Seep	Intermittent or continuous saline discharge at or near the soil surface under dryland conditions.
Salt Index	Expresses a fertilizer's potential to cause salt injury in germinating seedlings. It is based on a relative rating to sodium nitrate that is assigned an index value of 100.
Soil Solution	The liquid phase of the soil and its solutes, consisting of ions dissociated from the surfaces of the soil particles, and other soluble materials.
Tilth	The physical condition of the soil, especially in relation to its suitability for tilling, planting or growing a crop.

Ion Exchange in Soils

Ion exchange is the movement of ions (charged nutrients) between soil particle surfaces and the soil solution. It is the most critical soil process that affects crop nutrient availability.

Soil particle surfaces carry static electric charge. While soil particle surfaces can have both positive and negative charges, most Alberta soils carry a net negative charge. The location where ions interact with a charged soil particle is called an exchange site. Negatively charged exchange sites attract positively charged ions (cations) such as potassium

(K^+) or calcium (Ca^{2+}) and positively charged sites attract negatively charged ions (anions) such as nitrate (NO_3^-) and chloride (Cl^-).

Adsorption retains nutrients in the root zone making them easily accessible to growing crops. Adsorbed cations are loosely held to the negatively charged surfaces of soil particles. This association is strong enough that adsorbed ions resist being leached by the downward movement of water through the soil profile. However, it is also weak enough for adsorbed ions to be replaced by other cations in soil solution. This substitution, known as cation exchange, occurs largely through competition between ions for the negatively charged exchange sites on the particle surface. The common cations in soil are listed below, in order of increasing adsorption strength:

$Na^+ < K^+ = NH_4^+ < Mg^{2+} = Ca^{2+} < Al^{3+} < H^+$

The amount of exchangeable cations per unit weight of soil (on a dry basis) is referred to as cation exchange capacity (CEC). It estimates the number of exchange sites in a given soil sample that would be capable of holding positively charged crop nutrients. The larger the CEC, the more cations the soil can hold. Increasing the organic matter content of soils with low clay content will help to increase the CEC. Managing soil pH will also help optimize the CEC.

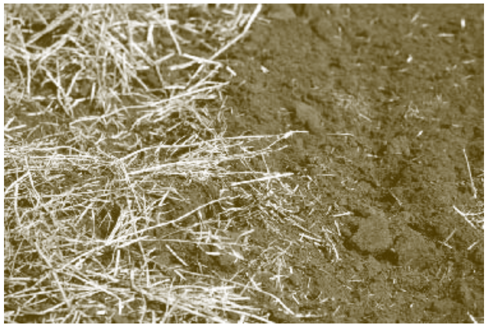
Soil Fertility Implications of CEC

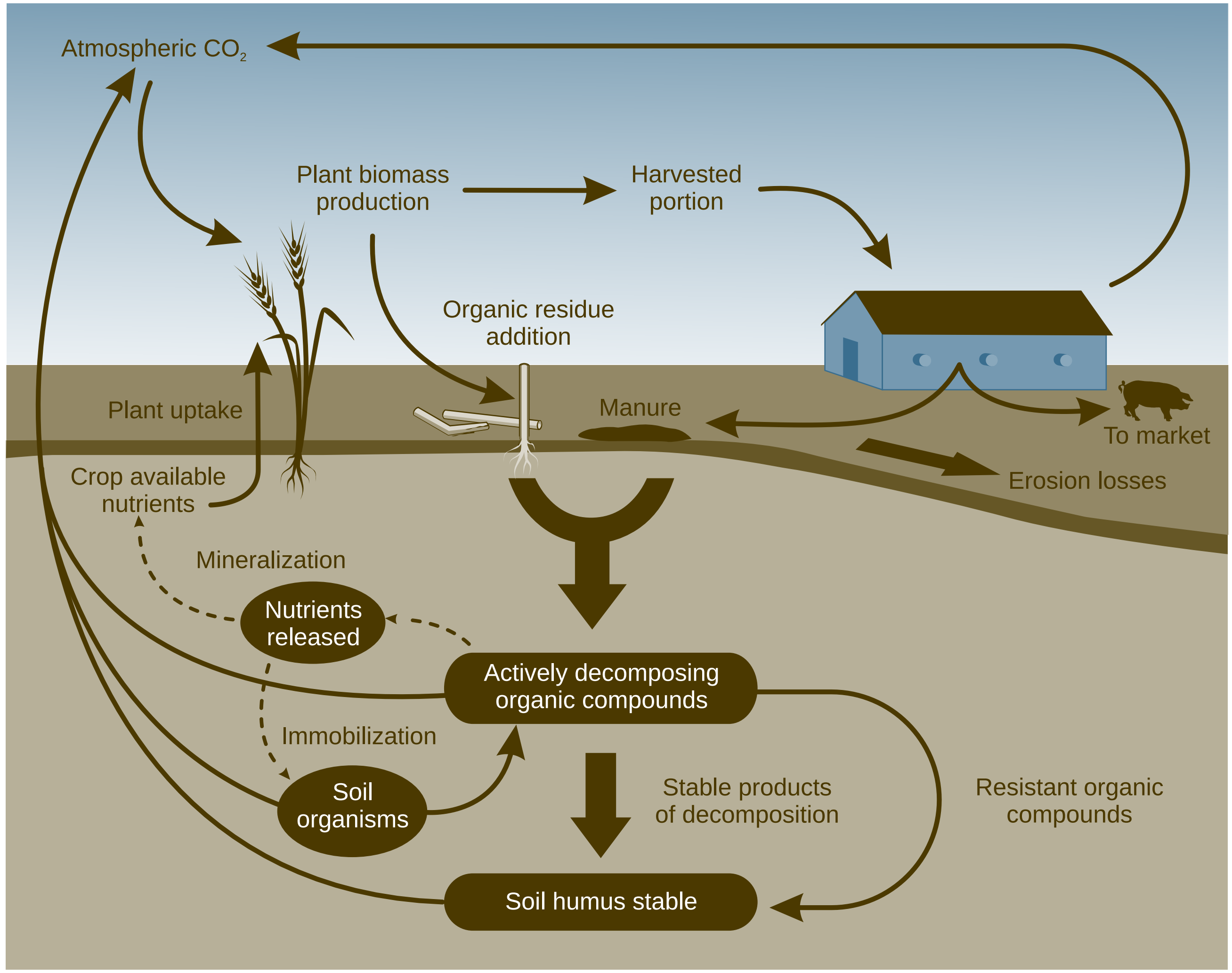
Two soil characteristics related to CEC are base saturation and buffering capacity. Base saturation refers to the percentage of the CEC occupied by K^+, Ca^{2+}, Mg^{2+}, and Na^+. Soils with higher percent base saturation have higher levels of available K^+, Ca^{2+}, and Mg^{2+} for growing crops.

Buffering capacity refers to the ability of a soil to replenish ions in soil solution. Soils with a high buffering capacity usually have large amounts of clay and organic matter. Soils with lower buffering capacity have a limited ability to replenish nutrients; therefore, they require more frequent nutrient additions to maintain fertility.

Organic Matter

Soil organic matter consists of materials, such as animal and plant residues, at various stages of decay. The organic matter content of a soil depends on the balance of two activities—the addition of organic residues to the soil and the decomposition of residues by soil macro- and microorganisms (Figure 2.2.1). The result of decomposition is a dark, stable end product (i.e., it does not change much with time) called humus. Over the long-term, however, all nutrients found in soil organic matter are converted into simple end products such as carbon dioxide, water and nutrients.





Created by Len Kryzanowski

Figure 2.2.1 The Agricultural Organic Matter Cycle

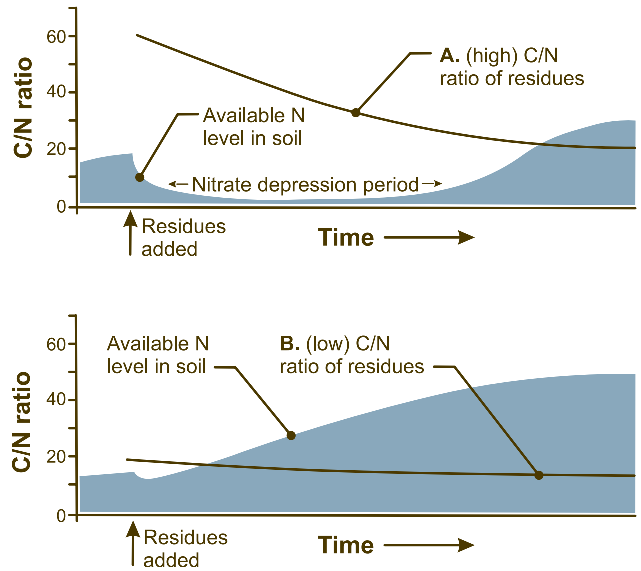
Generally, the environmental factors that influence plant growth also impact the activity of soil organisms and the rate of organic matter decomposition. These factors — aeration, moisture, temperature, and nutrient availability — are described in more detail below:

- Decomposition is an aerobic process (i.e., requires oxygen). Soil conditions that limit aeration (e.g., water logging, compaction) will slow decomposition.
- Decomposition is optimal when the soil is near or slightly wetter than field capacity. Extreme moisture conditions (i.e., too dry or too wet) can impede decomposition.
- Optimal soil temperature for decomposer microbes is in the range of 25 to 40°C. Soil temperatures in Alberta are typically below this range; therefore, decomposition is much slower during spring and fall.
- Soil organisms have specific nutrient requirements to function. Microbial growth will be limited if any nutrient is lacking in the system, resulting in a reduced rate of decomposition.

The rate of decomposition varies through the year, between years and even across the landscape as environmental factors change.

Carbon to Nitrogen (C:N) Ratio: Organic Matter Cycling and Nutrient Release

The C:N ratio in soils and residues has a significant impact on decomposition and nutrient release. The C:N ratio in soils is about 10:1. Adding organic residues to the soil changes the C:N ratio. Decomposition is slowed when C:N ratio is high (greater than 30:1) and rapid when C:N ratio is low (less than 20:1). Generally, N is released when C:N is less than 20:1, and N is immobilized when C:N is greater than 30:1 (Figure 2.2.2).



Adapted from Brady and Weil 2000

Figure 2.2.2 Effect of (A) High and, (B) Low C:N Ratio in Added Organic Residues on Soil Available N Level

Management Factors That Influence Organic Matter

Cultivation has the largest impact on soil organic matter content (Table 2.2.2). This management practice accelerates the loss of soil organic matter because:

- Cultivation aerates the soil and this promotes the activity of decomposer organisms.
- Bare soil warms faster in the spring and this increases the activity of soil organisms and creates a wider window for decomposition during the growing season.
- Cultivation reduces ground cover and this increases the risk of soil erosion. Surface soil is the most susceptible to loss and contains the majority of soil organic matter.
- Cultivation physically mixes crop residues into the soil where decomposition occurs.

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Cultivating fallow repeatedly promotes decomposition and organic matter loss throughout the season. Reducing tillage helps to preserve soil organic matter.

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An advantage of manure application (primarily solid manure) to soil is that it directly and indirectly contributes to soil organic matter. In contrast, commercial fertilizers indirectly contribute to soil organic matter by increasing crop yield and residue.

Table 2.2.2 Changes in Organic Matter Content (%) of Alberta Soils Due to Cultivation

Condition	% Organic Matter in Alberta Soil Zones				
	Black	Dark Brown	Brown	Dark Gray	Gray
Native state	6-10	4-6	4-5	4-5	1-2
Under cultivation	4-6	3-4	2-3	2-3	1-2

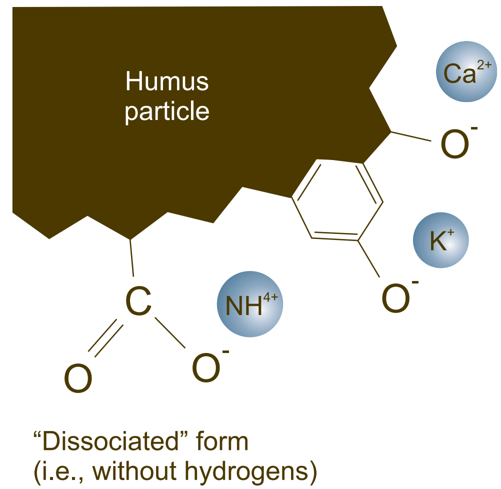
Source: Lickacz and Penney 2001

Management practices that help build soil organic matter include applying solid or composted livestock manure, more root and above ground crop residue production, reduced tillage, continuous cropping, direct seeding, avoiding straw removal, green manuring and perennial forage production. Optimizing soil fertility can also help build soil organic matter. Healthy, vigorous crops provide denser ground cover, which reduces the risk of erosion. High yield crops also leave greater volumes of organic residues in the form of roots, stems and other unharvested materials.

Soil Fertility Implications of Organic Matter

Organic matter has a large influence on soil fertility for crop production. It exerts this influence in several ways:

- It is an important source of nutrients required by crops and is a critical component of nutrient cycling in soils. Organic matter can be described as a "revolving nutrient bank account".
- It increases cation exchange capacity of soils by providing a large number of additional exchange sites (Figure 2.2.3). This additional exchange capacity is pH dependent.
- It improves soil structure, aggregate stability (measure of ability for soil particles to withstand disintegration) and tilth. These properties increase water infiltration and reduce water erosion, which is a significant mode of nutrient and organic matter loss.



Adapted from Brady and Weil 2000

Figure 2.2.3 Chemical Groups in Organic Matter Responsible for the High CEC of Organic Matter

pH

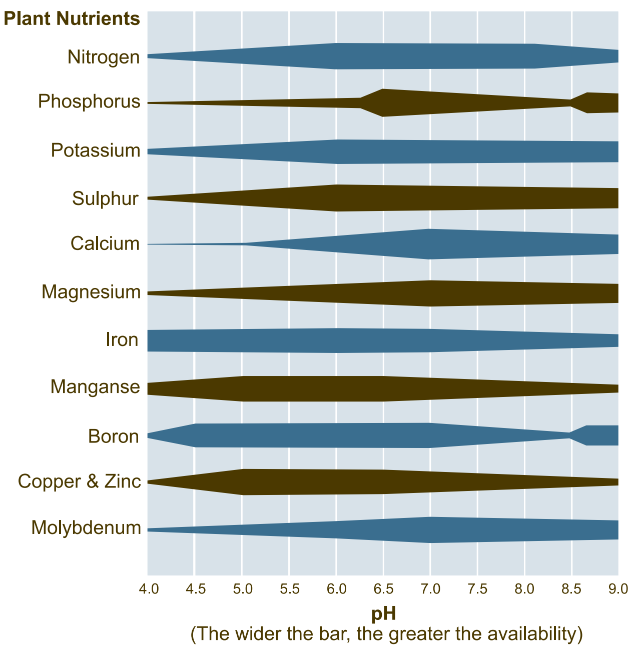
The pH of a soil is a measure of the concentration of hydrogen ions (H^+) in soil solution. It is expressed on a logarithmic (power of 10) scale, which ranges from 1 to 14. A one-point change on the pH scale represents a 10-fold change in the acidity of a solution (e.g., a solution with pH 4 has 10 times the concentration of hydrogen ions than a solution with a pH of 5 and 100 times more than a solution with a pH of 6).

A neutral soil has a pH near 7. Acidic soils have a pH of less than 6, while basic or alkaline soils have a pH greater than 7. Crops differ in their tolerance to pH conditions, but most crops grown in Alberta prefer a pH in the range of pH 6.5 to 7.

Soil Fertility and Management Implications of pH

There are several ways that pH affects soil fertility and management:

- Microorganisms involved in nutrient cycling are sensitive to large shifts in pH. Nutrient cycling is slowed or stopped if microbial populations are affected.
- Soil pH affects nutrient solubility and can alter the form and availability of nutrients (Figure 2.2.4). Under low pH conditions, some nutrients become less available to plants because their chemical structure changes (e.g., P). In other cases, nutrients become unavailable because they bind tightly to soil particles.



Source: AF

Figure 2.2.4 Nutrient Availability as Affected by pH

- Low pH conditions reduce soil base saturation by displacing plant nutrients (e.g., Ca^{2+} and K^{+}) from exchange sites with H^{+} and soluble aluminum (Al^{3+}) ions. Nutrients displaced from exchange sites can be lost or leached from the system and are no longer available to plants.
- Plant species vary in their acidity tolerance (Figure 2.2.5). This is strongly influenced by a plant's sensitivity to levels of soluble aluminum (Al^{3+}), which increases substantially under acidic conditions.
- Crops produced in soils outside their acidity tolerance range will result in reduced yields. Under acidic conditions, nutrient requirements should be adjusted on the basis of crop type and pH level for anticipated reduced yield potential.

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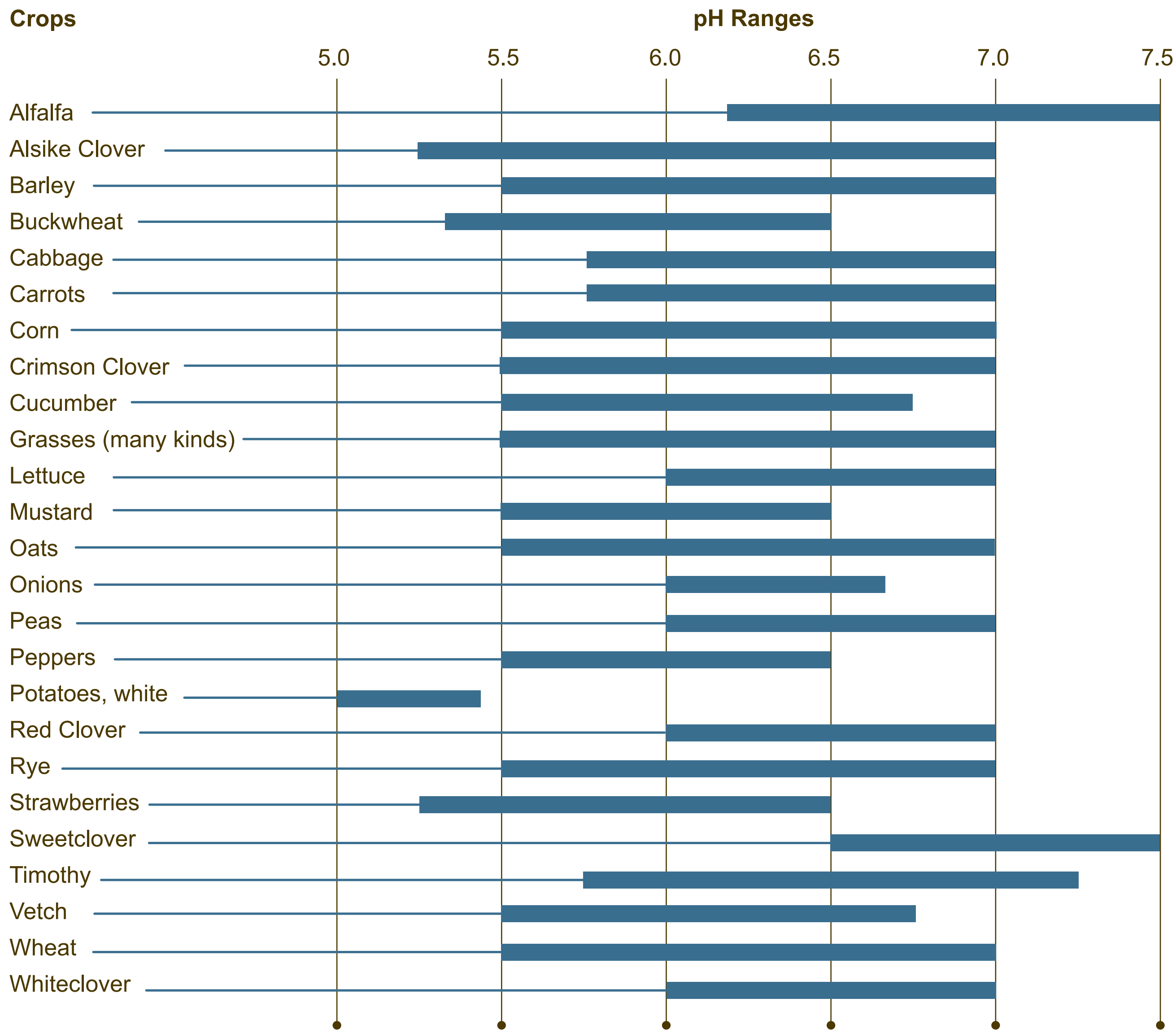
To contend with soil acidity, choose acid tolerant crops or consider liming the soil.

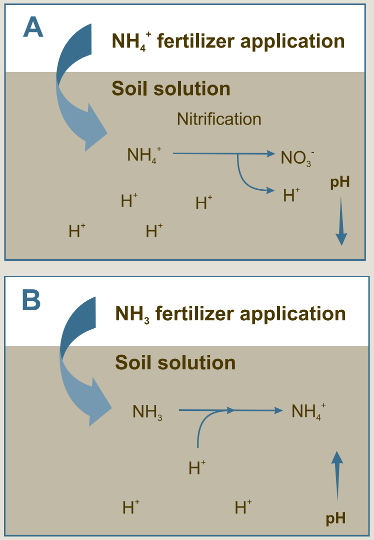


Source: Haulin et al. 2005

Figure 2.2.5 pH Tolerance Ranges for Selected Crops Grown in Alberta

Acidifying Effect of Fertilizers and Manure

Aside from the obvious boost in crop available nutrients, fertilizer application can also impact soil pH (Figure 2.2.6). The nitrification of ammonium from fertilizers, plant residues or manure will acidify soil.



Source: McCauley et al. 2003

Figure 2.2.6 Effect of Ammonium Addition on Soil pH

Soil acidification can be beneficial on alkaline soils, but detrimental on acidic soils. It is important to select an appropriate form and rate of fertilizer based on the soil pH conditions.

The relative acidity of fertilizer refers to the amount of calcium carbonate (kg) required to neutralize the acid formed from the application of 100 kg of the fertilizer. Note, that the relative acidity is based on total weight of fertilizer applied and not weight of nutrient applied. Based on a weight of applied nitrogen the relative acidity of some fertilizers is:

Ammonium Sulphate >>>> Urea = Anhydrous Ammonia

Table 2.2.3 Relative Acidity of Several Commonly Used Fertilizers

Fertilizer	Relative Acidity (kg $CaCO_3$/100kg)
Anhydrous Ammonia	148
Urea	84
Ammonium Sulphate	110
Urea-ammonium Nitrate	52
Monoammonium Phosphate	65
Potassium Chloride	0
Potassium Sulphate	0
Gypsum	0

Source: McCauley et al. 2003

Salinity

Soil salinity describes areas where soils contain high levels of salt. In western Canada, compounds responsible for soil salinity include sulphate salts of sodium, calcium and magnesium (Na_2SO_4, $CaSO_4$, and $MgSO_4$, respectively). Soil salinity is a serious soil quality issue in Alberta affecting more than 640,000 ha (1.6 million acres).

Saline soils have high concentrations of soluble salts in the surface soil layers. Excess salt impairs the ability of plants to efficiently absorb water and nutrients from the soil. By keeping the ion concentration in the root sap higher than in the soil water, plants can maintain an inward flow of water into their roots. However, higher concentrations of salt ions in soil solution shift the concentration gradient creating osmotic stress (Figure 2.2.7). Plants in osmotic stress use more energy to maintain an inward flow of water into their roots. As a result, less energy is available for tissue growth and crop yields are reduced.

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Liming acid soils is an ion exchange reaction. It has the net effect of raising pH, restoring the buffering capacity, and increasing base saturation.

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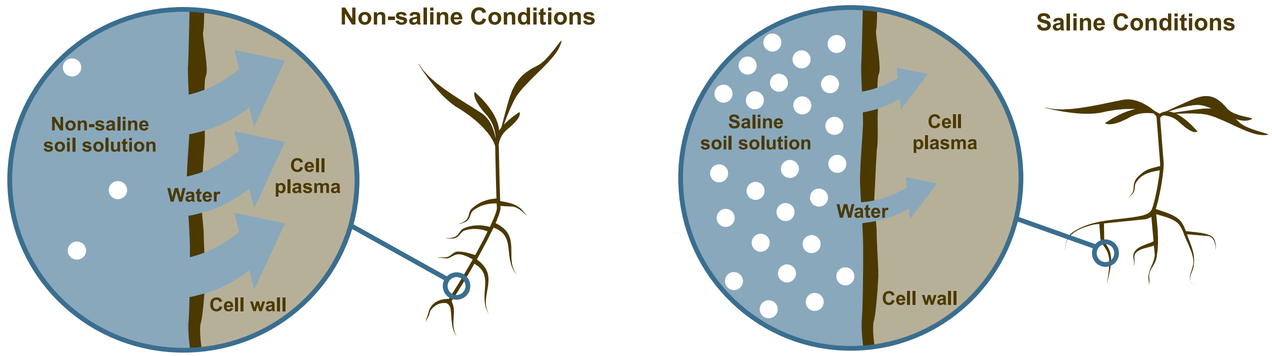
Solonetzic soils are not classified as saline, but are characterized by excessive levels of exchangeable sodium.



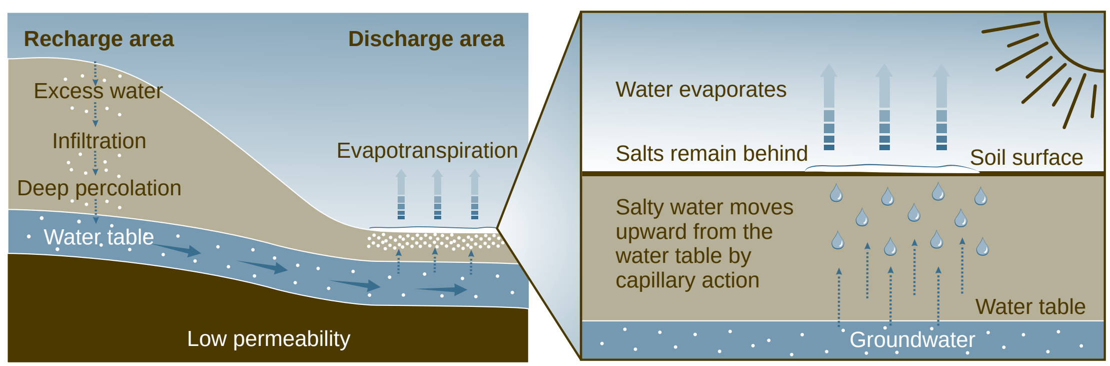
From Seelig 2000

Figure 2.2.7 The Impact of Soil Salinity on Water Uptake by Plants

The measure of soil salinity is electrical conductivity (EC), which is measured in decisiemens per metre (dS/m). Electrical conductivity reflects the total soluble salt concentration in the soil. Soil salinity can be determined in a laboratory by taking a water extract of a soil sample and measuring the conductivity in the extract using an EC meter. Salinity can also be measured in the field using an EM38 apparatus.

Salt affected soils are classified as saline, sodic or saline-sodic based on soluble salt content in the soil and the percentage of exchange sites occupied by sodium ions. Saline soils have an excess of soluble salts and sodic soils have high levels of exchangeable sodium. Saline-sodic soils are characterized by both problems.

Salinity is often placed into one of two categories: dryland salinity and irrigation salinity. Dryland salinity is caused by groundwater redistributing salts and accumulating these at the soil surface. When groundwater moves from upland to lowland areas, it accumulates salts and raises the water table in the lowlands (Figure 2.2.8). When the water table comes within two metres of the soil surface, capillary action raises the groundwater to the soil surface. When the water evaporates, salts accumulate in the root zone and topsoil (Figure 2.2.9). Dryland salinity is further influenced by activities of agriculture and land management.



Adapted from Wentz 2000

Figure 2.2.8 Generalized Saline Seep Formation

Photo courtesy AAFRD

Figure 2.2.9 Saline Seeps with Saline Groundwater on Surface

Irrigation salinity occurs when the salts from irrigation water are not sufficiently leached from the root zone. This is a problem in soils with poor drainage. Irrigation salinity can also result from excess water applications that raise ground water and dissolved salts into the root zone. As with dryland seeps, dissolved salts are left behind as water in the surface soil evaporates.

Soil Fertility Implications of Salinity

There are several ways that soil salinity affects fertility:

- Salinity reduces yield potential and therefore crop nutrient demand. The general reduction in crop yield on salt affected soils in Alberta has been estimated at 25%. Fertilizer and manure application should be adjusted to reflect this reduced yield potential.
- Salinity can cause nutrient imbalances as a result of high concentrations of salt ions in the soil. For example, excess sodium can lead to deficiencies in magnesium and calcium.
- Saline soils tend to have alkaline pH, which also affects nutrient availability.
- Sodic soils have structural problems that limit yield potential. Fertilizer and manure application should be adjusted to reflect these limitations.

Sodic Soils Quick Fact

Sodic soils contain high levels of exchangeable sodium. This reduces the ability of soil particles to cling together in stable soil aggregates. When wetted by precipitation or irrigation water, the soil aggregates in these soils easily break apart and puddling can occur. When the puddles dry, a solid crust develops on the soil surface. This crust can inhibit water and oxygen infiltration, as well as crop emergence, resulting in bare patches in fields.

Soil Salinity and AOPA

Manure has the potential to increase soil salinity because it contains 4 to 10% salt (depending on the species, diet formulation and salt content of the drinking water). This is a particular risk for fields that receive regular applications of manure and limited precipitation.

AOPA sets restrictions on manure application based on salinity. Manure cannot be applied in quantities that would raise the EC of the soil more than 1 dS/m after application. Furthermore, manure cannot be applied to soils with an EC measurement of 4 dS/m or more unless approved by the NRCB.

"Salt Effect" of Fertilizers

High rates of seed placed fertilizer can damage seeds and seedlings. One reason for this is the salt effect of fertilizer (i.e., fertilizer mimics the effect of soil salinity).

The potential of fertilizer to influence the salt level in soil solution is expressed as its salt index (SI). The higher the fertilizer SI, the greater the risk of salt burn to germinating seedlings (Table 2.2.4).

The SI is based on equivalent product weights rather than actual nutrients supplied. For example, urea (46% N) has about half the salt effect of ammonium sulphate (21% N) when applied at equivalent rates of N.

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Canal seepage is a form of irrigation salinity caused when water seeps from irrigation canals or drainage ditches. Because many canals are located along a topographic break, canal seepage can exaggerate natural salinity.

Table 2.2.4 Salt Index (SI) for Various Fertilizers

Fertilizer	SI ($NaNO_3$ = 100)
Anhydrous Ammonia	47.1
Urea	74.4
Ammonium Sulphate	68.3
Urea-ammonium Nitrate	63.0 (28-0-0) 71.1 (31-0-0)
Monoammonium Phosphate	26.7
Ammonium Polyphosphate	20.0
Potassium Chloride	120.1
Potassium Sulphate	46.0

Sources: Mortvedt 2001, McCauley et al. 2003

summary

- Positively charged ions (cations) are attracted and loosely held (adsorbed) to the negative charge of soil particles.
- Adsorbed cations can be exchanged for others in a process called cation exchange. The amount of exchangeable cations per unit weight of soil is referred to as the CEC.
- Cation exchange is a critical process for supplying nutrients to developing crops.
- Organic matter is an important source of nutrients. Soil organic matter content influences CEC and can be influenced by environmental conditions and management practices.
- Soil pH affects the availability of several nutrients essential for crop growth and development and also influences the activity of soil organisms.
- Salinity can limit crop growth by interfering with plant water uptake. This reduces yield potential and should factor into nutrient management.