Soil Fertility Handbook

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Cover images

FRONT COVER:

background:	Field of wheat
small left:	Manure injection into cover crops
small middle:	Long-term crop rotation and tillage system trial
small right:	Field of cabbages

BACK COVER:

background:	Field of wheat
small left:	Soil core and sampling bucket
small middle:	Harvested onions in field
small right:	Grain harvest into weigh wagon

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Preface

Fertile soils are the foundation of agricultural production. Effective management of nutrients and soil fertility is essential for sustainable and profitable crop production in Ontario and the rest of the world.

In this third edition of Ontario's *Soil Fertility Handbook*, we have provided the most up-to-date information on the principles that underlie effective management of nutrients. A new introductory chapter has been added and chapters have been re-ordered to transition more smoothly. Illustrations, diagrams and figures have been added and updated to clearly communicate key soil fertility concepts. Government, industry and the research community have worked together to ensure the book reflects the current needs of Ontario agriculture. Look inside for the latest information on topics such as nitrogen response in grain corn, trends in atmospheric deposition of sulphur and the fundamentals of plant nutrient uptake.

A number of great strides have been made toward more efficient nutrient use in recent years. Nitrogen rates, for example, have remained steady, while corn yields across North America have continued to rise. Challenges remain, however. Phosphorus losses to Lake Erie will need to be addressed in the coming years, as will the decline in organic matter of Ontario's soils. Soil compaction is another pressing concern that has a direct impact on crop nutrition. We believe that a sound understanding of soils, nutrients and their interactions is key to meeting these challenges head on.

Whether you're a farmer, advisor, researcher or student, we hope that you find the information contained within this handbook both practical and useful.

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1. The Nature of Soils and Soil Fertility

The Ontario *Soil Fertility Handbook* contains information on the fundamental concepts of soil fertility. If you have ever wondered how nutrients make their way to plant roots or why different soils vary in pH, the answers can be found within these pages. You can also find practical information in areas such as proper soil sampling techniques, soil test interpretation and fertilizer application methods.

Soil fertility is the ability of a soil to supply essential plant nutrients in adequate amounts and proportions for plant growth and reproduction. The physical nature and properties of a soil — including texture, porosity and mineral makeup — determine its inherent fertility. In this introductory chapter, we will explore these fundamental soil properties and consider the impact they have on productivity.

Soil horizons

Every soil has a profile – a series of layers from the surface to the parent material. These layers are called "horizons" and are designated by the letters A, B and C (see Figure 1–1).

The A horizon, or topsoil, is an organically enriched layer that contains the greatest proportion of plant roots. It is the zone in which organic matter accumulates. In Ontario's mineral soils, uncultivated topsoil depth is typically no greater than 30 cm (12 in.).

The B horizon is hidden from sight but has a large impact on important soil properties such as drainage. Materials such as iron and aluminum oxides, as well as clays, accumulate in the B horizon over time. The B horizon, or subsoil, contains less organic matter than the topsoil but typically has a higher proportion of small pores and may store a large portion of the water required for plant growth.
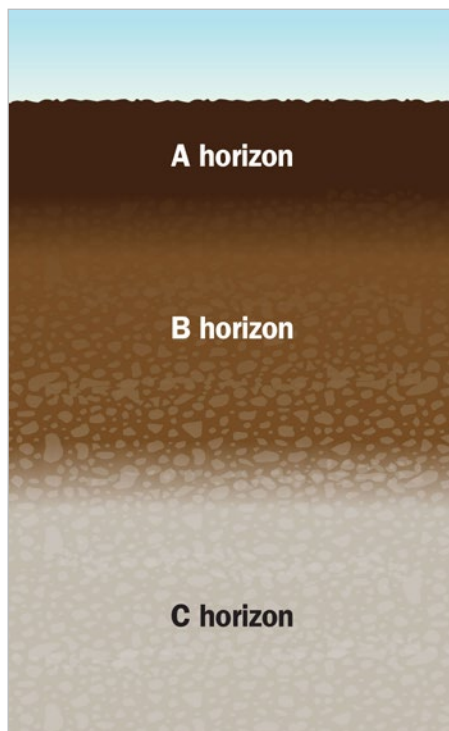
Figure 1–1. Generalized soil profile

The C horizon is parent material — the material from which the soil formed. In Ontario, the parent material could be anything from till to sand to a highly productive wind-blown material called loess. Much of the parent material in southern Ontario is till, deposited by the retreat of glaciers approximately 10,000 years ago.

Soil components

Soils are comprised of four main components. Often the ideal topsoil is shown as containing roughly 25% water, 25% air, 45% minerals and 5% organic content by volume (see Figure 1–2). In reality, these proportions vary widely depending on both soil type and management history, which in turn greatly affect a soil's productivity.
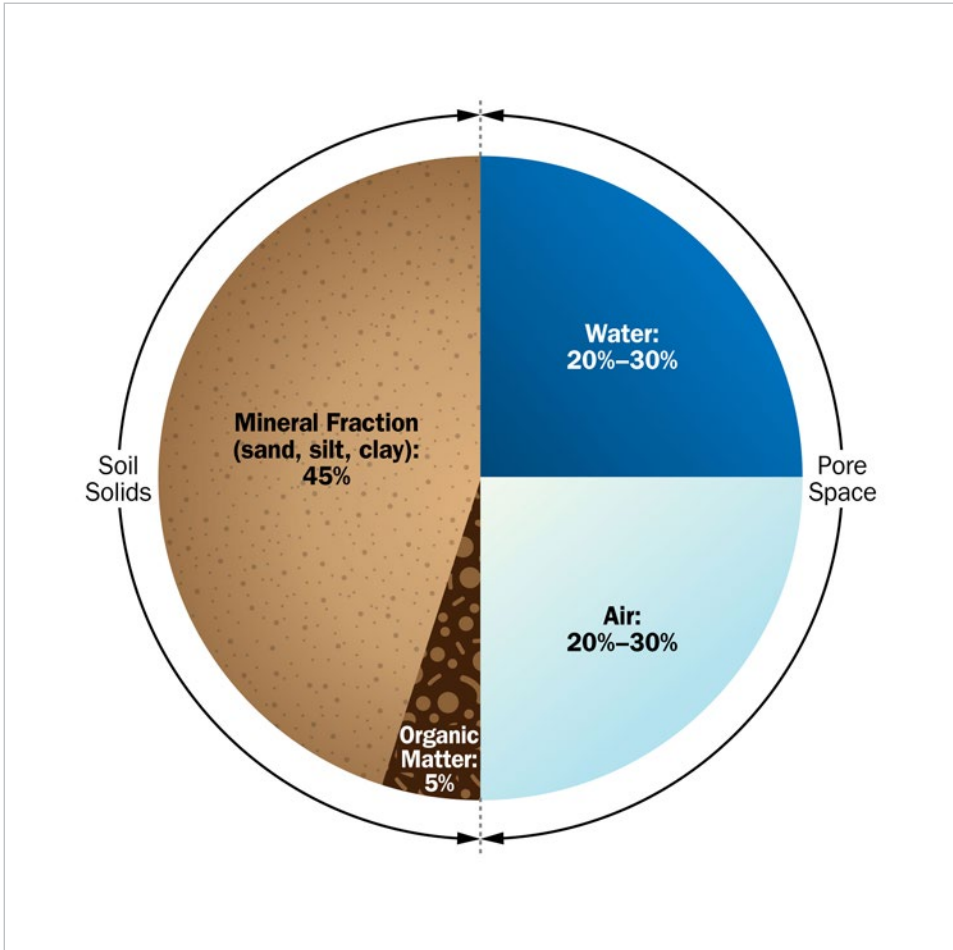
Figure 1–2. Components of an ideal soil, by volume

Soil components of minerals, water, air and organic matter interact to cycle and supply plant available nutrients. Biological and biochemical reactions occur constantly in soil, which help to replenish nutrients in response to plant uptake. All components — minerals, water, air and organic matter — are essential for this process to take place. In agricultural production, the objective is to maintain effective nutrient cycling and the soil's capacity to meet the nutrient requirements of plants (*The Nature and Properties of Soil, 15th edition*, Brady and Weil).

Soil minerals

All soils contain sand, silt and clay. Primary minerals include those that are found in sand and silt and closely resemble the materials from which they formed. Secondary minerals form from the weathering of primary minerals. An example is silicate clay, which has a high surface area and is negatively charged.

The proportion of sand, silt and clay depends on the soil's parent material and determines a soil's texture. Soil texture is an inherent property that cannot be changed. It plays an essential role in determining water drainage and availability, as well as the capacity of a soil to hold onto and exchange nutrients.

Soil water

Nutrients must be taken up by plants from soil water (also referred to as the soil solution), which is constantly drawn from and replenished. An excess of water, however, limits root nutrient uptake. Insufficient water, on the other hand, limits nutrient movement toward roots (see Figure 1–3). This will be discussed in Chapter 2 in terms of nutrient uptake pathways.
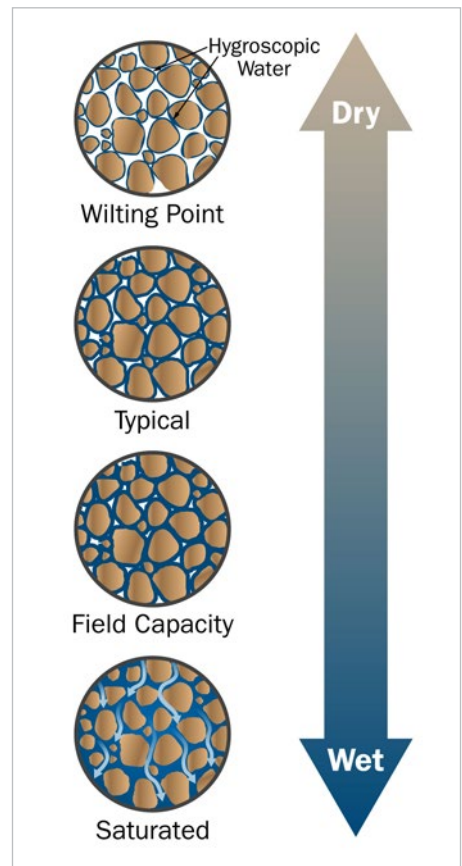
Figure 1–3. Soil water status across a range of moisture conditions. Downward arrows indicate drainage water.
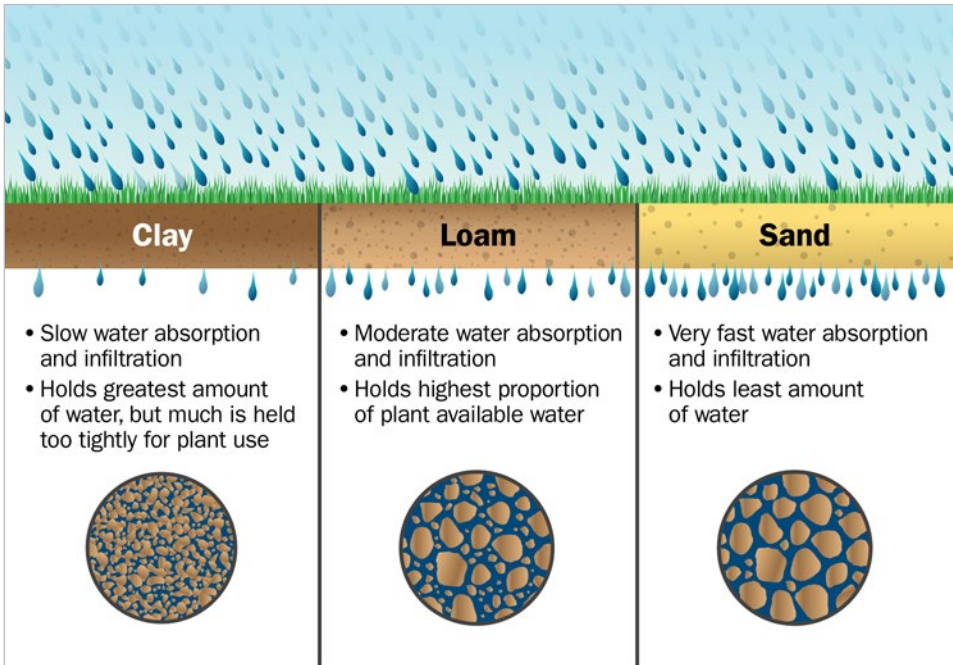
Figure 1–4. Drainage and water-holding characteristics of major soil textural classes

A soil's ability to hold water can be thought of as that of a sponge. After being saturated, water in soil will drain from the largest pores. It is held within smaller pores, where attraction with soil limits movement. A soil's texture and the type and proportion of its pores determine its ability to both drain and hold onto water (see Figure 1–4):

- A soil with a high percentage of large pores, such as a sand, will drain a relatively large amount of water quickly due to gravity.
- A clay soil, which contains many small pores and few large pores, will drain much less water and do so more slowly.
- An ideal soil is a well-structured medium-textured soil, which drains water adequately but also provides an ample amount of plant available water.

Soil air

Under moist but not saturated conditions, air occupies approximately 50% of the total pore space in an ideal soil. Soil aeration is critical — for gas exchange, root growth and soil life. When water drains after a rainfall, large pores become filled with air.

Air in soil is different from air in the atmosphere. It is generally quite humid and has a much higher carbon dioxide content, which is the result of the activity of soil organisms and plant roots.

A well-structured medium-textured soil provides an ideal proportion of pore sizes for aeration in both wet and dry conditions. Coarse-textured soils tend to have a large proportion

of air-filled pores. This allows for excellent gas exchange and root growth but can result in drought stress if rainfall is inadequate. The high percentage of small pores in fine-textured soils can result in low oxygen conditions during periods of high rainfall and also increase the risk of nitrogen loss through the process of denitrification.

Soil organic matter

Soil organic matter includes all carbon-containing materials in the soil. It is made up of microbial, plant and animal life at various stages along the spectrum of alive and intact to long-dead and decomposed. Though it is present in a relatively small quantity, organic matter has a large effect on almost all soil properties. Organic matter stores and supplies nutrients, improves soil structure and water infiltration, supports soil biological activity and buffers against changes in soil pH. You can learn more about organic matter and its role in soil fertility in Chapter 2.

Interaction of soil components

Soil fertility encompasses much more than just soil test values. The physical condition and quality of a soil, as affected by long-term management, have a profound effect on the supply of plant-available nutrients and the crop's ability to access these nutrients. So too does the soil's biological activity. The information found within this handbook is essential for sound management of nutrients in agricultural soils. It is most effectively applied in conjunction with best management practices that maintain or improve soil health over the long term.

"Healthy soils function more efficiently with less need for expensive human interventions and inputs than unhealthy and degraded soils." – page 48, *The Nature and Properties of Soils*, *15th edition*, Brady and Weil.

2. Nutrients

Since crop production removes nutrients from land, applying them back in some form is essential to the sustainability of agriculture. Nutrients are applied to replace nutrients removed by harvest, improve yield, enhance nutrition, and increase quality and utility of crops.

Specific markets demand quality, consistency and continuity of particular characteristics. Crop production has reached new levels of sophistication and continues to improve in a quest to meet consumer demands for choices of variety, nutrition and health benefits. Understanding the role that nutrients play in attaining these attributes is of utmost importance.

Nutrients reside in the soil in numerous forms and have many pathways of transport to roots, and each play specific roles in plants.

Nutrient forms

Nutrients are held in the soil matrix in many forms:

- dissolved in the soil solution
- held to soil surfaces
- tied to or contained within organic matter
- held as insoluble compounds
- fixed within clays

Dissolved in soil solution

For many nutrients, only a small proportion can be found in the soil solution (soil water) at any time. Only nutrients dissolved in the soil solution are available for absorption by plant roots. The largest proportion of any given nutrient exists in the soil in other forms of varying availability to the plant. As nutrients are removed from the soil solution by crop uptake, they are replenished from these other forms.

Held to soil surfaces

Cations

Most nutrients within the soil solution are present as ions and have either a positive or negative electrical charge. An ion with a negative charge is called an anion. A nutrient with a positive charge is called a cation.

Cations exist both in the soil solution and adsorbed to soil surfaces. They come from the weathering of soil minerals, the breakdown of organic matter and additions of mineral and organic fertilizers. Examples of cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), hydrogen (H^+) and potassium (K^+).

Cation exchange capacity

The dominant charge on soil colloids (clays and organic matter) is negative. Since opposite charges attract, most of the ions held in the soil this way are positively charged cations.

The number of cations that can be held, and therefore exchanged, is equivalent to the amount of negative charge. This amount is called the cation exchange capacity (CEC).

Cation exchange capacity is a measure of the ability of the soil to hold positively charged nutrients. It is expressed as centimoles of charge per kilogram of soil (cmol/kg). These units have replaced milliequivalents per 100 grams, but the numeric values remain the same: i.e., 15 cmol/kg = 15 milliequivalents/100 g.

The magnitude of the CEC depends on the texture of the soil, the types of minerals present and the percentage of organic matter. As the texture gets finer, the amount of surface area in each gram of soil increases. This creates more places where the negative charges can occur, and the CEC increases.

Cation exchange
Cation exchange is often presented as a static number. However, it is an active equilibrium or balance between ions in solution, on the soil surfaces and in other forms in the soil.

Cations are attracted to soil surfaces. The strongest attraction and greatest cation concentration exists near the surfaces and decreases farther away. Cations are constantly moving back and forth between soil solution and soil surfaces (see Figure 2–1), but the rate of movement to and fro is equal. The system is in equilibrium.

> ### Meanings of the word *mineral*
> The word mineral has several definitions with respect to soils and soil fertility:
> - *Mineral* in the geological sense refers to a naturally occurring chemical compound with a single specific composition: e.g., quartz.
> - *Mineral* can also refer to the inorganic form of a nutrient. For example, mineral fertilizers include products such as urea or mono-ammonium phosphate (MAP).
> - Finally, *mineral* can broadly mean the sand, silt and clay fraction of soil.

When a change occurs in the system, however, the balance of movement will shift. For example, if nutrients are removed from the soil solution by plant uptake, there will be a net movement off the soil surfaces until the equilibrium between solution and soil is re-established.

Clay minerals
The types of minerals in the clay fraction of the soil are different than the minerals in the coarser fractions. Instead of being round or angular, clay minerals are flat plates with negative charges concentrated around the broken edges of the plates. The amount of negative charge varies with the type of clay mineral (see Table 2–1).

Table 2–1. Typical CECs of clay minerals

Clay mineral	Cation exchange capacity (cmol/kg)
smectite	75–135
illite	15–40
kaolinite	3–15
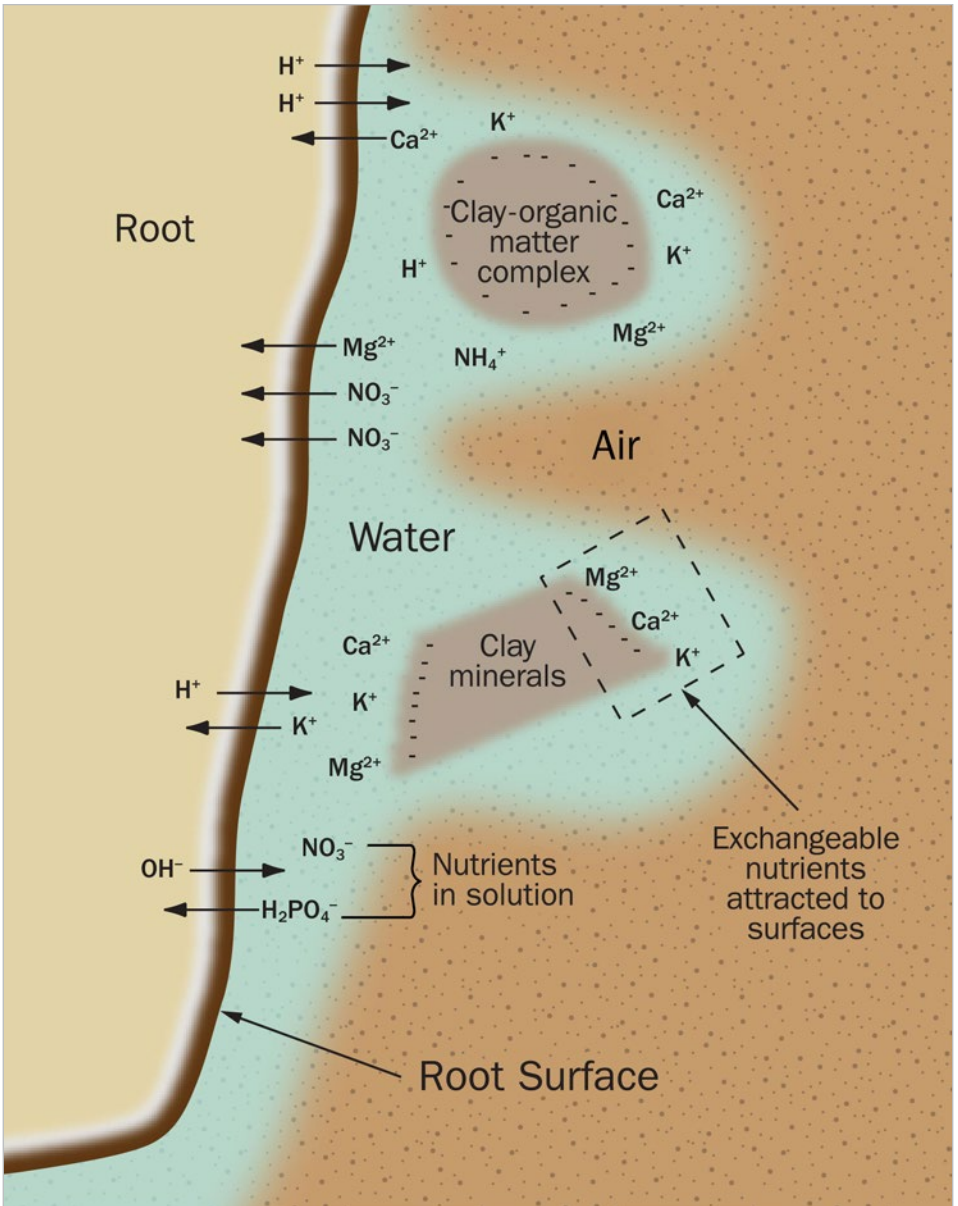
Figure 2–1. Cation exchange

The clay minerals in Ontario and surrounding regions are predominantly illite and smectite. Kaolinite clays are dominant in the strongly weathered soils of the southern U.S. but are uncommon in Ontario.

Organic matter carries a large negative charge. In sandy soils with low clay content, organic matter can account for the majority of the total CEC for the soil.

> **Absorb:** take in or make part of itself.
>
> **Adsorb:** cause a gas, liquid or dissolved substance to adhere in a thin layer to the surface of a solid.

Tied to organic matter

Organic matter in the soil consists of crop residues, microbial matter and organic materials in various states of decomposition. Plant nutrients are held within this organic matter and adsorbed to its surfaces. Table 2–2 provides typical CEC values of organic matter and of soil textural classes.

Nutrient release from organic matter

Nutrients from crop residues and manures are released to the soil solution in mineral forms through decomposition by soil organisms. These same organisms can absorb nutrients from the soil solution if they need them for their own growth and development. This frequently occurs with nitrogen when organic materials high in carbon are added to the soil. In such a scenario, microbes have an ample carbon source for food but need nitrogen for the proteins and amino acids in their bodies. Nitrogen is therefore absorbed from the soil and held unavailable within the microbes until some of the carbon compounds are digested. See Chapter 6, *Organic Nutrient Sources*.

Table 2–2. Typical CECs of soil textures and organic matter

Material	CEC (cmol/kg)
sandy soil	2–10
loam soil	7–25
clay soil	20–40
organic matter	200–400
muck >20% organic matter	25–100

Because microbial action mediates the release of nutrients from organic materials, it is affected by the weather. Conditions that are too cold, too wet or too dry can delay the release of nutrients, which can affect crop production. It is not unusual to see symptoms of nitrogen deficiency on corn or cereals following legumes or manure if the spring weather is cooler than normal. Breakdown of organic matter also plays an important role in micronutrient supply. For example, manganese deficiency can occur in cool, dry springs, and boron deficiency is common when soil conditions are dry.

pH effects

The cation exchange capacity of organic matter is greater than clay on an equal weight basis. Weak organic acids on the outside of stable organic matter particles are the source of negative charges. These sites are affected by pH. In acid soils, hydrogen ions bind so tightly that these sites are not available for nutrient exchange. This means that the CEC of organic matter is lower in acid soils than in alkaline soils.

Impact on non-nutrient properties

Though it is present in a relatively small quantity in most soils, organic matter has a large effect on almost all soil properties. In addition to its role in nutrient cycling, organic matter plays an important role in the water-holding capacity of the soil and in maintaining soil structure. Organic matter can be found as discrete particles but most commonly exists in an intimate relationship with clay and other soil particles to form aggregates. The breakdown of organic matter facilitated by soil microbes provides the glues that hold soil aggregates together.

Held as insoluble compounds

Several nutrients react strongly with other minerals in the soil to form insoluble or slightly soluble compounds. The best example of this is phosphorus.

Phosphate binds with iron or aluminum in acid soils or with calcium or magnesium in alkaline soils to form insoluble compounds. Phosphate also reacts with iron and aluminum oxides in the soil, forming compounds that are only slightly soluble.

Fixed within clays

Illite clays have spaces between the layers that closely match the size of a potassium ion. When potassium is added to these soils, the ions can move into these spaces and the clay layers collapse around them, which traps the potassium within the clay mineral, similar to eggs in an egg carton. Like potassium, ammonium is also subject to being trapped, or "fixed."

Nutrients fixed in this manner are slowly available to plants. They are not directly exchangeable but are released gradually as the clay minerals are weathered or dispersed by extreme drying, wetting, freezing or thawing.

Nutrient transport to roots

For nutrients to be absorbed into the plant, they must be in the soil solution and in close proximity to the root surface. Nutrients in soil solution move to the roots by three processes: root interception, mass flow and diffusion (see Figure 2–2). The relative contribution of each process to nutrient uptake is shown in Table 2–3.
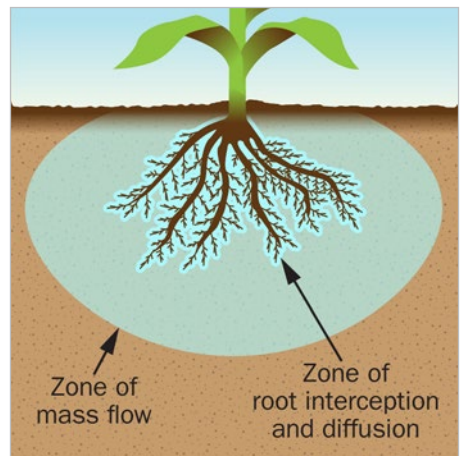
Figure 2–2. Movement of nutrients in the soil

Table 2–3. Relative significance of the ways nutrients move from soil to corn roots

Nutrient	Amount required for 9.4 t/ha (150 bu/acre) corn	Percentage supplied by		
		Root interception	Mass flow	Diffusion
nitrogen	170	1	99	0
phosphorus	35	3	6	94
potassium	175	2	20	78
calcium	35	171	429	0
magnesium	40	38	250	0
sulphur	20	5	95	0
copper	0.1	10	400	0
zinc	0.3	33	33	33
boron	0.2	10	350	0
iron	1.9	11	53	37
manganese	0.3	33	133	0
molybdenum	0.01	10	200	0

This example applies to a fertile silt loam soil near neutral pH. Proportions differ for different soil conditions.

Source: Stanley A. Barber, 1984. *Soil Nutrient Bioavailability.* New York: John Wiley & Sons.

Root interception

Root interception is the direct contact between roots and nutrients in the soil solution (see Figure 2–3).

Nutrient ions are absorbed by direct contact with the root and any associated mycorrhizae. Because this form of absorption is based on direct contact, the amount of nutrients available equals the amount of nutrients in the volume of soil in contact with the roots.

Roots of most crops occupy 1% or less of soil volume. However, as roots grow they take the easiest route through soil pores and planes of weakness between soil clods. Some pores such as worm burrows are nutrient enriched. The worms smear the burrow wall with their feces, which are high in available nutrients.

As a result, roots can contact directly a maximum of 3% of available immobile nutrients.
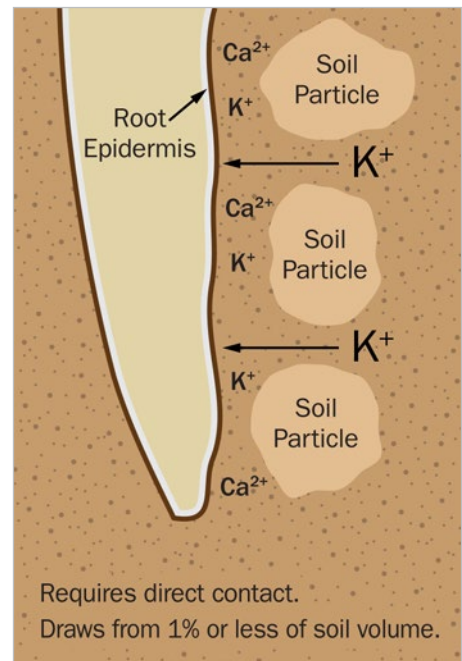
Figure 2–3. Root interception
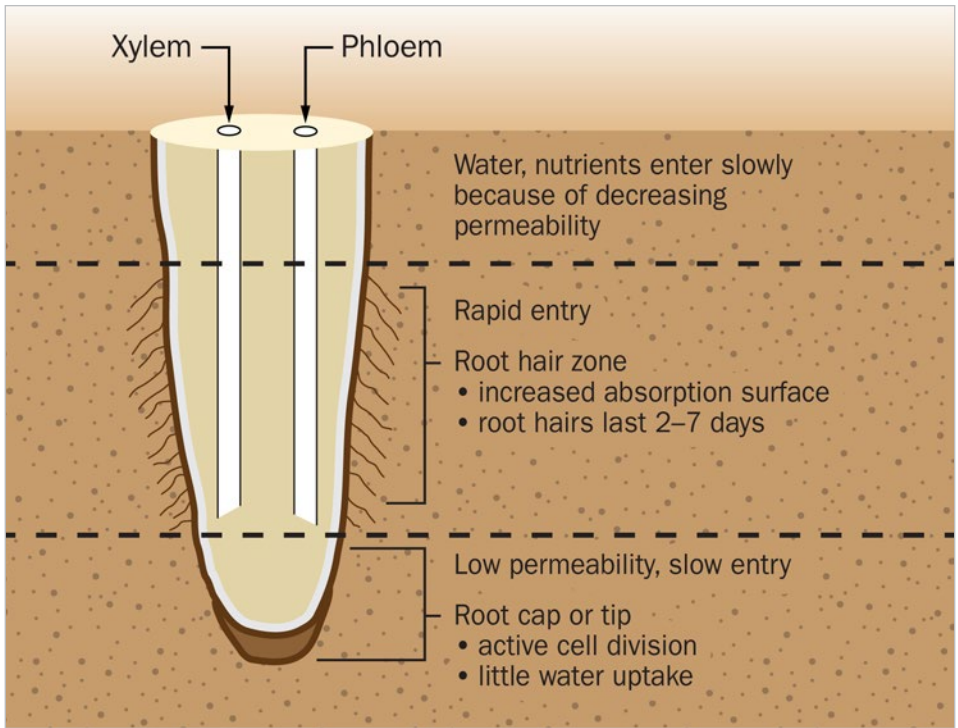
Figure 2–4. Root hair zone

Root structure varies from species to species. Root length directly affects the volume of soil that the root has contact with. Root hairs increase the soil volume from which the root can obtain nutrients, as shown in Figure 2–4. For example, onions have virtually no root hairs, while canola has some of the longest root hairs. Canola can thus access 20–30 times the soil volume that onions can.

Symbiotic relationships, such as the one with mycorrhizae (see following box), can increase the volume of soil from which nutrients can be accessed and absorbed.

Root exudates such as the mucilage that covers root surfaces, particularly the tip, can help increase uptake.

This gelatinous material is secreted by the cells at the root tip and the epidermis. It helps lubricate the root as it pushes through soil, prevents the root from drying out, and assists with nutrient uptake. Mucilage is particularly important in dry soils as it improves the soil-root contact and plays a role in the uptake of phosphorus and micronutrients. Root exudates also stimulate microbial activity in the root zone, which can increase nutrient cycling and availability relative to surrounding bulk soil.

Arbuscular mycorrhizal fungi (AMF)

The term mycorrhiza comes from myco, meaning fungi, and rhiza, meaning root. There are several different categories of mycorrhizae. Arbuscular mycorrhizal fungi are the most important type for agricultural crops. They have hyphal threads (root-like structures) that penetrate plant roots and act as an extension of the root system. Arbuscular mycorrhizal fungi naturally exist in association with approximately 80% of all land plants.

The relationship can enhance root interception of nutrients by increasing the soil volume that nutrients can be pulled from (see Figure 2–5). Some calculations suggest an increase of up to 10 times that of uninfected roots.

Although the benefit of this symbiotic relationship is most often associated with soils that are low in fertility, particularly in phosphorus, there is evidence that crops in highly fertile soils support AMF. Plants with a mycorrhizal association have an uptake rate of phosphorus per unit of root length that is 2–3 times higher than those without.

Researchers from the University of Nebraska-Lincoln (Grigera et al., 2007 and Tian et al., 2013) have made new findings about arbuscular mycorrhizal fungi. They have shown that the abundance of AMF in corn roots tends to increase throughout the growing season; that transport of phosphorus from AMF to corn peaks just prior to reproductive growth, when the rate of phosphorus uptake is highest; and that increasing nitrogen fertilization rate does not affect colonization rate of AMF in corn but reduces the abundance of hyphal threads in soil.

Most agronomic crops, with the exception of canola and other *Brassica* species, have arbuscular mycorrhizal fungi. AMF tend to thrive more in undisturbed soils, such as under no-till, or potentially with longer-term perennial crops such as trees.
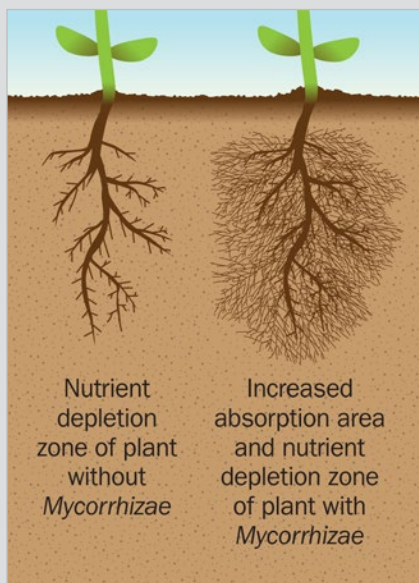
Figure 2–5. Impact of arbuscular mycorrhizal fungi on absorption area in soil

is the prime mode of transport for nutrients in solution such as nitrate, sulphate, chloride, boron, calcium and magnesium.

Mass flow plays a larger role in fertility when the plant is actively growing, as there is a greater transpiration flow. Less nutrient movement occurs at low temperatures because of a decreased transpiration rate, reduced plant growth and less evaporation at the soil surface.

Diffusion

Diffusion refers to the movement of ions from areas of high concentration to areas of low concentration.

As plant roots absorb nutrients from the surrounding soil solution, the nutrient concentration at the root surface decreases. This creates a nutrient gradient. Nutrients in higher concentrations in the soil solution diffuse towards the area of lower concentration: the root (Figure 2–7). This process is influenced by plant demand, soil moisture, soil texture and the nutrient content of the soil.

Diffusion is the key mode of transport for phosphorus and potassium. It is slow under most soil conditions and occurs only over tiny distances. Research suggests that in the time that nitrogen travels 1 cm, potassium travels 0.2 cm and phosphorus travels only 0.02 cm.

Figure 2–6. Mass flow

Mass flow

As a plant draws water from the soil, the water carries nutrients and other materials in solution towards the root (Figure 2–6). This is known as mass flow. Some mass flow is also caused by water losses from evaporation and water movement through capillary action.

The water use of the plant and the nutrient concentration in soil water determine the amount of nutrients that reach the plant. This

Figure 2–7. Nutrient uptake by diffusion

Phosphorus and potassium uptake is strongly tied to root hairs in many plant species. The smaller diameter of root hairs helps to maintain higher diffusion rates of phosphorus, which makes them more efficient than the main root. In soils low in extractable phosphorus, root hairs can account for 90% of total uptake.

Root hair formation is affected by the concentration and availability of nutrients such as phosphorus and nitrate. Soils with high concentrations of readily available phosphorus generally exhibit root structures with few and short root hairs. Root hair density and length increases greatly in soils low in phosphorus.

Plant uptake of nutrients

Generally, nutrient uptake refers to the uptake and transport of nutrients through the root system. While plants can also absorb nutrients through the stomata and cuticle of leaves and to some extent through developing fruit, roots are the primary path for nutrient absorption.

Plants take up nutrients through passive and active mechanisms. Nutrient ions move passively (a process requiring no energy expenditure) to a barrier through which they are then actively transported (a process that requires energy from the plant) to the plant organs that will metabolize the nutrient. This movement of ions occurs through plant cells and the liquid film lining the spaces between cells. Cations, such as potassium (K^+) and magnesium (Mg^{2+}), are taken up along the negatively charged surfaces of root cells. Root cells release positive hydrogen ions (H^+) to maintain electrical neutrality (see Figure 2–1). As a result, the soil solution becomes more acidic near the plant root. With the uptake of anions, such as nitrate (NO_3^-) and sulphate (SO_4^{2-}), soil solution pH near the root increases (becomes more basic).

Alternative uptake pathways

Most nutrient ions reach the leaf cells through the xylem (see Figure 2–8). However, nutrients can penetrate the leaves through the stomata and leaf cuticle to reach the free space between cells in the leaf and become available for absorption. Ions in rain water, in irrigation water or from foliar applications of fertilizer can follow this path.

Nutrient mobility within plants

Nutrient ions are translocated from plant roots to shoots and other plant parts as part of the water flows through the plant. The rate of water absorption and transpiration help determine how effectively the ions move through the plant. Some nutrient ions are quite mobile within the plant and will move through the phloem to areas of new growth from established growth (Figure 2–8). Others are less mobile, and some are completely immobile within the plant (Table 2–4).

Knowledge of the mobility of the various nutrients will aid in diagnosing field problems. Mobile nutrients like nitrogen or potassium are translocated out of older leaves to younger developing leaves. This causes deficiency symptoms to show up on older leaves first. Deficiencies of immobile nutrients, on the other hand, develop on new growth. Noting where symptoms occur can help identify which nutrients are deficient.
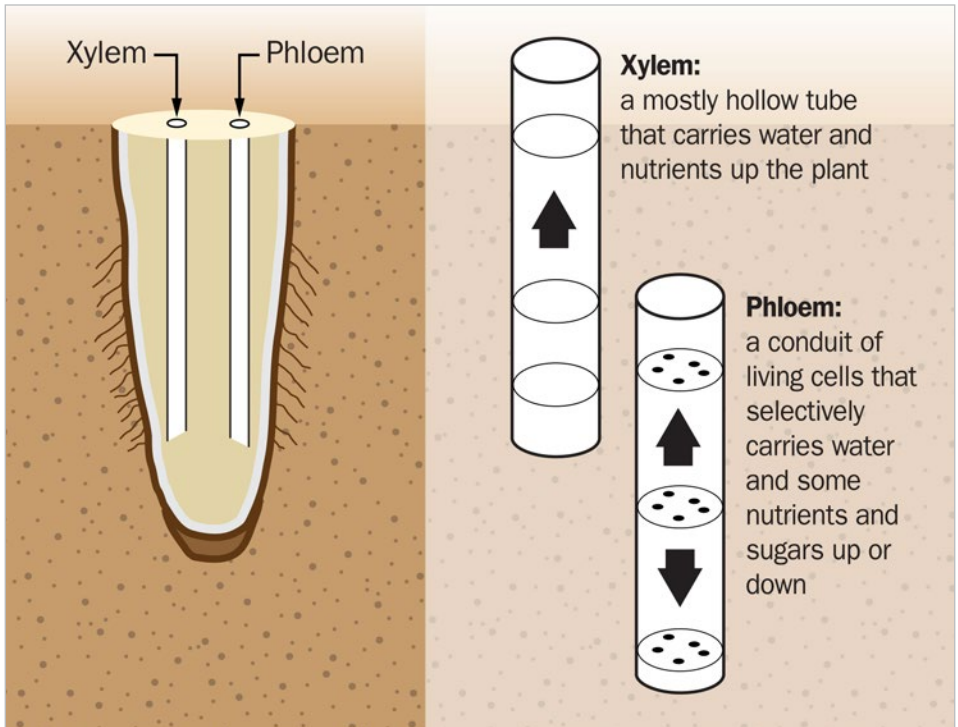
Figure 2–8. Xylem and phloem

Table 2–4. Form and mobility of nutrients and micronutrients in soil and plants

Nutrients	Mobility in soil	Plant available forms in soil	Mobility in plant
Primary nutrients			
nitrogen	medium	ammonium ion (NH_4^+),	high
	high	nitrate ion (NO_3^-)	high
phosphorus	low	phosphate ion ($H_2PO_4^-$), HPO_4^{2-}	high
potassium	low–medium	potassium ion (K^+)	high
Secondary nutrients			
calcium	low	calcium ion (Ca^{2+})	low
magnesium	low	magnesium ion (Mg^{2+})	high
sulphur	medium	sulphate ion (SO_4^{2-})	low–medium
Micronutrients			
boron	high	boric acid ($B(OH)_3$, borate ion ($H_2BO_3^-$)	low–medium
chlorine	high	chloride ion (Cl^-)	high
copper	low	cupric ion (Cu^{2+})	low
iron	low	ferrous ion (Fe^{2+}), ferric ion (Fe^{3+})	low
manganese	low	manganous ion (Mn^{2+})	low
molybdenum	low–medium	molybdate ion (MoO_4^{2-})	medium–high
zinc	low	zinc ion (Zn^{2+}), zinc hydroxide $Zn(OH)_2$	low

Role of nutrients in plants

The majority of plant tissue is made up of carbon, hydrogen and oxygen, all of which plants derive from water and carbon dioxide. The remaining essential nutrients are generally combined with these elements to play roles in the plant ranging from structural components to energy transfer and enzyme systems. For convenience, nutrients are divided into primary nutrients, secondary nutrients and micronutrients, reflecting the relative quantities required for plant growth and reproduction.

Adequate nutrients are required for optimum crop growth, and a deficiency of any of the essential nutrients will reduce yield and/or quality. The specific requirements for nutrients are also related to environmental factors, as is the reduction in growth caused by a deficiency. For example, a deficiency of potassium or chloride may increase the susceptibility of a plant to disease, so the response to these nutrients may be higher when disease is present. Determining nutrient requirements for crops is discussed more fully in Chapter 7.

Primary nutrients

A primary nutrient, or macronutrient, is required by plants in large quantities for basic plant growth and development. The six nutrients that fall into this category are carbon, hydrogen, oxygen, nitrogen, phosphorus and potassium.

Plants acquire carbon, hydrogen and oxygen from the air and water. The remaining macronutrients must be obtained from the soil. Fertilizer, manure, nitrogen fixation and mineral weathering replenish soil nutrients. Primary nutrients most frequently limit plant growth.

N Nitrogen

All nitrogen (N) present in the soil comes initially from nitrogen in the atmosphere. The air we breathe is 78% N by volume. However, it is largely unavailable to most plants and must be chemically converted from gaseous nitrogen (N_2) to a form that can be used by plants (ammonium or nitrate). Most nitrogen is taken up as nitrate (NO_3^-) by plants in agricultural soils, and only a small percentage is taken up as ammonium (NH_4^+). The various transformations that nitrogen undergoes, known as the nitrogen cycle, are illustrated in Figure 2–9.

In the soil, most of the nitrogen is present in organic matter. Soil reserves of organic N can be high, amounting to thousands of kilograms per hectare (pounds per acre). See sidebar.

How much nitrogen exists in soil?

Soils contain a large amount of nitrogen, though most exists as a part of organic matter and is only very slowly available.

Deep soil sampling at the long-term crop rotation and tillage system trial at University of Guelph's Ridgetown campus has shown just how much total nitrogen can be found in soil. Samples were taken to a depth of 1 m in 2006, 11 years after the trial was established, on a Brookston clay loam. On average, 9.4 t/ha (8,386 lb/acre) of total nitrogen was measured in the top 20 cm across all rotation and tillage treatments. Within the top metre, there was 22.9 t/ha (20,431 lb/acre) of total nitrogen.

Source: Van Eerd et al., 2014.

N_2 fixation

Nitrogen fixation includes any process that converts gaseous nitrogen (N_2) from the air to ammonium (NH_4^+) or nitrate (NO_3^-).

The chemical bonds between nitrogen atoms in N_2 are very strong. Industrial fixation uses high temperature and pressure, in the presence of a catalyst, to combine nitrogen gas with the hydrogen from methane to produce ammonia. This is the basis for the production of all other nitrogen fertilizer materials.
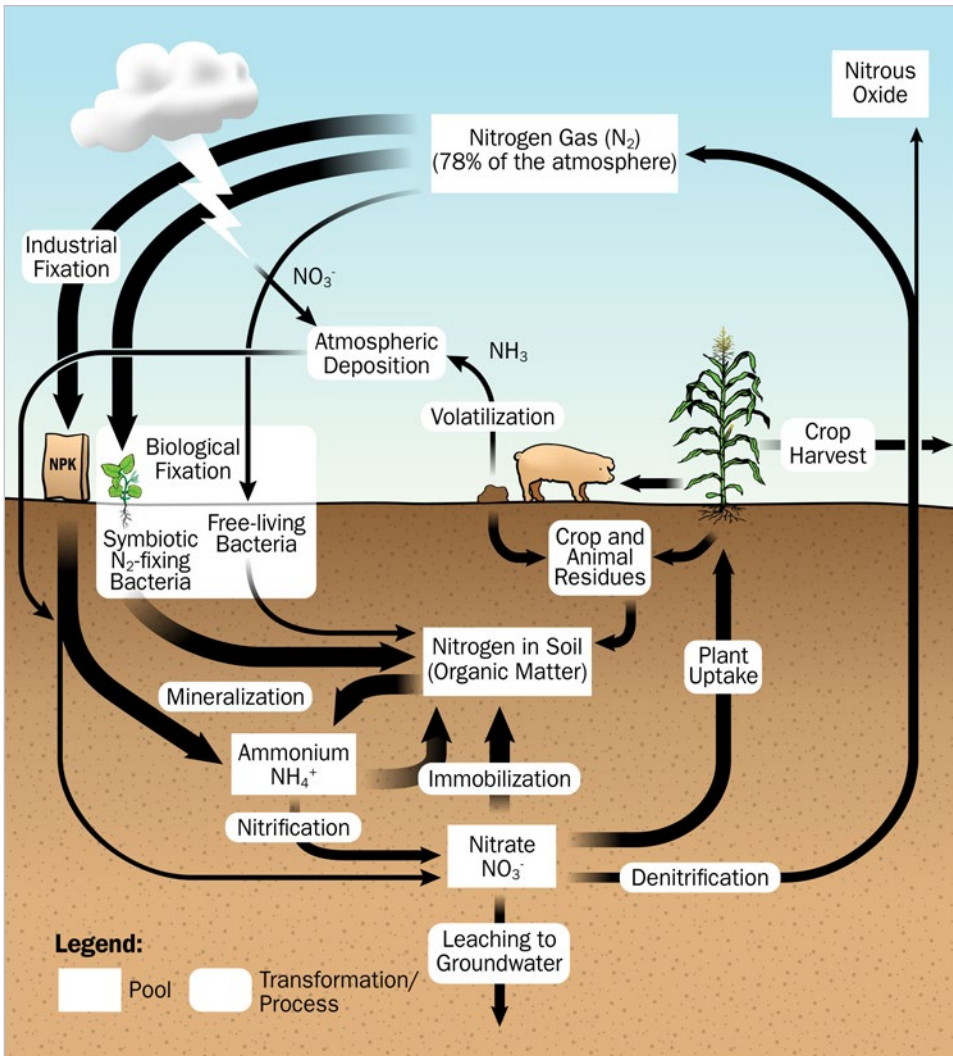
Figure 2–9. Nitrogen cycle

Biological N₂ fixation — symbiotic and non-symbiotic

Symbiotic nitrogen fixation involves a host plant and beneficial infecting bacteria. The most common and well known is the *Bradyrhizobium japonicum* rhizobia that infect soybean roots. There are a host of other beneficial rhizobia that infect legumes such as alfalfa and clovers (see Table 2–5). The host plant provides carbohydrates to the colonizing bacteria, which in turn fix atmospheric nitrogen in the nodule for transfer to the plant for protein synthesis. This activity is affected by soil N level, soil moisture, pH, plant stress and climate. Symbiotic fixation is slowed by high residual soil N. When the soybean plant needs nitrogen, it sends a biological signal from the roots, which exude a promoter protein to attract the rhizobia.

Table 2–5. *Rhizobium* species associated with specific legume crops

Rhizobium species	Legume crops
Sinorhizobium meliloti	alfalfa, sweet clover, fenugreek
R. phaseoli	beans
R. trifolii	clover (except kura clover)
R. lupine	lupines
R. leguminosarum	peas, vetch, sweet peas, lentils
Bradyrhizobium japonicum	soybeans
R. loti	trefoil

Non-symbiotic (free-living) organisms, such as *Azotobacter* sp. and *Azospirillium* sp., also fix nitrogen from the air. Average rates of fixation from non-symbiotic organisms in agricultural soils range from 5–20 kg N/ha (4.5–18 lb/acre) per year.

Other forms of fixation include lightning, which produces enough heat and electrical energy to combine nitrogen gas with oxygen to form nitrates. The amount of available nitrogen produced this way is small.

> The amount of nitrogen received in precipitation per year is estimated to be in the range of 2–15 kg/ha (2–13 lb/acre), with half or less of that value making up the amount fixed by lightning.

Mineralization

The nitrogen contained in organic compounds cannot be taken up by plants in substantial quantities. Mineralization is the microbial breakdown of these organic materials that releases the inorganic forms of nitrogen. The nitrogen is released initially as ammonium, which is rapidly converted to nitrate by nitrifying micro-organisms.

Immobilization

Immobilization occurs when NH_4^+ and NO_3^- are being taken up by soil organisms. Nitrogen becomes part of the body and processes of the soil organisms. If immobilization occurs because of an unfavourable C:N ratio, available nitrogen is consumed by soil bacteria and is unavailable to crops. Mineralization and immobilization occur at the same time, and the balance between the two is affected primarily by the carbon-to-nitrogen ratio of the organic materials in the soil. See Chapter 6 for more information.

Nitrification

This is the process by which soil micro-organisms convert NH_4^+ to NO_3^-, the form of nitrogen most readily taken up by plants.

Denitrification

Denitrification is the process whereby NO_3^- is converted to gaseous forms of nitrogen, including nitrous oxide (N_2O) and atmospheric nitrogen (N_2). Though the majority of N loss from denitrification occurs as N_2 gas, the loss of nitrous oxide has a significant impact on the environment as it has a global warming potential that is approximately 300 times greater than carbon dioxide. Denitrification occurs in soils with low oxygen and poor aeration, such as poorly

drained areas or areas where water temporarily ponds. Loss of nitrogen in saturated soils may be estimated from Table 2–6, which illustrates the potential loss associated with different soil temperature conditions.

Table 2–6. Potential for nitrate-N loss from saturated soils at different temperatures

Soil temperature (°C)	Potential denitrification rate (percentage of NO_3-N in soil)
< 12	1%–2% per day
12 to 18	2%–3% per day
> 18	4%–5% per day

Source: Hoeft, Robert, 2002.

Leaching

Leaching is the downward movement of nitrate-nitrogen through the soil profile due to excess water. The amount of nitrate loss and depth of movement will depend on the texture of topsoil and subsoil, initial moisture content, the amount of water entering the soil and the duration of the precipitation event. Leaching is more prevalent in the early spring and in the fall post-harvest period. Very little leaching occurs during periods of rapid crop growth. Nitrate-nitrogen leached beyond the crop rooting zone is unavailable to roots and can impact groundwater and surface water.

Careful management of irrigation is required to avoid excessive movement of nitrate-nitrogen. Nitrate won't be moved deeper by a single rainfall/irrigation event than the wetting depth for the net infiltration (precipitation or irrigation amount minus the amount of runoff and evapotranspiration). Figure 2–10 shows the variation in depth where rainfall or irrigation will wet the soil to field capacity in different texture classes. Field capacity is the maximum amount of water that can be held in the soil profile after natural drainage.

Role of nitrogen

Nitrogen is involved in many plant processes and structures. Compared to other nutrients, it is required in large amounts.

Nitrogen is a main component of amino acids, which form proteins within the plant. Enzyme proteins are important in a number of plant processes, particularly those which impact growth and yield. Protein is usually highest in the harvested part of the plant, hence it often is an important item in the nutritional value of the crop.

Nitrogen has an important role in the production of chlorophyll, which gives the green colour in plants. Chlorophyll is responsible for the conversion of sunlight to energy needed by the plant through the process of photosynthesis.

Soil Fertility Handbook
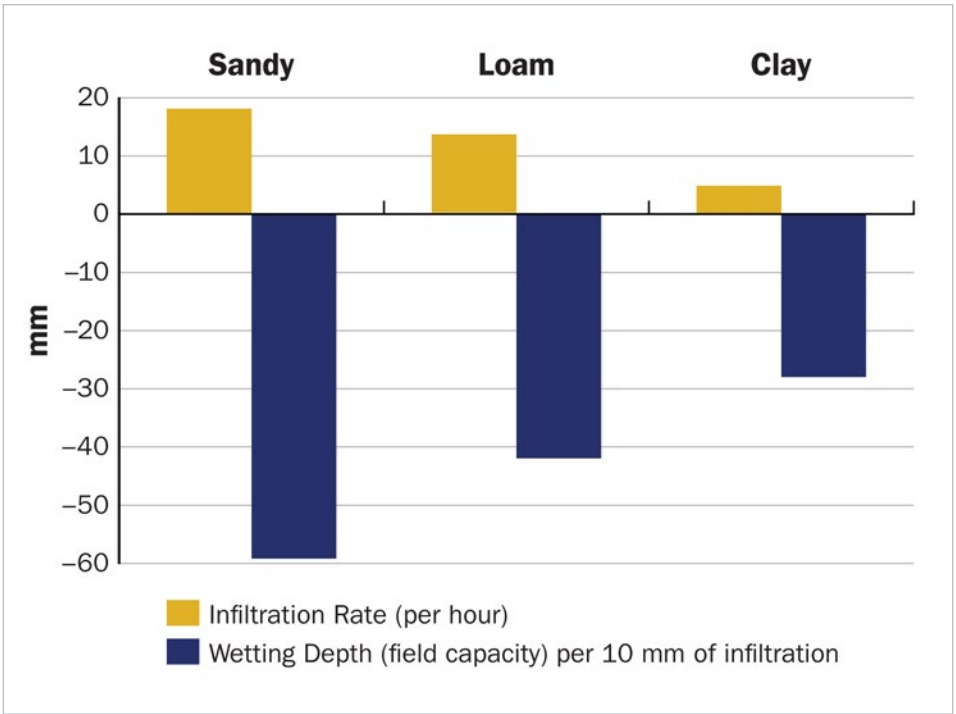
Figure 2–10. Moisture characteristics of different soil textures

Nitrogen deficiency

Nitrogen deficiency is relatively common in Ontario agriculture because of this element's mobility within the soil and its susceptibility to denitrification. The most common causes of nitrogen deficiency are under-fertilization, leaching, poor nodulation in legumes and denitrification caused by waterlogged soils. Conditions that delay mineralization, such as dry soil conditions or cold weather, can cause temporary nitrogen deficiency symptoms. The timing of nitrogen demand varies by crop, but N deficiency, if present, will often appear as uptake accelerates. For corn, this occurs around the V6 stage (Figure 2–11).

Nitrogen is a very mobile nutrient within plants. As a plant grows and develops, nitrogen can be moved or reallocated to the rapidly growing tissues. Consequently, symptoms will appear on the lower or older leaves first.
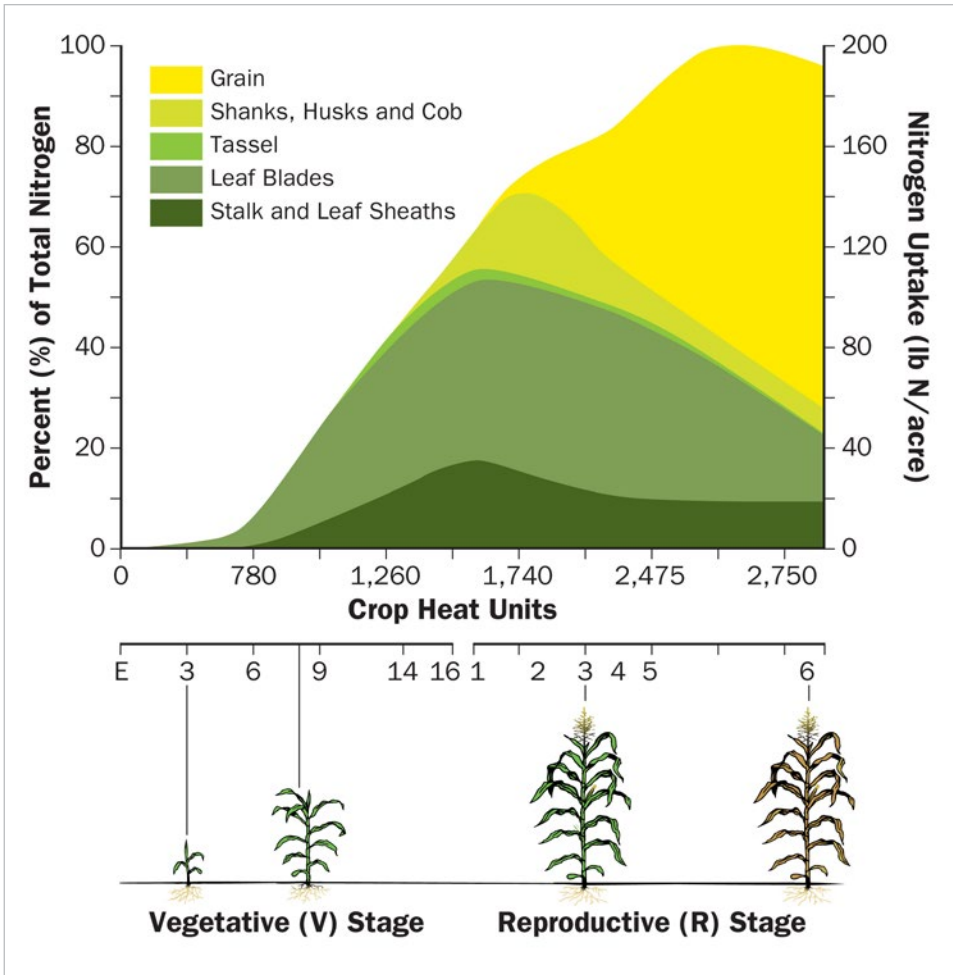
Figure 2–11. Generalized nitrogen uptake and partitioning in corn in relation to crop heat unit accumulation and crop growth stage. Adapted with permission from Iowa State University Extension. (The use of imperial measurement reflects the standards used in the industry.)

Carbon-to-nitrogen ratio

The carbon content of an organic material in relation to its nitrogen content determines mineralization or immobilization. Bacteria need nitrogen to decompose plant or other residues. Breakdown of organic material high in carbon will slow until a sufficient amount of nitrogen is present. Soil bacteria will consume available N for breakdown, which creates a risk of N deficiency in season until a favourable C:N ratio is established.

As a rule of thumb, mineralization occurs if the C:N ratio is less than 25:1. If it is greater than 25:1, immobilization occurs.

Symptoms

Corn:
- yellowish green colour in the whole plant in young plants; spindly stalks
- V-shaped yellowing along the midrib of older leaves, beginning at the tip (see back page)

Legumes, including soybeans, alfalfa:
- pale green, stunted and spindly plants
- in later growth stages, leaves turn yellow
- seen in alfalfa and soybeans on acid soils where nodulation is poor
- more common in soybeans during early spring as the plants switch from the nitrogen supplies of the seed to the nodules

Cereals:
- pale green and eventually yellow plants
- stunted and spindly plants

Winter wheat under nitrogen stress may be predisposed to take-all disease or septoria. When these diseases are present, there may be yield increases from higher-than-normal N applications.

Tomatoes, potatoes, peppers:
- in young plants, whole plants appear light green
- in older plants, older leaves yellow

Strawberries:
- pale, off-colour plants
- reduced growth

Vine crops:
- stunted leaf growth, pale foliage
- slender, hard and fibrous stems

Nitrogen can affect plant disease

Imbalanced plant nutrition, and particularly an excess of nitrogen, can lead to lush growth that is softer and less able to withstand disease. Excess nitrogen can also lead to dense plant canopies that trap humidity within the canopy and create conditions in which many fungal diseases thrive.

Ⓟ Phosphorus

Forms of phosphorus in soil

Phosphorus (P) occurs in soil in three basic forms: soluble P, labile P and non-labile P. Less than 5% of a soil's total phosphorus is available or slowly available to plants at any time. The rest is held in organic matter and a number of different mineral forms.

Soluble P

Monohydrogen phosphate $(HPO_4)^{2-}$ and dihydrogen phosphate $(H_2PO_4)^-$ are the soluble P forms found in the soil solution and used by plants. Soluble P is also a concern environmentally as it can be lost by movement of surface water overland or through tile drains.

Labile P

Another portion of phosphorus, labile P, is held by the surfaces of clay particles and mineralized from soil organic matter. As phosphorus is removed from the soil solution by plant uptake, more phosphorus is released from the soil into solution.

Non-labile P

In the soil, phosphorus reacts with ions such as aluminum, iron and

calcium and forms compounds with very low solubility. Some of the phosphorus also becomes adsorbed to clays and is virtually unavailable to plants. This is the non-labile pool of phosphorus in soil.

Phosphorus losses

Since phosphorus concentrations are relatively low in the soil solution and compounds resulting from chemical reactions between it and other elements have low water solubility, little of the available phosphorus is lost to leaching. Phosphorus can be lost, however, through surface runoff or tile drains via macropores, which are pathways such as large cracks and earthworm burrows (see Figure 2–12). Even though a small amount of soluble (dissolved) phosphorus is lost on average, it can have a significant impact on water quality. Particulate, or soil-bound phosphorus (labile and non-labile P), can be lost through the same pathways. Reducing erosion, applying phosphorus according to soil test values at a time when risk of runoff is low and avoiding non-incorporated broadcast applications are all ways to minimize risk of phosphorus loss. This topic is discussed further in Chapter 7, *Fertilizer Recommendations*.

Primary and secondary forms of phosphate

Plants absorb most of their phosphorus as an anion, either primary orthophosphate ($H_2PO_4^-$) or secondary orthophosphate (HPO_4^{2-}).

Studies indicate that plants prefer the primary form by about 10 to 1. But since the two forms interchange quickly in the soil, it's not important.

Soil pH influences the ratio. At pH 7.2, plants take up about equal amounts of primary and secondary orthophosphate. Below this level, they favour the primary form.

What about polyphosphates?

Polyphosphates are as effective as orthophosphates as sources of phosphorus for crops. Although plants can take up only some polyphosphate directly, most polyphosphates will convert to orthophosphate in the soil and then be available for uptake.

Turnover of phosphorus in the soil solution

If the soil solution has a phosphorus concentration of 0.01 ppm and the soil contains 30% moisture by volume, then the top 50 cm (20 in.) of this soil contains 0.045 kg/ha of soluble phosphorus.

To meet the crop uptake requirements for a 10,000 kg/ha corn crop (160 bu/acre), the soil solution would have to be replenished 667 times during the growing season. The labile P in the soil replenishes the P in soil solution. This labile P comes from soil minerals, previous P fertilizer applications and organic P sources.
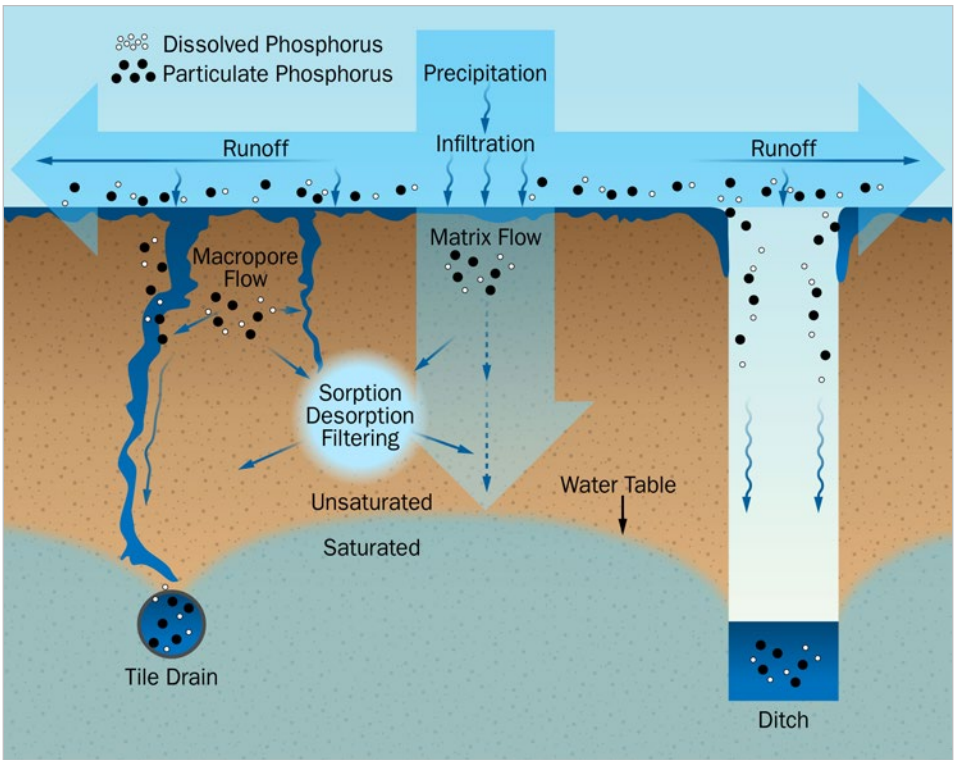
Figure 2–12. Pathways of phosphorus loss common to Ontario. Two forms of phosphorus – dissolved and particulate – can be lost by two main pathways: macropore flow to tile drains and surface runoff. Adapted with permission from Dr. David E Radcliffe, University of Georgia, 2015.

Factors affecting phosphorus availability

pH

At high pH values (> 7.5), phosphate reacts with calcium and magnesium compounds, which decreases its water solubility and plant availability.

In acidic soils (pH < 6.0), phosphate reacts with iron and aluminum to produce insoluble compounds and reduce plant availability.

Maximum phosphorus availability occurs at pH 6.0–7.0, where fixation is minimized. (See Figure 2–13.)

Moisture and temperature

Phosphorus moves through the soil primarily by diffusion. As soil moisture levels decrease, the water film surrounding soil particles becomes thinner, which makes diffusion more difficult.

Organic matter decomposition can be a source of phosphorus. Water and temperature play a role in the release of phosphorus from organic matter through mineralization. As temperature increases, the rate of mineralization increases and more phosphorus is released.
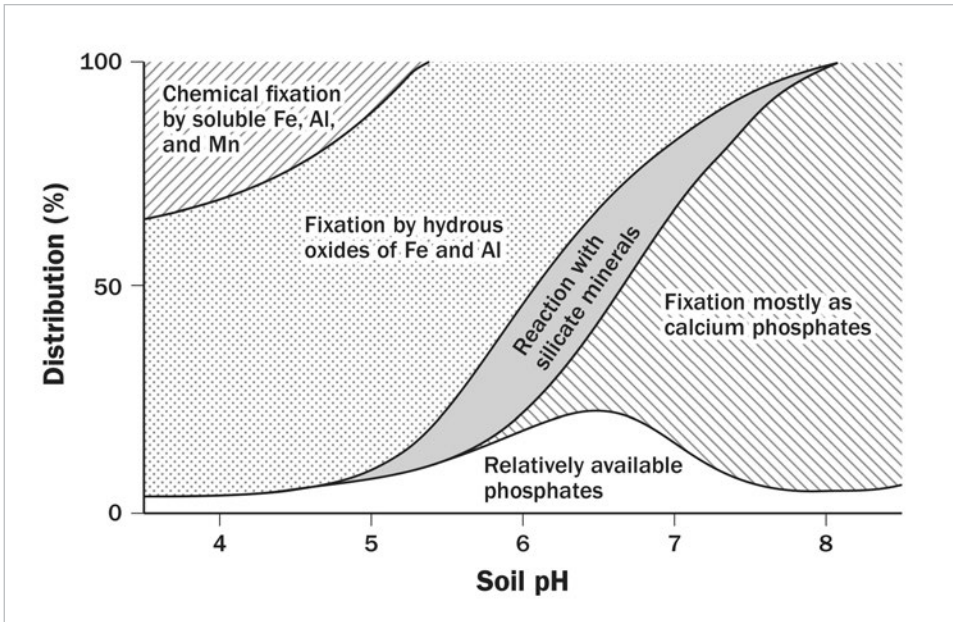
Figure 2–13. Effects of soil pH on forms of soil phosphorus

Fertilizer

In any given year, plants will use up to 30% of the phosphorus applied as fertilizer or manure. This depends on the background phosphorus content in the soil, placement of the fertilizer and the crop. The more phosphorus applied as fertilizer or manure, the more that is available to plants. The phosphorus not used by the crop in the year of application does have a residual value.

Time and placement of fertilizer

Movement of phosphorus by diffusion accounts for only millimetres each year. Banding phosphorus at planting time is more effective than broadcasting it, as banding decreases the amount of phosphorus that comes into contact with soil, which reduces phosphorus fixation. Applying phosphorus close to planting time also decreases fixation by minimizing the time between application and use by the plant.

Soil compaction can severely limit root expansion and limit surface area available for nutrient uptake. Starter fertilizers may help to alleviate the negative impact that soil compaction may have on phosphorus uptake.

Caution: Phosphorus deficiency in perennial crops (orchard, berries, vineyards) is difficult to correct. Soil test before establishing perennials to make sure there is enough phosphorus for the intended crop.

Clay content of soil

The higher the clay content of a soil, the more phosphorus becomes adsorbed and the less is in solution and available to plants. However, clay soils also have a greater reserve of phosphorus from which to replenish the soil solution supply as it is taken up by plants.

Crop residues

Tillage systems with large amounts of surface residue can have greater response to starter phosphorus because the residues keep the soil cooler and wetter, and the roots are therefore less able to extract phosphorus from the soil. Surface residues keep more water near the soil surface, allowing roots to continue taking up phosphorus from the topsoil later in the season. Organic residues on the soil surface can delay soil fixation of applied phosphorus. Thus, broadcast applications of phosphorus in no-till can be available to the crop, although this application method may not be desirable if there is risk of runoff and water contamination.

Relationship of phosphorus to other nutrients

Nitrogen

As nitrogen increases in the soil solution, the uptake of phosphorus increases. This effect could be caused by a decrease in pH when there is a greater amount of ammonium ions in the soil solution. Also, increased nitrogen accelerates the rate of translocation of phosphorus from the root to the plant shoot.

Zinc

Soils with a combination of a high level of phosphorus fertilization and low or marginal soil levels of zinc can result in zinc deficiency symptoms.

Role of phosphorus in plants

Like nitrogen, phosphorus is an important factor in many plant metabolic processes and structures, such as:

• photosynthesis and respiration
• energy storage and transfer (ATP)
• protein and carbohydrate metabolism
• cell division and enlargement
• structure of DNA
• component of cell membranes

The effect of the availability and supply of phosphorus on these plant processes and structures is reflected in specific aspects of crop growth.

Roots tend to proliferate in the parts of the soil most enriched by phosphorus. Overall, however, higher soil phosphorus levels reduce the total mass of roots. When phosphorus is limiting, plants adjust by shifting more resources to root production and less to top growth. Adequate phosphorus supplies, however, result in better winter survival of crops such as wheat and alfalfa due to increased energy and carbohydrate metabolism. Sufficient phosphorus hastens maturity of many crops, including corn, cereal grains and tomatoes. The reasons for this are not fully understood but could be related to enhancement of energy transfers or rates of cell division.

Phosphorus deficiency

Field crops such as corn and cereals usually take up a significant amount of their P when only 20% of the plant growth has occurred. This may be related to a plant's ability to take up P at rates greater than metabolic need when it is readily available and store it internally in cell vacuoles. This stored P may be used to buffer P needs during later growth stages.

Phosphorus does not move great distances in the soil at any time. Under poor growing conditions (e.g., cool, dry or saturated soils), a weather-induced phosphorus deficiency may appear. This type of deficiency tends to be the result of restricted root growth, not necessarily low soil phosphorus content. Phosphorus nutrition is a regulatory factor in seed development at the time of grain fill, as most of the seed's phosphorus requirements are translocated from the plant's leaves and stems. Purpling in plants is associated with phosphorus deficiency, but this symptom is unreliable. The production of anthocyanin, which creates the purple colour, is a standard stress response. Many other factors can induce purpling.

Phosphorus deficiency is harder to detect visually than a deficiency of nitrogen or potassium.

Symptoms
Corn:
• dark green plants

• may develop a reddish purple colouring on older or lower leaves first (although this can be hybrid-specific)
• purpling progressing up the plant as severity increases
• early growth often stunted: later stalks may be slender, shortened
• delayed maturity

Wheat (see back page):
• dark-green, slow-growing plants
• delayed maturity
• stunting and reduced tillering
• poor winter survival

Legumes, including soybeans, alfalfa:
• retarded growth; spindly, small leaflets; dark-green leaves
• perennial legumes like alfalfa also show poor winter survival

Tomatoes, peppers, potatoes:
• slow growth, delayed maturity, purple interveinal tissue on underside of leaves

Cole crops:
• purple leaves and stems
• stunting and slow growth

Potatoes:
• plants are stunted; leaves are dark green, and their margins roll upward
• early and late blight diseases may worsen with P deficiency

Strawberries:
• darker green or bluish-green foliage

Tree fruit:
• reduced shoot growth, flowering and fruit set
• rarely, dark-green to purple leaves

K Potassium

Forms of potassium in soil

Soil minerals are rich in potassium, although little is available to plants. Potassium is present in the soil in many forms.

Unavailable potassium

90%–98% of the soil's potassium is unavailable to plants. It is found in minerals such as mica and feldspar that are relatively resistant to weathering. However, over time and with continuous weathering, these minerals do slowly release potassium into the soil.

Slowly available potassium

1%–10% of total potassium in the soil is slowly available. It is trapped between layers of silica and alumina clays. These clays shrink and swell during dry and wet cycles. Potassium trapped between the layers of clay is released slowly during the swelling cycle and becomes unavailable during the dry or shrinking cycles.

Available potassium

1%–2% of the soil's potassium is readily available, held in the soil solution or in an exchangeable form with soil organic matter or clays.

In the soil solution, potassium maintains a dynamic equilibrium. Potassium ions that are taken up by plants are rapidly replaced by exchangeable potassium. The addition of potassium fertilizers increases the potassium in solution dramatically. Adsorption of potassium to clay and organic matter quickly re-establishes the equilibrium.

Factors affecting potassium availability

Soil temperature

Potassium moves to the plant root mainly by diffusion. As soil temperatures rise, the rate of diffusion, root growth and conversion from slowly available to available potassium increases. Together, these processes elevate levels of plant-available potassium.

Root systems

Diffusion can only move potassium small distances. Therefore, an extensive and actively growing root system is able to use more of the soil's available potassium.

Soil aeration

Under conditions of poor aeration (e.g., compaction, water-logged soils), the low oxygen levels decrease the uptake of potassium. This effect is more severe for potassium than for nitrogen or phosphorus.

Moisture

Lower soil moisture conditions decrease the movement of potassium to the root. Low moisture levels also result in more of the soil potassium becoming fixed between layers of clays.

Clay and organic matter content

Soils that are low in clay and organic matter have fewer exchange sites and therefore retain less potassium. High rainfall on these soils may result in the leaching of potassium ions. This is why sandy soils may need more frequent sampling and possibly more frequent applications.

Relationship of potassium to other nutrients

Magnesium

High potassium levels can reduce the uptake of magnesium. In some cases, this can result in magnesium-deficient plants. When large amounts of potassium are applied to low-magnesium soils, magnesium deficiencies may result.

In forages, low magnesium affects the nutrition of animals before it affects the growth of plants.

Dry cow rations

With more intensive forage management and more efficient use of the nutrients in manure, total potassium applications to some forage fields have been rising. When soil potassium levels are high, plants may take up more potassium than is needed for maximum yield.

This luxury consumption by alfalfa and forage grasses can lead to high levels of potassium in the forage part of the ration.

The level of potassium in dry cow forages can be a nutritional and health concern for dairy cows. In the 3–4 weeks prior to calving, excessive potassium in the diet can increase the incidence of milk fever and retained placentas. When cows consume a diet high in cations, their blood pH increases, which interferes with the cow's calcium metabolism. The maximum amount of potassium desired in dry cow diet varies. Generally, the forage potassium should be less than 2.5% on a dry matter basis. Addition of grains or corn silage during the 3–4 weeks before calving may help meet the rising energy demands and provide a better dietary ionic balance to reduce milk fever incidence by having a more favorable effect on blood pH.

Lactating cows generally do not have as much of a problem with excessive potassium. The diet of a lactating cow is higher in energy, supplied by grains and corn silage, which are lower in potassium.

Potassium levels in forage vary dramatically (Table 2–7). Forage analysis can aid in soil fertility management as well as improve livestock feeding. See a livestock nutrition specialist before changing feed rations.

Table 2–7. Potassium concentration in some forage samples

Forage Type	Average (%K)	High (%K)	Low (%K)
legume haylage	2.5	4.0	1.0
mixed haylage	2.5	4.6	0.7
grass haylage	2.4	4.6	1.0
legume hay	2.3	4.5	0.7
mixed hay	2.0	4.2	0.4
grass hay	1.9	4.8	0.9
corn silage	0.9	3.1	0.2

Data obtained from samples submitted for analysis to SGS Agri-Food Laboratories, Guelph, 2010–2017.

Role of potassium in plants

Plants need potassium in about the same amount as nitrogen. Potassium is unique in that it remains in a soluble form in the cell solution and does not become an integral component of the plant materials. It is involved in many plant processes. Potassium:

- promotes formation of structural components like lignin and cellulose, which play a major role in stalk strength and lodging resistance
- influences the uptake of carbon dioxide, photosynthesis and the regulation of stomatal opening in the leaves
- influences water uptake by roots
- influences starch and sugar content (and cell integrity), enhancing storage quality in potatoes, juice quality in grapes and the peelability and processing characteristics in whole-pack tomatoes
- aids in disease and insect resistance
- reduces the amount of soluble non-protein nitrogen in forages

Potassium deficiency

Since potassium is mobile within the plant, deficiency symptoms usually appear first on older leaves, often as a chlorosis (yellowing) or necrosis (browning) of the leaf margins.

The most common causes of potassium deficiency are under-fertilization, rotations that include many whole plant crops (e.g., alfalfa or corn silage), restricted root growth from soil compaction, or the early stages of conversion to reduced tillage systems on heavier soils. Dry weather conditions on sand soils are also a cause.

Symptoms

Corn:
- yellowing or browning of margins in older leaves
- stunted growth
- chaffy kernels, abortion of kernels at tip of cobs
- weaker stalks — lodging, stalk rots

Alfalfa:
- small white or yellow dots near the leaf margin (see back page)
- premature decline of alfalfa in mixed stands
- more winterkill
- slower regrowth

Soybeans, dry beans, snap beans:
- yellowing or browning of margins in older leaves (see back page)
- possible downward cupping
- reduced nitrogen fixation
- uneven maturity

Cereals:
- overall yellowing
- leaves that may be yellowed or bronzed along the outer edges
- excessive tillering in some cases

Tomatoes:
- yellowing of leaf margins
- yellow shoulders on ripe fruit (interferes with whole-pack recovery)

Grapes:
- bronzing edges on leaf
- leaf cupping

Potatoes:
- leaf scorch
- decreased yield

Cucurbits:
- chlorotic leaves
- irregular fruit development (narrow at stem end, large at blossom end)

Secondary nutrients

Calcium, magnesium and sulphur are required in moderate amounts. They are usually classified as secondary nutrients because they are less likely to limit crop growth. These nutrients are usually present in the soil in adequate amounts, although fertilization may be required for certain crops.

Ⓒⓐ Calcium

There are relatively large amounts of calcium in most Ontario soils because they were formed from calcium-bearing parent material.

Calcium in soil solution is absorbed by plant roots or enters the exchange complex of the soil and is held by negatively charged organic matter and clay colloids.

As with any cation, equilibrium exists between the solution phase and the exchangeable pool. If calcium in the solution phase is taken up by the crop or lost to leaching, calcium ions (Ca^{2+}) will be released from exchange sites to replenish the supply and re-establish equilibrium. Conversely, if the Ca^{2+} supply increases in the solution, more calcium will attach to the exchange sites.

The availability of calcium to plants is a function of:

- the total calcium supply
- soil pH — low pH soils are more likely to be low in calcium
- CEC — the ability of the soil to hold cations will determine the amount

of calcium that can be released and made available for plants

• soil type — in sandy soils, calcium is lost by leaching

Relationship of calcium to other nutrients

Calcium uptake is depressed by ammonium-based nitrogen as well as excessive potassium, magnesium, manganese and aluminum. Nitrate-nitrogen is a preferred nitrogen source where calcium supply may be marginal or critical for crop quality. When the plant takes up the negatively charged nitrate, it can more easily take up positively charged cations, including calcium.

Role of calcium in plants

Calcium is absorbed by plants as calcium ions (Ca^{2+}). It usually reaches the root surface by mass flow and root interception. Calcium is important in the stabilization of the cell wall and is involved in the formation and metabolism of the cell nucleus. Calcium pectate in cell walls provides a physical barrier to disease entry. Adequate levels of calcium have been shown to increase marketable yield by reducing physiological disorders.

Calcium serves a minor role as a catalyst in the activation of a few enzymes and the detoxifying of metabolic acids.

Calcium moves by mass flow caused by the demand for water by transpiration of the plant. Most of the calcium goes to large leaves where there is greater water need, often bypassing fruit, which has relatively little transpiration loss. Calcium disorders can develop as a result. Calcium moves in the xylem transport system, and deficiency symptoms appear in the new growth and terminal end growth.

Calcium disorders

Blossom end rot (BER) is a result of a lack of calcium in the tomato fruit (see back page). Often the soil has enough calcium, but the transpiration stream carries the bulk of the calcium through the plant to the leaves rather than to the fruit. Water stress, whether induced by root pruning, a restricted root system, excess nitrogen fertilization or just a lack of water, makes the plant more prone to this condition.

Trials have shown no advantage to applying calcium containing fertilizers such as calcium nitrate or applying foliar calcium to tomatoes. The problem is one of water management.

Tipburn in lettuce, blackheart in celery and potatoes, and bitter pit in apples are a similar expression of calcium deficiency. In many of these cases, foliar application of calcium may have some benefit for specific crops.

Calcium deficiency

Calcium deficiency is rare in Ontario. Calcium supply is generally adequate for most crops when soil pH is in the recommended range. A soil test of less than 350 ppm calcium has been cited in literature as being low enough that potatoes responded to added calcium with larger tubers, but not greater total yield (Ozgen, Palta and Kleinhenz, 2006).

When calcium deficiency occurs, symptoms are seen in actively growing tissues, because calcium is immobile in the plant once it is fixed in the cell structure.

Managing crops in low-calcium soils

There are some sandy, low-CEC, poorly buffered soils in Ontario with neutral pH that are low in calcium. These soils usually suffer from moisture limitations before any apparent calcium deficiency occurs.

These are desirable soils, however, for drip-irrigated crops. These modest levels of calcium may become limiting as water becomes non-limiting in this production system. An application of gypsum, limestone, calcium nitrate or calcium chloride to increase calcium content of such soils is worth considering.

Mg Magnesium

Magnesium levels vary widely across Ontario, due to differences in parent material. Like calcium, magnesium is strongly attracted to cation exchange sites, but leaches somewhat more readily.

Magnesium is present in the soil in solution and exchangeable forms, as well as slowly available forms like dolomitic limestone, clay minerals and feldspar. There are limited areas of soils where magnesium levels are higher than the calcium level. These soils are found more frequently in parts of eastern Ontario and are characterized by poor structure and poor internal drainage. Applications of calcitic limestone or gypsum may improve productivity of these soils.

Magnesium moves to the root by all three transport methods: mass flow, root interception and diffusion.

Relationship of magnesium to other nutrients

The availability of magnesium is influenced by several other nutrients. Potassium, if present at high levels and exchangeable, can interfere with magnesium uptake. Ammonium can also interfere with the availability of magnesium to plants. This occurs mostly when high rates of ammonium fertilizers are applied to soils low in magnesium.

Some research suggests that adequate magnesium levels encourage the uptake of phosphorus and its mobility in plants. Magnesium

---

is lost from soils by crop uptake, leaching and erosion.

Role of magnesium in plants

Magnesium has several roles in plant growth and development, including:

- the structure of chlorophyll molecules
- protein synthesis
- enzyme activation

Magnesium deficiency

Magnesium deficiency symptoms are frequently found in the lower leaves. This is due to the fact that magnesium, like nitrogen, potassium and phosphorus, is mobile in plants and can be moved to the new growth and reused. On some plants, magnesium deficiency shows as a crimson colour. On others, it appears as dead tissue between the veins or a pale green colour caused by low chlorophyll content.

Like calcium, magnesium deficiencies are often associated with low pH. Coarse-textured, acidic soils are more likely to develop a magnesium deficiency. Low-magnesium, coarse-textured soils that receive manure on a long-term basis may be prone to induced magnesium deficiency due to the high potassium content of manure, especially ruminant manure.

Grass tetany

Grass tetany or hypomagnesemia is a magnesium imbalance in ruminant livestock that results from consumption of feeds low in magnesium. The low magnesium content of the feed can be due to high rates of ammonium or potassium fertilizers being applied to the crop. A high protein content in the feed ration will also depress magnesium uptake within the animal.

Symptoms

Corn:
- initially yellow to white interveinal striping of older leaves, with the striped areas eventually dying
- often confused with zinc deficiency but striping with magnesium is definite, extends from base to tip in the leaf
- older leaves develop reddish to purple colour

Soybeans:
- pale green between veins on lower leaves during early growth
- leaf margins curling down; entire leaf yellow except at the base
- symptoms moving to middle leaves, creating the appearance of early maturity

Alfalfa:
- pale-green colour in older leaves
- stunted; low vigour; rusty specks develop into necrotic spots between leaf veins; leaf margins may die back
- poor nodule development

Cereals:
- lack of vigour; stunted, with reproductive delays
- large irregular spots uniformly across leaf tips and down leaf margins toward the leaf base on older leaves
- leaves may appear striped and may develop colours from pale green to yellow, reds and browns

Potatoes:
- chlorosis with green veins and brown spots on young mature leaves (leaf scorch between veins)
- in severe deficiency, leaves will dry off but remain attached; new leaves are green

Tomatoes:
- older leaves affected first
- veins dark green; interveinal areas become yellow; lack of nitrogen intensifies the symptoms

Celery, carrots:
- marginal necrosis and interveinal chlorosis on older leaves
- leaves curl up

Grapes:
- interveinal and marginal leaf necrosis
- interveinal yellowing or reddening
- development of brown-green patches

S Sulphur

Sulphur is an essential element for plant growth. Determination of sulphur status can involve soil testing, plant tissue analysis, observation and knowledge of crop-specific requirements. An Ontario accredited sulphur test is not currently available. While laboratories in Ontario offer sulphur soil tests, it is not possible to translate results into a sulphur recommendation as Ontario-specific calibration data is lacking. An inherent risk exists in using recommendations from other growing areas. Plant tissue evaluation along with sulphur strip trials in fields is useful to determine sulphur status of a particular cropping system. Crops with a known sulphur requirement, such as canola, require special attention.

The recent reductions in air-borne sulphur emissions (see Figure 2–14) and the use of more refined fertilizer products over the past several decades has led to a decline of sulphur deposition in the Great Lakes Basin. In the past, assumptions were made that soil sulphur supplies were adequate for crop production in Ontario. In more recent years, economic responses to sulphur fertilization have been observed in some instances for alfalfa. Visual deficiency symptoms have also been reported more frequently in winter wheat, and S fertilization has become commonplace in many regions.
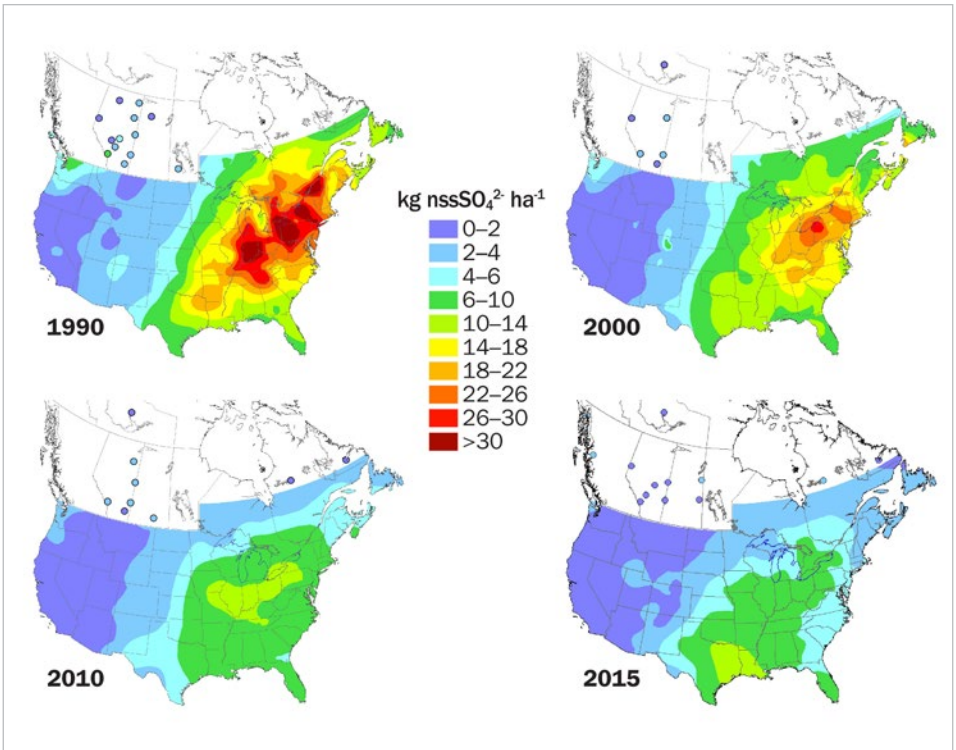
Figure 2–14. Annual wet sulphate deposition in North America from 1990, 2000, 2010 and 2015. **Note:** nssSO$_4^{2-}$ = non sea-salt sulphate-sulphur deposition.
Source: Environment and Climate Change Canada, 2018. © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment and Climate Change, January, 2018.

Acid rain and sulphur

Some parts of southern Ontario received up to 44 kg/ha (39 lb/acre) of sulphate-sulphur (SO$_4$-S) annually from acid rain and snow as recently as 1990. However, deposition currently only contributes 8–12 kg/ha (7–11 lb/acre) SO$_4$-S per year to the soils of southern Ontario. Northwestern Ontario receives even less sulphur.

The possibility for sulphur deficiency is often greatest for sandy soils low in organic matter. The sulphate form is highly soluble and subject to leaching losses. Sulphur losses can also occur with the loss of organic matter and topsoil by erosion. Given the reduction in atmospheric sulphate deposition in recent decades, deficiency symptoms in certain field crops (e.g., winter wheat and alfalfa) are appearing more frequently across a range of soil types.

Sulphur occurs in the soil in many forms, both organic and inorganic. The sulphate ion (SO_4^{2-}) is the form of sulphur available to the plant. Most of the sulphur in the soil is contained in organic matter. The transformation of sulphur between unavailable organic and inorganic forms and plant-available sulphate involves four main processes:

- mineralization
- immobilization
- oxidation
- reduction

Mineralization is the decomposition of organic matter where organic sulphur is broken down by bacteria into plant-available sulphate.

Immobilization is the opposite. Bacteria convert sulphate back to unavailable organic sulphur.

Soil temperature, pH or moisture conditions that affect microbial growth will affect the mineralization of organic matter and rate and amount of sulphate available to plants.

Oxidation is the reaction of sulphur with oxygen to form sulphate. This is an important process since some fertilizers are reduced forms of sulphur and this conversion makes them available to plants.

Reduction is the opposite process. Sulphate is stripped of its oxygen under anaerobic conditions. Soils that are poorly drained are subject to this reaction and can produce sulphide compounds under prolonged waterlogged periods.

Factors affecting sulphur requirements

Carbon-to-sulphur ratios
Sulphur undergoes many of the same mineralization and immobilization reactions as nitrogen in the soil. Adding residues with a wide C:S ratio (>200:1) can result in sulphur immobilization and temporary sulphur deficiencies. This is more common with mature crop residues like straw than with fresh materials like clovers and green manures.

Nitrogen-to-sulphur ratios
The ratio of N:S in plant tissues ranges from 7:1 to 15:1, depending on the species and the stage of growth. Crops that receive high rates of nitrogen when sulphur supply from the soil is low can suffer from induced sulphur deficiency. It is currently common practice for Ontario growers to apply 10–20 kg/ha (9–18 lb/acre) sulphate-sulphur to canola in spring along with approximately 130 kg/ha (116 lb/acre) nitrogen.

Role of sulphur in plants
Sulphur is a constituent of 2 of the 21 amino acids that form proteins. It also:

- helps develop enzymes and vitamins
- is involved in nitrogen fixation in legumes
- aids in seed production
- is needed for chlorophyll formation

Sulphur also adds colour, flavour and distinctive odours to plants such as garlic, onion and cabbage and puts the heat in horseradish.

Sulphur deficiency

Symptoms of sulphur deficiency are similar to nitrogen deficiency except that the entire plant remains light green, since sulphur is not mobile within plants.

Symptoms

Corn:
• in small plants, general yellowing of foliage, stunting and delayed maturity

Legumes, including soybeans, alfalfa:
• small, yellowish-green leaves at top of plant
• thin, erect stems, woody and elongated

Cereals:
• interveinal yellowing of youngest leaves (see back page)
• erect tillers

Potatoes:
• entire plant light green
• in severe deficiency, leaflets curl upward

Canola:
• newly emerged leaves are yellowish green with dark veins, cupped
• vegetative stage — cupped, purple leaves, few small pods, empty pods
• sulphur deficiencies can occur at any growth stage
• mild deficiencies give good vegetative growth but pale flowers and under-developed pods
• post-harvest regrowth of stubble
• root rots can cause deficiency symptoms to appear

Cucurbits (cucumber, melons):
• young leaves affected first
• veins becomes slightly lighter than interveinal areas
• stunting
• similar to N deficiencies, except symptoms observed in new growth first

Micronutrients

Micronutrients are as important as the primary and secondary nutrients but are needed in much smaller quantities by the plant and are often less prevalent in the soil. The need for these nutrients varies with crop, variety, soil conditions and farm management. General responses of various crops to micronutrients are shown in Table 2–8.

The use of micronutrients has increased over time. The need for micronutrient application may be increasing because of:

• continued high-yield cropping that may have depleted soil reserves
• more refined fertilizer materials with fewer impurities such as micronutrients
• specialized agriculture with fewer fields receiving manure
• soil degradation and erosion

Table 2–8. Response of crops to micronutrient fertilizers

LEGEND: — = crop-nutrient response interactions for which there are insufficient data

Crop	Manganese	Boron	Copper	Zinc	Molybdenum
alfalfa	low	high	high	low	medium
barley	medium	low	medium	low	low
clover	medium	medium	medium	low	high
corn	medium	low	medium	high	low
edible beans	high	low	low	high	medium
oats	high	low	high	low	low
rye	low	low	low	low	low
soybeans	high	low	low	medium	medium
wheat	high	low	high	low	low
asparagus	low	low	low	low	low
broccoli, cauliflower	medium	high	medium	—	high
cabbage	medium	medium	medium	low	medium
carrots, parsnips	medium	medium	medium	low	low
celery	medium	high	medium	—	low
cucumbers	high	low	medium	—	—
lettuce	high	medium	high	medium	high
onions	high	low	high	high	high
peas	high	low	low	low	medium
peppers	medium	low	low	—	medium
potatoes	high	low	low	medium	low
radishes	high	medium	medium	medium	medium
red beets	high	high	high	medium	high
spinach	high	medium	high	high	high
sugar beets	high	medium	medium	medium	medium
sweet corn	high	medium	medium	high	low
tomatoes	medium	medium	high	medium	medium
blueberries	low	low	medium	—	—

Highly responsive crops often respond to micronutrient fertilizer if the micronutrient concentration in the soil is low. Medium responsive crops are less likely to respond, and low responsive crops do not usually respond even at the lowest soil micronutrient levels.

Source: Vitosh, M.L., D.D. Warncke and R.E. Lucas, 1994. Publication E-486: *Secondary and Micronutrients for Vegetables and Field Crops*. Michigan State University.

Zn Zinc

Zinc is relatively immobile in the soil, which means that leaching does not pose a problem.

Zinc that may become available to plants is present in the soil solution as Zn^{2+}. It is held on the surfaces of clay, organic matter and soil minerals as exchangeable zinc or complexed with organic materials.

Zinc availability is reduced by:

• high-pH conditions, under which zinc forms insoluble compounds
• adsorption on the surfaces of clay, organic matter, carbonates and oxide minerals

Zinc is important in early plant growth and in grain and seed formation. It plays a role in chlorophyll and carbohydrate production.

Zinc deficiency

Zinc deficiencies are most often seen on high-pH soils, on soils with marginal zinc levels where there have been large applications of phosphorus, on sandy soils or on eroded or levelled soils where the subsoil is exposed. Deficiencies may also occur in organic (muck) soils.

Zinc deficiency is rarely seen on soils receiving manure, as manure generally contains zinc. Liquid swine manure, for example, can contain over 85 g of zinc/m^3 (about 3.5 lb of zinc/5,000 gal), while solid poultry manure may contain over 200 g/t (about 2 lb/5-ton application).

Symptoms

Because zinc is relatively immobile within the plant, deficiency symptoms develop first on young foliage.

Corn:
• usually seen in young plants as interveinal chlorosis on new leaves
• can appear as pale-to-white bands between the leaf margin and mid-vein in the lower part of the leaf
• in severe deficiency, new leaves emerging from the whorl completely white (white bud)

Legumes, including soybeans, alfalfa:
• thin, short stems, pale green to bronzed foliage with yellow mottling and some necrosis
• interveinal chlorosis that continues to develop and veins that appear darker green (unlike manganese deficiency, the chlorosis appears more mottled)

Tree fruit and strawberries:
• chlorosis of young leaves; green halo that appears along serrated margins of young immature leaf blades
• blind bud, little leaf and rosetting (small basal leaves forming on short terminals and lateral shoots of new year's growth)

Onions:
• stunted growth with twisted, yellow-striped foliage

Mn Manganese

Manganese in the soil exists in four main forms: mineral, organic, exchangeable and dissolved. Most of the manganese absorbed by plants is in the form Mn^{2+}. Soil contains large amounts of manganese but little is available.

The availability of manganese is influenced by:

- pH — as pH values rise, exchangeable manganese declines rapidly. Availability is greatest at pH 5.0–6.5.
- organic matter — high organic matter decreases the availability of manganese. This is of particular concern in vegetable production on muck soils.
- excessive water or poor aeration — this causes soluble manganese to increase
- other nutrients such as nitrogen — ammonium-based fertilizer has an acidifying effect, which can enhance uptake of manganese

Manganese is involved in photosynthesis and chlorophyll production. It helps activate enzymes involved in the distribution of growth regulators within the plant.

Manganese deficiency

Manganese deficiency is seen most frequently in soybeans on high-pH soils and in crops on muck soils and high organic matter mineral soils. Deficiencies can also occur in newly tiled fields. Mn deficiency is implicated in many diseases. Root rots may cause manganese deficiencies and reduced root growth from soybean cyst nematodes (SCN) may increase Mn deficiencies.

Symptoms

Soybeans, white beans:
- chlorotic conditions in younger leaves
- veins in the leaves will remain dark green, while between the veins the tissue will go yellow (see back page)

Small grains:
- pale yellow leaves; stunting; later tips of small grain leaves turn grey to white (grey speck in oats)

Red beets, sugar beets:
- russetting, curling and dwarfing of foliage

Lettuce, celery, onions:
- yellowing of leaves, stunting and delayed maturity

Early-season foliar application is more effective as a treatment for manganese deficiencies because soil-applied manganese converts rapidly to unavailable forms.

Soil-applied manganese may be useful in acidic, sandy soils. Banded applications result in higher manganese availability than broadcast applications.

> **Note:**
>
> On Red Delicious apples and some peach cultivars, manganese toxicity can occur on coarse-textured soils when pH is below 5.0.
>
> The symptoms, known as measles, are raised pimples on the bark underlain by dark brown spots. Correction sometimes is possible by the addition of lime to raise the pH.

Ⓑ Boron

Boron in the soil is present as soil solution boron, adsorbed boron and mineral boron. Boron uptake by plants is related to pH. Availability is best between pH 5 and 7. Availability decreases during periods of drought.

Boron plays an important role in the structural integrity of cell walls, fruit set and seed development, and carbohydrate and protein metabolism.

> **Note:**
>
> Crops vary widely in their requirements for and tolerance to boron. The line between deficient and toxic is narrow. Boron toxicity symptoms have occurred in seed and sweet corn and soybeans following red beets that had boron applied. Use boron with care and with consideration of the crop rotation.

Boron deficiency

Boron deficiencies are more likely with:

- dry soil
- soil pH extremes
- soils low in organic matter
- exposed or eroded subsoils

Symptoms

Symptoms of boron deficiency vary widely from plant to plant. Boron is poorly mobile within the plant.

Rutabaga:
- hollow centre, brown watery areas (water core)

Celery:
- stem cracked with brown stripes (cat scratches), heart blackened

Cole crops:
- hollow stems, brown curds, deformed buds

Apples:
- small, flattened or misshapen fruit; low seed count; internal corking, cracking and russetting; dead terminal buds, dwarfed, stiff, cupped and brittle leaves; blossom blast

Alfalfa:
- yellow-reddish top leaves; shortened internodes; poor seed set; terminal leaves form rosette; death of terminal bud (see back page)

Sugar beets, red beets, spinach:
- yellowing of leaves; spotting, cracking of root

Cereals:
- greater infection levels of ergot

Ⓒⓤ Copper

Copper is found in the soil solution, on clay and organic matter exchange sites, as part of soil oxides and in biological residues and living organisms. A large proportion, 20%–50% in some soils, is held in organically bound forms.

Availability of copper depends on:

- texture, because copper levels are lower in sands
- soil pH, because copper mobility decreases as pH rises
- soil organic matter — availability is extremely low in organic (muck) soils and can also be low in soils with very little organic matter

Some nutrients (such as zinc, aluminum, phosphorus and iron), if in high concentrations, depress copper absorption by plants.

Copper plays a role in chlorophyll production, as a catalyst for enzymes and perhaps in disease suppression.

Copper deficiency

Copper deficiencies are most common in crops grown on organic (muck) soils and sandy, high-pH, well-drained soils.

Symptoms

Carrots:
- pale root

Onions:
- tip dieback, curl and subsequent pig-tailing; thin, pale-yellow bulb scales

Cereal grains:
- pig-tail (leaf tip dies and may roll and curl to form pig tail)
- retarded stem elongation
- absence of grain heads
- grain that may be unusually high in protein

Lettuce:
- leaves lose firmness; yellow bleached stems

In Western Canada copper deficiencies were identified in the early 80s, and research has since identified millions of acres in the Prairies that are deficient in this essential nutrient. Copper deficiency is not common in Ontario.

Note:

Copper is needed in the feed rations of pigs, poultry and cattle but is toxic to sheep at fairly low levels.

In recent years, the application of pig manure to land used for hay or pasture has caused concern about copper toxicity for sheep producers. Hog manure varies from 2 ppm to 50+ ppm copper, with most in the area of 10 ppm. Forage or pasture plants will take up copper, and this can result in feeds that are toxic for sheep. Copper can accumulate in soils that have received repeated applications of pig manure.

Cl Chlorine

Chlorine is generally found in nature as chloride (Cl^-). In soil, chloride is readily soluble, highly mobile and easily taken up by plants. In Ontario soils, chloride levels are kept low due to leaching. Higher levels of chloride can be found in the lower slope positions of the field landscape where water accumulates and subsequently results in higher levels of chloride in plant tissue.

The availability of chloride is not affected by soil pH. The uptake and accumulation of chloride by plants is depressed by high concentrations of nitrate and sulphate.

Chloride in plants plays an important role in stomatal regulation and water flow. Chloride is also involved in photosynthesis.

Research outside Ontario suggests that chloride helps in the suppression of take-all, leaf rust and septoria in wheat and barley, as well as stalk rot in corn. Applying potassium as muriate of potash (0-0-60) may provide enough chloride to attain these benefits.

Some tree fruit and cane fruit crops are sensitive to chloride. Chlorides are also of concern in tobacco because of their effect on burn quality.

One letter makes a difference
Chlorine vs chloride

Some concern exists about the effect of chlorine from fertilizers like muriate of potash on soil bacteria. What is in the fertilizers, though, is chloride.

Chlorine and chloride are not the same and cannot be used interchangeably. Their behaviour and reactions in the soil and their effects on plants and micro-organisms are entirely different.

Chlorine (Cl_2) is a corrosive, poisonous gas used to make bleaching agents and disinfectants. When chlorine gas is dissolved in water, it forms a hypochlorite ion, the active ingredient in household bleach. Commercial liquid chlorine (compressed chlorine gas) is used as a water treatment to kill bacteria. Both hypochlorite and chlorine are effective bactericides.

Chloride (Cl^-) on the other hand, is the ionic form of chlorine found in nature. It has a negative charge and is most often associated with sodium (common salt) or other positively charged ions like potassium. It is non-toxic and readily absorbed and used by plants.

Compare the concentrations of chloride and chlorine in water. Sea water, which is teaming with bacterial life, contains chloride levels in the order of 20,000 ppm. Water treatment plants typically aim for chlorine levels of 1.7 ppm to disinfect the water.

Source: Eric Bosveld, The Agromart Group, 2006

Fe Iron

Iron is abundant in most soils, but its solubility is very low. The form taken up by plants is the ferrous ion (Fe^{2+}).

It has a number of functions within plants. Iron:

- is a catalyst in the formation of chlorophyll
- is required for plant respiration
- functions in the formation of some proteins

The greatest use of iron is in the turf, nursery and sod industries, where applications are used to give a darker green appearance to the foliage.

Iron deficiency

Iron deficiencies are rarely found in Ontario. When blueberries and rhododendrons are grown on soils with higher-than-recommended pH, iron deficiency can be a problem.

Factors associated with iron deficiency in other parts of the world are:

- imbalance with other metals such as molybdenum, copper or manganese
- excessive phosphorus in the soil
- plant genetics
- low soil organic matter
- a combination of: high pH (>7.8); high lime; wet, cold soils; and high bicarbonate levels (lime-induced chlorosis)

Symptoms of iron deficiency in:

Blueberries, rhododendrons:

- young leaves showing interveinal chlorosis or striping along the entire length of the leaf
- in severe cases, possible stunted growth

These crops perform best in acid soils because they have a high demand for iron.

Mo Molybdenum

Molybdenum is found in soil as non-exchangeable molybdenum in soil minerals, as exchangeable molybdenum on iron and aluminum oxides, in the soil solution and bound organically.

Availability of molybdenum is influenced by:

- Soil pH — as pH levels rise, molybdenum availability increases. Liming can improve the availability on acid soils.
- Aluminum and iron oxides — molybdenum is strongly adsorbed to these, which makes it less available.

Molybdenum is taken up by plants as molybdate (MoO_4^{2-}). Phosphorus enhances its absorption. However, deficiencies are most likely to occur under low soil-moisture conditions as this reduces mass flow and diffusion. There are also significant differences in sensitivity to low levels of molybdenum between plants and even between varieties of plants.

Molybdenum plays an important role in nitrogen metabolism within the plant and nitrogen fixation in legumes. It also plays a role in pollen viability and seed production.

Molybdenum deficiency

Symptoms

Legumes:
- poor nodule formation, nitrogen deficiency symptoms

Cole crops:
- early symptoms similar to nitrogen or sulphur deficiency: pale-yellow or light-green leaves, stunted plants that may show yellow mottling
- small necrotic areas of the leaf tissue followed by scorching and upward curling of the upper blade margins (whiptail in cauliflower)

Ni Nickel

Nickel is taken up by plants as Ni^{2+}. High levels in the soil can induce zinc or iron deficiency symptoms caused by competition between these cations. Nickel is an essential nutrient for legumes. It is important in nitrogen transformations as it is a component of the urease enzyme. Deficiency of nickel in agricultural soils is unknown.

Non-essential minerals

Although not essential for all plant growth, beneficial non-essential nutrients may be necessary for some plants or as a part of animal development. Undesirable, non-essential minerals may become a problem if the soil concentrations reach toxic levels, killing or harming the plant or passing the toxin along to the human or animal that eats the plant.

Beneficial minerals

Cobalt

Cobalt (Co) plays a role in forming vitamin B12 and enhances the growth of nitrogen-fixing organisms like *Rhizobia* and algae. Cobalt also plays a role in forming vitamin B12 in ruminants.

Sodium

Sodium (Na) plays a role in osmotic regulation, helping control the flow of water into and out of the plant. In some plants in low-potassium soils, sodium may perform some of the functions of potassium.

Sodium can have a toxic effect on plants. The large amount of rainfall and leaching in the spring and fall means that high-sodium soils are not common in Ontario. Areas with high sodium levels are usually associated with old oil wells, spilled brine or road salt application. Plant growth is reduced in these areas because of the toxic effect of excess sodium and the poor structure of sodic soils.

Silicon

Silicon (Si) can make up as much as 40% of unweathered sandy soils. Grasses contain 10–20 times the silicon concentration found in legumes and other broadleaves.

Silicon has been documented to reduce shading within a crop field by improving erect growth, decreasing lodging, increasing the resistance to root parasites and leaf and root diseases and preventing some nutrient toxicities.

Vanadium

Vanadium (V) is beneficial at low concentrations to micro-organisms, although there is no evidence it is essential for crop plants. It is thought to perform some functions in nitrogen fixation and may play a role in biological oxidation and reduction reactions.

Selenium

Selenium (Se) is not needed by plants but must be present in the feed for animal health. A deficiency in selenium results in white muscle disease, a form of muscular dystrophy in animals like cattle and sheep. Some areas of North America with semi-arid to arid climates such as California have soils with high selenium content. Much of Ontario, however, is deficient in selenium, and it is added to feed or given by injection to maintain animal health. In some cases it can be spread as a fertilizer, but the cost makes this rare in Ontario.

More problems with selenium deficiencies in livestock have been noted after cold, rainy growing conditions than hot, dry conditions. The use of nitrogen fertilizers to increase forage yields has lowered the selenium content of feed. The plant takes up the same amount of selenium, but it is spread across a larger plant and more biomass, diluting the selenium.

Undesirable elements

Lead

Lead (Pb), a heavy metal usually associated with industrial wastes, can be taken up by plants. The symptoms of toxicity are similar to iron deficiency; a yellowing of the plant with interveinal chlorosis.

Mercury and cadmium

Mercury (Hg) and cadmium (Cd) are heavy metals that can accumulate in tissues. Generally this is not a problem with plants, but the accumulation in human and animal tissues can have serious effects.

The level of heavy metals in sewage sludge will determine whether it can be applied to agricultural fields and if so, the rate and frequency of application. These metals do not move or get removed except in plant tissues, so they will accumulate in soil.

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3. Soil pH, Liming and Acidification

Soil pH

Soil pH is a measure of the hydrogen concentration of the soil solution. The pH scale runs from 0 to 14 with 7 being neutral, below 7 being increasingly acidic and above 7 increasingly basic. For every 1 unit of pH decrease, the hydrogen concentration increases 10 times. For instance, a soil that has a pH of 4 has 1,000 times more hydrogen in the soil solution than a soil with a pH of 7. For reference, the approximate pH of some common materials are: battery acid, 0.5; white vinegar, 3; pure water, 7; baking soda, 9; and household bleach, 12 (see Figure 3–1).

At the pH levels typical in soils, the hydrogen concentration itself does not have an appreciable impact on a plant. However, pH can impact other elements, including plant nutrients in the soil, and can have direct and indirect impacts on the activity of soil organisms that build soil structure, cycle organic matter or fix nitrogen in the nodules on the roots of legumes. It also impacts the performance and breakdown of some pesticides.
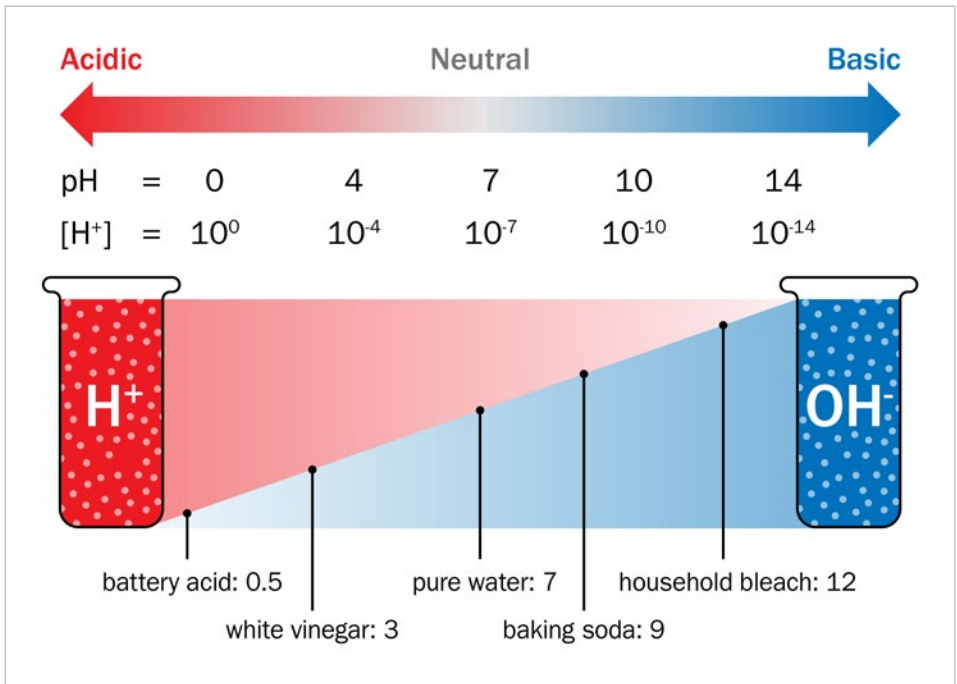
Figure 3–1. pH scale showing relative hydrogen ion (H^+) and hydroxide (OH^-) concentrations and pH values of common materials

Generally, plants take up nutrients only if they are dissolved in water. Soil pH influences the solubility of plant nutrients and other elements. Some nutrients are more soluble at high pH, others at low pH, and still others at ranges in between (Figure 3–2). This increase in solubility can also result in some elements, like aluminum and manganese, becoming toxic to the plant at low pH levels. Plant species differ in their requirements and tolerance of soil conditions that result from different pH regimes; however, they all generally have specific pH ranges at which they perform best. As such, monitoring and managing soil pH is one of the first steps in good soil management.

pH and metal solubility

Aluminum is contained in large quantities in soil mineral materials (sand, silt and clay). As pH decreases, the solubility of metals in soil, including aluminum, generally increases. Although aluminum is not a plant nutrient, plants do take it up. Above pH 5.7, the chemical forms of aluminum in soils are not toxic to plants; however, as pH drops below 5.7, forms of aluminum that can be toxic to plants increase rapidly with decreasing pH level. These toxic forms of aluminum can impact the roots of plants by slowing root elongation. The plant will continue to provide carbohydrates to the roots to fuel growth, but since elongation slows, the roots get wider, resulting in short stubby roots that have limited capacity for water and nutrient uptake. These forms of aluminum also react with soil

phosphorus, resulting in phosphorus compounds with very low solubility that are unavailable for plant uptake. In addition, the forms of aluminum that exist at low pH can restrict the formation of nitrogen-fixing nodules on the roots of legumes.

The solubility of another metal, manganese, also increases rapidly as pH decreases (see Figure 3–2). As with all plant nutrients, insufficient quantity is a problem for plant growth; however, having too much can be toxic for the plant. The pH at which manganese starts to become toxic varies depending on the amount of manganese in the soil, but it generally is not an issue until the pH drops below 5.0. However, increasing pH will decrease the availability of manganese, along with most other micronutrients (see Chapter 2). As such, it is possible to induce a manganese deficiency in a field when lime has been used to increase pH.

Aluminum, manganese and iron compounds abound in mineral soils but not in organic soils (mucks and peats). This limits the ability of these elements to interfere with the solubility of other nutrients in organic soils. Lower soil pH is, therefore, more acceptable for organic soils than for mineral soils (Figure 3–2).
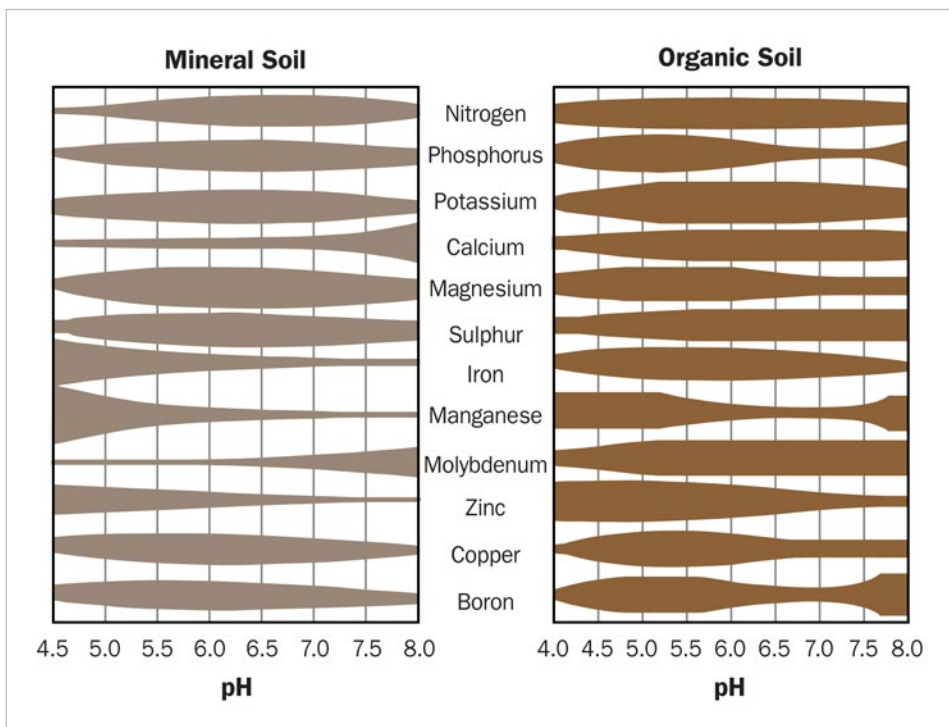
Figure 3–2. Impact of soil pH on nutrient availability in mineral and organic soils

Factors influencing soil pH

Parent material

The primary factor influencing the natural pH of a soil is the geological materials (soil parent material) that the soil has formed from. When the glaciers retreated from Ontario 10,000–15,000 years ago, the materials left behind were uniform in pH from the surface to bedrock. These materials were either deposited directly by the glaciers, deposited by meltwaters running from the retreating ice front or settled from the waters of post-glacial lakes. The nature of these glacial environments resulted in differences in the textures (sand, silt and clay) that were left behind

and went on to form our soils. In areas like Tillsonburg, that had fast-moving water coming from the glacial melt, all but the coarser materials were washed away. In areas where the meltwater formed lakes, like a significant part of Essex, Lambton and Kent counties, the clay and silt settled to the bottom resulting in very clay rich soils. In large areas of Wellington and Waterloo counties, the contents of the glaciers were simply deposited on the ground with little sorting by water, resulting in mostly loam textured soils.

The soils on most of southern Ontario, the Ottawa valley and the northern clay belt have formed on primarily limestone-based parent

material. This material will result in a soil pH of approximately 8.2. However, natural and manmade processes have led to acidification, resulting in the soil pH decreasing over time to a point where there are some instances of acid soils in these areas (Figure 3–3). The processes that make soils more acidic work on the layers of soil closest to the surface. Over thousands of years since the glaciers left Ontario, the acidified surface layers thickened as the added acids reacted with limestone contained in the soil. The soil horizons at depth are unchanged from what was deposited by the glaciers, and as such still contain high levels of limestone and have a slightly basic soil pH. This results in a typical soil profile that may be slightly acidic to neutral at the surface and more basic at depth. The parent material of most of Northern Ontario is largely acidic igneous geological materials (Canadian Shield), resulting in acidic soils predominating (Figure 3–3).
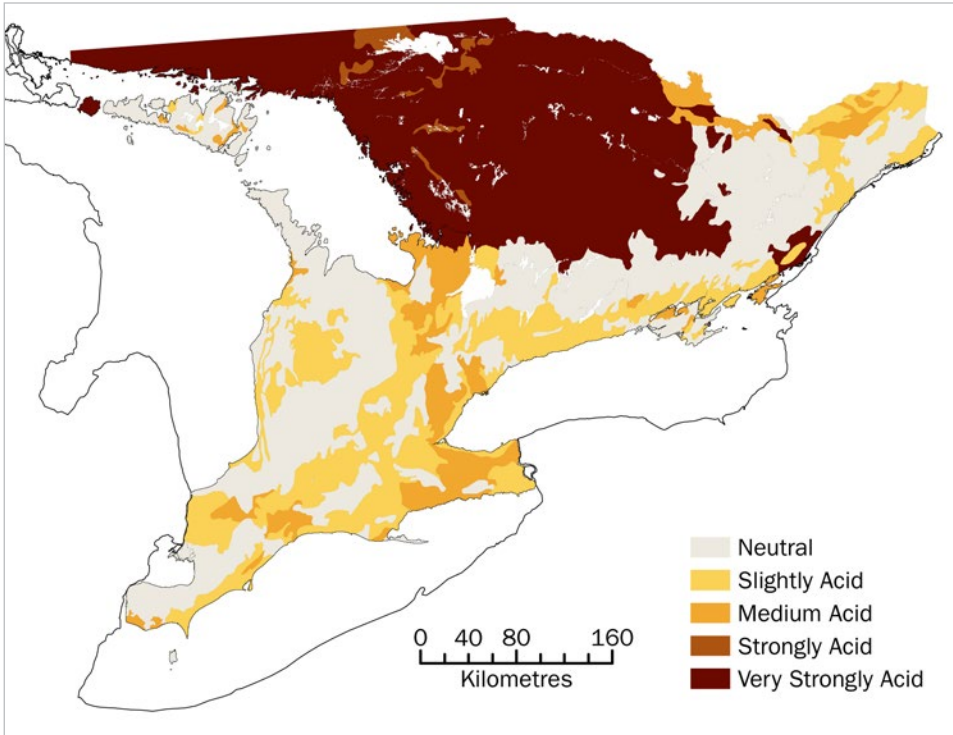
Figure 3–3. Surface soil reactivity in Southern Ontario. **Note:** Categories of acidity do not represent definite ranges of soil pH, but instead provide a general indication of variability as a reflection of parent material.

In addition to the geological materials that the soil formed from, the soil's cation exchange capacity gives soil buffering capacity (resistance to change in soil pH). The amount and type of clay and the amount of soil organic matter will impact how quickly a soil's pH may change. As such, a coarse-textured soil low in organic matter will have a relatively poor ability to resist pH change compared to clay soils with high organic matter.

How a soil becomes acidic

Precipitation

Pure rainwater is slightly acidic because carbon dioxide is dissolved in the water, forming carbonic acid. The amount of carbonic acid in rainwater is directly related to the amount of carbon dioxide in the atmosphere. As the carbon dioxide levels of the atmosphere increase, the pH of rainwater will decrease slightly. The amount of other acids, like nitric and sulphuric acid, is dependent on the amount of air pollution. The last 40 years have seen a decrease in emission of sulphur from areas that impact the rainwater in Southern Ontario. This reduction in pollution means that rainwater in Southern Ontario has become less acidic. The addition of acids creates a gradual reduction in pH at the surface of the soil as they percolate down through the soil over thousands of years. This is a normal part of soil development in humid climates.

Organic matter decay

As organic materials break down, decay releases organic acids into the soil. This also contributes to the reduction of soil pH in the surface layers of the soil, where most of the organic matter is present.

Fertilizer application

The microbial conversion of the ammonium form of nitrogen to the nitrate form is one of the biological processes that releases acid into the soil. Adding large amounts of ammonium-containing fertilizers can accelerate the decline in pH, particularly in sandy soils low in organic matter.

Urea and anhydrous ammonia do not contain the ammonium form of nitrogen but are converted to ammonium nitrogen when in contact with the soil. When ammonium, ammonia or urea forms of nitrogen from fertilizers or manure are used on sandy soil, the soil pH should be monitored regularly.

How soil becomes basic (alkaline)

Many of Ontario's agricultural soils are alkaline (pH greater than 7) at depths of only 30 cm (12 in.) or more and have a pH as high as 8.2 at about 1 m (39 in.). As a result, most agricultural soils in Ontario provide plants with ample supplies of basic nutrients such as calcium and magnesium within the rooting zone.

If soil pH is increasing over a series of soil tests, the likely causes are the following:

- The depth at which soil samples are collected has changed. It is much easier to collect soil samples to greater depth when the soil is moist and friable than when it is dry or compacted.
- Tillage is mixing soil from deeper in the profile with the soil being sampled. Some farmers see this as a way of increasing pH without liming, but it is rarely effective in making desirable changes in pH. The detrimental effects on soil structure and the dilution of nutrient and organic matter of the surface soil with sub-soil must be considered.
- Ditching or tile drainage has exposed sub-soil that is now being included in the soil sample.
- Erosion is removing the most acid surface layers. Subsidence (oxidation, shrinkage and disappearance) of a layer of muck overlying mineral soil has the same effect.

In Ontario, precipitation exceeds the water lost through evaporation and transpiration. The net movement of water through the soil is downward, and the net movement of basic cations is downward (albeit very slowly through all but coarse-textured soils).

Alkali soils (sodium saturated) and deposits occur in dry regions such as the Prairies where evaporation and plant transpiration exceed precipitation. As a result, the net movement of water is upward, which carries basic cations to the surface and makes the surface more alkaline.

Dealing with high-pH soils

It is important to assess soil pH levels through soil testing. The optimum soil pH range for most crops is 6.0–7.5. Even above 7.5, the impact of pH on field crop production is minor in most cases. Phosphorus availability is reduced somewhat, but this is reflected in the phosphorus soil test. As long as the recommended quantities of nutrients are applied for the given soil test, it should not affect crop production.

Don't try to reduce the pH of alkaline soils. If the soil pH is very high (7.8–8.2) then the soil will contain a high concentration of free lime (calcium carbonate). The soil is extremely well buffered and will resist any attempts to bring the pH down. Adding sulphur to acidify the soil will not be effective, but it will be costly.

Monitor crops for any signs of nutrient deficiencies induced by high pH. The most common deficiencies are manganese on soybeans or cereals or zinc on corn. If you see evidence of manganese deficiency, consider foliar application. For zinc deficiency, add zinc to the starter fertilizer.

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Symptoms of pH problems

One principle of good soil management is to adjust soil pH to the optimal range for the crops you are growing, and then tackle soil fertility issues.

Soil testing is the only reliable means to determine whether the pH needs adjusting.

However, some areas within a field may show symptoms of low pH, even though the average pH for the field is acceptable. These areas, which are often sandy knolls, should be tested separately.

Soil pH in starter fertilizer bands

Placed in a band, different fertilizers have different pH reactions when they initially dissolve. Di-ammonium phosphate (DAP) and urea initially raise the pH — but only when concentrated in a band. The higher pH can result in ammonium being converted to ammonia. This ammonia can be lost from the soil to the atmosphere and can be very harmful to plants if seedlings or roots come in contact with it. Although DAP delivers less risk of ammonia injury than urea per nitrogen unit, placing either urea or DAP with corn seed is not recommended. Use of DAP or urea in a band near the seedlings (for example, 5 cm (2 in.) below and beside) should also be limited, particularly in conditions that create high risk for ammonia injury, such as dry soil conditions in coarser-textured soils of higher-than-neutral pH.

Acidity in a phosphorus band has theoretical advantages in improving P availability in soils where the pH is neutral or higher. The pH in any band containing ammonium nitrogen may decline temporarily within the first weeks after application. When a plant takes up ammonium (a positively charged ion) as its nitrogen source instead of negatively charged nitrate, it releases a positively charged hydrogen ion to balance the charge inside and outside of the root. This can result in a decrease in the soil pH in an area of about 1–2 mm around the root called the rhizosphere. Although small, this area represents the full distance that phosphorus may travel towards the root in a given year due to its very low mobility. The reduction in rhizosphere pH caused by this process has been found to greatly enhance phosphorous uptake. Acidification of the band can also take place because nitrification (conversion of the ammonium to nitrate) generates acidity. In addition to increasing P availability, the lower pH in the band can also increase the availability of several micronutrients (for example, zinc, manganese, iron and copper).

Symptoms that may indicate a soil pH problem include:

- short stubby roots
- poor nodulation of forage legumes even though the seed was inoculated (pale green colour results from the poor nodulation)
- only oats harvested, even though mixed grain was planted (barley is more sensitive to acid soil)
- poor persistence in perennial forages with adequate drainage and fertilization
- presence of mosses and weeds such as wild strawberry, devil's paintbrush and sheep sorrel
- poor performance of soil-applied triazine herbicides like atrazine and metribuzin
- longer-than-expected carryover of imazethepyr (Pursuit)

Do not make a diagnosis based only on symptoms. Always take a soil test to confirm pH problems.

Buffer pH

H$^+$ and cation exchange sites

Soil pH is a measure of the hydrogen contained in the soil water, while buffer pH is a measure of the soil's ability to resist changes in pH. Since hydrogen is a cation, it can exist both in the soil water and on the soil's cation exchange sites. The negative charges of cation exchange sites are always fully occupied with positively charged cations like calcium, magnesium and hydrogen. In addition, all of these cations are constantly cycling on and off of the cation exchange sites. This results in an equilibrium concentration between all cations in the soil solution and those on the exchanges sites. As such, when new hydrogen (acid) is added to the soil, the equilibrium between hydrogen in the soil solution and hydrogen on the exchange sites is offset and a new equilibrium forms. This results in some of the newly added hydrogen moving to the exchanges sites.

Since only the hydrogens in the soil solution are measured in soil pH, the fact that some of the newly added hydrogen ends up on the exchange sites reduces the extent to which the pH changes. In addition, although the cation exchange sites are always fully occupied, they cannot be filled beyond capacity. As such, a soil with a greater cation exchange capacity can hold more hydrogen ions, keeping them out of the soil solution and resulting in even less pH change when acid materials are added.

Reserve hydrogen

This process also works in reverse. When you attempt to increase pH by using lime to react with hydrogen ions in solution, more hydrogen is released from the exchange sites to maintain the balance between hydrogen on the exchange sites and those in solution. These hydrogens are often called "reserve hydrogen," and the process by which the soil resists changes in pH is called the soil's buffering capacity.

Differences in buffering capacity

Soils differ in their buffering capacity depending mostly on the amount and type of clay in the soil and the soil organic matter content, both of which contribute to the soil's cation exchange capacity. In general, the greater the cation exchange capacity, the greater the buffering capacity of the soil. A simple measurement of soil pH does not reflect its ability to resist changes in pH; it only measures those hydrogens that are in the soil solution.

Buffer pH measurement

Buffer pH (pH_B or BpH on soil test reports) is a direct measure of the soil's ability to resist pH change. It is a pH measurement taken after the soil sample has been mixed with a buffered solution. The solution itself resists change in pH. See Chapter 5, *Soil, Plant Tissue and Manure Analysis*, for more detail.

The pH resulting when the soil is mixed with buffer solution is well correlated to the amount of limestone needed to adjust soil pH to a target level. Buffer pH is a simple, inexpensive and accurate means of determining lime requirements.

Recommendations from soil tests for crop nutrients are based on the relationship between soil test levels and crop response to the addition of nutrients. The buffer pH test differs in that it relates soil test levels to the soil response to the addition of lime.

The actual lime recommendation depends on the target soil pH that you would like to achieve for the crop, as well as the buffer pH. Different crops require different pH ranges as seen in Table 3–1.

Table 3–1. Guidelines for lime application to Ontario crops

Crops	Soil pH below which lime is beneficial	Target soil pH[1]
Coarse and medium-textured mineral soils (sand, sandy loams, loams and silt loams)		
perennial legumes, oats, barley, wheat, triticale, beans, peas, canola, flax, tomatoes, raspberries, strawberries, all other crops not listed below	6.1	6.5
corn, soybeans, rye, grass, hay, pasture, tobacco	5.6	6.0
potatoes	5.1	5.5
Fine-textured mineral soils (clays and clay loams)		
alfalfa, cole crops, rutabagas	6.1	6.5
other perennial legumes, oat, barley, wheat, triticale, soybeans, beans, peas, canola, flax, tomatoes, raspberries, all other crops not listed above or below	5.6	6.0
corn, rye, grass hay, pasture	5.1	5.5
Organic soils (peats/mucks)		
all field crops, all vegetable crops	5.1	5.5

[1] Where a crop is grown in rotation with other crops requiring a higher pH (for example, corn in rotation with wheat or alfalfa), lime the soil to the higher pH.

After determining the target pH and measuring your soil's buffer pH, the quantity of lime required can be determined using the information in Table 3–2. Note that the amounts of lime recommended in Table 3–2 are based on a standardized liming material. Different liming materials differ in their ability to neutralize pH. Therefore, the amount of lime required needs to be adjusted for the specific properties of the lime to be used.

Table 3–2. Lime requirements to correct soil acidity based on soil pH and soil buffer pH
Ground limestone required — t/ha (based on an Agricultural Index of 75)

Buffer pH	Target soil*pH = 7	Target soil pH = 6.5 (Lime if soil pH below 6.1)	Target soil pH = 6.0 (Lime if soil pH below 5.6)	Target soil pH = 5.5 (Lime if soil pH below 5.1)
7.0	2	2	1	1
6.9	3	2	1	1
6.8	3	2	1	1
6.7	4	2	2	1
6.6	5	3	2	1
6.5	6	3	2	1
6.4	7	4	3	2
6.3	8	5	3	2
6.2	10	6	4	2
6.1	11	7	5	2
6.0	13	9	6	3
5.9	14	10	7	4
5.8	16	12	8	4
5.7	18	13	9	5
5.6	20	15	11	6
5.5	20	17	12	8
5.4	20	19	14	9
5.3	20	20	15	10
5.2	20	20	17	11
5.1	20	20	19	13
5.0	20	20	20	15
4.9	20	20	20	16
4.8	20	20	20	18
4.7	20	20	20	20
4.6	20	20	20	20

* Liming to pH 7.0 is recommended only for club-root control on cole crops.

Limestone quality

Two parameters are normally used when assessing the quality of agricultural limestone (i.e., its ability to neutralize pH). They are the neutralizing value and the fineness rating.

Neutralizing value

Acidity is neutralized when hydrogen ions (H^+) react with other compounds to form water (H_2O).

Certain compounds that fall into the general categories of carbonates, hydroxides and oxides are normally used to neutralize acidity. Carbonates are most commonly used for agricultural purposes because they are readily available from the sedimentary limestone rocks found in many parts of the province and are relatively inexpensive.

When ground limestone is used, it is the carbonates in the lime that neutralize the acidity. The following reaction describes how calcium carbonate reacts with two hydrogen ions to produce water and carbon dioxide (CO_2). The up arrow indicates that the carbon dioxide is given off as a gas. This helps to keep the reaction from reversing itself.

$$CaCO_3 + 2H^+ \rightarrow H_2O + Ca^{2+} + CO_2 \uparrow$$
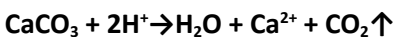
This reaction is essentially the same as when vinegar, an acid that releases hydrogen ions, is added to baking soda (sodium bicarbonate).

Hydroxides (OH^-) combine directly with hydrogen ions (H^+) to form water (H_2O). Oxides of calcium, magnesium and potassium can combine with water to form hydroxides. Potential liming materials such as wood ash that contain oxides and hydroxides are normally the result of heat treatment or combustion. They tend to have high pH values and are more caustic to handle than limestone.

The neutralizing value of a material is its ability to neutralize acidity relative to the ability of pure calcium carbonate. Because it is a relative value, it is expressed as a per cent of calcium carbonate's ($CaCO_3$) ability to neutralize acidity (see Table 3–3). Pure magnesium carbonate has a higher neutralizing value than calcium carbonate because magnesium atoms weigh less than calcium atoms. However, one magnesium carbonate molecule will neutralize as much acidity as one calcium carbonate molecule.

Pure compounds are never used for liming because they are too expensive. Normally, we use a source such as crushed limestone in which at least one of these compounds is found in relatively high proportions.

The pH of a material suspended in water is not a good indicator of its neutralizing ability. For example, the pH of a potassium hydroxide may be greater than 13 (basic and caustic). The pH of a solution of calcium carbonate may only be 8.2, yet the calcium carbonate is a more effective liming agent.

Table 3–3. Neutralizing values of some liming materials

Liming material	Formula	Neutralizing value relative to calcium carbonate
calcitic lime (calcium carbonate)	$CaCO_3$	100
magnesium carbonate	$MgCO_3$	119
dolomitic lime (calcium magnesium carbonate)	$CaMg(CO_3)_2$	109
calcium hydroxide	$Ca(OH)_2$	135
calcium oxide	CaO	179
magnesium hydroxide	$Mg(OH)_2$	172
magnesium oxide	MgO	250
potassium hydroxide	KOH	90
gypsum (calcium sulphate)	$CaSO_4 \cdot 2H_2O$	0
wood ashes	n/a	40–80

Limestone is a sedimentary rock formed from corals in warm oceans. Limestone rock is not pure carbonate-minerals. Silts, clays, sand and other materials also accumulated in ocean bottoms. The degree of inclusion of these contaminants affects the purity of the limestone and therefore the neutralizing value.

Fineness

To be effective, any liming material must dissolve. Limestone does not dissolve quickly like salt or sugar, and its rate of dissolution decreases as pH increases. The surface area of the limestone must be maximized to get satisfactory rates of dissolution. This is accomplished by having tiny particle sizes.

The fineness of liming materials is measured using sieves. The sieves are numbered according to the numbers of wires per inch and the size of the spaces between the wires. A #10 sieve has 10 wires per 25 mm (1 in.), with openings that measure 1.65 mm per side.

Any material passing through a #60 sieve (0.25 mm per side) is considered to be fully effective. Material that passes through a #10 sieve (1.65 mm per side) but not a #60 sieve is considered only 40% effective. Materials that do not pass through a #10 sieve are considered ineffective. Table 3–4 illustrates how the fineness rating for limestone is calculated.

Table 3–4. Determining a fineness rating for limestone

In this example, 75% of the sample passed through a #10 sieve and 40% passed through a #60 sieve.

Particle size	Percentage of sample (A)	Effectiveness factor (B)	(A) x (B)
coarser than #10	25	0.0	0
between #10 and #60	35	0.4	14
finer than #60	40	1.0	40
Fineness rating	**100**	—	**54**

Federal government standards dictate that liming materials be labelled with the percentages of the material that pass through a #10 and a #100 sieve (0.15 mm per side). In Ontario, we use the #10 and #60 sieves to help determine the quality of agricultural limestone. It should feel like finely ground flour.

It is usually not economical to crush materials to the fineness needed to make effective agricultural limestone. Estimated usage in Ontario is a modest 100,000–300,000 t/year. By comparison, retail sales of fertilizers in Ontario peaked in 1985 at 1,162,000 t. The limestone is usually crushed for other purposes such as aggregate for construction or to produce limestone fluxes for smelting. Fine material is not wanted for those purposes and is sieved out. This by-product may be sieved further to yield agricultural lime.

Dolomitic or calcitic lime

Liming materials made of crushed limestone rock are generally divided into two groups, calcitic and dolomitic, based on their content of calcium and magnesium.

Pure calcium carbonate (calcite) contains 40% calcium. Pure dolomite contains 21.7% calcium and 13.1% magnesium.

The division between calcitic and dolomitic limestones is not absolutely defined. Any limestone that is dominated by calcium and contains very little magnesium is considered calcitic. A 2006 survey reported eight

sources of dolomitic lime and eight sources of calcitic lime in Ontario. (*Sources of Agricultural Limestone in 2006*. Ontario Ministry of Agriculture, Food and Rural Affairs, 2006)

When liming is recommended, dolomitic lime should be used on soils with a magnesium soil test of 100 ppm or less. When the magnesium soil test is greater than 100 ppm, either calcitic or dolomitic limestone can be used. Many Ontario soils contain lots of calcium or magnesium or both. High soil test values of either are not a concern and should not influence the choice of calcitic versus dolomitic limestone.

Anyone selling materials as an agricultural fertilizer source of calcium or magnesium must supply a guarantee of analysis. The calcium and magnesium content of the material are expressed as %Ca and %Mg.

Liquid lime

Lime suspensions, liquid lime and fluid lime are all names for a system of suspending lime in a fluid. The limestone used in suspensions is usually very fine and suspended in water or liquid fertilizer. Typically, suspensions contain 50%–75% liming material, 0.5%–5.0% clay and a small amount of a dispersing agent. The remainder is water or liquid fertilizer.

Suspended lime is usually associated with a fineness rating of 100 (passes through a #100 sieve). Lime that passes through a #60 sieve is considered 100% effective. Anything finer is not any more effective.

There is no evidence that liquid lime is more effective than regular lime.

Granulated or pelletized lime

Some companies are promoting the use of granulated lime. This material is a finely ground lime that is formed into granules similar in size to fertilizer granules. This helps overcome many of the difficulties handling and spreading regular lime because regular fertilizer equipment can handle it.

The pelletized lime is not more effective than regular lime, and the same quantity of material is required to neutralize pH.

The choice of liming materials must be based on the cost, availability and agricultural index of the product.

Alternative liming agents

Many industrial by-products can be used as liming materials — wood ash, cement dust, beet lime, industrial precipitator sludges, slags and biosolids. Each must be evaluated for its ability to neutralize acidity, for metal content, and sometimes for organic compounds. A certificate of approval must be obtained from the Ministry of the Environment, Conservation and Parks (MOECP) before spreading it on agricultural land. Guidelines for the Utilization of Biosolids and Other Wastes on Agricultural Land, available from offices of the MOECP or the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), describe the criteria by which the material will be evaluated.

Agricultural limestone has a pH of about 8.2. Some alternative liming agents, such as wood ash, may have a much higher pH. Extra caution must be taken when handling high-pH materials. Seedling injury may occur if crops are seeded soon after a high-pH material has been mixed into the soil.

Agricultural index

The agricultural index is an indicator of limestone quality that combines the neutralizing value and the fineness rating into a single value (see Figure 3–4).

The agricultural index can be used to compare the ability of agricultural limestones to neutralize soil acidity. The higher the agricultural index, the more effective the limestone is on an equal weight basis.

$$\text{Agricultural index} = \frac{\text{Neutralizing value} \times \text{fineness rating}}{100}$$

Figure 3–4. Agricultural index

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$$\text{Amount of lime to apply} = \text{recommended amount} \times \frac{75}{\text{Agricultural index of lime used}}$$

Figure 3–5. Amount of lime to apply

The average agricultural index of limestones sold in Ontario has been around 75. Limestone recommendations based on Ontario-accredited soil tests in Table 3–2 are based on the assumption that the limestone used has an agricultural index of 75. Limestone recommendations should be adjusted according to the actual agricultural index of the limestone used. This calculation is illustrated in Figure 3–5.

The agricultural index of limestones sold in Ontario from 18 quarries in 2006 ranged from 36 to 102. The average was 74 (*Sources of Agricultural Limestone in 2006*. OMAFRA, 2006).

Transportation to the farm usually accounts for most of the cost of using agricultural limestone because of its weight and volume. In general, using lime from the closest quarry will be the most economical. The cost per hectare should be calculated by multiplying the cost of each source applied to the field by the amount of lime required per hectare. This allows a fair comparison of alternative sources.

Lime application

Spreading
Conventional fertilizer spreaders are not designed to handle lime, and the material will bridge in the spreader box. Commercial spreaders designed to handle lime are advised.

Check the distribution pattern by using the same method you would to check the distribution of manure from a manure spreader (laying 1 m x 1 m (39 in. x 39 in.) plastic sheets, collecting and weighing the amount of lime spread on each sheet, and comparing lime spread across the width of distribution).

Because lime is finely ground powder, wind affects distribution patterns. Spreading in calm conditions is advised. Operators should be protected against dust hazards. Lime will drift over considerable distances even in moderate winds.

If lime must be stored on the farm prior to spreading, protect it from the elements and from drifting away. Lime will consolidate into unusable clumps if it gets wet.

Incorporation
As agricultural limestone does not dissolve quickly, it must be mixed uniformly with the soil to be effective. Tillage implements that mix the soil, such as the disc (offset disc-harrow), do the best job.

In no-till soils, correcting pH is a challenge. If the entire plow layer

(15 cm (6 in.)) is acid, then tillage to incorporate limestone is the only practical option.

This does not mean that liming and no-till are completely incompatible. In no-till soils where nitrogen fertilizers have been surface-applied, a shallow layer of acid soil can develop. Sample the top 5 cm (2 in.) layer to check the surface pH. Frequent applications of low rates of limestone can neutralize the acidity in this zone.

Many farmers apply and incorporate a fraction of the total lime recommended over several years. This helps ensure the lime will be more uniformly distributed and mixed by tillage. This is an excellent preventive measure but will not correct severe acidity.

Time to work

Agricultural limestone does not dissolve quickly. The rate at which each limestone particle dissolves depends on how finely the limestone is ground (see Figure 3–6). The rate of dissolution decreases as the pH of the soil increases (which is the desired result of liming). After dissolution, the lime must diffuse through the soil and interact with the acidity held in the soil solution and on the cation exchange sites. Dry or frozen soil conditions will increase the length of time required for this reaction to happen. As a result, it takes time for the full effects of liming to be realized. This may be up to 3 years.

For crops sensitive to low pH, like alfalfa, it is especially important to get the lime applied well in advance of seeding.
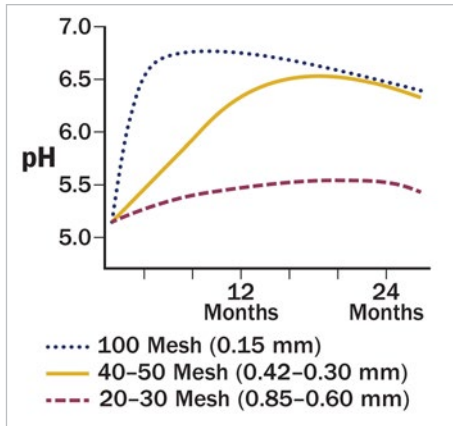
Figure 3–6. Reaction time for lime materials of different fineness

What about gypsum?

Gypsum is not a liming material, even though it is widely promoted as a source of calcium or sulphur and as a soil conditioner. Gypsum is used as a conditioner for sodic soils (salt-effected soils), which are present on the Prairies but not in Ontario.

The chemical make-up of gypsum is calcium sulphate, which breaks down into calcium and sulphate ions when dissolved in the soil water. Although the calcium displaces hydrogen from the cation exchange sites, this hydrogen then combines with the sulphate in the soil solution to form sulphuric acid, leaving no net effect on soil pH.

Gypsum is promoted as a calcium source because it is more soluble than lime in alkaline soils. While this is true, the solubility is still quite low (gypsum is the main ingredient in wallboard), so that you need large amounts to provide a significant amount of calcium. It is also a good source of sulphur where the need has been documented.

Soil acidification

Occasionally, growers want to lower the pH of their soil. This is a requirement for most commercial blueberry sites in Ontario and for home gardeners who want to grow rhododendrons and azaleas. These plants thrive in soils of pH 4–5 and develop micronutrient deficiencies when the soil pH rises above these levels.

Growers with alkaline soils (i.e., pH 7 or higher) may think lowering the pH will improve nutrient availability. However, most crops thrive at soil pH levels from 6–8, and the negative effect of low soil pH is much greater than the penalty for high soil pH. In addition, it is much cheaper to add extra nutrients than to lower soil pH.

Lowering soil pH

Soil pH is reduced by increasing the number of hydrogen ions in the soil, either directly by the addition of acids or by adding materials that will form acids when they react with the soil. Nitrogen fertilizers that contain ammonium will acidify the soil, as will elemental sulphur and iron or aluminum sulphate. Oxidized sulphur is available in the form of aluminum sulphate or iron (ferrous) sulphate, but these materials are required in much larger amounts than elemental sulphur (4 times and 8 times respectively).

For crops like blueberries, which enjoy a high level of organic matter, the addition of acidic peat moss will have the double effect of increasing organic matter and lowering soil pH.

Check that the pH of the peat is low, as several brands of peat moss raise the pH for use in potting mixes. For large areas, peat moss will be too expensive, and it is usually applied only in the rooting area of the plants.

Taking a soil test before the sulphur is applied and then 3 months after will provide baseline information on soil pH. Annual soil testing to monitor pH is important.

Soils that can be acidified

The success of soil acidification will depend on the soil's buffering capacity. In general, it is easier to modify a sandy soil with low organic matter and low exchange capacity than a clay soil with high exchange capacity. On highly buffered soils, the reduction in soil pH may be short-lived. The other factor in soil acidification is the amount of free lime in the soil. Soils above a pH of 7 often contain undissolved calcium and magnesium carbonates, which react immediately with the acid produced by the sulphur, neutralizing it and preventing the desired drop in pH.

The natural soil pH also has an effect on the ease of lowering the pH. Remember that the pH scale is logarithmic: to move from 7 to 5 is 10 times more difficult than to move from 6 to 5. Soils with a natural pH of two units above the desired pH are almost impossible to alter. For example, if 750 kg/ha of sulphur is required to reduce the soil pH from 6 to 5, it could easily take 8,000 kg of sulphur or more to reduce the pH from 7 to 5, plus enough sulphur to neutralize any free lime that is in the soil at the higher pH.

For home gardens, replacing soil with acidic soil or building a raised bed of acidic peat may be more practical.

There are often patches in fields that show greater resistance to lowering pH. Symptoms of nutrient deficiency (e.g., nitrogen in blueberries) are a good indication of areas that need separate treatment. Test and treat these areas individually.

Using sulphur

Sulphur (S) is the most economical way to lower soil pH, though still expensive. This involves a biological process where certain soil bacteria convert elemental sulphur to sulphate-sulphur. During this process, acid is formed. The drawbacks to using elemental sulphur are:

- A soil must have a viable population of the correct bacteria
- It is a slow process requiring time, as well as appropriate soil temperature and moisture conditions for microbial activity. It takes 3 months to 1 year for the reaction to be complete.
- Many soils need yearly applications of sulphur to maintain a lower pH

Table 3–5. Sulphur for soil acidification

Soil type	For each 1.0 pH unit	For each 0.1 pH unit
sand	350 kg/ha (313 lb/acre)	35 kg/ha (31 lb/acre)
sandy loam	750 kg/ha (670 lb/acre)	75 kg/ha (67 lb/acre)
loam	1,100 kg/ha (980 lb/acre)	110 kg/ha (98 lb/acre)

Example: The initial pH of a sandy loam soil is 6.2, and the desired pH for blueberries is 4.8. The soil pH must be lowered 6.2 to 4.8 = 1.4 units. Therefore, 1.4 x 750 = 1,050 kg/ha of sulphur must be applied.

Guidelines for the amount of sulphur that is required to lower soil pH are shown in Table 3–5. When treating the soil with sulphur to lower the soil pH, apply sulphur before the planting is established, and incorporate it throughout the soil. Powdered sulphur acts more quickly than granular sulphur but is also more expensive and unpleasant to spread. Sulphur can be applied in any season.

Alternatives to elemental sulphur are listed in Table 3–6, with conversions between the materials.

Table 3–6. Relative effectiveness of various materials for reducing soil pH

Material	Chemical formula	Per cent sulphur	Kg of material to neutralize 100 kg of calcium carbonate*
elemental sulphur	S	100	32
granular sulphur	S	90	36
sulphuric acid	H_2SO_4	32	98
iron sulphate	$FeSO_4 \cdot 7H_2O$	11.5	278
aluminum sulphate	$Al_2(SO_4)_3$	14.4	114
ammonium sulphate	$(NH_4)_2SO_4$	23.7	66

* These are theoretical values, based on all the material reacting with the soil to produce acidity. Actual values will be less than this, often by as much as 50%, because of immobilization of the materials on soil surface, in soil microbes or by plant uptake.

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4. Sampling

Sampling soil

Farmers sample soil to:

- determine fertilizer and lime requirements
- diagnose problem areas
- monitor soil fertility levels

Sample collection

Soil can be sampled at any convenient time, but it is done primarily in the fall after harvest. This leaves enough time to get the analysis back from the laboratory and make plans for next season. For consistency, it's a good idea to sample soils at about the same time each year and following the same crops in the rotation.

Sampling every 3 years is enough for most soils. You may need to sample sandy soils more frequently, as nutrient levels may change rapidly. This is particularly true with crops that remove large quantities of potassium, such as tomatoes, silage corn and alfalfa. An effective approach is to sample one-third of your fields each year so that the whole farm is done once every 3 years. Where a particular fertility problem occurs, you should sample the area more frequently. Sample the good areas of the field separately from the poor areas.

You can choose to take a composite sample or several point samples. Composite samples represent the fertility of an entire field at lower cost.

The number of soil cores required to characterize a field depends on the topography and variability of soil within the field, the type of farm and the number and type of crops grown.

Taking samples

For standard Ontario fertility soil tests, soil cores are pulled from a depth of 15 cm (6 in.), as this reflects the fertility level of the soil where the bulk of most crop root systems are. Samples taken from a shallower depth will overestimate the nutrient levels, while deeper samples may underestimate them. In fields containing two or more distinct soil types, sample each type individually. Sample problem areas separately. To make sure the samples you collect are representative of the field, avoid sampling:

- in areas close to gravel or paved roads, since road dust will influence the soil test values
- in dead furrows
- on highly eroded knolls
- where organic waste or lime has been piled

If you are interested specifically in any of these areas, take a separate sample.

> **Note:** It is impossible to split a sample of moist soil into two identical sub-samples without special equipment. Much of the variation in results between samples sent to different labs occurs because the samples really are different.

Use stainless steel

Use a commercial soil probe or auger that is stainless steel rather than galvanized. Pails should be clean and made of plastic or non-galvanized metal, especially if you are sampling for micronutrients. This will avoid contaminating the sample. Labs prefer to work with a full sample box, so collect enough soil to get a composite sample that will fill the box (see Figure 4–1).

Mix

Mix the cores together thoroughly in the pail, crushing clods and removing stones and crop residue. Fill the sample box or bag with a representative sample from the soil. Careful sampling and mixing is essential to ensure the accuracy of the composite sample.

2,000,000 kg/ha
(Furrow slice)

15 cm

100 m   100 m

10 kg soil in pail, mixed well

500 g soil in box sent to lab

Dried, ground, mixed by lab

2 mL analyzed
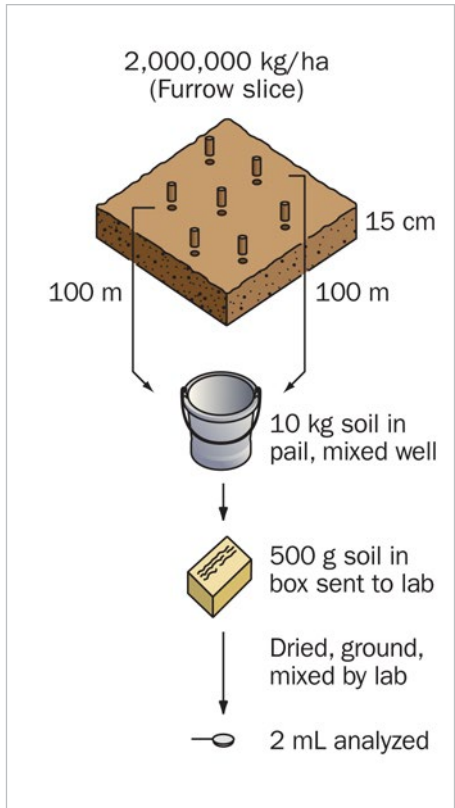
Figure 4–1. Field to pail to lab

Exception — sampling for nitrate

Soil nitrate is not included in a regular soil test. Instead, nitrogen recommendations included on most soil test reports are based on your crop plans.

Timing of nitrate samples is critical because soil nitrate levels will vary greatly throughout the year due to leaching and microbial activity. Collect samples at planting time for corn or barley or before side-dressing corn. Sample collection at side-dressing will detect more of the nitrate from organic sources such as manure or legumes. Nitrate samples are taken at a 30 cm (1 ft) depth. Follow the same sampling pattern and mixing procedure as for a standard soil sample.

Handle the soils with care. They should be stored at temperatures below 4°C until they are analyzed. Soil storage at 4°C for periods ranging from 1–7 days was compared to either freezing or air drying the soil samples before extraction in a 2007 study involving 66 soils from Ontario (Oloya et al., 2007).

One day after sampling, about 70% of the inorganic nitrogen was in the nitrate form and the remaining 30% was ammonium. As the moist soils were stored at 4°C for longer periods, ammonium was slowly converted to nitrate through the nitrification process (Figure 4–2). This conversion would have been even greater if the soils were stored at room temperature.

Freezing increased soil ammonium levels by 22%, and air drying increased soil ammonium levels by 37%. Soil nitrate levels were also increased but to a lesser extent. Therefore, freezing or air-drying is not recommended, especially when ammonium values are of interest.

It is recommended that the soils be stored at 4°C and extracted field moist within 4 days of sampling.

Figure 4–2. Impact of sample handling on soil mineral N content.
Source: Oloya, T.O., C.F. Drury and K. Reid, 2007

Date/Time	Field Name/No.	Operation	Details

Example Codes: PL = plant, SP = spray, SC = scouting, SA = sampling, TI = tillage, HV = harvest, M = manure application, FE = fertilizer application, VI = visual inspection

Figure 4–3. Example field crop records

Keeping records

Label all soil samples for the lab. Number them in such a way that you can later relate the analysis to a particular field. Keep a record for yourself of the samples you have taken and where they were taken on the farm. See Figure 4–3.

Also keep records on the crops grown in each field, fertilizer applied, weather conditions and final yields. Put this information together with the soil sample analyses. These records will help you detect trends from year to year, make management decisions and pinpoint trouble spots.

A number of software systems are available to assist in organizing crop production information, and most crop consultants offer recordkeeping as part of their service. With the massive increase in the amount of data generated by combine yield monitors and intensive soil sampling, computerized recordkeeping is essential.

Soil variability

Soil varies across wide areas of the landscape and also within the space of a few centimetres. Variability impacts crop growth as well as sampling strategies and fertilizer application. Significant variation can exist within the rooting zone of a plant. However, this may have no effect on its growth since roots proliferate in zones of optimum fertility.

Large or rapid variations in soil fertility over a larger area can affect crop growth but may not be practical to manage. For example, soil nutrient content may vary greatly within an area of 18 m by 30 m (60 ft by 100 ft), but it is smaller than the area covered by one pass of the spreader. In other words, it is smaller than the minimum management area. In general, this variation is important in deciding the number of cores required for a representative sample.

While soil type has an influence on variation, the overriding factor

is management, particularly the amount and type of fertilizer and manure applied to each field over the years. It is difficult to predict which nutrients might be limiting yield in a particular field without a soil test. The goal of a soil sampling program is to predict the most profitable rate of fertilizer for the field or part of a field. To design a good program, it is important to know the potential for economic return to management, the probable variability within each field, and the resources available (see Chapter 7 for more information).

What causes soil to vary?

Variability stems from the soil-forming factors (parent material, topography, biological activity, climate and time) as well as from management history (tillage, fertilization and crop residues).

Tillage-induced variation is created when the mouldboard plow and other implements pull soil off the tops of knolls and deposit it downslope. This creates areas on the knolls of low organic matter, low fertility and often higher pH (see Figure 4–4).

Several years of applying fertilizer and manure unevenly may also create variability in soil fertility. The consolidation of small fields into larger ones makes the variation greater. When crop residues are left unevenly distributed, they also contribute to variable soil fertility.
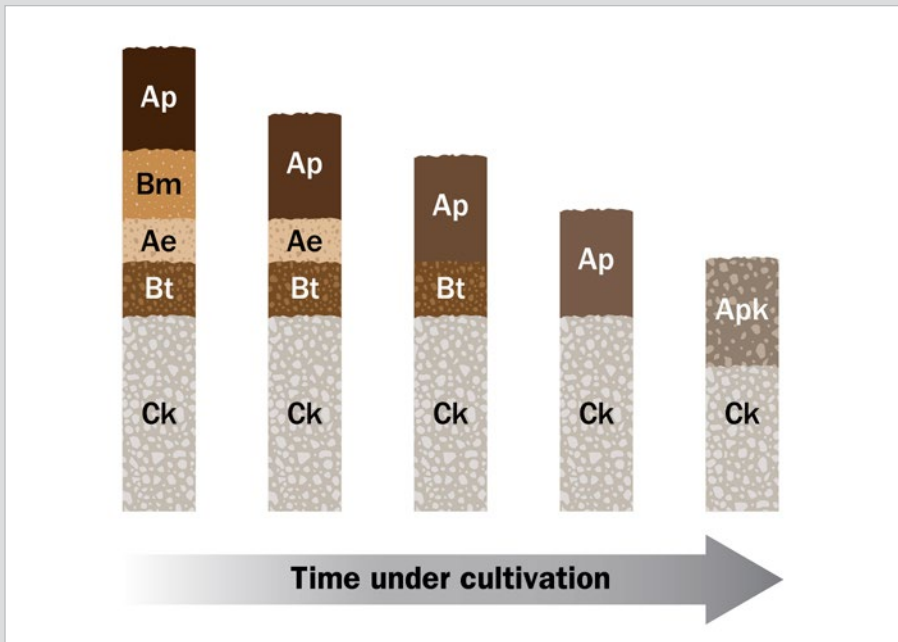
Figure 4–4. Soil profile change on a knoll over time due to tillage-induced erosion. Mixing of Ap horizon with Ck horizon results in an Apk, which has diluted organic matter and elevated soil pH.

Sampling strategies

Composite samples

The most common soil sampling strategy is to take one composite sample from each field (see Figure 4–5). Usually the maximum field size for a composite sample is 10 ha (25 acres). The number of cores in each composite sample should be at least 20, no matter how small the area, to average out small-scale variations. This strategy is appropriate where:

- the value of the crop is low
- there is low potential for return to variable fertilization
- there is little variation in soil fertility
- the entire field is high enough in fertility that no response to fertilizer is expected

In the case of very low soil test levels from a field, it is generally safe to assume that the entire field will respond to fertilization. If the test levels of the composite sample are very high, it is likely that while there will be considerable variation, the whole field will be high enough so that even the lowest-testing areas will not likely respond to added fertilizer.

For a more complete discussion of the development of Ontario's soils, see the OMAFRA/Agriculture and Agri-Food Canada booklet *Best Management Practices — Soil Management.*

Do not sample old barnyards or manure piles

Avoid laneways, headlands, dead furrows
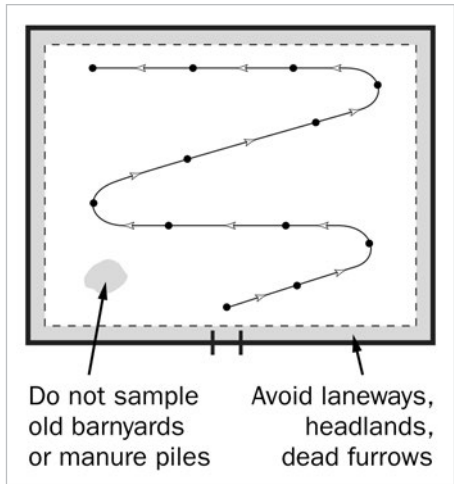
Figure 4–5. Composite sampling

Georeferencing (grid sampling)

Georeferencing, or systematic soil sampling, uses global positioning system (GPS) technology and geographic information system (GIS) techniques to collect soil sample data and present it in map form (Figure 4–6). This technique has been called grid sampling. The most common spacing between sample sites is 1 ha (2.5 acres).

A common practice is to create a field boundary with GPS and mapping software. A grid pattern is superimposed on the map to serve as a guide for sample collection. Each sample point is logged. The evenly spaced sample points allow a degree of statistical validity.
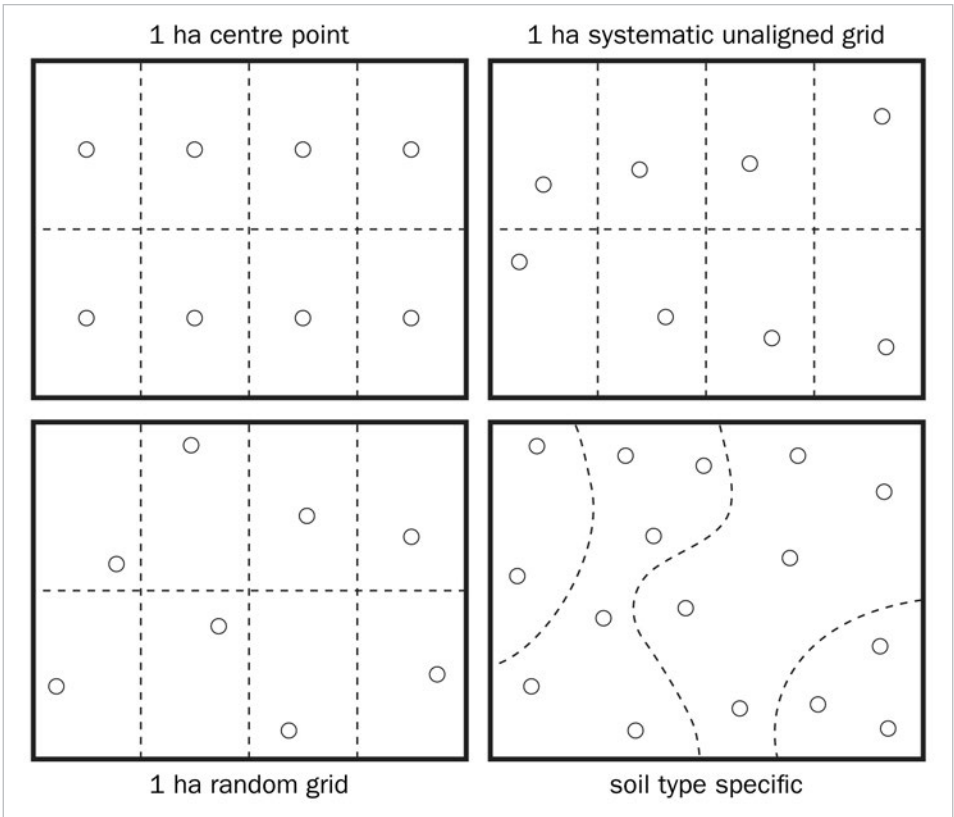
Figure 4–6. Georeferenced sampling

After lab analysis, the nutrient values from each sample are merged with the map data using GIS software. Comparing the information from a 1 ha sampling scheme to that of composite sampling on a 40 ha (100 acre) field would give 40 sample values versus a typical composite plan of four. Having 10 times more data represented in map form heightens the awareness of the spatial variability of nutrients, which may affect management decisions.
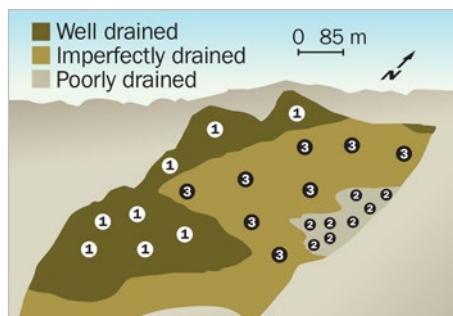
Figure 4–7. Basic management zones based on topography and drainage

Management zone samples

A growing practice is sampling by management zone, which involves taking a composite sample from distinct areas of the field that can be managed separately.

Grid sampling may be suitable to provide a baseline understanding of management zones but generally does not align with variability. Subdividing a field into zones according to soil type or series, texture, topography, drainage and/or crop characteristics is the preferred approach. A simple method is to sketch the known variation in texture or topography (see Figure 4–7), field history or manure history on a map, and sample those areas separately. This does not allow for automated generation of prescription application maps but may be suitable for some operations.

Measurements from yield or elevation maps or data generated by crop or soil sensors can be used to create management zones. Elevation data can be acquired from the guidance system on a farm implement — a high-quality GPS signal is best.

Normalized yield maps can also be used to determine areas of the field that are consistently lower or higher yielding, according to single or multiple crop types. Yield maps can be used with other maps and farmer knowledge to refine sampling zones. Once management zones are defined and sampled, the assignment of input prescriptions requires agronomic knowledge to match recommendations to the soil test characteristics of the specific zones.

For more detailed information on defining management zones, refer to the Soil Fertility and Nutrient Use chapter of Publication 811, *Agronomy Guide for Field Crops*.

Special sampling conditions

No-till

Fertilizer recommendations are based on the nutrient content of the top 15 cm (6 in.) of soil. Therefore, sampling depth for nutrients is the same in reduced tillage systems as in conventional tillage. Nutrient stratification can occur under no-tillage systems.

The exception to this is soil pH. Where nitrogen is surface-applied in a no-till system, a shallow layer of acidic soil may develop. A separate, shallow sample (5 cm (2 in.)) can be taken to check for this. **Note:** adjust for the shallow depth of sample when using the liming recommendations in Chapter 3, Table 3–2.

No-till, strip-till, banded fertilizer and injected manure

Fields in long-term no-till or strip-till with a history of banded fertilizer or injected manure pose extra challenges because nutrient additions are concentrated in parts of the field.

Table 4–1 can be used as a guide for collecting soil samples from fields with a history of banded nutrients. The sampling strategy in these scenarios involves collecting samples from concentrated nutrient areas of the field in a proportion that reflects the volume of soil that they occupy.

Collecting soil samples for problem diagnosis

Where soil fertility is suspected as the cause of reduced crop growth or yield in part of the field, it is important to sample these areas individually to confirm your diagnosis. Sample nearby good areas and compare them with the problem areas. Be sure to take at least 8–10 cores for each composite sample to ensure the sample is representative of the area. Nutrient deficiencies in plants may be due to either inadequate concentration of nutrients in the soil or inability of the plant to access the nutrients due to restricted root volumes. Any problem diagnosis should consider both of these factors.

Keep a detailed record of the location of problem spots. Continue sampling problem areas every year or every other year until the fertility levels are adequate.

Table 4–1. Sampling guidelines to account for banded nutrients

Band spacing	Placement	Collect
76 cm (30 in.)	planter	1 core within the band for every 20 out of the band
30 cm (12 in.)	planter	1 core within the band for every 8 out of the band
76 cm (30 in.)	strip till, manure injector	1 core in the zone for every 3 out of the zone, where zone of influence is 25 cm (10 in.) wide
unknown	planter	paired sampling: 1 random core followed by a second core 50% of the band-spacing distance from the first sample, perpendicular to the band direction
to determine with any spacing	planter	$S = 8 \ [x \div 30 \ cm] \ (S = 8 \ [x \div 12 \ in.])$ where S = number of cores between bands (outside influence of band, 5 cm for planter placed fertilizer) x = band spacing in cm or inches

Source: Publication 811, *Agronomy Guide for Field Crops* (2017 edition)

Sampling plant tissue

Farmers sample plant tissue from:

- perennial tree fruit, berries and grape crops to determine fertilizer recommendations
- annual crops to diagnose fertility problems, particularly micronutrient deficiencies

Tree fruit, berries and grapes

Take tissue samples from fruit trees between July 15 and 31. Take samples of grape petioles between September 1 and 15. These dates correspond to standard nutrient levels of mature leaves (Table 4–2), against which your tissue samples will be compared in the lab.

Table 4–2. Recommended timing and plant parts for tissue sampling

Crop	Timing	Plant part
cereals	at heading	top 2 leaves
corn	3–5 leaf stage	whole plant (zinc and phosphorus only)
	silking	middle third of ear leaf
edible beans	first flowering	top fully developed leaf (3 leaflets + stem)
forages	late bud	entire above-ground portion
soybeans	first flowering	top fully developed leaf (3 leaflets + stem)
broccoli, cauliflower	start of head formation	midrib of young, mature leaf
cabbages	at heading	midrib of wrapper leaf
carrots	mid-growth	petiole of young, mature leaf
celery	mid-growth	petiole of newest elongated leaf
lettuce	at heading	midrib of wrapper leaf
onions	minimum 3 times/season	tallest leaf
potatoes	early, mid or late season	petiole of 4th leaf from tip
spinach	mid-growth	petiole of young, mature leaf
sugar beets	12 weeks	youngest mature leaf
tomatoes	early bloom	petiole of 4th leaf from tip
blueberries	late July-early August	mature mid-shoot leaves of current year growth
grapes	September 1–15	petioles from mature leaves of fruiting canes, remove leaf immediately
raspberries	late July	fully expanded leaves from fruiting cane
strawberries	fruiting plants: late June / non-fruiting plants: early-to-mid-August	fully expanded recently matured leaflets only (remove petiole immediately)
tree fruits	last 2 weeks of July	mature mid-shoot leaves of current year growth at shoulder height
tobacco	at topping	10th leaf from top
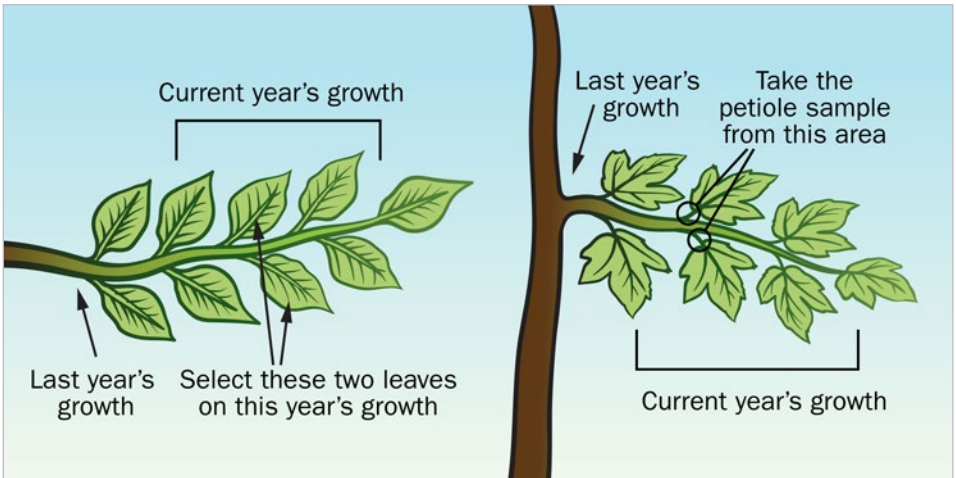
Figure 4–8. Where to sample

Sample each cultivar, age, rootstock, and block of fruit trees separately. Collect at least 100 leaves for each sample. The best way to get a representative sample is to take 5 leaves each from 20 trees. Do not combine healthy and unhealthy leaves. See Figure 4–8.

To sample grape vines, select only the stems (petioles) of mature leaves. Keep cultivar, rootstock, and blocks of different ages separate. Ideally, collect petioles from a number of different rows in a block. Collect at least 100 petioles for each sample. For *Vinifera* and French hybrid varieties, collect 150 petioles.

Field-grown crops

Take samples from at least 50 plants collected randomly from across the field. Keep in mind the lab needs at least a 250 g (9 oz) fresh weight sample.

Use Table 4–2 to find the right time to sample, as you want your samples to be comparable to the standard values. Collect samples from the appropriate location on the plant according to its growth stage (Table 4–2 and Figure 4–9).
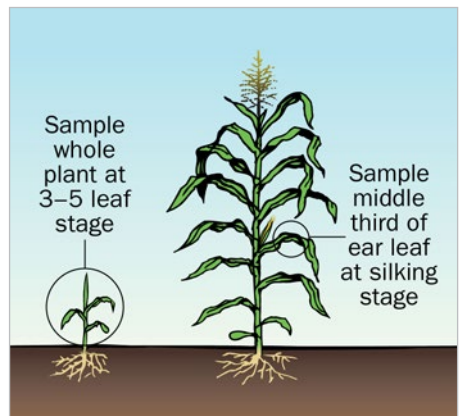
Figure 4–9. Where to take tissue samples for corn

Sampling recommendations for horticultural and field crops

The most common errors in collecting plant tissue samples are:

- not collecting enough material
- collecting chlorotic or dead tissue or insect-damaged leaves
- collecting plant tissue contaminated with soil
- shipping the sample in plastic bags

Do not sample tissue to which foliar fertilizers have been applied.

Collecting tissue samples for problem diagnosis

Tissue samples can be valuable for confirming nutrient deficiencies in plants, particularly for micronutrients. Follow proper sampling technique, as described earlier, and be sure to collect a large enough volume of plant tissue that the analysis can be completed. Sample separately from normal growth (good) and affected (poor) areas. Do not sample dead plants (see Figure 4–10). Take soil samples from the same areas to check pH and nutrient status.

To get a diagnosis, you may have to sample outside the recommended times, and thus the nutrient contents may not necessarily correspond to the values at the standard times. Compare healthy and affected areas. Critical values for tissue concentration may be misleading in any case, since the concentration of nutrients in unhealthy plants may be high simply because there is not enough tissue to dilute the nutrients.

Shipping

Put leaf or petiole samples into paper bags, not plastic, or they will sweat and rot. Label each bag so that you will be able to relate the analysis to the specific block in the orchard or location in the field.

Keeping records

Keep records of each block or field sampled, including variety and year. Keep the analysis with the records of fertilizer applied, weather conditions and final yields. This will help determine trends in fertility levels.
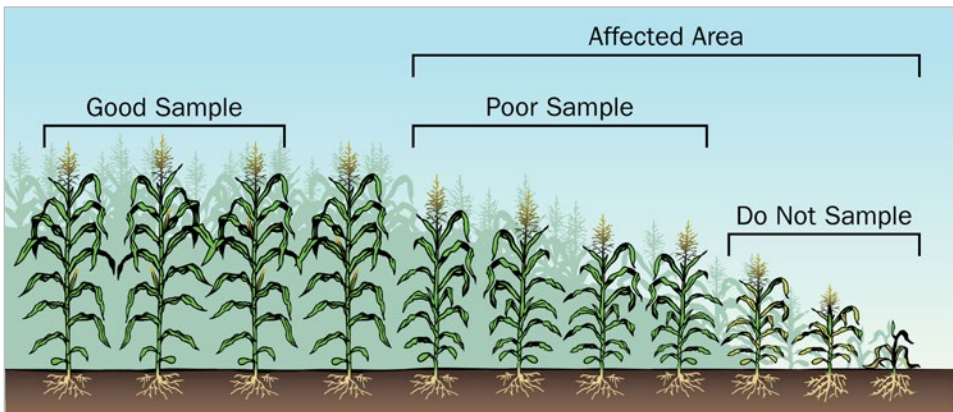
Figure 4–10. Tissue sampling to diagnose problems

Sampling manure

Farmers sample manure to:

- determine, in advance, the amount and kind of nutrients to be applied
- help determine requirements for additional nutrients

Sampling liquid manure

For liquid manure, take a sample each time the storage is emptied until you gain a sense of the average nutrient values. Manure applied from a storage emptied in spring will be different from the manure applied from the same storage emptied in late summer.

Agitate the storage completely. In a plastic pail collect samples from various depths of the storage, as it is being emptied. Mix 10–20 of these samples thoroughly and transfer a portion to a plastic jar.

The jar should only be half full to avoid gas buildup and explosion. Seal it tightly and put it in a plastic bag that is securely tied.

Store the sample in a cool place until shipping.

Sampling solid manure

For solid manure, take a sample every time the storage is emptied until you gain a sense of the average nutrient values. Then you can sample every few years or when you make a major change in manure source or in management, such as changes to ration, bedding or storage methods.

Solid manure is more difficult to sample randomly. On clean cement or plywood, take samples (a forkful) of manure from various loads leaving the pile or from various parts of the pile. Chop the manure with a shovel or fork and mix the samples together as thoroughly as possible. Divide the manure into four portions and discard three.

Continue mixing and dividing the manure until you can fill a plastic jar or shipping container — about half a litre.

Place the tightly covered sample in a plastic bag and store it in a cool place until shipping.

> Ship manure samples early in the week so that they reach the lab before the weekend.

Manure varies from farm to farm

Several factors affect the quantity of nutrients in manure. Some classes of livestock have manure with higher nutrient content. For example, poultry manure usually has a higher value for all nutrients than dairy manure. Within the poultry category, broiler manure is usually higher in nutrient value, especially phosphorus and potassium, than manure from laying hens.

The nutrient content of manure usually reflects the type of ration being fed to the livestock. Thus, manure from young animals being fed a concentrated ration has a higher

nutrient content than livestock fed a lower-quality feed. Properly balanced rations give optimum performance with the least throughput into the manure.

The amount and type of bedding affects the concentration of nutrients in the manure. Wood chips or wood shavings have a higher carbon-to-nitrogen ratio (500:1) than grain straw (80:1). The higher the carbon-to-nitrogen ratio, the more nitrogen can be tied up while carbon compounds are being broken down, which affects the amount of crop-available nitrogen.

Added liquids from any source dilute the nutrient concentration of the manure. A dairy manure with added milk house washwater and yard runoff needs a much higher application rate for similar nutrients than, for example, hog manure from a barn with wet-dry feeders.

Losses from storage can have a large impact on the nutrient content of manure. Runoff from a solid manure pile can wash away a significant portion of the nitrogen and potassium, while most of the phosphorus remains bound in solid forms. This is not only an environmental risk but a waste of resources.

Sampling to diagnose deficiencies and toxicities in the field

Explaining trouble spots in a field requires an open mind and examination of all the information available. When scouting a field for problems, check:

- soil for differences in structure, texture, horizons, compaction and the standard soil fertility analysis
- plants for growth stages, varieties, planting dates, planting depths, tissue colours suggesting deficiencies and disease, root development
- for pests like weeds, insects and diseases and for pest-control effects

Follow up with an overview of the crops in the area. Look at a circle of at least one concession to see if the problem is specific to one field or a general issue.

Do an overview of the entire field before moving to the specific site. Compare the good to the poor if you can. Look for patterns that can help identify the causes of poor growth:

- **strips or rectangular patterns.** These suggest application problems, particularly if they are repeated across the field.
- **vector-driven diseases.** Barley yellow dwarf, for instance, can be distributed by insects that sometimes float in on the prevailing wind and leaves a pattern much the same as snow drifting across the field. If the area

in the shadowed side of trees is unaffected, that's an indication of something being vector-driven.

- **the impact of wheel tracks.** These can be positive or negative. Normally, wheel tracks cause compaction and poor growth. Generally, areas can be measured and compared to the wheel spacing from weight-bearing wheels on farm equipment. However, on occasion slight packing from wheel traffic may improve seed-to-soil contact, resulting in earlier emergence, particularly on very loose soils.

Patterns can be difficult to see if they appear and disappear. Sometimes the problems are not severe, but if soil or weather conditions within a field change just a little, they may worsen. For example, soybean cyst nematode may not show symptoms in a field for years despite a gradually increasing population. It may finally give rise to typical symptoms in sections of the field where there is another stress such as compaction.

Look at crop production records for general trends in yield or quality. Whether a problem manifests in all crops in the rotation or only one can provide hints about the cause of the problem.

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5. Soil, Plant Tissue and Manure Analysis

Profitable crop production depends on applying enough nutrients to each field to meet the requirements of the crop while taking full advantage of the nutrients already present in the soil. Since soils vary widely in their fertility levels, and crops in their nutrient demand, so does the amount of nutrients required.

Soil and plant analysis are tools used to predict the optimum nutrient application rates for a specific crop in a specific field.

Soil tests help:

- determine fertilizer requirements
- determine soil pH and lime requirements
- diagnose crop production problems
- determine suitability for biosolids application
- determine suitability for specific herbicides

Plant tissue tests help:

- determine fertilizer requirements for perennial fruit crops
- diagnose nutrient deficiencies
- diagnose nutrient toxicities
- validate fertilizer programs

Soil analysis

Handling and preparation
When samples arrive for testing, the laboratory:

- checks submission forms and samples to make sure they match
- ensures client name, sample IDs and requests are clear
- attaches the ID to the samples and submission forms
- prepares samples for the drying oven by opening the boxes or bags and placing them on drying racks
- places samples in the oven at 35°C until dry (1–5 days) (nitrate samples should be analyzed without drying)
- grinds dry samples to pass through a 2 mm sieve, removing stones and crop residue
- moves samples to the lab where sub-samples are analyzed

What's reported in a soil test
Commercial soil-testing laboratories offer different soil testing/analytical packages. How the laboratory reports the results will also differ between labs. It is important to select an analytical package that meets your requirements. Analyses common to almost all soil test packages include: pH, buffer pH, phosphorus, potassium and magnesium.

Soil pH is included in almost all soil tests. Although it is not a nutrient, soil acidity or alkalinity has a great influence on the availability of nutrients and on the growth of crops. The buffer pH will also be reported for acid soils to determine the lime requirement.

The main nutrient analyses reported are phosphorus, potassium and magnesium. These represent the nutrients, aside from nitrogen, most commonly applied as fertilizer. Some labs include an analysis for calcium.

Nitrate-nitrogen analysis is performed on a separate soil sample taken to a greater depth.

Micronutrient tests are not performed as frequently but are becoming more popular. Zinc and manganese have tests that are well calibrated with crop requirements, and these are performed almost routinely. Other micronutrients (copper, iron, boron) are not well calibrated, but some reports include them.

Sulphur tests are becoming more common in Ontario as atmospheric depositions of sulphur from air pollution decrease, but they are not well calibrated with crop requirements.

More labs are routinely analyzing for organic matter. It is often used as an indicator of soil quality and also tied to herbicide recommendations.

Soils with suspected excess salts can be analyzed for electrical conductivity.

See the next page for more detail on what is included in a typical soil test report.

How the numbers are reported

Soil test results are expressed in many ways, particularly when dealing with labs from outside Ontario. Most Ontario labs express results as milligrams per litre of soil (mg/L): that is, the weight of nutrient extracted from a volume of soil. This is close in value to the weight-by-weight measure of milligrams per kilogram of soil (mg/kg), which is equivalent to parts per million (ppm).

Some labs, particularly in the United States, express soil test results as pounds per acre of available nutrient, which is confusing since the soil test results don't reflect a physical quantity. An acre-furrow slice weighs about 2 million pounds. The results can be converted back to parts per million by dividing by 2. For example, if soil test phosphorus is 120 lb/acre, divide by 2 to get 60 ppm.

Quebec results are expressed as kg/ha. Use the following formula to convert these results to ppm:

$$\text{kg/ha} \times 0.455 = \text{ppm}$$

It is also important to know which extractants have been used to perform the soil test.

Information found on a soil test report

General Information

- **Sample number** — This is provided by the grower relating the sample results to a particular field.
- **Lab number** — This is assigned by the lab, to track the sample through the various analytical steps.

Analytical Values

- **Soil pH** — Every report should include soil pH, measured in a soil-water paste.
- **Buffer pH** — Buffer pH is only measured on acid soils (normally where soil pH < 6.0).
- **Phosphorus (ppm)** — Ontario accredited soil tests must include the results from the sodium bicarbonate extraction (Olsen method). Some labs will also include results from Mehlich or Bray extractions. The method and the units should always be shown.
- **Potassium, magnesium (calcium, sodium) (ppm)** — The cations are measured in an ammonium acetate extract, with the results reported as mg/L of soil or ppm. Calcium and sodium are sometimes also reported.
- **Nitrate-N (ppm)** — This is not part of a regular soil test, since the interpretation of results is only valid for a deeper sample taken at planting time or before side-dressing.
- **Sulphur (S) or sulphate (SO$_4$-S) (ppm)** — This optional test has not been calibrated. It should be used on deeper samples, similar to nitrate.
- **Micronutrients (ppm)** — Mn and Zn are the only micronutrients with an Ontario accredited test. These are reported as a manganese index and a zinc index (see "Derived Values" below). Values may be reported for other micronutrients, but Ontario research has not shown reliable correlation to plant availability.
- **Organic matter (%)** — This is an optional test. Note carefully whether the result reported is for organic matter or organic carbon.
- **Electrical conductivity (EC) (millisiemens/cm)** — This optional test indicates the presence of excessive salts in the soil.

Derived Values

- **Zinc and manganese index** — These are calculated from the analytical result and the soil pH.
- **Cation exchange capacity (CEC) and base saturation %** — These numbers are calculated from the soil pH and analytical results for K, Mg and Ca. They may be skewed in high pH soils by the presence of free lime. Ontario fertilizer recommendations are not affected by CEC or base saturation.

Nutrient Recommendations

- **Fertilizer and lime recommendations** — These will only be printed if information about the crop to be grown has been provided. The analytical results can be used to determine nutrient requirements for specific crops from tables in the appropriate production recommendations. Some labs will give Ontario recommendations where requested. Often the labs will provide their own recommendations.
- **Adjustments to fertilizer recommendations** — Adjustments for manure application or for a previous legume crop will be included in the fertilizer recommendations if the information is provided.
- **Notes and warnings** — Some reports will include additional information based on the crop and soil test data.

Note: Ratings for soil test values are based on the soil test result and the crop to be grown.

Extractants

Analyzing soils to determine fertilizer requirements is complicated because we are trying to estimate how much nutrient is available from a specific soil to a wide variety of crop plants throughout the entire growing season. This would be simple if soils had uniform nutrient distribution, all the nutrients were wholly available for plant uptake and there were only one method by which plants took up nutrients. However, soil is an extremely complex medium with a wide variety of physical, chemical and biological interactions occurring simultaneously. The interactions at the soil-root interface are even more complex and less well understood.

An example of this complexity is phosphorus. The most common chemical form of phosphorus in the soil is phosphate. In neutral-to-alkaline soils, phosphate will combine with calcium. In neutral-to-acid soils, it will bind to iron or aluminum. Phosphate also reacts with various clay minerals or organic compounds to form complex combinations, and it may be present in the organic fraction of the soil or the soil biomass. All these forms are available to a greater or lesser degree to plants through a variety of processes, which we try to measure with a single, rapid chemical test.

Every chemical analysis has two steps. First, the compound being analyzed is converted to a form that can be measured. Then this material is analyzed.

However, because we are estimating only the available portion of the nutrient in the soil, the first step differs from a normal chemical analysis. In the case of soil tests, the soil is first treated with an extractant to remove a portion of the nutrient that is related to the amount available to plants. This extract is then analyzed to determine the amount of nutrient that was extracted.

Choosing an extractant

To be useful in predicting crop needs, an extractant must provide the best possible estimate of the amount of additional nutrient needed for optimum crop yields. This is complicated to measure, so the assessment of extractants is more commonly made by measuring how well the extractant estimates the nutrients available to plants in the range of soils tested in the lab or in a region. The extractant must also be relatively inexpensive and easy to use, involve as few toxic or corrosive chemicals as possible and use procedures that are reproducible from lab to lab.

No extractant pulls out the exact fraction available to plants. Each has strengths and weaknesses specific to various soils. The choice of an extractant should be governed by how appropriate it is to the soils in question and by the availability of data relating it to crop response. See Chapter 7 for more details.

First was water

The first extractant used for soil testing was water. This removed only the portion of nutrient present in the soil solution. While this fraction is immediately available to plants, it is only a tiny part of the total available nutrient in the soil. It is not well related to the total nutrient supply, since soils vary tremendously in the nutrient reserve they hold.

Researchers had noted that plant roots excrete weak acids from their surfaces, so the next step was to experiment with acid solutions. From there, the range and variety of extractants has proliferated as researchers seek better and more appropriate extractants for a wide range of soil conditions. These extractants are often named for the scientist who developed it or the main ingredient in the extracting solution.

Regionally specific

The choice of an extractant is specific to each region, since the most appropriate extractant depends to a large extent on the soils of that region.

The first step in determining an appropriate extractant or soil test method is to collect samples of a wide range of soils from across the region and then to grow plants in each soil. These plants are harvested, weighed and analyzed to find the amount of nutrient taken up by the plants from the different soils.

Different extractants are used to remove nutrients from the soils, and the extracts are analyzed. The final step compares the results of the extractions with the amount taken up by the plants, which is the measure of the nutrient-supplying capacity of the soil. The extractant that is chosen for a region is normally the one with the highest correlation (agreement) to the plant uptake.

Soil test extractants for phosphorus can be broadly divided into acidic and alkaline solutions. The acidic solutions (used in the Bray and Mehlich methods) are generally used in areas with acidic soils. In alkaline soils, these extractants underestimate the amount of available phosphorus because the acid is partly neutralized by the free lime in the soil. See Table 5–1.

The alkaline extractants (sodium bicarbonate, ammonium bicarbonate) give more consistent results over a wide range of soil pH. Potassium, calcium and magnesium are extracted using another similar cation, usually ammonium, to remove them from the cation exchange complex. Micronutrients may be extracted using a chelating agent or weak acid to remove them from the soil.

Table 5–1.   Correlation of extractable P with P uptake in controlled greenhouse conditions

Extractant	All soils[1] correlation (r^2)*	pH>7.0[2] correlation (r^2)*	pH 6.1–7.0[3] correlation (r^2)*	pH<6.1[4] correlation (r^2)*
sodium bicarbonate	0.74	0.79	0.64	0.87
ammonium bicarbonate	0.73	0.71	0.63	0.95
Bray-Kurtz P1	0.54	0.52	0.33	0.73
Bray-Kurtz P2	0.65	0.60	0.40	0.90
Mehlich III	0.66	0.57	0.40	0.93

[1] n = 88 soils
[2] n = 46 soils
[3] n = 30 soils
[4] n = 12 soils

*An r^2 of 1.00 is complete agreement.

Source: T.E. Bates, "Prediction of phosphorus availability from 88 Ontario soils using five phosphorus soil tests," *Communication in Soil Science Plant Analysis* 21 (1990): 1009–1023.

Following the choice of extractant, field trials are carried out to determine the optimum fertilizer application for each soil test level with different crops. These calibrations are unique to the extractant and are expensive. Inevitably, there is resistance to changing the soil test extractant unless an alternative method has a large advantage.

Extractant results are not interchangeable

Different extractants will often give widely different values from the same soil. The amount of phosphorus extracted by a sodium bicarbonate solution, for example, may be one half or less of that extracted by a Bray P1 extractant. In the proper conditions, however, both could provide an index of phosphorus availability to crops. Problems arise if someone uses the numbers from one test with fertilizer recommendation tables developed for a different test.

The results from different extractants are not related perfectly to one another. While there is a trend that as the soil test level for one extractant increases, the others increase as well, there are exceptions. Even where the extractants increase consistently, the relationship between extractants is often different at low soil test values than at high soil test values. For this reason, converting values from one extractant to another should be avoided. Know which extractant is being used and use those results with fertilizer recommendation tables developed for that extractant.

Quality control

As with any chemical process, quality control must be used to ensure that results from each lab are accurate. This is accomplished in Ontario through an accreditation program administered by the Ontario Ministry of Agriculture, Food and Rural Affairs. The details of this program will keep changing over time, but the basic principles will remain the same.

Goals of a lab accreditation program

The goals of a lab accreditation program are to:

- ensure that participating labs complete analytical tests that fall within the range of expected results of the accreditation program
- provide consistent results from any of the accredited labs
- encourage the use of appropriate soil test extractants (see Table 5–2) for which there is a body of fertilizer response calibration data for Ontario soils
- promote the use of accredited labs
- promote the use of fertilizer guidelines based on Ontario research

Accredited labs follow a quality control program that ensures best results. Each lab has one or two standard soils that are included in each analytical run to ensure the results are consistent. Standard solutions are prepared carefully and used to calibrate the instruments and to check their calibration periodically. Recordkeeping and tracking are used for trouble-shooting problems and ensuring the performance of the lab over time.

An external assessment program provides an additional check on the system. This allows comparison between labs and helps catch any problems that have been overlooked by the lab's internal quality control.

Table 5–2. Soil test methods accredited in Ontario

Tested for	Testing method
soil pH	saturated paste
lime requirement	SMP buffer pH
phosphorus	sodium bicarbonate (Olsen)
potassium, magnesium	ammonium acetate
zinc index	DTPA, modified by soil pH
manganese index	phosphoric acid, modified by soil pH
soil nitrate	potassium chloride extraction

Soil pH

Soil pH is the measurement of the hydrogen ion activity or concentration in the soil solution. This activity affects the availability of most nutrients and controls or affects most biological processes.

The hydrogen ion concentration is measured with a pH electrode. The heart of the electrode is a glass bulb that is only porous to hydrogen ions. As the positive ions move into the electrode, a current is set up that is measured with what is essentially a voltage meter. The voltage reading of several standards is read and a graph set up. The voltage readings of the samples are then compared to the graph and given pH values.

There is some debate about what soil-to-water ratio is best for measuring pH. Usually, soil pH is measured using de-ionized water to form a saturated paste or a 1:1 or 1:2 soil-to-water ratio. Saturated paste is the accredited method in Ontario, and liming recommendations are based on this method. The measured pH tends to increase as the amount of water added to the soil increases. The difference will be greatest in the soils with the lowest buffering capacity: i.e., coarse sands.

Other methods employ calcium chloride solutions to prepare the paste or slurry, reducing the amount of interference from high salt levels. This method tends to give a lower pH reading than slurry with pure water.

The saturated paste is prepared by adding just enough water to the soil sample to completely saturate it without leaving any free water. Properly preparing a saturated paste is time-consuming and difficult, but it provides a closer approximation of the pH at the root-soil interface than the more dilute slurries.

The little "p" in pH

In math, "p" is used to denote the negative log of a given value. In the case of pH, it is the negative log of hydrogen ion (H) concentration in the solution.

Pure water contains some molecules that have broken apart into individual ions, either hydrogen (H^+) or hydroxyl (OH^-). **water (H_2O) = H^+ + OH^-**

In pure water, there is an equal amount of hydrogen and hydroxyl ions, and the pH is neutral (see Figure 3-1). If you were to count the number of H^+ ions in pure water, you would find **1/10,000,000 moles of H^+ ions per litre of water.**

In scientific notation, this is 10^{-7} H^+ ions, and the negative log of this number is the positive value of the little number on top, or 7. As the concentration of hydrogen ions increases, the value of the pH decreases and the solution becomes more acidic.

Since this is a logarithmic scale, a pH of 6 is 10 times more acid than a pH of 7.

A pH of 5 is 10 times more acid than a pH of 6, and 100 times more acid than a pH of 7.

Buffer pH

Shoemaker, McLean and Pratt (SMP) method

The measurement of soil pH is used to indicate whether a field requires lime. Depending on the crop, soils with a pH less than 6.1 need lime, and a buffer pH measurement is performed to determine how much lime is required.

The buffering capacity of the soil is its ability to resist changes in pH. In an acid soil, this ability to resist change is due to the reserve acidity. This reserve acidity is due to hydrogen, aluminum and other cations that are held on the cation exchange complex. The greater the reserve acidity, the more lime is required to bring the pH into optimal range.

This reserve acidity is measured by adding a buffer solution (SMP) to the soil sample and reading the pH of the soil and buffer mixture after a half hour. This buffer resists change in pH and starts out at a pH of 7.5, but the soil acidity reduces the pH of the buffer in proportion to the amount of reserve acidity in the soil. If the pH of this mixture is low, the soil has a high reserve acidity and requires a large amount of lime to neutralize it.

The lime requirement is calculated according to formulas in Table 5–3.

Table 5–3. Calculating lime requirements

pH to which soil is limed	Equation
7.0	lime (t/ha)* = 334.5 − 90.79 pH_B ** + 6.19 pH_B^2
6.5	lime (t/ha) = 291.6 − 80.99 pH_B + 5.64 pH_B^2
6.0	lime (t/ha) = 255.4 − 73.15 pH_B + 5.26 pH_B^2
5.5	lime (t/ha) = 37.7 − 5.75 pH_B

* Lime requirement is calculated at tonnes of lime per hectare with an agricultural index of 75 (see Chapter 3, Table 3–2, for more details).

** pH_B = buffer pH

Example calculation. Determine the lime requirement for a soil with a buffer pH (pH_B) of 6.5 in order to achieve a desired pH of 7.0:

334.5 − (90.79 x 6.5) + 6.19 x $(6.5)^2$ = 5.9 t/ha lime required

Soluble salts

Soluble salts in soils can result from excessive applications or spills of fertilizers and manures, runoff of salts applied to roads and chemical spills. There can also be high salt levels in areas affected by brine seeps or spills from recent or historical oil and gas exploration. High concentrations of soluble salts in or near a fertilizer band can restrict plant (root) growth severely without seriously affecting the salt concentrations in the rest of the soil. It is difficult to identify excess salts in a starter fertilizer band because of the limited volume of soil affected and because the excess salts can dissipate quickly into the surrounding soils with rainfall.

Soluble salts also interfere with the uptake of water by plants. A given amount of salt in a soil provides a higher salt concentration in soil water if the amount of water is small. Plant growth is most affected by soluble salts in periods of low moisture supply (drought) and in soils with low water-holding capacity (e.g., sands and gravels).

Soluble salts can be measured in the lab by measuring the electrical conductivity of a soil-water slurry. The higher the concentration of water-soluble salts, the higher the conductivity. Table 5–4 provides an interpretation of soil conductivity reading for Ontario field soils in a 2:1 water:soil. This slurry is prepared by mixing one volume air-dried soil with two volumes of water.

For greenhouse soils, the OMAFRA-accredited soil test uses a larger soil sample and measures conductivity on a saturation extract.

Table 5–4. Interpreting soil conductivity readings in field soils

Conductivity "salt" reading millisiemens/cm	Rating	Plant response
0–0.25	L	suitable for most if recommended amounts of fertilizer used
0.26–0.45	M	suitable for most if recommended amounts of fertilizer used
0.46–0.70	H	may reduce emergence and cause slight to severe damage to salt-sensitive plants
0.71–1.00	E	may prevent emergence and cause slight to severe damage to most plants
1.00	E	expected to cause severe damage to most plants

Testing for nitrate-nitrogen

Nitrate-nitrogen content of the soil at planting time can be used to fine-tune nitrogen fertilizer applications for corn and spring barley or for nitrogen applications to corn at sidedress timing (pre-sidedress nitrate test or PSNT). Extensive calibration work has not been carried out in Ontario for other nitrogen-using crops such as wheat, canola or most horticultural crops. Work has been done with potatoes and tomatoes, but results did not lead to definite recommendations.

Routine nitrogen analysis is not done on soil samples because nitrate contents vary greatly from week to week; nitrate-nitrogen samples are taken to a greater depth than standard soil tests; and samples must be handled carefully to prevent changes in the soil nitrate content.

Some users request analysis for ammonium nitrogen as well as nitrate, even though it is not used for recommendations. The same extraction method is used, although a different analytical procedure is used on the extract. If the sample is to be analyzed for ammonium, it should be refrigerated. Drying the sample will invalidate the ammonium nitrogen test (see Chapter 4, *Sample collection* section).

Methods

Nitrate-nitrogen is present in the soil almost exclusively within the soil solution and is extracted easily. The standard extractant used is a potassium chloride solution.

A sample of the soil is mixed with the potassium chloride solution at a ratio of 1 part soil to 5 parts extracting solution, shaken for half an hour and then filtered. The extract is analyzed using an auto-analyzer, which measures the intensity of colour produced after mixing the extract with specific chemicals.

Portable field sensors are becoming available commercially. Careful operation and calibration by the user needs to be fully understood. These sensors do provide rapid on-site analysis and reduce the costs of couriering samples to commercial labs. It is advised to participate in a check sample program to verify equipment performance and verify results.

Comments

- This method produces highly reproducible results and is relatively straightforward.
- Soil nitrate values generally increase by 30% from early May (pre-plant timing) to early June (pre-sidedress timing). Ensure that the soil test lab is aware of your sample timing.
- Interpretation of the soil nitrate test is complicated by the variability of soil nitrate contents within the field.
- Soil nitrate content may underestimate the amount of available nitrogen where organic sources of nitrogen have been applied (e.g., livestock manure, sewage sludge, legume plowdown) and have not had a chance to mineralize. Research is under way to develop soil tests for the easily mineralizable portions of soil and added organic matter.

Phosphorus

The three common methods for extracting available phosphorus are Olsen (sodium bicarbonate), Bray P1 and Mehlich III (see Table 5–5).

Whatever methodology is used, the next step is to determine the concentration of phosphorus in the extract. Several analytical methods can be used, some of which are related to a specific extractant. The most common involves adding molybdenum as a colour reagent. It will form a blue colour when combined with phosphorus. The greater the concentration of phosphorus, the more intense the colour.

The Olsen extractant is very alkaline, so it tends to react differently with the colour complex than the Bray or Mehlich do. As well, the Bray or Mehlich extracts tend to have higher phosphorus concentrations than the Olsen, so the standards used in the analysis are different.

Table 5–5. Phosphorus extractants

Method	Extracting solution	Solution pH	Where it's used
sodium bicarbonate	0.5 M $NaHCO_3$ solution, 1 part soil to 20 parts solution, shaken for 30 min at room temperature	8.5	Ontario, Iowa, most western states
Bray P1 (weak Bray)	0.025 M HCl + 0.03 M NH_4F, 1 part soil to 10 parts solution, shaken for 5 min	2.5	Michigan, Ohio, Indiana, Illinois, eastern states
Bray P2 (strong Bray)	0.1 M HCl + 0.03 M NH_4F, 1 part soil to 10 parts solution, shaken for 5 minutes	2.5	early 1960s in Ontario before sodium bicarbonate
Mehlich III	0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA, 1 part soil to 10 parts solution	2.5	Quebec, Maritime provinces, Pennsylvania, southeastern states

Sodium bicarbonate method (Olsen)

The sodium bicarbonate method (also called the Olsen method) is the one recommended for use in Ontario.

This extracting solution has a pH of 8.5 and so is best used with a soil pH range from 6.0–8.0. The calcium phosphates in the soil and some of the organic phosphates are dissolved by the sodium bicarbonate. The sodium bicarbonate method will predict the relative available phosphorus in a wide range of soil types.

Comments

- Requires a longer shaking time than the Mehlich or Bray (a half hour, as opposed to 5 minutes).
- The sodium bicarbonate method is very sensitive to temperature, pH and shaking times, so that uniform conditions are required throughout the analysis to ensure consistent results. Olsen found that the extractable phosphorus can increase almost 0.5 ppm for a 1°C increase in temperature of the extracting solution between 20°C and 30°C.

Bray P1

The Bray extraction solution contains hydrochloric acid and ammonium fluoride, which form an acidic solution. This tends to simulate an acid soil environment. This test is better for acidic than for alkaline soils.

The Bray extractant tends to extract more phosphorus than the sodium bicarbonate method. At high pH values, the acid nature of the extracting solution may dissolve the calcium phosphates, over-estimating the available phosphorus. However, the free lime in the soil may also neutralize the acid nature of the extracting solution, making it less effective. These two situations indicate that the Bray P1 extraction provides unpredictable results under alkaline conditions.

A modified Bray P2 (strong Bray) extractant was used in Ontario during the 1960s, using a more concentrated acid to overcome the neutralizing effect of alkaline soils. It was replaced by the sodium bicarbonate extractant, which was more consistent over the range of soils in Ontario.

Mehlich III

The Mehlich III is a multi-element extracting solution composed of acetic acid, ammonium fluoride, ammonium nitrate and the chelating agent ethylene diamine tetra-acetic acid (EDTA). It combines chemicals from Bray P1, ammonium acetate and DTPA extracting solutions.

Mehlich III extracts phosphorus with acetic acid and ammonium fluoride. It extracts potassium, magnesium, sodium and calcium with ammonium nitrate and nitric acid and extracts zinc, manganese, iron and copper with EDTA.

This method is often used because of the savings in analysis time. When used with an inductively coupled plasma (ICP) machine capable of running simultaneous elements, this method is appealing for soil labs. The value measured using an ICP may be different from the value measured by a colour reaction, although the reasons for this are not clear. These should be considered to be two separate tests, with different interpretations for making fertilizer recommendations.

Because of its acidic nature, the Mehlich III solution is best suited to acidic soils and is routinely used in Quebec and the Maritimes. The relatively high acid concentration in this extractant means it will perform adequately in slightly alkaline soils, but inconsistently in soils with high carbonate (free lime) content.

Potassium, calcium, magnesium, sodium

Potassium, magnesium, calcium and sodium are positively charged. They are all cations. They can all be extracted by the same solution, since the mechanism is to flood the soil with another cation to displace them from the exchange complex.

Potassium and magnesium are the cations that most often limit crop production, and they are measured routinely in Ontario. Potassium is absorbed by the plant in larger quantities than any other element except nitrogen.

Calcium supply is generally adequate if the soil pH is suitable for crop growth, so it is not measured by all labs. Calcium contents are often high enough that extra dilutions are required to bring the extract within the operating range of the lab equipment, adding extra time and inconvenience.

Sodium is not an essential nutrient for crop production and is analyzed only where environmental contamination is suspected.

The presence of free lime in calcareous soils complicates the measurement of calcium and magnesium. This free lime is partly dissolved by the ammonium acetate solution and causes extra calcium and magnesium to show up in the extract. The amount of lime dissolved will depend on the pH of the extracting solution and the ratio of soil to extracting solution, so it is important for labs to follow analytical procedures exactly.

Ammonium acetate

The most common cation used for extracting soil cations is ammonium from ammonium acetate.

The availability of potassium is influenced by the drying temperature of the soil. Temperatures higher than 35°C tend to cause the potassium to be bound up on the exchange sites. This is the reason that at least two days of lab time is spent drying. Speeding up the process would either leave water in the soil, affecting the final concentration of the nutrients,

or over-heat the soil, making the readings for potassium inaccurate.

After extraction, the cations in the ammonium acetate solution are measured.

Mehlich III

The Mehlich III extractant can be used for potassium and other cations as well. The ammonium ions from ammonium nitrate and ammonium fluoride behave the same way as the ammonium from ammonium acetate, displacing the cations from the exchange sites. The concentration of the cations are then measured in the extract.

The Mehlich III method extracts amounts of potassium from the soil comparable to the amounts extracted by the ammonium acetate method.

Sulphur

There is no standard accepted sulphur soil test or calibrated sulphur fertilizer recommendations for Ontario. Soil test labs in Ontario have not routinely analyzed for sulphur in the past. Sulphur concentration in the soil is affected by leaching and mineralization, which make it difficult to correlate soil test values to plant uptake. It is likely that sulphur test results will be more meaningful from a 30 cm sample rather than a 15 cm sample.

Labs will do sulphur analyses on request. The most common technique is to extract sulphur from the soil using a calcium phosphate solution. The amount of sulphate in the extract is measured by adding barium to form barium sulphate crystals and measuring the turbidity of the resulting suspension or by reducing the sulphate to sulfide and measuring it through a colour-forming reaction. Other labs may analyze sulphate-S in the calcium phosphate extract or in a Mehlich III extract using an ICP.

Micronutrients

Because micronutrients are generally found in extremely low levels in the soil, estimates of their concentrations are generally less reliable than the measurement of macronutrients.

Micronutrient tests are difficult to correlate with plant uptake because:

• the concentrations in the extracting solutions may be near the detection limit of the equipment
• there is potential for contamination of the sample from sampling tubes, pails or dust
• soil pH, organic matter, clay content and mineralogy can affect both the extractions and the plant availability of micronutrients

In Ontario, tests have been accredited for zinc and manganese. The other micronutrients are not well enough correlated to be used for fertilizer recommendations. Tissue analysis should be the primary tool in diagnosing deficiencies of these elements. The soil test can be useful, however, as a secondary tool.

Micronutrient extraction

Most of the micronutrients are chemically active and would form insoluble compounds with an extracting agent, making them difficult to measure. Chemists get around this by using chelates or weak acids to extract micronutrients. Chelates are organic compounds that "complex" the micronutrient metal ions, binding to the ion at more than one point and wrapping themselves around it. This keeps the ions in the solution and allows them to be separated from the soil for measurement.

The most common chelating agents are diethylene triamine penta-acetic acid (DTPA) and ethylene diamine tetra-acetic acid (EDTA). While both behave similarly, they have slightly different affinities for different metal ions.

By varying the pH, chelating agents can be adjusted to extract specific nutrients. DTPA is adjusted to a pH of 7.3 for most soil extractions. Triethanolamine is added to the extracting solution to buffer it against pH changes during the extraction. Calcium chloride is also added to prevent the calcium carbonate in calcareous soils from dissolving.

Zinc

DTPA extraction

For this extraction, the soil is mixed with a 0.005 M DTPA solution at a ratio of 1 part soil to 2 parts solution and shaken for 1 hr. The zinc in the soil is complexed by the DTPA and held in the solution.

Following extraction and filtering, the zinc content in the extract is measured.

Comments

• The extraction process does not reach equilibrium, so it is necessary to maintain strict procedures with regard to shake time, speed and filtering for the tests to be consistent.
• The high soil-to-solution ratio (1:2) makes it difficult to filter out adequate sample sizes. Filtration may take several hours to overnight.
• The long shake and filtration time makes DTPA extraction one of the most time-consuming processes in the lab.
• This analysis is susceptible to contamination during the soil sampling process. In the field, be sure to use only plastic or stainless-steel equipment. The use of galvanized or iron implements will contaminate the sample with zinc or iron.

Zinc Availability Index

The availability of zinc is influenced more by soil pH than by the amount of nutrient in the soil. Soil tests in Ontario for zinc report an availability index instead of, or in addition to, the nutrient analysis.

Formula to calculate the zinc index:

Zinc index = 203 + (4.5 x DTPA extractable zinc in mg/L soil) – (50.7 x soil pH) + (3.33) x (soil pH)^2

Interpreting the Index
- greater than 200 — suspect contamination of the sample or field
- 25–200 — adequate for most field crops
- 15–25 — adequate for most field crops but bordering on deficiency for corn
- less than 15 — likely deficient for corn and zinc fertilizer should be applied

Mehlich III extraction

The EDTA in the Mehlich extractant behaves much like DTPA. There has not, however, been as much work done with the Mehlich extractant in Ontario, so its results should be used with caution.

Manganese

Phosphoric acid extraction

In Ontario, a weak phosphoric acid solution is used as an extracting solution with a 1:10 soil-to-water ratio. Other areas may use the DTPA extractant, but the phosphoric acid method has given more consistent results in Ontario.

Comments
- Manganese is extracted from the soil much more quickly by phosphoric acid than by EDTA.
- Manganese availability is also influenced by soil pH.
- The ratio of soil to extracting solution is much lower than with DTPA, so that the samples filter rapidly.

Manganese Availability Index

The availability of manganese is influenced much more by soil pH than by the amount of nutrient in the soil. Soil tests in Ontario for this nutrient report an availability index instead of, or in addition to, the nutrient analysis.

The values are indices of manganese availability based on phosphoric acid extractable soil manganese and soil pH.

Where soil pH ≤ 7.1:

Mn Index = 498 + (0.248 x phosphoric acid extractable Mn in mg/L soil) – (137 x soil pH) + (9.64) x (soil pH)^2

Where soil pH > 7.1:

Mn Index = 11.25 + (0.248 x phosphoric acid extractable Mn in mg/L)

Interpreting the Index
- greater than 30 — adequate for field crops
- 15–30 — adequate for most field crops but approaching deficiency for oats, barley, wheat and soybeans
- less than 15 — likely insufficient for oats, barley, wheat and soybeans.

Iron and copper

Neither iron nor copper has a soil test that correlates well with plant uptake or fertilizer response in Ontario. Copper deficiency has been observed on muck soils in Ontario but is rare on mineral soils. There are no confirmed cases of iron deficiency in Ontario.

Plant analysis is a much more reliable indicator of the availability of these nutrients.

Boron

There is no accredited test for boron in Ontario. To give a rough indication of availability, boron can be determined by extracting with hot water using barium chloride to flocculate the soil. Boron in the extracting solution can be read using a colour-forming reaction or ICP.

Because levels of boron are often less than 1 ppm, it is much more difficult to get an accurate measurement than it is for other soil nutrients. As well, the borate ion is mobile in the soil so that concentrations fluctuate, depending on leaching and mineralization.

Plant tissue analysis is a much more sensitive indicator of boron availability than a soil test.

Organic matter

Soil organic matter content is not used to adjust fertilizer recommendations in Ontario, but it plays an important role in soil fertility.

Organic matter contributes to the soil's cation exchange capacity and enhances its ability to hold nutrients available for plant uptake. Through microbial action, many nutrients also cycle through organic and mineral forms, so that organic matter is a reservoir of slowly available nutrients. Adequate organic matter is essential for soil tilth and water-holding capacity. The level of organic matter is also important for the activity of several herbicides.

Determining soil organic matter has taken on new importance with the need to understand the dynamics of soil carbon in relation to greenhouse gas emissions or sequestration. Soil management can influence the net movement of carbon into or out of the soil, and this can create opportunities for farmers to participate in carbon credit programs. Evaluation of the effectiveness of these programs will require precise measurements of changes in soil organic matter content.

There are two approaches to measuring soil organic matter:

- The first is to measure the amount of organic carbon in the soil, using either wet chemistry or a combustion analyzer, and to multiply this weight by a factor to convert it to organic matter.

- The second approach is direct measurement of the weight of organic matter lost from the soil when it is burned, called loss on ignition (LOI).

Organic carbon measurements are more precise than LOI, particularly on soils with low organic matter contents, but they require either aggressive chemicals to dissolve the organic compounds or specialized equipment.

The measurements of organic matter and organic carbon are fairly well correlated, but the carbon content of organic matter can vary depending on the source and age of the material. This will lead to slightly different measurements, depending on the method used.

In Ontario, the loss on ignition method has been determined to be sufficiently precise for farm soils. Most scientific research, however, uses the increased precision of organic carbon determinations. Soil organic matter content is about 1.8 to 2.0 times the organic carbon content.

Loss on ignition (LOI)

LOI is a direct measure of soil organic matter content. Samples are placed in a muffle furnace overnight at 425°C, and the weights before and after ashing are compared. Higher temperatures must be avoided because any carbonates present in the soil will break down, increasing the measured organic matter content. Pre-drying the samples at 120°C will reduce the variability of this test.

Determining organic carbon

Modified Walkley Black

The Walkley Black method operates on the principle that potassium dichromate oxidizes soil carbon. The potassium dichromate changes colour depending on the amount it is reduced, and this colour change can be related to the amount of organic carbon present. The final solution is read on a spectrophotometer and compared to a chart or a standard.

Comments

- This method measures organic carbon rather than organic matter. The conversion factor itself may be a source of error. Also, some organic compounds are not completely oxidized by the dichromate, resulting in low test values.
- This method cannot be used with soils containing over 7.5% organic matter.
- The reagents used in this analysis are toxic and must be disposed of as hazardous waste.

Combustion furnace

This furnace burns the sample at a temperature of more than 900°C and measures the concentration of carbon dioxide released — the total carbon. The results are fast and accurate, but the equipment is expensive.

Then, another sample is ashed overnight in a muffle furnace to remove the organic carbon. The inorganic carbon (carbonate) in the residue is measured. Organic carbon is the difference between the total carbon and the inorganic carbon.

Soil texture

Texture estimation

Soil texture is not measured in most soil samples but is estimated by hand. Soil texture is recorded on most soil reports as a letter. The four categories are C (coarse), for sand or sandy loam; M (medium), for loam; F (fine), for clay or clay loam; and O (organic).

These are used only to give the client a rough idea of the texture. It is sometimes a useful check that the samples are from the right fields.

Texture measurement

Soil texture can be measured by dispersing the soil in a high-sodium solution such as Calgon or triple sodium phosphate and measuring the amount of soil settling out over time. This method is based on the fact that large particles will settle out faster than finer ones. Between half a minute and 1 minute after agitation, all the sand will have settled. Between 6 hr and 24 hr after, all the silt will have settled out, leaving the clay in suspension. The technique uses a pipette or hydrometer to measure the concentration of soil in suspension at these times.

The technician uses a pipette to sample the solution. The solution from the pipette is dried in an oven and the amount of soil in the pipette is determined by weight.

Alternatively, the technician can use a special hydrometer to measure the density of the suspension. As the soil settles out of suspension, the density decreases and the hydrometer sits lower in the water.

The pipette method is more accurate than the hydrometer method but more expensive and time-consuming.

Ordinarily, organic matter does not significantly affect the texture measurement. An amount for organic matter can be deducted from the silt or clay fraction. Or, before determining texture, the organic matter can be removed by chemical means.

Once the proportions of sand, silt and clay have been determined, the texture class is determined as shown in Figure 5-1.

Particle sizes of the soil fractions

Sand	0.05–2 mm
Silt	0.002–0.05 mm
Clay	<0.002 mm

Particles larger than 2 mm (gravel and stones) are not included in determining soil texture.
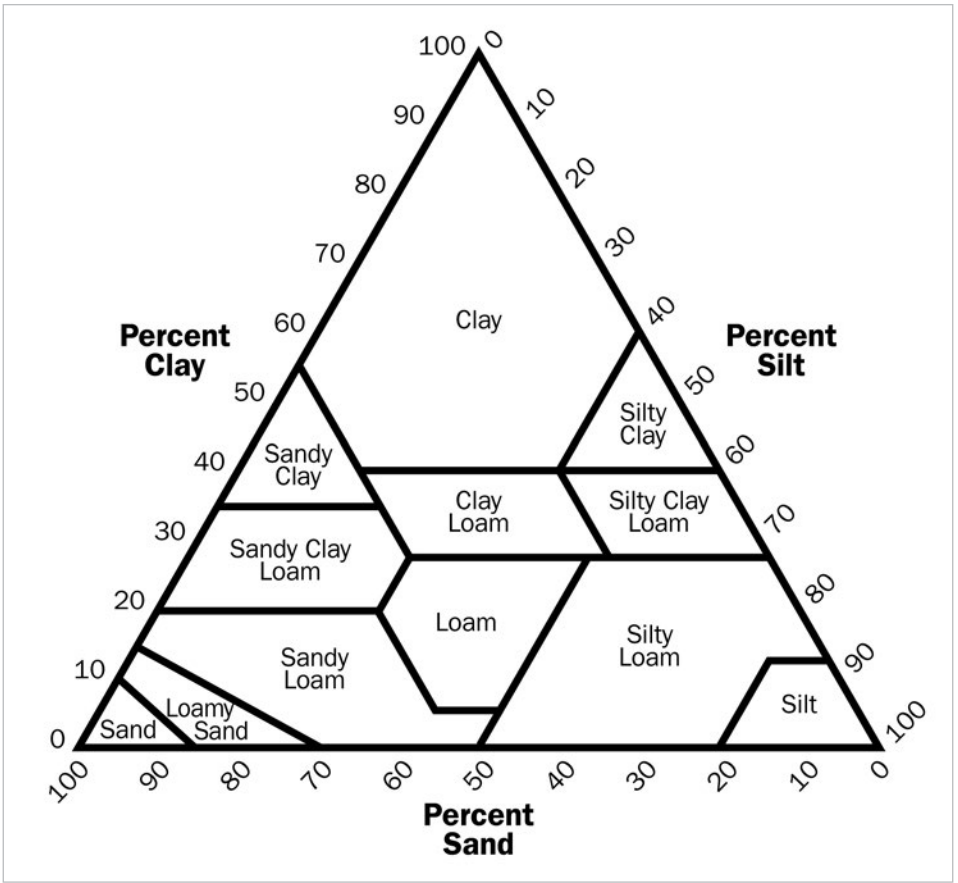
Figure 5–1. Soil texture triangle.
This figure shows the relationship between the class name of a soil and its particle size distribution. The points corresponding to the percentages of silt and clay in the soil are located on the silt and clay lines respectively. Lines are then projected inward, parallel in the first case to the clay side of the triangle and in the second case to the sand side. The name of the compartment in which the two lines intersect is the class name of the soil.

Cation exchange capacity and per cent base saturation

Cation exchange capacity (CEC) and per cent base saturation are not used for fertilizer recommendations in Ontario. In calibration trials where these factors have been considered, the accuracy of fertilizer recommendations has not been improved and has sometimes been decreased.

Many soil test reports do, however, include these determinations. They are useful as a general indication of soil fertility and can point towards some potential production problems. Understanding how these numbers are derived can help keep them in perspective.

> **Note:**
>
> Cation exchange capacity is measured in units of electrical charge rather than weight, since the weight per unit charge of the cations varies greatly.
>
> CEC is expressed as centimoles of positive charge per kilogram (cmol+/kg). This is preferred to milliequivalents per 100 grams, but the numbers for each are the same. To convert from parts per million to centimoles per kilogram, the ppm is divided by 10 times the atomic weight of the cation divided by its charge. For example, a soil test for magnesium (atomic weight 24, charge 2+) of 480 ppm would give a value of 480/[(24*10)/2] = 4 centimoles per kilogram.

Cation exchange capacity

Cation exchange capacity (CEC) is a relative reflection of the total ability of the soil to hold cation nutrients — its potential fertility. For a full discussion, see the beginning of Chapter 2.

Cation exchange sites are the major source of available cations for plant uptake. CEC may be measured directly or estimated by adding the total cations measured in a soil test.

Estimating CEC

The cation exchange capacity is often estimated from the nutrients extracted by ammonium acetate. This estimation assumes that only the nutrients occupying the cation exchange sites are extracted, which is not always the case. The presence of calcium carbonate (lime) in soils with high pH may distort the values for cation exchange capacity because the ammonium acetate will dissolve some of this calcium as well.

Another quick method of estimating CEC is to use the percentage of clay and organic matter. Multiply the percentage of clay by 0.5 and the percentage of organic matter by 2. The sum of these figures estimates the cation exchange capacity of the soil.

Formula for estimating cation exchange capacity

bCEC value = (Ca value ÷ 200) + (K value ÷ 390) + (Mg value ÷ 120)

(bCEC = cation exchange capacity occupied by bases)

Where each of the Ca, K and Mg values (mg/kg of soil) is obtained from the ammonium acetate extraction. This equation converts them to the centimole per kilogram value.

A factor is also added for the H^+ content of the soil:

- if the pH is between 6.0 and 7.0, then CEC value = bCEC value + 1.2
- if the pH is greater than 7.0, then CEC value = bCEC value.
- if the pH is less than 6.0, then CEC value = bCEC value + {1.2 x [70 − (pH_B x 10)]}. (pH_B = buffer pH)

This formula, developed in Michigan, takes into account the pH of the soil and the electrical charge of each cation. It does not take into account the presence of other cations such as aluminum or the amount of calcium or magnesium dissolved from free carbonates in the soil.

Another quick method of estimating CEC is to use the percentage of clay and organic matter. Multiply the percentage of clay by 0.5 and the percentage of organic matter by 2. the sum of these figures estimates the cation exchange capacity of the soil.

CEC measurement

A more accurate indication of the cation exchange capacity can be obtained by measuring it in the lab. The process involves saturating the soil with a particular marker cation, forcing all other cations off the exchange sites. This marker cation is then itself extracted with the ammonium acetate solution. This solution is then analyzed for the quantity of marker cation, which represents the total cation exchange capacity.

Barium is a good marker ion because it is not a common element in the soil and it has a strong enough affinity for the exchange sites to force the other cations off.

Per cent base saturation

The per cent base saturation is the ratio of basic cations to the cation exchange capacity expressed as a percentage (see per cent base saturation equations following). The term is often used loosely and sometimes refers to each individual cation or to the sum of all the basic cations.

Care must be taken when calculating and interpreting the values for per cent base saturation because the values depend on the how the CEC is obtained. For example, a potassium saturation value derived from a CEC estimate in a calcareous soil will be misleading because of the artificially high values for calcium and magnesium.

As a rule, per cent base saturation should increase with increasing pH and soil fertility.

Lab equipment

Auto analyzer

This machine automates the repetitive tasks of chemical analysis. The concentration of most elements in a soil or plant extract can be measured by reacting them with specific compounds to produce a coloured reaction product. The intensity of the colour is related to the concentration of the nutrient element.

In the auto analyzer, small samples of extracts, separated from each other by air bubbles, are drawn into fine plastic tubing. Other chemicals are introduced into the tube in proper proportions and mixed. The mixture might be heated or cooled or passed over a catalyst. The end product is passed through a photocell to measure the intensity of colour produced. A specific analysis track is necessary for each nutrient being tested, although they can often be set up in parallel, so that one set of samples can undergo two or more analyses.

These machines are commonly used in the analysis of nitrate, ammonium and phosphorus.

The auto analyzer is much faster than manual analysis but must be carefully calibrated with a range of stock solutions for accurate correlation to actual concentrations. Constant quality control is necessary.

Atomic absorption

This equipment uses a flame to break the extract down into its elements and then passes a beam of light through the flame to measure the absorption of light by those atoms. Each element absorbs light of a specific wavelength, so a light source is used with a wavelength specific for the element being tested. The concentration of the element is proportional to the amount of light absorbed. The flame temperature is important to ensure the compounds are broken down into atoms.

Because the atoms that make up the air also absorb light, this method cannot be used for elements with absorption wavelengths in the range of the elements found in air. This means that atomic absorption spectrometry cannot be used to measure nitrogen, phosphorus, sulphur or boron. This method can be used for several micronutrients (Fe, Mn, Zn, Cu, etc.) and alkaline earth elements (K, Ca, Mg).

Emission spectrometry

At very high temperatures and in strong electrical fields, atoms can become excited and emit light.

Each element emits light at specific frequencies, which can be measured by a photocell. The intensity of light emission indicates the amount of each element present.

An inductively coupled plasma spectrometer (ICP) or a direct coupled plasma spectrometer (DCP) can rapidly measure the concentration of elements in a solution. A tiny sample of soil or plant extract is simultaneously passed through a torch that produces high temperatures and through a strong magnetic field to excite the atoms. When the excited atoms return to their stable state, they emit light waves at specific wavelengths. The intensity of the emission indicates the amount of each element present.

This instrument produces accurate measurements of total elements present in the extracting solution over a relatively wide range of concentrations, but it must be carefully calibrated with stock solutions for each element.

In Ontario with the bicarbonate extractant, ICP analysis is not used due to mechanical difficulties with the solution itself.

Laser analysis
Laser-induced breakdown spectroscopy (LIBS) uses an instrument that requires no special extractants or chemicals, creates no waste, takes 3,000 readings per sample and converts total values into calibrated extractable values.

Organic materials (plant tissue and manure)

Handling and preparation

Plant tissue
Plant tissue samples may be sent to the lab in fresh condition or air dried if they cannot be shipped immediately. Samples should never be dried in an oven, since high temperatures can affect the analysis.

It is critical to avoid contamination from soil, dust or fertilizer. Ship the samples in paper bags, never plastic, to avoid condensation and mould.

At the lab, the samples are identified, logged and dried. The dry samples are ground to a particle size of 1 mm or less and stored in airtight containers until analysis.

Manure
At the lab, liquid manure samples are analyzed as they are received. Containers are mixed by inverting them several times before sampling.

In the case of solid manure, part of the sample is tested for nitrogen. The balance is dried in an oven at 100°C overnight, and then ground to pass through a 1 mm screen and stored in an airtight container until analysis. Moisture content of the manure is determined in the drying process.

Nitrogen

Kjeldahl method

Until the 1990s, nitrogen in manure was most often measured using a lab analysis test called total Kjeldahl nitrogen (TKN). TKN is an environmentally "unfriendly" method, using sulphuric acid to digest the organic material, with the help of a catalyst (usually mercury oxide, selenium or copper). Currently, Ontario labs use the Dumas combustion method and report that result as total nitrogen. Before the combustion method (Dumas) was economically available, TKN was the standard method. As a result, total N and TKN are often synonymous; however, NO_3-N is not measured in the TKN, which does make a difference on certain products such as leachates.

Combustion (Dumas) method

This method determines total nitrogen (ammoniacal, protein and nitrate sources) in organic materials. Samples are ignited in a furnace and the gases are collected. Oxygen, carbon dioxide and moisture are removed, and the nitrogen gases are determined by thermal conductivity.

In general, nitrogen determination by combustion results in slightly higher values than the conventional Kjeldahl method because the Kjeldahl method accounts only for the protein and ammoniacal sources of nitrogen.

Comments

- Uniformity of particle size and fineness is essential. A particle size of 1 mm diameter or less is recommended.
- Frequent calibration and maintenance of reagents in the instrument are crucial.

Ammonium nitrogen

Ammonium nitrogen in liquid manure can be measured using an ammonium-specific electrode. In either solid or liquid organic materials, the ammonium nitrogen can be measured by steam distillation or by extracting the ammonium with a KCl solution and measuring the concentration in the extract. Ammonium nitrogen can be lost during sample drying, so either the determination should be made on fresh samples or the sample should be acidified before drying to retain the ammonium.

Plant available nitrogen from manure or biosolids can be more accurately determined if both the ammonium and organic nitrogen are known, rather than just total nitrogen. Organic nitrogen is assumed to be the total nitrogen content minus the ammonium nitrogen. Nitrate content in raw manure samples is generally insignificant and not measured.

Calcium, phosphorus, potassium, magnesium, manganese, copper, iron, boron

The concentration of these elements is determined after oxidizing (ashing) the plant tissue and then dissolving the ash in acid. The samples are burned at 500°C for 2 hr. The acid digests are then analyzed for their nutrient contents. Some elements, such as phosphorus, potassium, boron and copper, tend to volatilize at elevated temperatures.

Regulated metals in biosolids

There are currently 11 metals that cannot exceed specified limits in a non-agricultural source material if it is going to be applied to land. These are arsenic, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, selenium and zinc. Levels of these metals are determined by dissolving the organic material in a strong acid and then analyzing the concentration of these elements in the digest. Mercury is determined using a slightly different procedure to prevent the release of toxic mercury vapour.

Seven of the regulated metals are also essential nutrients for either plants or animals. The concentrations determined in this procedure are useful indicators of the potential for buildup of these elements to harmful levels in the soil, but they are not always good indicators of availability for uptake by plants.

Other resources

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6. Organic Nutrient Sources: Manure, Biosolids, Legumes

Organic nutrient sources are materials that contain carbon and were once part of a living organism. The most commonly used organic nutrient sources on Ontario farms are livestock manure and residues from crops like forage legumes. There are also materials from municipal or industrial sources known collectively as non-agricultural source materials (NASM) that are suitable for land application (e.g., biosolids). Urea fertilizer, while it contains carbon in its chemical structure, is manufactured, and so it is not normally considered to be an organic nutrient source.

For management purposes, organic nutrient sources can be divided into two groups: land-applied materials and crop residues. The land-applied materials, such as manure, biosolids and compost, can be applied at different rates, timings and locations to meet the nutrient requirements of a particular crop in a field. In contrast, crop residues are limited to the field where they were grown. While any type of crop residue will influence the cycling of nutrients through the soil, forage legumes provide the greatest quantity of nutrients to the following crop. Cover crops may also be used to capture excess nutrients and relay them to the next crop.

> ### Organic Nutrients — Not just for organic agriculture
>
> While organic agriculture uses organic nutrient sources, these materials fit just as well in a conventional cropping system. The key in both systems is managing the organic materials to provide nutrients, in available forms, to the crop while avoiding over-application. The difference is that in conventional systems the grower has the option of making up any nutrient shortfall in the organic materials with commercial fertilizer. Organic farmers will also occasionally use supplemental nutrients but from a more restrictive list of permitted substances.

Nutrients from land-applied materials

Similarities among materials

There is a wide range of organic materials that can be used as nutrient sources but they have some characteristics in common. They all contain a mix of mineral nutrient sources and organic materials, in various proportions that depend on livestock ration, feedstock, carbon sources, amount and type of bedding or dilution materials, as well as material storage and/or treatment.

The mineral forms of nutrients in an organic material are chemically identical to the nutrients in

commercial fertilizer and are in the form that crops can take up immediately. However, nutrients in commercial fertilizers can be lost to the environment more easily than the same nutrients bound within an organic compound. In manure, for example, the nitrogen is split between organic compounds and ammonium. The ammonium nitrogen is the same chemical compound as aqua ammonia or as anhydrous ammonia that has dissolved in soil water. Ammonium is immediately available for plant uptake, but like aqua ammonia, if this material is left on the soil surface, it will vaporize into the air and be lost as ammonia. This results in a significant reduction in available nitrogen from manure that is not incorporated into the soil. The proportion of ammonium nitrogen in various organic materials is shown in Table 6–1.

Organic compounds are less subject to loss. They are not available to plants until they are mineralized (broken down to the mineral forms) by bacteria and other soil organisms or by chemical reduction. The speed at which mineralization happens depends on how easy or difficult the organic compounds are to break down, the soil conditions (temperature, moisture, aeration, pH, etc.) and the physical contact between the materials and the soil.

Whether the material is of human or animal origin matters less than how it has been managed. Each material will go through similar chemical and biological transformations in the soil.

Table 6–1. Proportion of total nitrogen present as ammonium*
(typical values expressed as % of total N, as applied to land)

Nutrient type	Ammonium-N
liquid hog	66%
liquid dairy	42%
liquid beef	43%
liquid poultry	67%
solid hog	26%
solid dairy	21%
solid beef (high bedding)	12%
solid horse	15%
solid poultry (broilers)	6%
solid poultry (layers)	46%
composted cattle manure	0.6%
municipal sewage biosolids:	
aerobic	1.6%
anaerobic	35%
dewatered	12%
lime stabilized	trace
paper mill biosolids	trace
spent mushroom compost	5%

* As the liquid concentration of the material increases, the ammonium content also increases. *Source:* NMAN3 manure database

Differences between materials

The fundamental difference between different types of manure and between manure and other organic amendments is the amount and type of dilution material added or removed and the treatment or processing of materials they are applied to land. On most livestock farms, the urine and feces are diluted with either bedding to form a solid manure or water to form a liquid. All of the resulting material is usually applied to land. Municipal sewage biosolids, on the other hand, are highly diluted when they enter the treatment plant.

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The goal of sewage treatment is to remove and clean most of the water for release into the environment. The remaining portion (a by-product of this process) is either further processed for a specific market (e.g., N-Viro) or is applied to land.

Livestock type and diet

Manure will vary between farms in form and nutrient content. Livestock species vary in the type of ration they are normally fed, with ruminants generally receiving diets that are high in forages, while monogastric (hog or poultry) diets are more concentrated. This means that ruminant manure will contain more fibre and have a lower nutrient concentration than most hog or poultry manure. Rations for young livestock are normally higher in protein and minerals than the feed for mature animals, so the nutrient content of the manure will also be higher from these animals. Changes in the ration, such as the inclusion of the enzyme phytase in the diet or amino acid balancing to reduce protein requirements, will have significant effects on the nutrient content of the manure excreted by the animal. Average macronutrient and micronutrient contents for various manure types are shown in Table 6–2.

Some manures undergo further treatment for a variety of purposes. Liquid-solid separation, for example, can be used to separate manure solids for re-use as a thin layer of bedding. Composting is an aerobic process that greatly reduces manure volume and can improve spreadability. Carbon- to-nitrogen ratios and moisture content are extremely important in composting: if the material is properly managed and cured, N is incorporated into organic compounds and there is negligible nitrate or ammonium remaining. Anaerobic digestion is a process that converts part of the organic compounds in the manure into methane gas for heating or electrical generation and leaves much of the nitrogen in the ammonium form.

Options to Reduce the Nutrient Content of Manure

- **Balance the ration properly.** Nutrients in excess of livestock requirements will simply be excreted in the manure. Phase feeding and split-sex feeding will match nutrient needs at different stages in production. A manure analysis that includes micronutrients can be useful in comparing manure nutrients to average values for a specific livestock type.
- **Minimize feed wastage.** Inspecting, adjusting and cleaning feeders regularly and using feed equipment designs that minimize spillage will reduce feed nutrients in manure.
- **Add phytase enzyme to rations** for hogs or poultry and reduce supplemental phosphorus accordingly. This enables them to digest much of the phosphorus in grains that would be otherwise unavailable and therefore bypassed to the manure.
- **Balance the amino acids in the feed** so the livestock have enough to meet their needs without feeding excess protein. This will reduce the nitrogen content of the manure.

Table 6–2. Average nutrient analyses of liquid and solid livestock manures

Data from manure analysis provided from Ontario laboratories collected between 1992 and 2018. Micronutrient data is obtained from a smaller subset of data. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

LEGEND: — = data not available   Aver. DM = average dry matter   comp. = composite

Manure type	Manure sub-type	Aver. DM (%)	Total N[1] (%)	NH₄-N (ppm)	P (%)[2]	K (%)	Ca (ppm)	Mg (ppm)	S (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)
Liquid livestock manures												
Hogs	sows (SEW)	1.7	0.24	0.18	0.06	0.11	550	275	50	60	20	10
	weaners	2.3	0.28	0.19	0.09	0.15	775	400	150	75	25	15
	finishers	4.9	0.52	0.36	0.15	0.27	1,900	1,500	700	115	50	40
	farrow to finish	3.8	0.43	0.29	0.10	0.21	1,500	650	300	100	35	25
Dairy	comp.	8.6	0.39	0.16	0.09	0.25	3,500	1,100	350	35	15	30
	thick	14.1	0.53	0.18	0.14	0.31	4,250	3,350	500	115	35	95
	fluid	4.4	0.25	0.12	0.04	0.19	2,500	700	300	100	35	30
	watery	1.1	0.12	0.06	0.02	0.11	375	150	45	45	15	5
Beef	comp.	8.6	0.37	0.15	0.08	0.23	4,000	1,850	350	50	10	50
Runoff	comp.	0.6	0.05	0.03	0.01	0.08	250	110	50	5	3	2
Mink	comp.	3.6	0.45	0.26	0.12	0.10	1,000	285	450	80	5	10
Veal (milk-fed)	comp.	1.5	0.08	0.06	0.02	0.18	—	—	—	—	—	—
Chickens	layers	9.9	0.81	0.56	0.27	0.29	15,000	850	1,500	70	10	65
	pullets	15.3	1.04	0.62	0.40	0.34	22,000	1,000	—	80	10	85
Biosolids	aerobic	2.0	0.12	0.01	0.06	0.00	—	—	—	—	—	—
	anaerobic	4.4	0.28	0.08	0.14	0.00	—	—	—	—	—	—
Solid livestock manures												
Hogs	comp.	30.8	0.93	0.29	0.49	0.57	5,000	2,050	—	160	75	150
Dairy	light bedding	21.2	0.69	0.16	0.20	0.60	7,000	2,500	1,000	90	25	90
	heavy bedding	41.0	0.82	0.11	0.21	0.66	10,000	4,500	550	50	20	90
Beef	light bedding	24.1	0.70	0.14	0.22	0.55	8,500	3,500	—	100	30	100
	medium bedding	34.5	1.03	0.20	0.37	0.74	10,000	3,200	—	140	30	110
	heavy bedding	45.6	1.34	0.25	0.54	0.87	11,500	3,000	—	150	30	120
Sheep	comp.	32.2	0.87	0.28	0.34	0.76	14,000	3,800	—	240	20	140

[1] Total N = Ammonium-N + Organic-N

[2] % P = total phosphorus

Table 6–2. Average nutrient analyses of liquid and solid livestock manures

Data from manure analysis provided from Ontario laboratories collected between 1992 and 2018. Micronutrient data is obtained from a smaller subset of data. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

LEGEND: — = data not available   Aver. DM = average dry matter   comp. = composite

Manure type	Manure sub-type	Aver. DM (%)	Total N[1] (%)	NH$_4$-N (ppm)	P (%)[2]	K (%)	Ca (ppm)	Mg (ppm)	S (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)
Solid livestock manures (continued)												
Dairy goats	comp.	35.7	1.04	0.28	0.28	1.03	15,000	1,100	—	50	20	50
Compost	cured	45.7	0.84	0.00	0.26	0.45	21,000	4,000	1,350	80	40	110
	immature	47.2	1.32	0.12	0.41	1.05	25,000	3,600	1,350	85	40	110
Veal (grain fed)	comp.	30.5	0.79	0.14	0.19	0.51	7,000	3,000	—	75	10	65
Horses	comp.	37.4	0.50	0.07	0.15	0.43	9,000	2,500	—	70	25	110
Mink	comp.	45.8	3.28	1.42	1.82	0.79	20,500	2,000	6,800	800	30	140
Chickens	layers	37.3	2.07	0.81	1.00	0.98	48,000	600	3,000	230	30	220
	pullets	42.6	3.19	0.70	1.38	1.39	—	—	—	—	—	—
	broilers	66.1	3.12	0.66	1.41	1.79	21,571	800	3,500	380	50	350
	broiler-breeder growers	62.8	1.88	0.29	1.42	1.29	—	—	—	—	—	—
	broiler-breeder layers	65.1	2.21	0.32	1.58	1.56	—	—	—	—	—	—
Turkeys	toms	52.3	2.62	0.87	1.38	1.59	12,700	2,800	—	—	—	—
	poults	70.5	3.31	0.66	0.90	1.22	—	—	—	—	—	—
	breeders	54.8	2.16	0.86	1.30	1.35	23,000	7,000	—	—	—	—
	broilers	61.8	3.35	0.60	1.21	1.42	26,000	7,000	—	500	200	530
Biosolids	comp.	32.1	3.76	0.64	1.31	0.11	—	—	—	—	—	—

[1] Total N = Ammonium-N + Organic-N
[2] % P = total phosphorus

Manure handling and treatment

The manure handling and collection system in the barn will mix the manure with various dilution materials. In solid manure systems this is the straw or wood shavings used for bedding, while in liquid systems it is water spilled from drinkers or washwater. There is tremendous variability in the amount of dilution in various systems. Typical amounts of available nutrients for various manure types and organic amendments are shown in Tables 6–2 through 6–7.

Table 6–3. Approximate amounts of available nutrients from liquid manure types (as applied) — kg/m^3

| Type of manure | Manure sub-type | Aver. dry matter (%) | Nitrogen[1] | | P$_2$O$_5$[3] | K$_2$O | Number of samples |
| | | | Fall applied[2] | Spring applied | | | |
			kg/m^3				
Hogs	sows (SEW)	1.7	0.8	1.6	0.6	1.2	327
	weaners	2.3	1.0	1.9	0.8	1.6	77
	finishers	4.9	1.8	3.3	1.4	2.9	458
	farrow to finish	3.8	1.5	2.8	0.9	2.3	119
Dairy	composite	8.6	1.2	1.8	0.8	2.7	2,449
	thick	14.1	1.6	2.1	1.3	3.3	724
	fluid	4.4	0.8	1.3	0.4	2.1	532
	watery	1.1	0.4	0.8	0.2	1.2	128
Beef	composite	8.6	1.1	1.6	0.7	2.5	154
Runoff	composite	0.7	0.2	0.3	0.1	1.0	49
Mink	composite	3.6	1.6	3.1	0.9	1.0	22
Veal (milk-fed)	composite	1.5	0.2	0.4	0.2	1.9	3
Chickens	layers	9.9	2.8	4.8	2.5	3.1	81
	pullets	15.3	3.6	5.8	3.7	3.7	11
Biosolids	aerobic	2.0	0.4	0.8	0.6	0.0	10
	anaerobic	4.4	1.0	1.7	1.3	0.0	39

[1] Useable N = amount of nitrogen available assuming material incorporated within 24 hr

[2] Assumes an application date of early October

[3] The available P$_2$O$_5$ represents half of the phosphorus contribution that is available shortly after application. The remaining phosphorus becomes available by the following year.

Data from manure analysis performed at University of Guelph, Stratford Agri-Analysis, A&L Canada Labs and Agrifood Labs between 1991 and 2018. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

Available phosphate is calculated as 40% of total phosphate in the manure. Available K$_2$O is calculated as 90% of the total K$_2$O.

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Table 6–4. Approximate amounts of available nutrients from liquid manure types (as applied) — lb/1,000 gal

| Type of manure | Manure sub-type | Aver. dry matter (%) | Nitrogen[1] | | P$_2$O$_5$[3] | K$_2$O | Number of samples |
| | | | Fall applied[2] | Spring applied | | | |
			lb/1,000 gal				
Hogs	sows (SEW)	1.7	8.4	16.3	5.5	11.9	327
	weaners	2.3	9.8	18.9	8.3	16.2	77
	finishers	4.9	18.2	33.4	13.8	29.2	458
	farrow to finish	3.8	15.1	28.2	9.2	22.7	119
Dairy	composite	8.6	11.7	18.1	8.3	27.0	2,449
	thick	14.1	15.9	20.9	12.9	33.5	724
	fluid	4.4	7.5	13.4	3.7	20.5	532
	watery	1.1	3.6	8.4	1.8	11.9	128
Beef	composite	8.6	11.1	16.3	7.4	24.8	154
Runoff	composite	0.7	1.5	2.9	0.9	9.7	49
Mink	composite	3.6	15.8	31.4	9.2	9.7	22
Veal (milk-fed)	composite	1.5	2.4	3.7	1.8	19.4	3
Chickens	layers	9.9	28.4	47.6	24.8	31.3	81
	pullets	15.3	36.4	58.5	36.8	36.7	11
Biosolids	aerobic	2.0	4.2	7.8	5.5	0.0	10
	anaerobic	4.4	9.8	17.4	12.9	0.0	39

[1] Useable N = amount of nitrogen available assuming material incorporated within 24 hours

[2] Assumes an application date of early October

[3] The available P$_2$O$_5$ represents half of the phosphorus contribution that is available shortly after application. The remaining phosphorus becomes available by the following year.

Data from manure analysis performed at University of Guelph, Stratford Agri-Analysis, A&L Canada Labs and Agrifood Labs between 1991 and 2018. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

Available phosphate is calculated as 40% of total phosphate in the manure. Available K$_2$O is calculated as 90% of the total K$_2$O.

Table 6–5. Approximate amounts of available nutrients from solid manure types (as applied) — kg/tonne

Type of manure	Manure sub-type	Aver. dry matter (%)	Nitrogen[1] Fall applied[2]	Nitrogen[1] Spring applied	P_2O_5[3]	K_2O	Number of samples
			kg/tonne				
Hogs	composite	30.8	3.7	3.6	4.5	6.2	80
Dairy	light bedding	21.2	2.1	3.0	1.8	6.5	86
	heavy bedding	41.0	2.5	1.3	1.9	7.1	278
Beef	light bedding	24.1	2.1	2.7	2.0	5.9	416
	medium bedding	34.5	3.1	4.2	3.4	8.0	203
	heavy bedding	45.6	4.0	5.3	5.0	9.4	157
Sheep	composite	32.2	2.6	2.8	3.1	8.2	73
Dairy goats	composite	35.7	3.1	3.9	2.6	11.1	45
Compost	cured	45.7	3.4	1.0	2.4	4.9	37
	immature	47.2	5.3	5.2	3.8	11.3	40
Veal (grain fed)	composite	30.5	2.4	2.6	1.7	5.5	16
Horses	composite	37.4	1.5	-1.3	1.4	4.6	41
Mink	composite	45.8	16.4	21.8	16.7	8.5	104
Chickens	layers	37.3	10.4	12.6	9.2	10.6	224
	pullets	42.6	16.0	23.2	12.7	15.0	78
	broilers	66.1	15.6	18.8	13.0	19.3	193
	broiler-breeder growers	62.8	9.4	7.8	13.1	13.9	26
	broiler-breeder layers	65.1	11.1	10.7	14.5	16.8	74
Turkeys	toms	52.3	13.1	15.5	12.7	17.2	33
	poults	70.5	16.6	20.0	8.3	13.2	2
	breeders	54.8	10.8	10.5	12.0	14.6	12
	broilers	61.8	16.8	21.9	11.1	15.3	6
Biosolids	composite	32.1	15.0	30.8	12.1	1.2	89

[1] Useable N = amount of nitrogen available assuming material incorporated within 24 hr

[2] Assumes an application date of early October

[3] The available P_2O_5 represents half of the phosphorus contribution that is available shortly after application. The remaining phosphorus becomes available by the following year.

Data from manure analysis performed at University of Guelph, Stratford Agri-Analysis, A&L Canada Labs and Agrifood Labs between 1991 and 2018. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

Available phosphate is calculated as 40% of total phosphate in the manure. Available K_2O is calculated as 90% of the total K_2O.

Table 6–6. Approximate amounts of available nutrients from solid manure types (as applied) — lb/ton

Type of manure	Manure sub-type	Aver. dry matter (%)	Nitrogen[1] Fall applied[2]	Nitrogen[1] Spring applied	P_2O_5[3]	K_2O	Number of samples
			lb/ton				
Hogs	composite	30.8	7.4	7.1	9.0	12.3	80
Dairy	light bedding	21.2	4.1	6.1	3.7	13.0	86
	heavy bedding	41.0	4.9	2.5	3.9	14.3	278
Beef	light bedding	24.1	4.2	5.5	4.0	11.9	416
	medium bedding	34.5	6.2	8.4	6.8	16.0	203
	heavy bedding	45.6	8.0	10.7	9.9	18.8	157
Sheep	composite	32.2	5.2	5.5	6.3	16.4	73
Dairy goats	composite	35.7	6.2	7.8	5.2	22.2	45
Compost	cured	45.7	6.7	1.9	4.8	9.7	37
	immature	47.2	10.6	10.4	7.5	22.7	40
Veal (grain fed)	composite	30.5	4.7	5.2	3.5	11.0	16
Horses	composite	37.4	3.0	-2.5	2.8	9.3	41
Mink	composite	45.8	32.8	43.6	33.5	17.1	104
Chickens	layers	37.3	20.7	25.2	18.4	21.2	224
	pullets	42.6	31.9	46.4	25.4	30.0	78
	broilers	66.1	31.2	37.6	25.9	38.7	193
	broiler-breeder growers	62.8	18.8	15.7	26.1	27.9	26
	broiler-breeder layers	65.1	22.1	21.4	29.1	33.7	74
Turkeys	toms	52.3	26.2	31.0	25.4	34.3	33
	poults	70.5	33.1	40.0	16.6	26.4	2
	breeders	54.8	21.6	21.1	23.9	29.2	12
	broilers	61.8	33.5	43.9	22.3	30.7	6
Biosolids	composite	32.1	30.1	61.5	24.1	2.4	89

[1] Useable N = amount of nitrogen available assuming material incorporated within 24 hr

[2] Assumes an application date of early October

[3] The available P_2O_5 represents half of the phosphorus contribution that is available shortly after application. The remaining phosphorus becomes available by the following year.

Data from manure analysis performed at University of Guelph, Stratford Agri-Analysis, A&L Canada Labs and Agrifood Labs between 1991 and 2018. Micronutrient concentration is highly dependent on animal diet, so will vary widely between farms. An actual analysis is the best source of information.

Available phosphate is calculated as 40% of total phosphate in the manure. Available K_2O is calculated as 90% of the total K_2O.

Table 6–7. Typical nutrient contents of municipal organic amendments (dry weight)

LEGEND: — = data not available

Type of amendment	Material	Aver. dry matter (%)	Total Nitrogen (%)	NH_4-N (%)	Usable N in year applied (%)	Available P_2O_5 (%)	Available K_2O (%)
				Dry matter basis			
Municipal sewage biosolids	aerobic	1.7	5.0	0.01–0.75	0.08	2.5	>0.01
	anaerobic	3.0	6.4	0.33–3.4	2.7	3.3	>0.01
	dewatered	26	3.6	0.35–0.65	1.0	2.5	>0.01
	pelletized	—	—	trace	0.8	4.5	>0.01
Paper mill biosolids	primary	50	0.3	trace	0.1	trace	trace
	primary + secondary	32.8	2.5	—	1.4	.08	0.02
Distillers grains	dried	90	5.0	0.5	3.0	1.5	1.2
Other organic amendments	anaerobic digestate	3	5–10	7.0	8.3	3.3	3.7
	leaf-yard waste compost	60	1.6	trace	0.5	0.6	1.0
	food-waste compost	70	3.3	0.1–0.4	1.1–1.4	1.5	1.9
	spent mushroom compost	35	2.1	trace	0.63	0.75	1.25
Processed biosolids	biosolids pellets	92	4.7	0.13	1.1–1.6	4.2	0.2
	LysteGro	12–15	5.6	2.9	0.35	5.25	2.25
	N-Viro	75	0.74	0.03	0.75	1.0	4.25

The quality and nutrient content of non-agricultural source materials is unique and must be determined on a case-by-case basis. Generators are required to sample and analyze these materials on a regular basis. This information should be used to determine accurate application rates for crop fertility requirements.

Biosolids

Sewage biosolids enter the treatment plant as an extremely dilute liquid material, since water is used as the carrier to transport these materials to the plant. Prior to nutrient management planning requirements for land application of biosolids, the sewage biosolids could contain significant quantities of contaminants if the system collected wastewater from industrial as well as domestic sources. Sewer use bylaws in most communities have now restricted these contaminants to very low concentrations so the biosolids produced by the plant meet the criteria for a non-agricultural source material (NASM) plan.

During the treatment process, the solids are concentrated and the phosphates are precipitated out of the water in insoluble forms, while most of the potassium remains in solution and is not retained. The biosolids at the end of the process contain both organic and ammonium nitrogen, plus a significant amount of phosphorus. The availability of this phosphorus to plants may vary depending on the specific treatment process used. These biosolids may undergo further treatment before land application, which can significantly alter the quantity and availability of the nutrients.

Additional non-agricultural source materials

Other materials from industrial or municipal sources may be suitable for land application. These can vary widely depending on the source of the material and the treatment to which it has been subject. Paper mill biosolids are primarily carbon compounds, with relatively low amounts of nutrients. Leaf-yard waste composts will vary widely in nitrogen, phosphorus and potassium contents, depending on the source of the feedstock material. These materials need to be assessed on a case-by-case basis if they are to be used as a nutrient source. Typical values for some non-agricultural source materials are shown in Table 6–7.

The physical and chemical characteristics of the various manure types and biosolids overlap. This means that the management to optimize the use of the nutrients from these materials will be the same and will depend more on the characteristic of the individual material rather than the source. However, non-agricultural source materials (NASM) are subject to additional rules intended to ensure that their application is done in a way that benefits crop production.

Factors affecting nutrient availability to the crop

Nitrogen

Crops take up nitrogen in its mineral forms, as either nitrate (NO_3^-) or ammonium (NH_4^+). This means the ammonium portion of the manure is immediately available to the crop while the organic nitrogen needs to be mineralized before it can be used. For optimum use of the nutrients in manure, they should be available where and when the crop can utilize

them. It is not always easy — or even possible — to meet this goal, however, with current manure management options.

Ammonia volatilization

Ammonium nitrogen can easily convert to ammonia gas when manure is exposed to the air, resulting in the loss of a large part of the available N from the manure. Conditions that favour rapid loss of ammonium-N from the surface of the soil include: a high concentration of ammonium in the manure, a high pH in the manure, warm temperatures, dry soils and windy conditions. Crop canopy or residue has an inconsistent effect on ammonia volatilization. It can reduce the amount of loss from manure placed below the cover but can actually increase loss from manure spread on top of the canopy because of increased surface area. Incorporation of the manure effectively stops ammonia volatilization, since any ammonia that is released is quickly re-absorbed in the soil water and adsorbed on the surfaces of clay particles.

Mineralization

The organic nitrogen in manure needs to be converted to ammonium before it is available for plant uptake. This happens when microbes feed on the organic compounds and release ammonium as a waste product. The rate of mineralization increases when conditions are favourable for microbial activity. The nature of the organic materials in the manure will also affect the rate of mineralization.

Solid manure applied in late summer or early fall will have a higher rate of mineralized nitrogen available for the following crop compared to the same manure applied in spring. With spring-applied manure, about 20% of the organic N from ruminant manure is considered to be available in the first cropping season after application, while up to 30% of the organic N from poultry manure is available.

Mineralization will be slow when soil conditions are cool. This can lead to temporary nitrogen deficiency during cool spring weather in crops that are planted on manured fields. A starter application of nitrogen can help to overcome this.

Immobilization

When materials high in carbon (such as manure with a high volume of straw, or primary papermill biosolids) are added to the soil, soil nitrogen can be immobilized by microbes while they break down the carbon compounds (see *Carbon-to-Nitrogen (C:N) Ratio*, below, and Table 6–8). This can reduce the nitrogen availability to crops if these materials are applied before planting. There is potential for using these materials to tie up soil nitrogen in the fall, to reduce leaching losses over winter, but the effectiveness has not been proven.

Carbon-to-Nitrogen (C:N) ratio

The C:N ratio is the balance between the amount of carbon in an organic material and the amount of nitrogen. The carbon is a constituent of organic compounds like cellulose, lignin and protein, which are food sources for soil micro-organisms. As the micro-organisms multiply to take advantage of increased food supply, they also need nitrogen. If there isn't enough N in the organic material, they will absorb nitrogen out of the soil to meet their needs. This immobilized N will be released after the extra carbon is used up and the microbial population starts to die off.

As a rule of thumb, mineralization occurs if the C:N ratio of the organic material is less than 25:1, while immobilization occurs if the C:N ratio is greater than 25:1. Additionally, the balance between mineralization and immobilization will depend on temperature and moisture conditions, as well as the nature of the organic material.

Table 6–8. Typical C:N ratios of some common materials

Material	C:N Ratio
soil micro-organisms	7–9:1
soil organic matter	10–12:1
alfalfa	13:1
fall rye:	
vegetative	14:1
flowering	20:1
mature	80:1
cereal straw	80:1
corn stalks	60:1
sawdust	200–400:1
paper mill biosolids:	
primary	80–100:1
secondary	7–10:1
distillers grains	9:1
solid cattle manure	15–30:1
solid poultry manure	5–10:1
composted manure	10–40:1
yard waste compost	15–40:1
spent mushroom compost	15–30:1

Phosphorus

Forms in manure

Most of the phosphorus in manure is associated with the solid portion and is found in either in the orthophosphate form (PO_4^{3-}) or in readily degraded organic compounds. This means that, chemically, the phosphorus in manure does not differ greatly from the phosphorus in fertilizer. The proportion of various forms of P are determined by livestock species, age, ration and bedding type and by manure storage method. In Ontario, the availability of manure P ranges from 40%–80% to that of fertilizer P. However, temperature, soil moisture and soil

pH affect the P mineralization rate such that only 40% of the manure P is assumed to be available in the year of application.

A portion of the inorganic phosphorus in manure is water soluble, which makes it mobile and susceptible to runoff with surface water. This portion is measured as wet extractible phosphorus (WEP) and will vary with diet. It may also be related to the amount of phytase enzyme in the livestock digestive system. Cattle produce sufficient phytase naturally, while hogs and poultry produce very little and may have the enzyme added to the diet.

Greenhouse studies have shown that equal amounts of phosphorus from either liquid hog manure or fertilizer, when mixed evenly with the soil, result in equal plant uptake. The difference in apparent availability of the phosphorus could stem from the inability to place the manure in a band close to the seed for maximum availability and from uneven application rates across the field.

Contribution to soil test levels

Regular soil testing is the best method to track the buildup of soil phosphorus in individual fields. Nutrient management plans in Ontario credit 80% of the total P in the manure towards building soil fertility. The remaining 20% is assumed to be tied to soil particles or moved off the field with surface runoff or soil erosion.

Treatments to reduce phosphorus availability

Many municipal biosolids are treated with alum, iron sulphate or lime during the secondary treatment process to remove phosphate from the discharge water. A similar treatment is used in some poultry barns. This causes a high proportion of the P to be tied up in insoluble aluminum, iron or calcium phosphates, which can greatly reduce the nutrient availability from these materials in both the short and long term. Tissue analysis at plant pollination will indicate nutrient uptake in plants where these materials are utilized.

Potassium

Most of the potassium in manure is associated with the liquid portion, and essentially all of the potassium in manure is in soluble forms and available to crops. With solid manure, losses can occur from storage if runoff is not contained. In the past, high rates of manure application on dairy farms resulted in luxury consumption of K by alfalfa and mineral imbalances for dry cows in the dairy ration. In recent years, however, K levels in many forage fields have been declining to levels where winter survival could be impacted. Sewage biosolids contain very little potassium, since it is not retained with the solids during the treatment process.

Phosphorus and potassium content of manure varies significantly from farm to farm. The best estimates come from lab analysis.

Secondary and micronutrients

In addition to N, P, K and organic matter, manure contains significant quantities of calcium, magnesium, elemental sulphur and micronutrients. Deficiencies of these elements are uncommon on farms that regularly apply livestock manure.

Greenhouse nutrient feedwater and non-agricultural source materials (NASM), including sewage biosolids, also contain micronutrients. The levels will often depend on the type of facility and/or the mix of residential, institutional and industrial contributors to the system. Trace elements (heavy metals including arsenic, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, selenium and zinc) and some of the micronutrients and sodium are regulated under the *Nutrient Management Act*. The levels of these elements are limited in biosolids, and if the guidelines are exceeded, the material cannot be used for land application. Most manure types are low in these elements, unless they have been added to feed to reduce antibiotic use (e.g., copper or zinc). The rate or frequency of manure application may need to be limited for these specific manures.

Predicting available nutrients from land applied materials

Optimizing the use of nutrients in organic materials depends on knowing how much nutrient is in the material being applied and what proportion of that will be available to the crop. Since most nutrient response calibrations have been done with mineral fertilizers, the availability of nutrients from organic sources is often expressed relative to fertilizer.

Tables that provide average nutrient values for various types of manure and biosolids, such as those in this chapter, are good planning tools. Given the variability among nutrient sources, however, analysis of the material will give better information if the sample collected is representative of the material to be land applied.

Interpreting manure analyses

Results from a manure analysis must be read carefully, since there can be wide variation in how the results are expressed. The analytical results may be expressed as a percentage of the dry matter in the manure or as a percentage of the fresh (wet) weight. Furthermore, the results may have been converted into a fertilizer replacement value, based on information provided when the sample was submitted.

The sidebar below gives the formulas for calculating the available phosphorus and potassium and the conversions from percentages to the commonly used units of weight.

Calculating available phosphorus and potassium from manure

Total P to available P$_2$O$_5$

% P x 2.29 = % total P$_2$O$_5$

% total P$_2$O$_5$ x 0.40 = % available P$_2$O$_5$ in application year

% total P$_2$O$_5$ x 0.80 = % available P$_2$O$_5$ for soil buildup

Total K to available K$_2$O

% K x 1.20 = % total K$_2$O

% total K$_2$O x 0.90 = % available K$_2$O

Most labs in Ontario report the amount of available P$_2$O$_5$ and K$_2$O from manure, but occasionally you see a sample reported as %P and %K. If this occurs, you will have to convert the figures to match the units of the fertilizer recommendation.

Conversion from per cent to units of weight

% available nutrient to unit of weight

% available nutrient x 10 = kg/t

% available nutrient x 20 = lb/ton

% available nutrient x 10 = kg/1,000 L = kg/m^3

% available nutrient x 100 = lb/1,000 gal (Imperial)

Total N vs. ammonium vs. organic N

In most organic materials, nitrogen exists in ammonium and organic forms, so the total N is the sum of these two quantities. Measurements made in the lab are actually of total N and ammonium N, and the organic N is determined by subtraction.

Greenhouse nutrient feedwater and some composted materials may contain a significant amount of nitrate-N. Check with the lab that the compost analysis package includes all aspects relevant to nitrogen availability: nitrate, ammonium and total N, as well as C:N ratio.

Estimates of available N from manure can be made as a proportion of the total N, which assumes that both the manure and the application management are "average." This is a good general tool for planning the distribution of manure among different fields. More precise estimates of available N from manure can be made following application when the precise timing, weather conditions at and after application and the time before incorporation is known. Using the actual split between ammonium and organic N from the manure analysis can also make more precise estimates.

Impact of application timing and method

Application timing and method has the greatest impact on nitrogen availability, and much less on phosphorus or potassium. Manure sources should not provide more than two-thirds to three-quarters of the nitrogen needs for a corn crop in order to avoid over-application of phosphorus and to ensure N availability to the crop when mineralization is slow or delayed in cool conditions. Because there are varying proportions of mineral and organic N in organic materials, the impact of application timing and method is not the same for all materials. Figure 6–1 shows pathways and relative quantities of uptake and loss, depending on manure source and application timing and method.

Ammonia volatilization results in an immediate loss of available N. The amount lost varies with the time between application and incorporation and the conditions at the time of application. Ammonium N that is retained in the soil can still be lost following conversion to nitrate, either through leaching or denitrification. Organic materials that are high in ammonium nitrogen will provide the greatest amount of N to the crop when they are applied as close to the time of N uptake by the crop as possible.

N from manure is in both mineral and organic forms, in varying proportions. Some of the N is lost to the air or water, some remains in the organic form and the balance is available to be taken up by crops (see Figure 6–1).

Organic N is not available to the crop until it has mineralized to ammonium. This process proceeds slowly when soils are cold. Materials that are predominantly organic N (e.g., solid beef or dairy manure) will show much less difference in N availability between spring and fall application, since the loss of the mineral N is balanced by greater availability of the organic portion. Where solid manure with high organic N and very low ammonium N are applied in late summer (e.g., after cereal grain harvest), the N available to the following crop is maximized. If the same materials are applied in early spring and incorporated, the ammonium N is retained and time is provided for mineralization to occur, but often not in time to meet the N needs of grain corn. A similar benefit could be gained from a late fall application of this material, as it is applied to soils that are already cold enough to inhibit nitrification. The difficulty with this approach is the variability of fall and winter weather conditions.

Due to the higher proportion of ammonium relative to organic N in liquid manure, fall application results in greater losses, including through leaching, than spring application. Surface application elevates the amount of ammonium N lost through volatilization. Spring injection of liquid manure maximizes the nitrogen available for plant uptake, as it more closely matches the period of crop demand and minimizes the risk of N loss to volatilization and leaching (Figure 6–1).
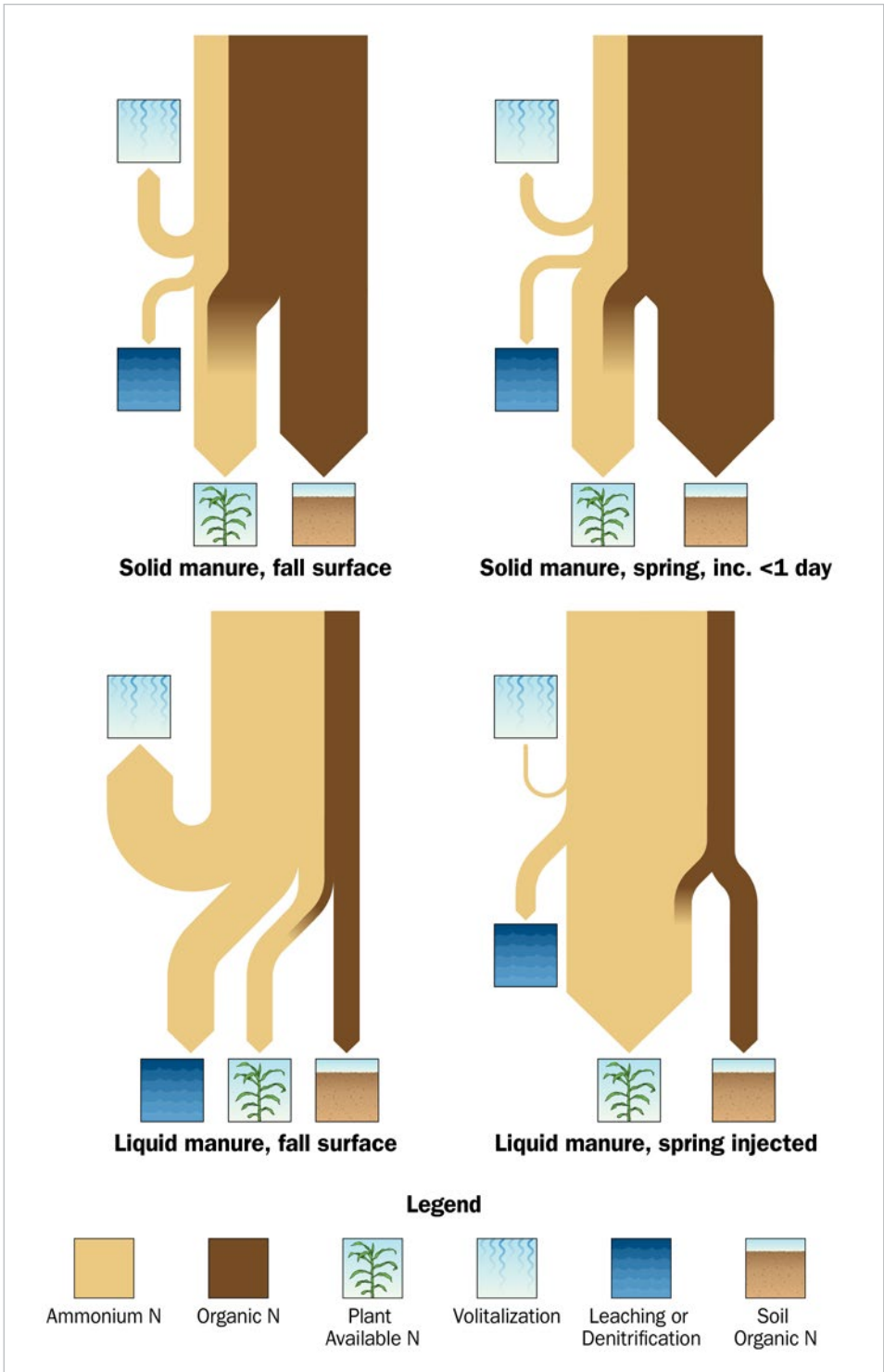
Figure 6–1. Impact of manure type and application method on fate of manure nitrogen

Solid manure, fall surface

Solid manure, spring, inc. <1 day

Liquid manure, fall surface

Liquid manure, spring injected

Legend

Ammonium N   Organic N   Plant Available N   Volitalization   Leaching or Denitrification   Soil Organic N

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Impact of treatment systems — composting, anaerobic digestion, etc.

Treatment systems change the form of the nitrogen in the material and can also significantly reduce the nitrogen content of the material. Sampling and analysis are critical to knowing what value to place in a treated material and how best to manage it.

Composting is an aerobic process that seeks to convert most of the nitrogen in the material to an organic form. This is accomplished by adding materials with a high C:N ratio to manure or biosolids and then providing conditions that encourage microbial growth. In a properly managed composting system, most of the nitrogen is taken up by the microbes as they consume the high-carbon material. In improperly managed compost, up to half of the total N can be lost through volatilization. Not all of the nitrogen is bound in organic forms in finished compost. Because of the aerobic conditions, the mineral N that remains is primarily in the nitrate form. Composts can be surface applied with negligible loss of N through volatilization, but the availability of the organic N depends on conditions that favour mineralization.

Anaerobic digestion is used to reduce odours and pathogens in organic materials, as well as to produce methane gas that can be used for heating or electricity generation. The end product has lost much of the readily degraded organic material and has a greater proportion of the N in the ammonium form than the original material did. This increases the immediate availability of the N from the digested material, but it should be incorporated quickly. Volatilization losses from surface application of this material will generally be greater than from undigested materials.

Calculating plant-available nitrogen (PAN) from organic sources

For general planning, nitrogen availability from organic materials can be estimated from table values. For fine-tuning fertilizer application rates, however, a more precise estimate is desirable. This involves estimating the retention of ammonium N in the manure, mineralization from the organic N pool, and losses from the soil between manure application and crop uptake. See below for an example of how to calculate plant available nitrogen from an organic nutrient source.

Calculating total nitrogen (TN)

Total N	= Organic N	+ Ammonium N (NH_4-N)	+ Nitrate-N (NO_3-N)
	= $(TN - NH_4 - NO_3)$	+ NH_4-N	+ NO_3-N

Calculating plant-available nitrogen (PAN)

PAN	= **(TN − NH$_4$ − NO$_3$)**	+ **NH$_4$-N**	+ **NO$_3$-N**
	× availability factor	**× availability factor**	**x availability factor**

PAN spring	= $(TN - NH_4 - NO_3)$	+ NH_4-N	+ NO_3-N
	× Table A	× Table B	× Table C

PAN fall	= $(TN - NO_3)$		+ NO_3-N
	× Table C		× Table D

Table A: Estimated percentage of organic nitrogen available in year of application (as applied)

% Organic N = % Total N - % NH_4-N
(ppm NH_4-N/10,000 = % NH_4-N)

Liquid	Solid
[% organic N – (% DM ÷ 50.93)]	[% organic N – (% DM ÷ 61.44)]
x 100 = lb/1,000 gal x 10 = kg/1,000 L or kg/m³	x 20 = lb/ton x 10 = kg/tonne
Example: Liquid Dairy Manure	**Example:** Solid Broiler Manure
(4.5% DM, 0.25% Total N, 0.12% NH_4-N, 0.04% P, 0.19% K)	(70% DM, 3.12% Total N, 0.6% NH_4-N, 1.4% P, 1.8% K)
Available Organic N = [(0.25 – 0.12) – (4.5 ÷ 50.93)] = (0.13 – 0.09) = 0.04%	Available Organic N = [(3.12 – 0.6) – (70 ÷ 61.44)] = (2.52 – 1.14) = 1.38%
0.04% x 100 = 4 lb/1,000 gal 0.04% x 10 = 0.4 kg/m³	1.38% x 20 = 27.6 lb/ton 1.38% x 10 = 13.8 kg/T

Adapted (K. Reid) from J. Lauzon & K. Janovicek, University of Guelph, 2013. The table is based on an evaluation of data from 180 field sites that measured crop yield response to manure.

Logic behind equations: Available manure organic N = organic N x (carbon content of manure x carbon retained by soil life x C:N ratio of soil life) x conversion factor (% to lb per ton or per 1,000 gal)

Assumptions:
· Organic N (%) = Total N (%) – Ammonium N (%)
· Average carbon content of manure is 42% of manure dry matter
· Retained carbon is 37.4% for liquid manure and 31% for solid manure
· The C:N ratio of soil life is 8:1

Table B: Estimated proportion of ammonium nitrogen from manure retained in year of application (spring applied)

		Incorporated					Not incorporated		
	Injected (covered)	1 day	2 days	3 days	4 days	5 days	Bare soil	Residue	Standing crop (below canopy)
average (factor)	1.00	0.75	0.60	0.50	0.45	0.40	0.35	0.50	0.66
cool (<10°C)	1.00	0.85	0.70	0.60	0.55	0.50	0.45	0.66	0.75
warm (>25°C)	1.00	0.65	0.50	0.40	0.35	0.30	0.20	0.35	0.55

Adapted from J. Lauzon & K. Janovicek, University of Guelph, 2013. The table is based on an evaluation of data from 180 field sites that measured crop yield response to manure.

Table C: Estimate of available nitrogen from manure applied in late summer or fall, as a proportion (factor) of total N applied

		Available nitrogen [1,2]				
		incorporated (<24 hr)			not incorporated	
Manure form	Type of manure	Late summer	Early fall	Late fall	Early fall	Late fall
solid	solid cattle/sheep/horse	0.21	0.31	0.34	0.21	0.21
	solid swine/compost[3]	0.30	0.40	0.45	0.40	0.45
	solid poultry/mink	0.41	0.53	0.61	0.37	0.32
liquid	liquid cattle	0.25	0.27	0.31	0.24	0.24
	liquid swine	0.22	0.38	0.47	0.25	0.25
	liquid poultry/mink[3]	0.26	0.33	0.51	0.26	0.39
	liquid biosolids	0.33	0.37	0.42	0.34	0.36

Available N in manure = Total N (from analysis) x available N (factor from Table)

[1] Assumes a spring-planted full-season crop (e.g., corn).

[2] Accounts for ammonia loss to atmosphere and mineralization of organic N.

[3] These coefficients are based on assumed N availability given the characteristics of each manure type, since there are no direct measurements of N availability for these materials.

Adapted from J. Lauzon & K. Janovicek, University of Guelph, 2013. The table is based on an evaluation of data from 180 field sites that measured crop yield response to manure.

Table D: Estimated percentage of nitrate-nitrogen available in year of application (all seasons)

LEGEND: Late summer = up to Sept 20, Early fall = Sept 21 to Nov 9, Late fall = Nov 10 to winter

	Incorporated (within 24 hr)					Not incorporated				
								Pre-plant[1]		
	Late summer	Early fall	Late fall	Pre-plant[1]	Side-dress[1]	Late summer/ early fall	Late fall	Bare soil	Residue	Side-dress
Nitrate-N retention	0.1	0.2	0.5	0.95	1.0	0.1	0.40	0.85	0.75	0.85

Source: Adapted from Barry, Beauchamp et. al., University of Guelph, 2000

[1] Assumes a spring-planted crop; side-dress refers to application to a growing crop.

Available nitrogen from previous manure applications

Most of the available (mineral) nitrogen in manure is used by the crop or is lost during the first season following application. The remaining organic nitrogen becomes available in small, diminishing quantities in the succeeding years. This availability is most often assumed to be 10% of the organic N applied 1 year ago, 5% from 2 years ago and 2% from 3 years ago. This is not normally enough to make a practical difference in nitrogen recommendations from a single application of manure. However, where solid manure is applied regularly to the same field, there can be significant residual nitrogen.

Calibrating application equipment

Calibrating manure application equipment is essential to ensure both the accuracy of the rate applied and uniformity of application. Several methods can be used to measure spreading rates.

For solid materials:

- Method A: Use a spreader with a load cell or weigh a load and measure the area it covers.
- Method B: Spread a metre-square plastic bag on the ground and spread solid manure on it as you would on the field. Weigh the manure (minus the weight of the plastic) and find the equivalent in Table 6–9.

To determine uniformity of application, weigh manure as described above in several areas of the field. Side-by-side application and beginning versus end of load applications often have different volumes, as do areas of overlapping application.

Table 6–9. Solid manure application calibration using 1 m x 1 m (40 in. x 40 in.) sheet

Weight/sheet		Application rate	
kg	lb	t/ha	tons/acre
0.5	1	3.6	1.6
1	2	7.2	3.2
1.5	3	10.8	4.8
2	4	14.3	6.4
2.5	5	17.9	8.0
3	7	25.1	11.2
5	10	35.8	16.0
7.5	15	53.8	24.0

Estimating the rate of solid manure applied by spreader volume is not recommended due to the variation in manure bulk density (see Table 6–10, *Densities of manure*) and in how high the spreader is heaped.

Table 6–10. Densities of manure

Type of Manure	kg/m³	lb/ft³	lb/bu
Liquid	1,000	62.4	80
Semi-solid	960	60	76
Thick solid	800	50	64
Light solid	560	35	45

For liquid materials:

The use of flow meters and GPS equipment aids in calibration and recordkeeping of manure application rates. Where this equipment is not available, the application rate can be determined from the volume of the tanker divided by the area covered by one tanker-load.

The area covered by a tanker-load of manure can be calculated two ways:

- Method A: from the width of spread, the speed of travel and the time it takes to empty the tanker.
- Method B: by placing a series of straight-walled containers (e.g., pails) on the ground you intend to cover. Spread the manure, and then measure the depth of manure in the container and determine the application rate from Table 6–11.

For both solid and liquid materials, take overlap into account, particularly for low dry matter material or greenhouse nutrient feed water irrigation systems.

Table 6–11. Liquid manure application calibration using a straight-walled pail

Depth of manure		Application rate	
mm	in.	L/ha	gal/acre
2.5	⅒	25,000	2,265
3.1	⅛	31,000	2,825
6.3	¼	63,000	5,650
9.4	⅜	94,000	8,500
12.5	½	125,000	11,325
15.6	⅝	156,000	14,150
18.8	¾	188,000	17,000
25	1	250,000	22,650

Nutrient management planning

Nutrient management planning is simply matching the needs of the crop and the nutrients already in the soil with the nutrients available from manure or other organic sources, and then balancing any deficits with mineral fertilizer. Many jurisdictions, including Ontario, have legal requirements for nutrient management planning. Although it is a regulatory requirement on some farms, in reality every farm can benefit from planning to optimize their nutrient use.

Whole-farm nutrient balances: Where does Ontario fit?

Some critics imply that intensification of agriculture will inevitably lead to excesses of nutrients and over-application of manure. For justification, they point to areas like North Carolina and Delaware, where regions within these states have expanded livestock and poultry production beyond the capacity of the land base to absorb nutrients. The result has been significant degradation of the surface and groundwater quality in these regions, as well as complaints about odour and poor air quality.

The situation in Ontario is much different. In 2002, the State of Delaware had almost 1 nutrient unit /ha, averaged over all the cropland in the state, while North Carolina had 1.25 nutrient units/ha. In contrast, in the 2001 Census of Agriculture, the province of Ontario had 0.65 nutrient units per hectare. (The figure for all of Canada was 0.43 nutrient units/ha.) A nutrient unit is the number of livestock that produce the lesser of 43 kg of nitrogen or 55 kg of phosphate (fertilizer replacement value), and it is used to compare different livestock on an equal nutrient basis.

It is certain that there are some small areas of nutrient excess, but the problem is one of distribution rather than over-supply.

Challenges with different livestock intensities

Livestock farms can be roughly divided into three classes, based on the intensity of their production. Each class has very different challenges in nutrient management.

The members of the first group are highly intensive, with a significant portion of the livestock diet coming from feed purchased rather than grown on-farm. This results in a surplus of nutrients coming onto the farm over what is sold as meat, eggs and milk. These farms are faced with the challenge of exporting manure to other farms or having a buildup of nutrients in their soils from over-application of manure.

The second group represents farms where the nutrient inputs to the farm in feed and fertilizer are close to balanced with the exports in meat, eggs and milk. Most of the feed is grown on-farm, and the manure is returned back to that land base. The challenge on this farm is distributing the manure properly among the available fields. Mineral fertilizers will still need to be used on most of these farms to balance the nutrients supplied by manure.

The third group has very low livestock intensities and does not generate nearly enough manure to meet the requirements for crop production. If these farms do not apply nutrients in the form of mineral fertilizers or import organic nutrient sources such as compost or biosolids, productivity will gradually decline as nutrients are exported off the farm.

Optimizing manure as a nutrient source

The value of manure as a fertilizer has been limited by uncertainty about the quantity of nutrients in the manure, the availability of these nutrients and the amount that is actually applied to the field. Following a systems approach to manure utilization can remove much of this uncertainty.

Manure application should aim to supply up to about three-quarters of the nitrogen requirements of the crop. During application, samples should be collected for analysis, and records should be kept of actual application rates, time to incorporation and weather conditions at application. This will allow a more accurate estimate of the nutrients available from the manure, and any deficits can be supplied with an application of mineral fertilizer.

Crops that benefit

Grain corn is a common recipient of manure because it has a high demand for nitrogen and is often grown as a feed crop on livestock farms. Using manure to supply all the nitrogen required by a corn crop, however, provides more phosphorus and potassium than the crop removes from the soil. Over the years, the concentrations of these two nutrients in the soil can become excessively high.

This buildup can be alleviated. Grain corn can be rotated with other crops that use large quantities of phosphorus and potassium, such as alfalfa. Or, the manure application rates

can be reduced to two-thirds or three-quarters of the nitrogen requirements and the balance supplied as nitrogen fertilizer. This brings the additions of phosphorus and potassium more into line with the amount removed by the crop.

For summer application to standing crops such as corn or forages, rates should be kept below 40 m³/ha (4,000 gal/acre) and less for highly concentrated manures. Application to forages should be done as soon as possible after harvest to avoid tire tramping damage and nitrogen burn (from ammonia) to new leaf growth.

Older forage stands with higher grass content benefit most from the manure nitrogen.

Manure applications to cereal crops, spring grains or soybeans should be done with caution, since too high a rate will increase the incidence of lodging.

No-till and manure

Manure is still one of the factors that makes livestock farmers think twice about no-till. Farmers who have to deal with manure but also engage in a no-till cropping system have to compromise — some tillage or some loss of nutrients from manure.

Crop rotation is important in no-till and reduced tillage systems. The most popular options are as follows:

- **Apply manure to wheat fields after harvest and follow with shallow tillage.** This allows faster breakdown of the wheat residue and alleviates risk of allelopathic interference for the planned corn crop while minimizing soil disturbance and reducing risk of compaction. This system also makes good use of manure nutrients, especially if combined with a fall cover crop. On sandy soils prone to leaching, application rates should reflect the quantity and type of nitrogen being applied. In most cases, solid manure containing a higher percentage of organic nitrogen will have less risk of loss through leaching.

- **Use manure on forages.** Although not the most economic use of manure nitrogen, legume forages require the phosphorus and potassium. Grassy forages will make more efficient use of nitrogen and also benefit from the P and K.

- **Use a strip-till system** where manure can be applied and incorporated into 15–20 cm (6–8 in.) deep strips during fall or spring. Using a guidance system, a crop can be planted into the same strip. Nutrients are placed near where the crop can utilize them, and the area between the strips remains un-tilled with full residue cover.

- **Side-dress liquid manure into a standing corn crop by injection.** The manure reaches the crop when the nutrients are most needed, and the risk of compaction is often lower. The biggest drawback is the time requirement. Injector design must be considered to minimize the risk of plant damage and reduced plant populations.

Environmental concerns

Using manure or other organic nutrient sources for crop nutrient needs is better for the environment. As with any nutrient source, however, using too much or not applying it carefully can cause harm from contaminated streams, runoff and leaching.

Avoid spreading manure in winter on frozen or snow-covered soils or in early spring when soils are saturated, due to the potential for runoff to surface water. Frozen soils cannot absorb the nutrients that are applied, and there are no growing crops to utilize them. Apply manure during dry, mild periods when applied manure can be immediately incorporated. Application on fields with growing crops or high residue that are far from surface water are also options for the situations where winter spreading may be necessary. Manure should not be spread adjacent to surface water. A vegetated buffer will help to trap material that runs off the field and help keep it out of streams and lakes.

Rain can cause organic nitrogen to wash into streams if manure has been applied to unprotected cropland. Phosphorus can be carried to streams either as dissolved reactive phosphorus carried in surface water or phosphorus attached to soil particles. Minimizing runoff from fields that receive manure will reduce the risk of nutrients and harmful pathogens reaching streams and waterways.

Flow into tile drains can become contaminated if manure enters a catch basin. With liquid manure, a 9-m (30-ft) buffer should be maintained around a catch basin or surface inlet while a 4.5-m (15-ft) buffer is suggested with solid manure. Another option is to block the tile run during and after spreading. All tile inlets should be regarded as direct connections to surface water and managed accordingly.

Flow can also become contaminated if manure travels through soil cracks and macropores to the tiles (see Chapter 2, Figure 2–12). This problem is most likely to occur in clay or clay loam soils where there is shrinking and swelling of the soil. A light tillage pass before spreading will disrupt the channels and significantly minimize the risk of movement. Blocking the tile run during and after spreading may also work.

Safe utilization of manure above crop requirements

Large livestock operations on a small land base have special challenges. To avoid over-application of nutrients, exporting manure to non-livestock farms or composting operations may be needed. If this is not possible, limit manure applications to the phosphorus requirements of the crop. Although the risk from excess nitrogen leaching is minimal on heavy-textured soils, losses through denitrification can be substantial, and this leads to greenhouse gas emissions. Nitrogen-based application rates can also result in over-supply of P and K. Excess P is a

concern if it can reach surface water, leading to algae blooms. High rates should not be applied in areas where there is the potential for surface runoff or erosion. Incorporating the manure may also help to reduce the concentration of P in runoff water.

Long-term value of manure

The benefits of manure application on-farm extend beyond the year of application. Here is a summary of the benefits:

- Manure helps replenish available phosphorus and potassium in soils. Soil testing is the best way to estimate the long-term availability.
- Manure adds secondary nutrients, micronutrients and organic matter to soil.
- It adds organic nitrogen, which becomes available (in diminishing quantities) in the years following application.
- Added organic matter will improve soil structure and moisture-holding capacity.
- Added organic matter also increases the capacity of the soil to hold nutrients.
- Fields that receive regular applications of manure have fewer problems with soil crusting.
- Manure application adds microbial diversity and provides a food source for soil micro-organisms, which in turn promote larger root systems and better tolerance to dry weather.

Regulatory requirements

Every province and state has some type of regulatory control on the application of manure and biosolids, greenhouse nutrient feedwater and other organic amendments. This ranges from environmental protection laws that apply to everyone to specific regulations that dictate when and where a particular material can be applied. In Ontario, the first category is represented by the *Environmental Protection Act (1990)* and the *Ontario Water Resources Act (1990)*, which lay out penalties for anyone who pollutes surface water or groundwater or causes an adverse effect. The federal *Fisheries Act* also mandates that no deleterious substance can be allowed to enter surface water. In the second category, the *Nutrient Management Act (2002)* gives force to regulations on the storage, handling and land application of materials containing nutrients.

It is important to be aware of the most recent versions of any specific laws and regulations that apply in the jurisdiction where application of organic materials is planned.

Manure

Manure applications on livestock farms in Ontario are regulated under the *Nutrient Management Act (2002)*, which gives force to Ontario Regulation 267/03 (as amended). Phased-in farms are required to complete a nutrient management strategy. Farms with over 300 nutrient units or within 100 m of a municipal well are

required to complete a nutrient management plan (NMP) and to follow it for any nutrient applications. Growers and advisors should refer to the regulation for details. The most current version of the regulation can be found at ontario.ca/laws.

Non-agricultural source materials (NASM)

Non-agricultural source materials, or NASM, include treated and recycled material from non-agricultural sources, like leaf and yard waste, fruit and vegetable peels, food processing waste, pulp and paper biosolids and sewage biosolids, that are applied to agricultural land to provide a beneficial use. These materials are placed into categories based on environmental risk (metals, odour, pathogens). In Ontario, NASM are regulated under the *Nutrient Management Act*, where materials such as sewage biosolids must meet quality criteria for pathogens and metals before they are approved for land application. Biosolids must be applied according to the criteria set out in a NASM plan.

A NASM plan is similar to an NMP because both documents deal with the land application of nutrients and both documents address sensitive features such as watercourses and wells. The NASM plan, however, is done on a field-by-field, where-applied basis and includes testing of the materials and the soils for 11 metals. It can include other requirements such as limits on fats, oil and grease, boron or sodium.

NASM plans include restrictions on setbacks from surface water and limits on the application to fields with pH under 6.0 and/or fields with phosphorus soil test levels over 60 ppm, as well as time between application and the harvest of various crops.

Detailed requirements for non-agricultural source material application can be found in the most recent version of the *Nutrient Management Act*, Ontario Regulation 267/03 at ontario.ca/laws.

Greenhouse nutrient feedwater (GNF)

Many greenhouse operations use circulation systems to deliver water and fertilizer to greenhouse crops that are grown without the use of soil. There are times when the nutrient solution is no longer suitable for growing greenhouse crops, at which point the nutrient solution can be used to fertilize other agricultural crops. Greenhouse nutrient feedwater (GNF) is the nutrient solution removed from a closed circulation system at a greenhouse operation that is registered under the Greenhouse Nutrient Feedwater Regulation, O. Reg 300/14.

Similar to other nutrients regulated under the *Nutrient Management Act*, there are restrictions on rate of nutrients applied, timing of application and setbacks from sensitive features. Full details of requirements can be found at ontario.ca/laws.

Nutrients from crop residues

Cover crops and crop residues provide many benefits in a cropping system, including nutrient sequestration, soil erosion control and improved nutrient cycling. As crop residues break down, they can provide significant quantities of nitrogen to succeeding crops. The value of legumes is well established in this regard, but there is also potential for nitrogen mineralization from the residues of non-legume crops. Conditions where this can be significant are where large quantities of residue are left following harvest (as in some horticultural crops) and the residue is relatively immature. This is a source of nitrogen that has been under-utilized.

Legumes are unique among crops because they form symbiotic relationships with bacteria (Rhizobia) that convert nitrogen from the air into ammonium, which is then available to plants. The legumes grown primarily for seed production, such as soybeans, use all of this nitrogen for crop growth and yield and leave little or none in the soil for the next crop.

Perennial forage legumes, on the other hand, are a source of additional nitrogen because they tend to fix more nitrogen than is needed for the current crop. The nitrogen from legumes is held almost completely in the organic form and is not available until the residues are broken down. This residual nitrogen must be considered when planning a fertilizer program for the succeeding crop. Cool spring weather may delay this process.

When considering the effects of legumes on the growth of succeeding crops, it is important to separate the effect of physical properties, such as improved soil structure and tilth, from the effect of residual nitrogen. The effect of a red clover cover crop on such properties has been shown to benefit the yield of the following corn crop in Ontario, even with the application of sufficient fertilizer nitrogen (Table 6–12).

Table 6–12. Grain corn yields with or without underseeded red clover

Year	Corn yield without red clover kg/ha (bu/acre)	Corn yield with red clover kg/ha (bu/acre)
2010	11,675 (186)	12,428 (198)
2011	9,855 (157)	10,169 (162)
2012	10,985 (175)	11,550 (184)
2013	13,621 (217)	13,433 (214)
2014	11,926 (202)	14,312 (228)
2015	13,621 (217)	14,123 (225)
2016	11,926 (190)	12,554 (200)
Average (2010–2016)*	11,989 (191)	12,554 (200)

* indicates statistically significant difference at P = 0.05.

Note: Grain corn yields from a corn-soybean-wheat rotation with or without underseeded red clover (red clover first seeded in 2009) from the long-term rotation tillage system trial at the University of Guelph, Ridgetown. Fertilizer nitrogen applied to corn at 202–269 kg/ha (180–240 lb/acre).

Source: Dr. Dave Hooker, University of Guelph. 2010–16.

Legumes in a cropping system

The predominant forage legumes included in Ontario crop rotations are alfalfa, red clover and trefoil. Alfalfa and trefoil are usually harvested as hay and maintained for at least 2 years. Red clover is usually included as a cover crop following small grains, with growth terminated at the end of the first year or early during the next growing season, just before corn planting.

The greatest benefits of forage legumes occur during the first year after plowdown. However, there may be residual benefits during subsequent years. Late May soil nitrate-nitrogen concentrations and indexed yields presented in Table 6–13 show that potential nitrogen availability and yield increases following forage legumes can be greater in the first year of corn and beyond.

Total nitrogen accumulation

Plowdown red clover, established as a cover crop following cereals, can also accumulate a substantial amount of nitrogen — about 40 kg/ha (35 lb/acre) for every tonne per hectare of top growth. A relatively thick 30 cm (1 ft) tall stand of plowdown red clover produces about 4 t/ha (2 tons/acre) of top growth containing about 160 kg N/ha (140 lb/acre). However, more typical plowdown red clover yields when established as a cover crop following cereals range from 1–3 t/ha (0.5–1.5 tons/acre). Nitrogen and biomass contribution does not come only from the top growth. Red clover root growth will increase 4 to 6 times if plowdown in the fall is delayed from September 1 to October 15. Most of the roots — up to 75% — are located in the top 15 cm (6 in.) of the soil.

Table 6–13. Effects of crop rotation on post-planting soil nitrate-N concentration and corn yields

| | First-year corn | | Second-year corn | |
Rotation	Soil NO$_3$-N kg/ha	Yield %	Soil NO$_3$-N kg/ha	Yield %
continuous corn	9.1	100	9.5	100
soy–soy–corn–corn	12.6	104	10.6	97
soy–wheat–corn–corn	10.9	104	12.0	98
soy–wheat + clover–corn–corn	16.7	107	12.7	99
alfalfa–alfalfa–corn–corn	17.8	108	14.7	102

Effects of crop rotation on soil nitrate-N concentration 2 weeks after planting and on corn yields. Amounts are indexed relative to continuous corn for the first and second year of production. From a long-term rotation experiment.

Source: T. Vyn, Crop Science Department, University of Guelph.

Available nitrogen from legumes

Not all the nitrogen produced by a legume crop is available. The rate of mineralization may limit the availability of the nitrogen during the time when the subsequent crop needs it. Some of the nitrogen may be incorporated into soil organic matter or lost through volatilization or leaching. Despite this, the amount of nitrogen available from forage legumes can be considerable, often totally fulfilling the nitrogen requirement of a succeeding corn crop.

Accurately predicting the nitrogen available from forage legumes is difficult and depends on a number of factors, including the amount of legume growth, spring temperatures and soil moisture conditions, the tillage system and the timing of legume kill.

Obviously not all the recommended nitrogen credits should be applied if legume growth is poor or if the stand is variable across the field. However, when excellent legume (alfalfa, trefoil or red clover) growth has occurred, the recommended credits (Table 6–14) are quite conservative. Several Ontario studies indicate that fertilizer nitrogen is not required when corn is planted following excellent perennial forage legume stands.

The potential nitrogen availability from forage legumes to corn can be reduced if May and June weather conditions are extremely dry or wet. Excessive rainfall can result in denitrification or leaching losses. If soil conditions are extremely dry, especially during May or June, mineralization rates of legume-nitrogen can be decreased, thereby decreasing the amount available to corn.

How much is a full stand?

A full stand of clover, alfalfa or trefoil is anything greater than 120 plants per m² (12 plants per ft²). Therefore, a 50% stand is 60 plants per m² (6 plants per ft²), and a 33% stand is 4 plants. The nitrogen credit is the same whether the space between plants is empty or filled with grass and weeds.

Table 6–14. Adjustment of nitrogen requirement (i.e., N credit) following legumes

| Type of crop	kg/ha	lb/acre
established forages — less than ⅓ legume	0	0
established forages — ⅓–½ legume	55	50
established forages — ½ or more legume	110	100
perennial legumes seeded and plowed in same year	78 (for field corn)	70 (for field corn)
	45 (all other crops)	40 (all other crops)
soybean and field bean residue	30 (for field corn)	27 (for field corn)
	0 (all other crops)	0 (all other crops)
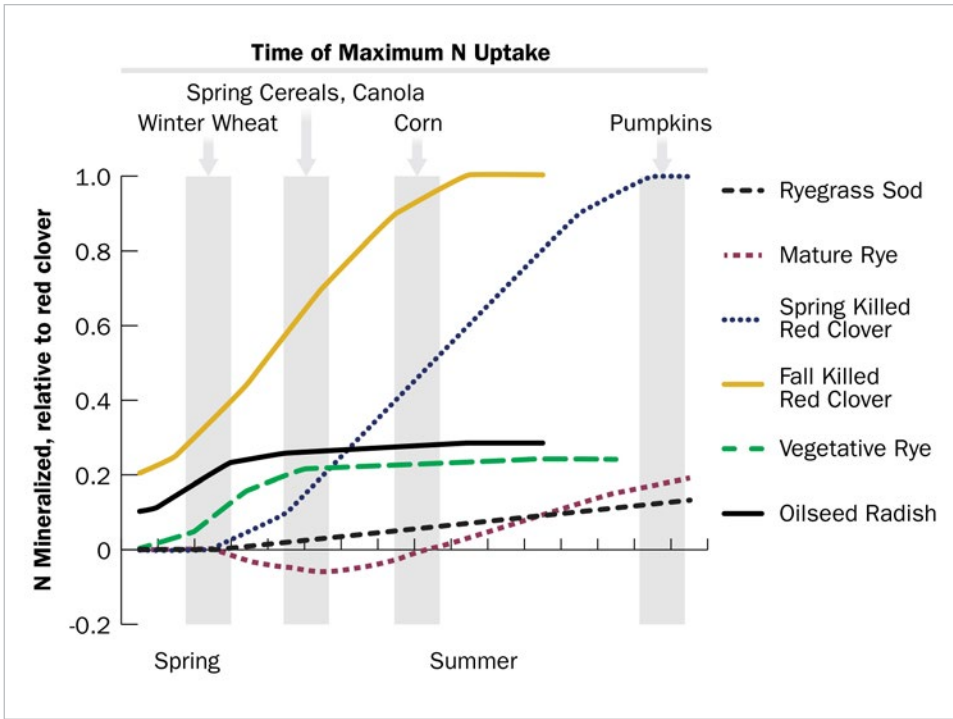
Figure 6–2. N mineralization from cover crop residues — relative time and amount

Optimizing nitrogen recovery

To be useful, the nitrogen from manure or crop residues must be released when the crop needs it. If the nitrogen is mineralized too soon, it can move deeper in the soil profile where it may be beyond the reach of roots. If it is released too late, the crop suffers from a shortage. This is illustrated in Figure 6–2.

Tillage systems that mix the legume top growth into the soil (mouldboard plow, chisel plow, disc) release the nitrogen from the crop residues faster than in a no-till system. Analysis of N response data in corn shows about 10% less nitrogen availability from a red clover cover crop in no-till than tilled systems.

Also, studies in no-till systems using red clover indicate that even though spring-killed red clover accumulated more nitrogen, fall-killed red clover produced greater corn yields in the absence of fertilizer nitrogen and required less fertilizer nitrogen to optimize yields. This suggests that nitrogen mineralization from fall-killed red clover is more available when the corn plant needs it than spring-killed red clover in no-till systems (Figure 6–2). A simple credit system can provide a general idea of nitrogen availability (see Table 6–14). The variability in the growth of the crop (and hence, the amount of nitrogen in the residue), together with the variability in the soil and weather conditions that control mineralization, mean that the

precise N availability will vary from year to year. However, soil nitrate tests can help to predict the need for supplemental nitrogen.

Nitrogen availability from non-legume residues

Many horticultural crops are harvested before the plants reach physiological maturity, and a relatively small part of the plant is removed from the field. This leaves a large quantity of green, succulent material in the field, which can rapidly break down to release mineral N into the soil. In cases where multiple crops are grown in the same field, this nitrogen can reduce the fertilizer requirement of the succeeding crops.

Cover crops for nitrogen management

Relatively good stands of actively growing cover crops, including legumes such as red clover, will take up (i.e., sequester) significant amounts of nutrients, including soil mineral nitrogen. Cover crops following winter wheat in Ontario have reduced the level of nitrate left in the soil in October and November by 50% compared to where no cover crop was planted. Figure 6–3 shows how much residual soil nitrate cover crops remove from the soil following a vegetable crop. This results in less nitrate-N available to be lost over winter.

Under optimal growing conditions, non-legume cover crops (ryegrass, cereal grains) can take up substantial amounts of soil mineral nitrogen. Oilseed radish has been reported to contain up to 100 kg/ha of nitrogen in above-ground growth under optimal growing conditions.

Although non-legume cover crops can sequester a significant amount of nitrogen, subsequent crop (i.e., corn) yields may not be increased to the same extent as following legume cover crops. To date, it has been difficult to show a consistent reduction in N fertilizer requirement for crops grown following a non-legume cover crop. The amount of growth, C:N ratio and spring weather conditions will impact nutrient cycling and nitrogen mineralization.

Cover crops vary widely in the timing of nitrogen mineralization (See Figure 6–2). Oilseed radish (OSR) and spring cereals tend to start to release nitrogen early in the spring, when it may be subject to losses.

Some cover crops, like ryegrass, are extremely resistant to breakdown. Although they absorb significant quantities of nitrogen, little is released to the next crop during the growing season.
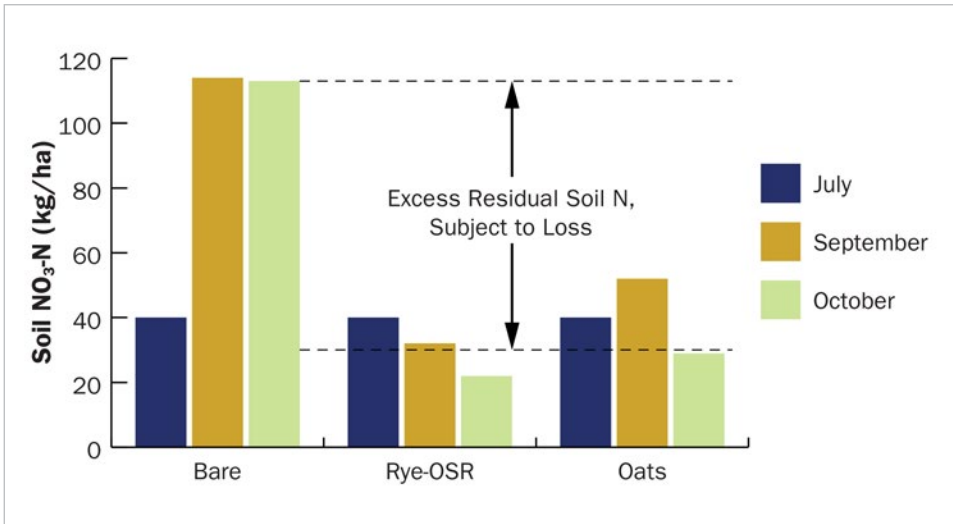
Figure 6–3. Nitrogen immobilization by various cover crops following cucumbers.
Source: Dr. Laura Van Eerd, University of Guelph, Ridgetown. 2004.

There are circumstances where cover crops can inhibit the growth of the following crop. A heavy layer of crop residue can keep the soil cool and wet in the spring, slowing crop germination and development as well as slowing nutrient mineralization. It may physically impede the operation of planting equipment, reducing the stand. It may also harbour pests like slugs or nematodes, which can harm the crop. Cover crops are one part of a cropping system, and their integration often requires adjustments in other parts of the system to maximize benefits and minimize crop production risks.

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Statistics Canada. 2001 Census of Agriculture.

7. Fertilizer Recommendations

Arriving at a correct fertilizer recommendation depends upon several factors related to both crop response to applied nutrients and a producer's objectives. Crop and site-specific fertilizer recommendations are developed using information from:

- soil testing
- tissue analysis
- specific requirements for crop quality
- desired economic and production goals
- production practices
- potential environmental risks

Factors limiting yield response to fertilizer

Many interacting factors affect a crop's yield response to fertilizer applications. Some of these factors are within a producer's control, while others are not. General production practices — how a producer manages water, soil, insects and crop diseases — can improve or reduce yield response to applied fertilizers. These factors are summarized in Table 7–1.

Table 7–1. Factors limiting crop response to applied fertilizers

Category	Factor	How it affects response	Example
soil water management	dry soil	reduces nutrient flow to roots and within plant	boron deficiency in alfalfa
		limits root growth and activity	lack of response to surface-applied fertilizer
		increases salt concentration	risk of fertilizer burn
	wet soil	reduces root growth and ability to absorb nutrients	yellow corn in flooded soil
		changes chemical state of nutrients in low-oxygen soils	denitrification of N; enhanced Mn availability in tire tracks
	cold, wet soils	reduces growth and activity of roots	phosphorus deficiency in corn seedlings
crop rotation	soil structure	affects proportion of soil volume that roots will explore	higher optimum P & K levels in corn in compacted soil
	residual nutrients in the deeper soil profile	deeper rooted crops within a rotation will use nutrients from lower in the soil profile	sugar beets and carrots pull N from deep in the soil profile
	previous crop	affects accumulation and availability of soil nutrients	corn following alfalfa rarely needs N fertilizer
		crops that form mycorrhizal associations	early P uptake of corn (a mycorrhizal crop) may be decreased if the previous crop was non-mycorrhizal (e.g., canola)

Table 7–1. Factors limiting crop response to applied fertilizers

Category	Factor	How it affects response	Example
agronomic factors	choice of tillage system	more tillage leads to less mycorrhizae	greater response to starter P in conventionally tilled than no-till soils
		tillage increases N mineralization	increased N credit where red clover cover crops are tilled
		deep tillage can dilute soil nutrient concentrations	low fertility on eroded knolls where tillage brings subsoil to the surface
		no-till leads to stratification of immobile nutrients	increased corn response to banded K in no-till
pest control	weeds	high soil fertility favours crop and weed growth	banding fertilizer places nutrients where they are less accessible to weeds
	diseases	root diseases affect the root surface area and uptake of nutrients	white beans with root rots require more N
	nematodes	nematodes interfere with root uptake efficiency	soybean cyst nematode increases optimum soil K level
agronomic factors	cultivar/hybrid selection	genetic differences create different rooting habit	potato varieties with smaller root systems tend to respond to higher levels of fertility
		genetic differences create different end uses/quality	N recommendations for wheat and potatoes are specific to cultivar
		genetic differences create different susceptibility to diseases	wheat cultivars susceptible to disease respond more to N when diseases are controlled, with response depending upon timing of fungicide application and growing season conditions
		in corn, genetic differences create different responses to delayed N application	some corn hybrids are less responsive to late-season N applications than other hybrids, although the response may also be related to growing season conditions
	lodging	where crops are susceptible, excess N reduces yield by increasing lodging	optimum N rates are lower for cereals susceptible to lodging
	plant population and spacing	populations with higher yields remove more nutrients	in maximum yield research, high corn populations have sometimes been shown to respond more to fertility

Developing fertilizer recommendations

The need for additional fertilizer is determined through a diagnostic approach. It is essential for managing soil fertility and making recommendations. The tools of the diagnostic approach are:

- soil testing
- plant analysis and tissue testing
- visual nutrient deficiency symptoms

The challenge in making any fertilizer recommendations based on such a diagnostic approach is determining an effective and economical rate of fertilizer. There are two common methods in developing fertilizer recommendations from soil test results: the "sufficiency" approach and the "buildup and maintenance" approach. Both concepts have their own strengths and weaknesses that depend upon the producer's crop production objectives. Neither system will be effective, however, without soil test calibration.

Soil test calibration

Since its inception, soil testing has been used for most of the major crops produced in Western Europe and North America. Soil testing can index the availability of a wide range of plant nutrients and monitor changes in the levels of soil fertility over time.

No reasonable fertilizer recommendation can be made without assessing the fertility of the soil — directly or indirectly. For annual crops, soil testing is the most common basis or starting point. For perennial horticultural crops, tissue testing is the foundation of fertilizer recommendations.

The soil test provides only an index of availability of a nutrient. This index must be calibrated against actual measurements of crop response in the field.

Different interpretations of soil test calibration are possible. One approach places more emphasis on crop response to applied nutrient. Another considers the yield in relation to the soil test level of a nutrient.

It is not possible to rely solely on the soil test for recommendations. The test does not reflect the external variables such as cool growing temperatures or high rainfall after the soil sample was taken. Nor does the soil test predict whether the crop will be managed to its full yield potential. External factors that affect the yield response to applied fertilizer must be considered in addition to the soil test.
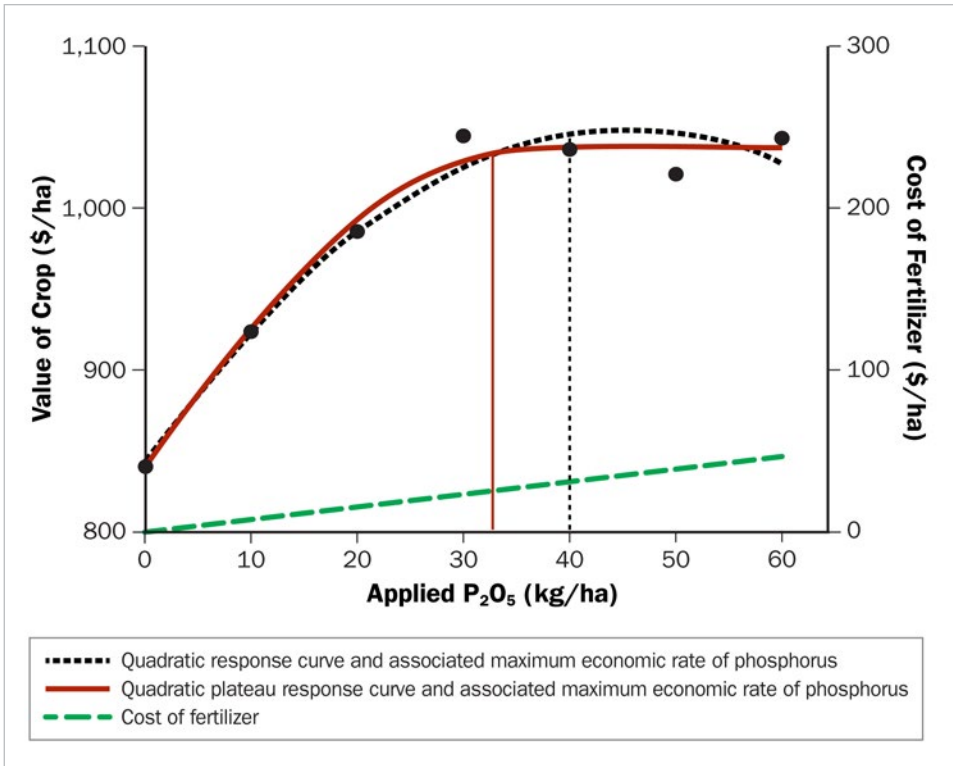
Figure 7–1. Corn yield response to phosphorus fertilization

Yield response to fertilizer applied

Field experiments are used to determine how much nutrient is required for each soil test level. This is determined by applying at least four different rates, including a zero rate, of a nutrient to different plots of a fairly uniform soil and under conditions where only the nutrient of interest is limiting crop production. A graph is developed by plotting the yields against the fertilizer rates applied. The resulting graph is used to define a response curve. Two common response curves are shown in Figure 7–1. A mathematical equation is fitted to the yield data. In this case, the dashed curve represents the data fitted to a quadratic model, while the solid curve represents the data fitted to a quadratic plateau model.

By knowing the response curve, it is possible to use fertilizer price information. As shown in Figure 7–1, this information can be used to calculate the economically optimum fertilizer rate to apply (vertical lines). As the rate of fertilizer applied increases, the slope of the response first increases, then decreases. At the point at which the vertical lines in Figure 7–1 intersect their respective response curve is the maximum economic rate of fertilizer. After this point, the increase in crop

yield returns no more value than the increase in fertilizer cost. This is the highest fertilizer rate that can be justified in 1 year.

Choosing a yield response equation

Fertilizer response trials, no matter how extensive, produce data for yield responses at discrete points: either fertilizer additions or soil test levels. These data are fitted to a curve, and the equation for this curve is used to predict fertilizer requirements more precisely. The type of equation used to describe this curve can influence the results.

No one curve is clearly better than any other for describing how crop yields increase with fertilizer additions. The common element of most equations is that the calculated response to fertilizer decreases as the amount of fertilizer added increases, so that at some point, the value of the added yield is less than the cost of additional fertilizer needed to achieve that yield. The point where the incremental increase in yield value equals the added cost of fertilizer to achieve that incremental yield increase is the maximum economic yield.

The quadratic equation, the quadratic-plateau equation (solid curve in Figure 7–1) and the Mitscherlich equation (Figure 7–2) are the most common ones used to fit fertilizer response data. A quadratic equation (Yield = $a + bx - cx^2$, where x is fertilizer rate and a, b and c are constants used to fit the curve) gives a curve that shows large responses to fertilizer at low rates, gradually decreasing so that eventually there is no more response to added fertilizer, then turning down so that it predicts a decrease in yield with added fertilizer. Such an equation is often adequate for data that show a distinct decrease in yields at higher fertilizer application rates (e.g., cases where excessive lodging or increased disease in a cereal is due to high fertilizer N applications). However, it tends not to fit data very well when yields clearly level off. In this instance, a quadratic plateau model often gives a better fit to the data in the responsive range (see solid regression line in Figure 7–1).
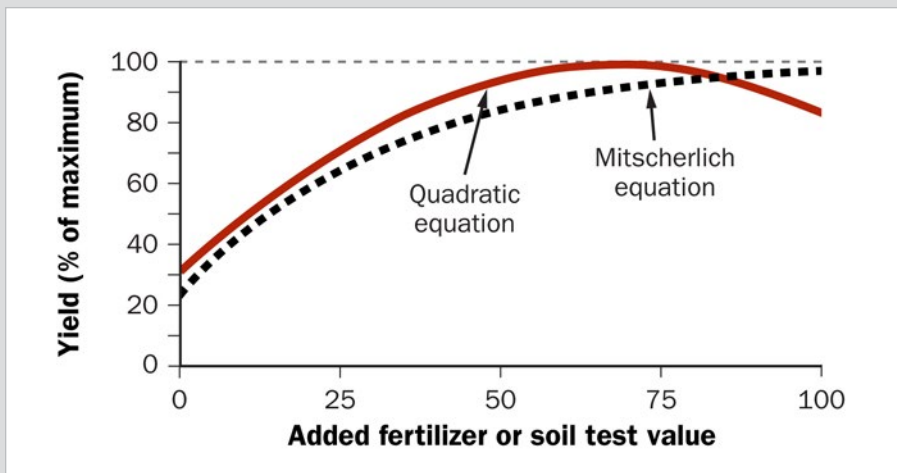

Figure 7–2. Comparison of two different response curves

(continued from previous page)

Compared to the quadratic models, the Mitscherlich equation has a similar form in the lower parts of the curve, but it never reaches a maximum yield and thus is less suitable for data sets where an obvious maximum crop yield was obtained or yields declined at higher fertilizer application rates. The Mitscherlich equation is RY (relative yield) = 1 − $(10^{(-x+b)*c})$ where x is either fertilizer added or soil test value and b and c are constants relating to the efficiency of fertilizer use.

These equations may give similar maximum economic yield figures at moderate fertilizer and crop values. The differences arise if the value of the crop is high or the cost of the fertilizer is low. In this case, the Mitscherlich equation predicts a significantly higher maximum economic yield than the quadratic models.

Yield response equations are useful tools for predicting maximum economic fertilizer rates, but like any tool, they have limits. Although the Mitscherlich and quadratic equations have similar shapes in the lower parts of the curve, the Mitscherlich equation never reaches the maximum yield, while the quadratic equation reaches the maximum and then begins to drop off, and the quadratic-plateau equation reaches a maximum and levels off. It is extremely important not to extrapolate any curve beyond the data used to generate the curve. The risk of incorrect interpretation is too great.

Response to soil test level

Soil test calibration relates crop responses to soil test levels. This is most important for soil-immobile nutrients like phosphorus and potassium.

To determine this relationship, scientists conduct experiments in which soil test values are adjusted to various levels. At each level, two yields need to be measured: the yield without the applied nutrient and the yield with a non-limiting rate (more than the plant could possibly use) of applied nutrient. Relative yields (the unfertilized yield as a fraction of the non-limited yield) are plotted against soil test level. This determines the critical level above which the crop rarely responds economically to the applied nutrient.

Probability of response versus soil test level

When experiments are conducted over many years, a single response curve accurately represents the average. However, it may not represent actual results in a given year. Recognizing the variability in yield response leads to different approaches to interpreting the soil test results. In this approach, the frequency of positive yield responses is plotted against the soil test level. The soil test rating then becomes an index of the probability of response to the nutrient.

Table 7–2. Probability of response to added nutrients at different soil test levels

Level of soil fertility*	Response rating	Probability of profitable response	Optimum fertilizer rates
low	high response (HR)	most cases	high
medium	medium response (MR)	about half the cases	medium
high	low response (LR)	occasional	low
very high	rare response (RR)	sporadic	very low
excessive	no response (NR)	negligible	nil

* Adding nutrients to soils that already have above-optimum levels of nutrients may reduce crop yields or quality by interfering with the uptake of other nutrients.

Table 7–2 describes the probability of response to added nutrients at different soil test levels. In general, crops grown in soils with low soil tests will respond to added nutrients most of the time, and the optimum rate of fertilizer to apply will be high. On soils with high levels of fertility, profitable responses to fertilizer occur only rarely, and optimum rates of application are lower.

Profitable responses to starter or seed-placed phosphorus in some crops continue to higher soil test levels than those resulting from broadcast applications.

Do high soil nutrient levels harm the environment?

Losses of nutrients from soil can harm water quality. The risk depends on the source of nutrient and pathways of transport. Higher soil nutrient levels increase the source, but do not affect the transport pathways. This is why soil test level is one component of the Phosphorus Index. For phosphorus, on land where risks of erosion and runoff are high, controlling soil test P levels is relatively more important. Phosphorus can also be lost through preferential/macropore flow through to tile drains. In situations where transport pathways are relatively minor, soils with greater soil test P values may pose relatively little risk of harm to water quality. Regardless of soil test level, applying nutrients at the proper rate, time and place will help to minimize nutrient losses to the environment. This is important, as it has been suggested that relatively small losses of phosphorus (i.e., above 2.3–4.6 kg P_2O_5/ha in some instances) could be detrimental to water quality.

Developing fertilizer recommendations: "fertilize the crop" or "fertilize the soil"

There are two approaches to making fertilizer recommendations. One is to "fertilize the crop," often called the *sufficiency approach*. The second is to "fertilize the soil," frequently called the *buildup and maintenance approach*. Table 7–3 summarizes these two approaches to making fertilizer recommendations and Table 7–4 indicates factors that favour one over the other.

Table 7–3. Sufficiency versus buildup approaches to developing fertilizer recommendations

Assumptions, strengths and challenges	Sufficiency approach	Buildup and maintenance approach
assumptions	• cost of the applied nutrient is paid for by the yield increase in the current crop • no economic value is directly assigned to the residual effect of the fertilizer (though residual fertilizer above crop removal will contribute to the soil test value) • the yields obtained at low soil test levels with high added fertilizer are about the same as the yields at high soil test levels with less added fertilizer	• nutrient to be applied is not irreversibly fixed by the soil • nutrient is not subject to losses from the soil by leaching or volatile escape • producer can profit from future returns to investments in soil fertility • application of nutrient at crop removal value will maintain the soil test levels
strengths	• in a single-year analysis, gives the greatest net return to fertilizer, and typically is the most profitable over multiple years as well • can be used for both mobile and immobile nutrients	• accounts for residual benefits of initial fertilizer applications during buildup phase • gives the greatest assurance that crop yields will not be limited by nutrients • in fields with variable soil tests levels in the crop-responsive range to fertilization, higher application rates may provide greater yield response than expected based on the field average soil test value
challenges	• can be difficult to predict precisely the most economic rate for a particular set of circumstances because response can vary with soil, tillage practice, variability in soil, crop variety and the weather • entails a greater risk of under-fertilizing, especially in fields that have extremely variable soil test levels	• applies only to immobile nutrients and therefore is not appropriate for nitrogen • requires amortization of fertilizer costs over several years to obtain full economic return • site-specific conditions or farm practices will affect the profitability of building and maintaining the soil test level at or above the critical level • entails a greater risk of over-fertilizing and nutrient losses from soil and/or nutrient application

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Table 7–4. Which system?

Uncertainty exists in dealing with any biological system. We cannot predict exactly how crop yields will react to a specific set of factors or changes in commodity and fertilizer prices. However, there are factors that favour each system.

Factors favouring sufficiency approach	Factors favouring buildup and maintenance approach
• short land tenure, annual rental agreements • desire to not spend any more than necessary • low crop value, high fertilizer prices • alternative uses for capital with higher rate of return • nutrients easily lost from the soil • limitations to yield other than fertility • expectation that crop value and fertilizer prices will remain stable • availability of equipment and ability to directly fertilize each crop each year	• long-term land tenure • desire to ensure fertility is not a limiting factor • high-value, high-yielding crops that are responsive to higher fertility levels • no other use for capital or large investment in equipment • low-cost source of nutrients like manure or biosolids • nutrients held in soils in available forms without appreciable losses or conversion to unavailable forms • expectation that crop value and fertilizer prices will rise • rotational crops that require a high level of soil fertility • desire for flexibility to skip applications in years of high fertilizer prices or when weather conditions make application difficult

The sufficiency approach aims to supply the needs of the current crop. This approach is the basis for Ontario recommendations as well as for those in some adjoining states, including New York. It considers the amount of nutrient available from the soil based on a soil test. Recommendations for applied fertilizer are made that aim to provide an optimum payback in increased value of the current crop. It is the approach of choice for nutrients that are subject to losses from the soil, like nitrogen. It can also be used for other nutrients, including phosphorus and potassium.

Building the soil test level to a specific target is not the goal of this method, as it is the crop response to added nutrient that is deemed important. Higher amounts of fertilizer are recommended at low soil test levels, and lower amounts at high soil test levels. As a result, this method tends to build up low-soil-testing soils and

draw down higher-soil-testing soils. How quickly these changes occur depends upon crop yields (i.e., crop removal) and may be field- or site-specific.

The buildup and maintenance approach emphasizes soil fertility levels rather than direct crop response to applied fertilizer. In the buildup phase, fertilizers are applied to build or increase the soil test values to a critical level at which crop growth is not likely to be limited by the nutrient. The maintenance phase involves adding nutrients to replenish nutrients removed by crops based on estimates of crop removal and amount of fertilizer required to change the soil test values. For soils above the targeted range, nutrient recommendations decline to zero.

The benefits of an investment in building up soil fertility do not all occur in 1 year. While the costs and

returns to added fertilizer in a single year may only justify fertilizing to 90%–95% of maximum yield, adding the returns to residual fertility over a much longer term could potentially justify fertilizing for a greater percentage of maximum yield (Reetz and Fixen, 1992), providing the yield increase is of enough value to justify the higher fertilizer cost. Studies conducted that compare the different approaches over multiple years typically find little difference in crop yields between the recommendation systems, with higher fertilizer input costs associated with the buildup and maintenance approach (Olsen et al., 1982; Murdock, 1997).

It is important to consider all the costs of this approach, including amortizing the investment over several years. The cost of investing includes both interest rates and opportunity costs. If other opportunities for investment yield better returns, it would be better not to invest in the additional fertilizer for building soil test levels.

Many commercial, state and university labs, including Pennsylvania, Ohio, Michigan and Indiana, use the buildup and maintenance approach. Major differences between laboratory recommendations can occur when using this approach. Assumptions used for increase in soil test values per unit of fertilizer and the time allowed for the buildup will affect recommendations. Initial soil test levels may also affect the rate of change in soil test values relative to the amount of nutrient added as fertilizer or removed in crop yield from the soil. Regular soil testing remains an important nutrient management tool with the buildup and maintenance approach.

The basis for sufficiency recommendations for corn in Ontario

Table 7–5 compares the current OMAFRA phosphorus recommendations for corn with predicted phosphorus requirements based on 78 different phosphorus fertilizer response trials for corn conducted in Ontario (1969–2010). The data illustrate that current sufficiency recommendations are for the most part providing optimum fertilization of the crop.

Table 7–5. Comparison of sufficiency recommendation to regression-predicted maximum economic rate of phosphorus

Soil test P (Olsen) (ppm)	Sufficiency recommendation (kg P_2O_5 ha^{-1})	Regression-predicted recommendation (kg P_2O_5 ha^{-1})
0–3	110	110
4–5	100	60
6–7	90	40
8–9	70	30
10–12	50	10
13–15	20	10
16–20	20	10
21–30	20	10
31–60	0	10
>60	0	0

(*Source:* Janovicek et al., 2015)

Example of soil test calibration using sufficiency and buildup and maintenance approaches

Examples of corn yield response curves at three levels of soil test phosphorus, each at a different site, are shown in Figure 7–3. The soil test extractant was sodium bicarbonate. The most economic rates were calculated on a corn price of $170 per tonne and a fertilizer price of $1.20 per kilogram of fertilizer phosphorus (P_2O_5).
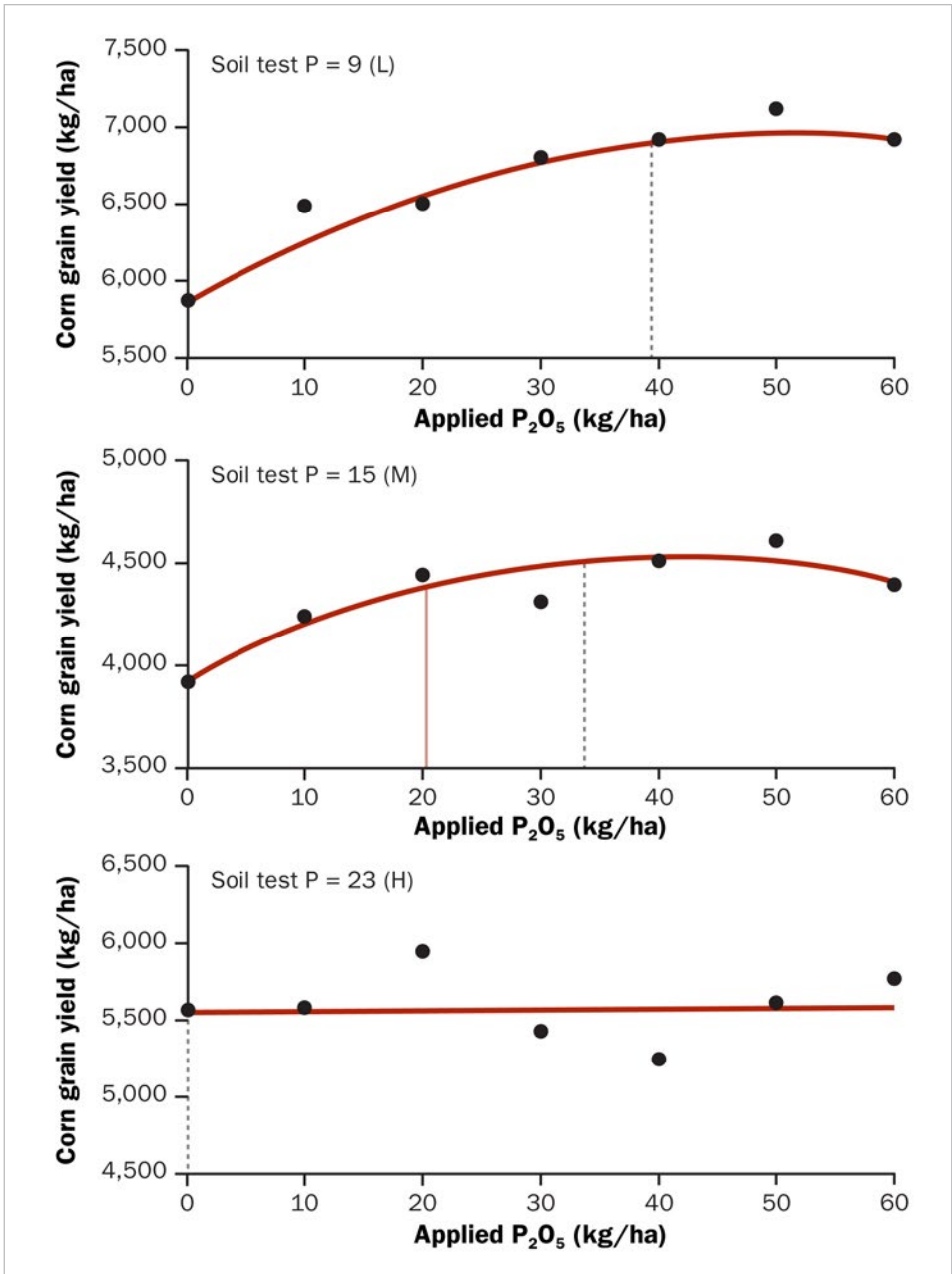
Figure 7–3. Corn yield response curves from experiments at three sites in Ontario with differing levels of soil test phosphorus. Vertical lines indicate the most economic rate using a quadratic (dashed) or quadratic-plateau (solid) regression model.

Table 7–6. Comparison of phosphorus recommendations from different approaches based on Figure 7–3

Soil test P (ppm)	Buildup and maintenance		Maximum economic rate		Current Ontario recommendation (sufficiency)*	
	P₂O₅ (kg/ha)	Yield Response (kg/ha)	P₂O₅ (kg/ha)	Yield Response (kg/ha)	P₂O₅ (kg/ha)	Yield Response (kg/ha)
9	120	1,062	39	1,056	70	1,062
15	64	553	21	528	20	519
23	55	0	0	0	20	0

*OMAFRA Publication 811, *Agronomy Guide for Field Crops* (2017)

Maximum economic rates

Relying strictly on the sufficiency approach, from this one-year set of data, would result in the maximum economic rates of phosphorus fertilizer additions shown in Table 7–6.

This table is only an example. A larger number of experiments are needed to assemble a complete recommendation table. Different soils may show different response curves at the same soil test level. For this reason, the three sites chosen for the example show some difference from the current recommendations.

Current recommendations are based on the sufficiency approach, but allowances have been made for soil variability and for starter responses, particularly for phosphorus. They are derived from a far greater number of experiments than in the example and thus are more appropriate to use as general guidelines.

Critical soil test level

Using the phosphorus response data for corn from the same source as we used for the sufficiency approach example in Figure 7–3, Figure 7–4 shows relative yield of unfertilized corn as a per cent of fertilized corn yield. The horizontal line is set at 95%, and the relative yield chosen as economically attainable. The vertical line is positioned so that the fewest points are in quadrants B and D. This line represents the critical level.

In this case, a critical level of 16 ppm is suggested. With the buildup and maintenance approach, above this level you would recommend maintenance doses only. Below this level, the amount of fertilizer recommended is that required to raise the soil test level plus maintenance (see Figure 7–5). Rates recommended will vary according to length of time allowed for buildup.
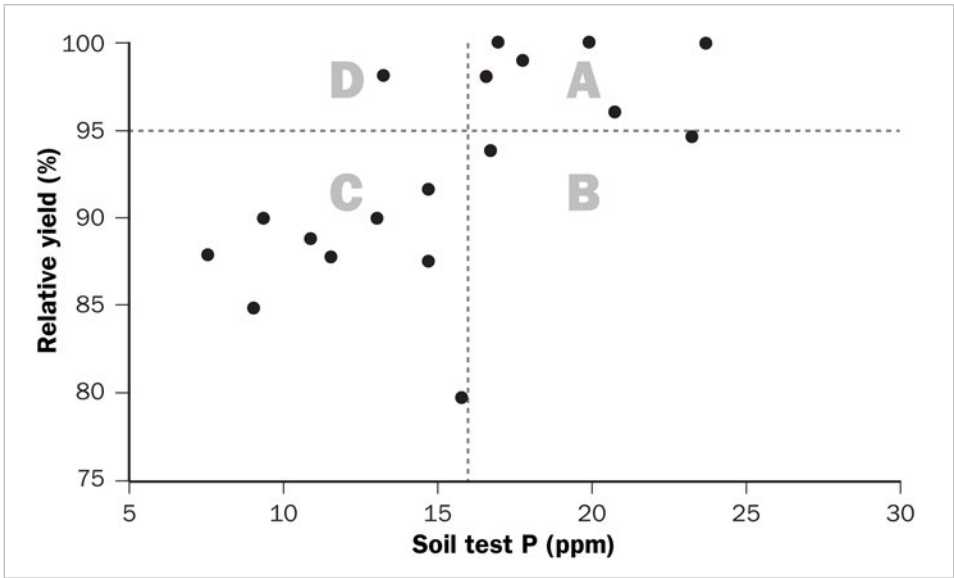
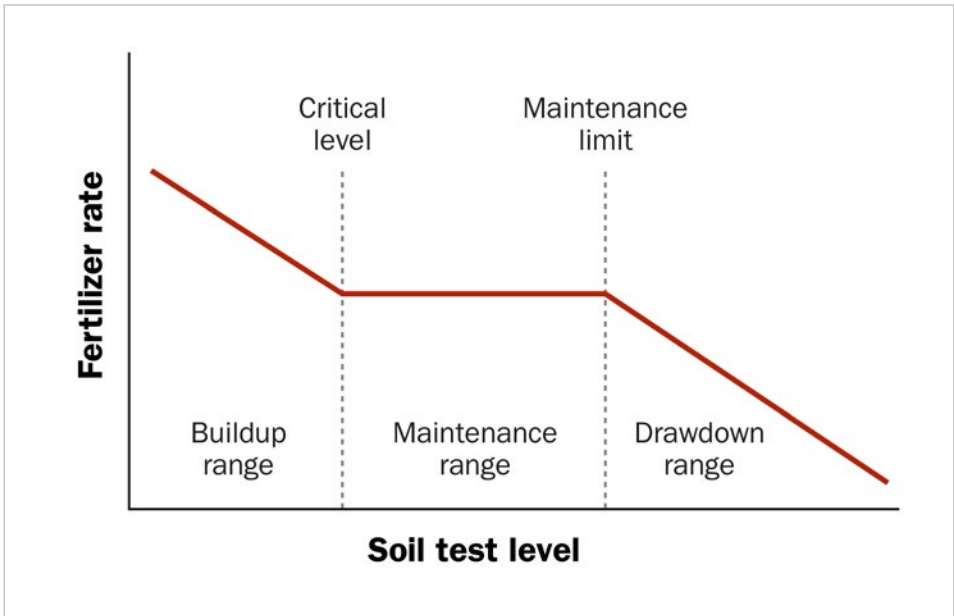**Figure 7–4.** Defining the critical soil test level

Figure 7–5. Buildup and maintenance approach to calibration

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Assumptions and calculations

Recommendations based on the buildup and maintenance approach are shown in Table 7–6. They assume three things:

- It takes 37 kg P_2O_5/ha to increase the soil test by 1 ppm (Richards et al., 1995).
- The target is building the soil test level to the critical level over 4 years.
- The maintenance value is equal to the expected crop removal of 55 kg P_2O_5/ha (based on a ~150 bu/acre or 9.4 tonnes/ha corn crop).

Figure 7–6 illustrates the calculation for the phosphorus recommendation. In this example, the existing soil test level is 9 ppm. The recommended rate is calculated as the target soil test level (16 ppm), less the existing soil test level (9 ppm), multiplied by the amount needed to raise the soil test one unit (37 kg P_2O_5/ha), divided by the number of years (4), plus maintenance (55 kg P_2O_5/ha). The maintenance value should reflect the overall productivity of the site, although research has shown that crop phosphorus removal does not predict changes in soil test P values very well over a wide range of soils (Alvarez and Steinbach, 2017). This may reflect inherent differences between soils with respect to the amounts and forms of soil phosphorus that contribute to plant-available pools over longer periods of time. It may also reflect the fact that plants are utilizing phosphorus from deeper in the soil profile than the soil sampling depth of 15 cm (6 in.).
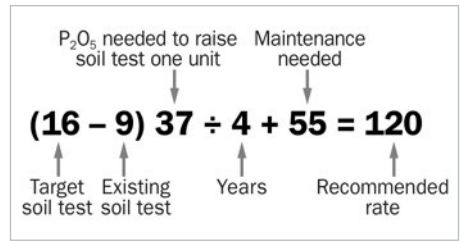
Figure 7–6. Buildup and maintenance requirement calculation

The fertilizer amounts in Table 7-6 for buildup and maintenance are higher than those for the sufficiency approach, even though the same data are used. An economic justification for these rates is quite complex and not universally applicable to all situations. The yield difference between the crop at or above the critical soil level and the yield obtained using the most economical rate at a lower soil test determines the net profitability of the buildup and maintenance approach.

In practice, maintenance applications are recommended over a range of soil test levels. Beyond the maintenance limits, the rates begin to decline.

Maintenance is based on removal by crop and has no direct bearing on crop response. Therefore, the maintenance portion should be based on average crop yield for the field rather than a yield goal.

Table 7–7. Average fertilizer cost and crop yield response value of phosphorus recommendations from different approaches based on Figure 7–3 and for the first 4 years of the program

Soil test P (ppm)	Buildup and maintenance			Maximum economic rate			Current Ontario recommendation*		
	Fertilizer cost (ha/yr)	Yield response (ha/yr)	Profit** (/ha/yr)	Fertilizer cost (ha/yr)	Yield response (ha/yr)	Profit** (/ha/yr)	Fertilizer cost (ha/yr)	Yield response (ha/yr)	Profit** (/ha/yr)
9	$144	$180.50	$36.50	$46.80	$179.50	$132.70	$84	$159.20	$75.20
15	$76.80	$94	$17.2	$25.20	$89.80	$64.60	$24	$77.80	$53.80
23	$66	$0	–$66	$0	$0	$0	$24	$0	–$24

* OMAFRA Publication 811, *Agronomy Guide for Field Crops* (2017)

** Profit is based solely on response to fertilizer and is calculated as the difference between crop value ($170/tonne) and fertilizer cost ($1.20/kg P_2O_5).

Comparison

Table 7–7 presents the average yearly costs and returns of the various programs for the first 4 years (i.e., the buildup phase), illustrating the additional revenue that needs to be generated to cover the initial cost of increasing soil test P levels. Direct comparisons of these two approaches over multiple years often show little difference in yields but higher fertilizer costs with the buildup and maintenance approach recommendations provided by individual laboratories or consultants (Olsen et al., 1982; Murdock, 1997). Recommendations that included micronutrient and secondary nutrient applications also had much higher fertilizer costs, with no observed yield benefit (Olsen et al., 1982).

Figure 7–7 illustrates the long-term potential profitability of these approaches for phosphorus application relative to the current recommendation. Initial profits are higher with the most economical approach method, diminishing with time due to under-fertilization as soil test P levels decrease between soil sampling periods. For the buildup and maintenance approach, profit is less during the buildup phase and remains lower for several decades. This period of time would be greater if credit was given to potential interest earned on capital not invested in fertilizer to build the soil test level.

Using the most economical rate approach, the soil test level is predicted to decrease to a value of approximately 8 ppm. The buildup and maintenance approach would maintain the soil test level at 16 ppm, while the current recommendation would see soil test values fluctuate between 9 and 11 ppm. The reader is cautioned that the above example is based on a limited data set and would surely vary with location. The results do, however, support the published research to date that has found no economic advantage to the buildup and maintenance approach due primarily to higher input costs with no appreciable impact on yields.
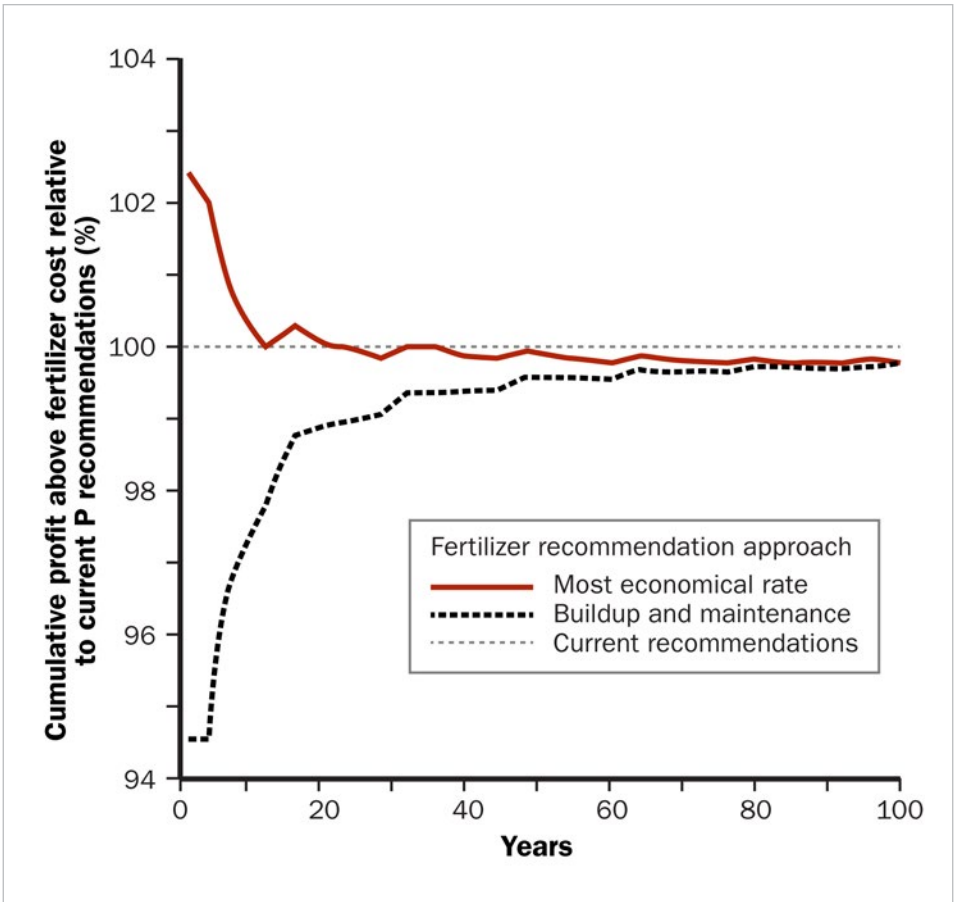
Figure 7–7. Comparison of profit for fertilization approaches relative to Ontario's current recommendations

Yields were assumed to follow the yield response curve observed in Figure 7–3 and relative yield in Figure 7–8. The buildup and maintenance approach was assumed to give the predicted maximum yield in each year, while predicted yields for the other two approaches varied according to changes in soil test level and fertilizer application rate as illustrated in Figure 7–9. Note that in Figure 7–9, the yield response to applied phosphorus diminishes as soil test P increases.

To simplify the example, there was no accounting for additional revenue from potential interest on the capital used to purchase the fertilizer for the buildup and maintenance approach. Other assumptions included: soil testing performed once every 5 years; soil test P values changed based on amounts of P removed by crop (55 kg P_2O_5/ha/year) or added as fertilizer; and a fertilizer cost of $1.20/kg P_2O_5 and corn value of $170/tonne.
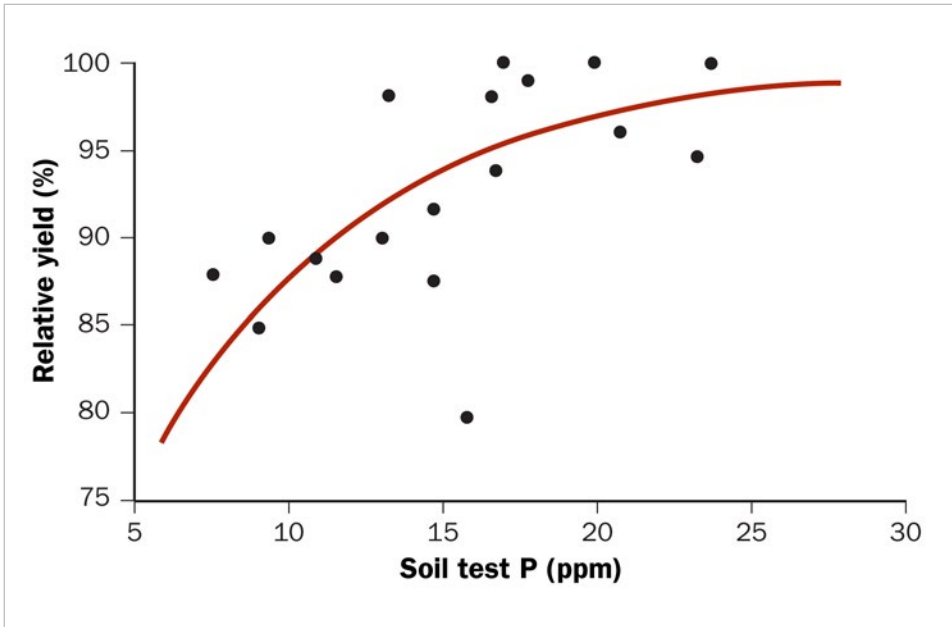

Figure 7–8. Relative yield at different soil test levels
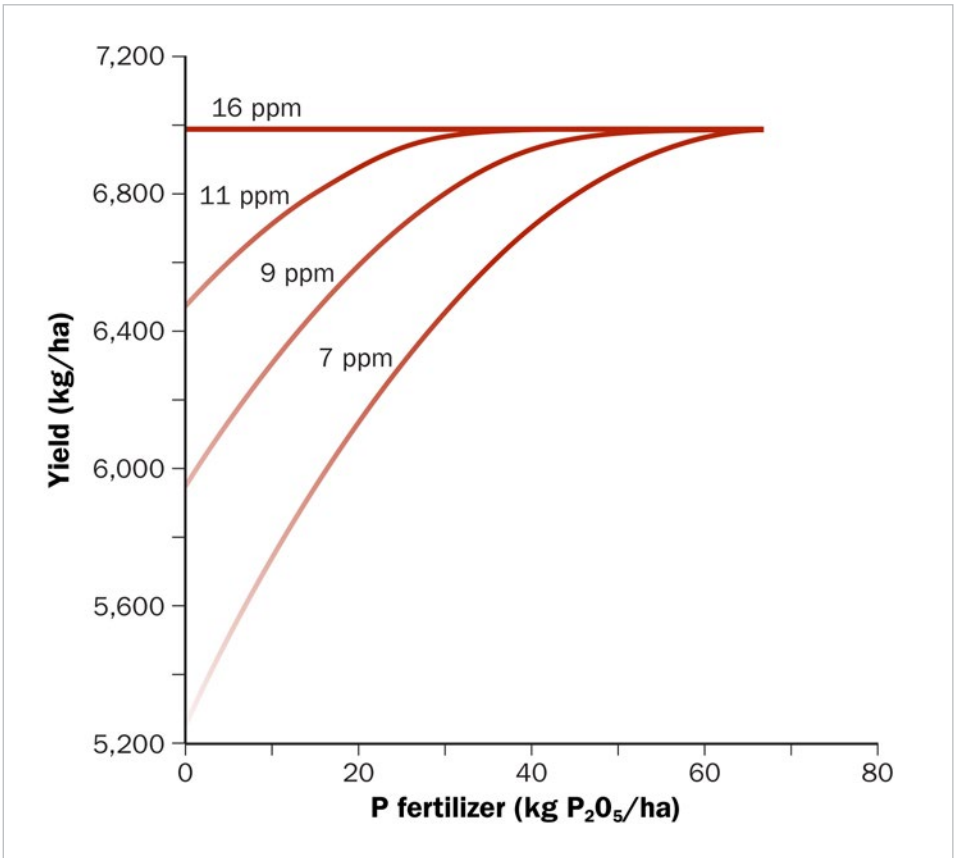
Figure 7–9. Predicted effect of changes in soil test P on crop response to applied fertilizer P. **Note:** Numbers on the curves indicate soil test P level.

Other things to consider

Yield goal

Expected yields have often been used in making fertilizer rate decisions. Obviously, the final yield is what pays for the input costs, so that higher-value crops tend to receive more fertilizer because it takes less of a crop response to cover the fertilizer expense. Basing fertilizer application rates on crop removal will clearly result in higher application rates as yields increase but does not necessarily mean a higher fertilizer requirement for the crop. There is little scientific evidence to support the direct relationship between yield goal and fertilizer requirement. However, one must remember newer varieties/hybrids/cultivars are potentially more efficient at using all resources available to them (i.e., water, light and nutrients, whether from soil or fertilizer) to produce yield (Mueller and Vyn, 2016). In terms of nitrogen fertilization, yield response to applied N is much better correlated to fertilizer N requirement than the absolute yield or yield goal of the crop (Lory and Scharf, 2013; Kachanoski et al., 1996).

In the long term, higher yields remove more nutrients from soil and require more to be added if the desire is to maintain the soil test levels. Regular soil testing will monitor changes in soil test levels in the plow layer. Soils with high yield potential have deep topsoil and excellent structure. This allows roots to explore larger volumes of soil for nutrients and moisture. Given that plant roots will take nutrients from below the top 15 cm where the soil test is taken, one might expect applications based on crop removal to slightly increase soil test levels.

Response to fertility is only one component of crop yield. For example, research at the Ridgetown Campus recorded a corn yield of 18.4 tonnes/ha (293 bu/acre) in 1985 on research plots near Chatham (Stevenson, 1983). Many factors contributed to the high yield, including soil properties, irrigation and high inputs of fertilizer and manure nutrients. The most important factors, however, were considered to be hybrid selection and population.

Basic cation saturation ratios and percentages

The ratios or percentages of the basic cation nutrients — calcium (Ca), magnesium (Mg) and potassium (K) — are sometimes used as indicators of their availability. The aim is to recognize interactions among the cations.

These basic cations are known to have antagonistic effects on each other. This means a very high soil test level of one cation may reduce the availability to plants of one of the others. For practical purposes, these interactions are only important when one of the nutrients is approaching deficiency.

The basic cation saturation concept originated in New Jersey in the 1940s (Bear et al., 1945). In a series of greenhouse experiments over 8 years, infertile, acid soils were limed and fertilized to grow alfalfa, and the cation saturation of the soils was measured. The investigators suggested the cation exchange complex should be occupied by 65% calcium, 10% magnesium, 5% potassium and 20% hydrogen. It is important to note that the crop grew well with these levels of nutrients in the soil, but this does not imply that these exact proportions are required for crop growth.

In many trials since the original study, crop growth has not been adversely affected over a wide range of Ca:Mg:K ratios or percentages, as long as one of the nutrients was not clearly deficient. A study on alfalfa and trefoil in New York State found that Ca:Mg ratios ranging from 267:1 to 1:1 had no significant influence on yields (Reid, 1996).

There are two main drawbacks to the use of basic cation saturation ratios or percentages in making fertilizer recommendations:

- No economic analysis is included in the recommendations, particularly on soils high in calcium and magnesium. The cost of these fertilizer programs can be extremely high.

- Many alkaline Ontario soils have high levels of carbonate minerals. These minerals can be dissolved by the soil test extractant, releasing calcium and magnesium into the extract. This will inflate the calculated CEC and the calcium and magnesium percentages, leading to unrealistically high potassium recommendations.

The basic cation saturation ratio concept does have merit in recognizing extremes in the ratios between cations, especially in soils with very low CEC and fertility. In particular, potassium can interfere with magnesium uptake. Extra care must be taken to ensure adequate magnesium supplies where soils test high in potassium and low in magnesium. This interaction is particularly important in the management of ruminant nutritional problems such as grass tetany.

Adjusting potassium recommendations for cation exchange capacity (CEC)

Some states adjust potassium recommendations for CEC. In Michigan, Ohio and Indiana, the potassium recommendations increase with increasing CEC. This recommendation is based on trials in southern Ohio. Clay soils in this area can fix significant amounts of potassium. This leads to a greater requirement for potassium on the heavier textured soils, both for optimum crop yield and to build the potassium soil test levels. The younger soils of northern Ohio contain more native potassium in the clays and do not fix potassium as readily. In these soils, the clay content or CEC has only a very minor effect on the amount of potassium required.

In New York, for a given level of soil test potassium, potassium recommendations are higher on sandier, low-CEC soils. Research there has shown that soils higher in clay release more potassium through weathering, so that less potassium fertilizer is required for optimum crop yields.

Ontario research has not found any significant effect of CEC on the amount of potassium required.

Spatial variability

Most fertilizer calibrations have been done on small plots where soil fertility is relatively uniform. Most fields, however, show large variations in soil test levels. Ontario fields that have been intensively sampled show a coefficient of variation of 18%–54% for nitrate, 20%–140% for phosphorus, 12%–70% for potassium and 50%–60% for micronutrients.

This variation in soil test values means that part of the field has above-average fertility and a lower-than-average response to applied fertilizer. Another part of the field has below-average fertility and shows a larger-than-average response to fertilizer.

The yield gain from extra fertilizer on the low-testing areas generally is larger than the cost of the extra fertilizer on the high-testing areas.

As the field becomes more variable, the part that is highly responsive becomes larger in relation to the low- or no-response part of the field. The net result is that, in variable fields, the most profitable single rate of fertilizer to apply to the whole field is higher than the requirement for a uniform field.

An example of the effect of variability in soil test values on optimum fertilizer rate is shown in Table 7–8. Note how spatial variability increases the optimum constant rate of potassium, particularly in high-testing soils.

If the spatial variability within a field can be mapped accurately, the same yields could be attained with less increase in fertilizer use than shown in the table. This could be done by using variable rate application of fertilizer on the most responsive areas. However, sampling fields on the scale of one sample per hectare or acre can miss some of this variability. The variable-rate technology for such applications is available, but the development of accurate application maps is still very challenging.

In fields with highly variable soil test values, you can improve profitability of fertilizer use with variable rate application, providing that significant areas of the field are in the responsive soil test range.

Table 7–8. Influence of variability in soil test K values on optimum K fertilizer rate in Ontario

Average soil test K ppm	Optimum K$_2$O rate (kg/ha) at differing levels of variability in soil test values		
	Low	Moderate	High
45	100	101	106
90	50	58	77
135	0	30	58

Source: Kachanoski and Fairchild, 1994. Coefficient of variation for low variability site = 0%, moderate = 53% and high = 131%.

Cost of under- versus over-fertilizing

In yield response curves (e.g., Figure 7–3), the slope decreases as applied fertilizer increases. Therefore, the change in yield for a given percentage of under-fertilization is greater than the change in yield for the same amount of over-fertilization (see Table 7–9).

If you are unsure whether a recommendation is accurate, erring on the side of over-fertilization entails smaller profit losses than those arising from under-fertilizing. The actual difference depends on the shape of the response curve. This is most likely to be apparent for nutrients such as nitrogen, where yield increases are relatively linear until a plateau is reached.

For nutrients that can have a negative environmental impact, such as nitrogen and phosphorus, over-fertilization is a concern. It's important to make every attempt to be accurate in determining recommendations and to use every means possible to get information on the particular recommendation.

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Table 7–9. Effect of under-fertilizing versus over-fertilizing on net return for grain corn

LEGEND: MERN = maximum economic rate of nitrogen

Fertilizer rate kg N/ha (lb N/acre)	Yield t/ha (bu/acre)	Crop value	Nitrogen cost	Net return	Difference
		$/ha ($/acre)			
90 (81) ⅓ less	9.3 (148)	1,466 (594)	119 (48)	1,347 (545)	- 84 (34)
135 (121) recommended	10.2 (163)	1,610 (652)	179 (73)	1,431 (579)	–
181 (161) ⅓ more	10.7 (171)	1,687 (683)	239 (97)	1,448 (586)	+17 (7)
148 (132) MERN	10.7 (171)	1,686 (682)	196 (79)	1,490 (603)	+59 (24)

Price assumptions: Corn @ $4.00/bushel; N @ $0.60/lb.

Recommended nitrogen rate based on Ontario Corn Nitrogen Calculator. Previous crops included grain corn, soybeans, edible beans and cereals. Sites with forage grasses, forage legumes or cover crops as previous crop were excluded.

Source: mean of 96 fertilizer N rate trials from the Ontario corn nitrogen database, 2005–2017.

Agronomic and environmental impacts of fertilizer application

Under the humid conditions of eastern North America, the amount of mineral nitrogen left in the soil post-harvest is a reliable indicator of the risk of loss through either leaching or denitrification. Post-harvest residual nitrate levels increase greatly when application rates exceed the amount required for optimum yield. This is clearly shown in Figure 7–10, where the crop yield plateaus while the level of residual soil N continues to increase.
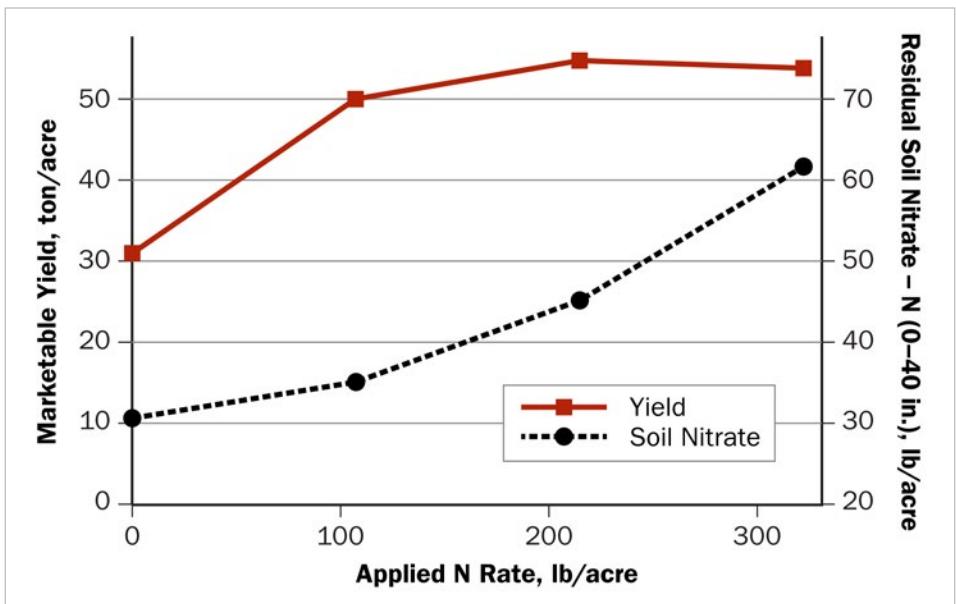

Figure 7–10. Tomato response to nitrogen. (The use of imperial measurement reflects the standards used in the industry.) *Source:* T.Q. Zhang, Agriculture and Agri-Food Canada, 2005.

Nitrogen fertilization:
rate, timing, weather and planting dates

Given that weather affects the rate at which fertilizer nitrogen is lost from the soil, a crop's demand for nitrogen and the rate at which organic nitrogen in the soil is mineralized and made plant-available, it is little wonder that we see yearly variations in crop fertilizer requirements and responses to applied nitrogen. Recent studies (Tremblay et al., 2012; Xie et al., 2013; Kablan et al., 2017) and evaluations of corn nitrogen response datasets in neighbouring states and Quebec suggest that response to nitrogen fertilizer is greater in fine-textured versus medium-textured soils, and yield responses to in-season (side-dressed) nitrogen applications are greater with increased rainfall.

The series of studies demonstrate that the year-to-year variability in optimal nitrogen rate is more dependent on the distribution of rainfall than the overall amount of rainfall or crop heat units (CHUs), although CHUs are still important. In growing seasons with low CHUs and increased variability of rainfall patterns, responses to in-season nitrogen applications decrease. Well-distributed rainfall and higher CHUs lead to higher optimal in-season nitrogen application rates. Precipitation prior to side-dressing appears to be more strongly correlated to fertilizer nitrogen yield responses than rainfall after side-dressing. Late planting results in greater variability in the optimal nitrogen rates than planting on optimal planting dates.

Side-dressing and possibly further splitting the application of nitrogen on corn might be one way to minimize losses while allowing for fertilizer rate adjustments based on growing season conditions and planting dates. With later nitrogen applications after side-dressing, the additional cost of the application is an important consideration in determining the overall economic benefit.

Developing fertilizer recommendations:
the Ontario Corn Nitrogen Calculator

Ontario's nitrogen recommendations for corn were updated in 2006. Data was collected from 41 years of N trials, and response curves were re-calculated to fit a quadratic-plateau model. Optimum rates of N for each site-year were determined, and the factors with the greatest impact on optimum N rates were used to develop a model to predict N requirements for individual fields.

The factors included in the model were the yield potential for the field (average yield for the past 5 years), soil texture, previous crop, crop heat unit rating, application timing and the relative price of corn and nitrogen fertilizer.

More information on the Ontario Corn Nitrogen Calculator can be found at www.gocorn.net.

Crop nutrient uptake and removal per unit of yield

Nutrient uptake refers to the maximum quantity of nutrient taken up into the above-ground portion of the crop. Nutrient removal is the amount of nutrient removed in the harvested portion of the crop. The two are nearly equal in crops harvested as whole plants like silage corn, alfalfa and cabbage.

The amounts shown in Tables 7–10 and 7–11 are based on Ontario field data where possible and general North American crops where local data were insufficient. To do precise nutrient budgeting, it is necessary to have the particular crop analyzed for nutrient content.

The forage crop figures are specific to Ontario and are ranges observed in samples submitted for analysis to Agri-Food Laboratories, Guelph, over 5 years in the early 1990s.

Table 7–10. Field crop nutrient removal in Ontario

LEGEND: — = Data not available

Crop	Unit	N*	P_2O_5	K_2O	Ca	Mg	S
Grains and oilseeds (at marketing moisture content)							
grain corn	kg/t	11.5–17.7	6.6–7.9	4.6–5.2	0.12	1.55	1.2–1.3
	lb/bu	0.7–1.0	0.37–0.44	0.26–0.29	0.007	0.087	0.07
soybean	kg/t	62.3–66.7	13.3–14.7	23.0–23.3	3.0–3.7	2.3–3.0	0.67
	lb/bu	3.7–4.0	0.80–0.88	1.38–1.40	0.18–0.22	0.14–0.18	0.033
winter wheat	kg/t	19.1–20.9	9.1–10.4	5.78–6.22	0.44	2.67	1.33
	lb/bu	1.15–1.25	0.55–0.63	0.35–0.37	0.027	0.16	0.08
barley	kg/t	18.1–23.1	7.78–8.33	5.28–7.22	0.56	1.11	1.67
	lb/bu	0.87–1.11	0.37–0.40	0.25–0.35	0.027	0.053	0.08
oat	kg/t	19.6–25.0	7.92	5.83–6.25	0.833	1.25	2.08
	lb/bu	0.63–0.80	0.253	0.19–0.20	0.027	0.04	0.067
winter rye	kg/t	19.3–21.8	6.07–8.21	6.07–6.43	1.07	1.43	1.79–3.57
	lb/bu	1.08–1.22	0.34–0.46	0.34–0.36	0.06	0.08	0.10
dry beans	kg/t	83.3	27.8	27.8	2.22	2.22	5.56
	lb/bu	2.50	0.83	0.83	0.067	0.067	0.167
canola	kg/t	40.0–44.4	22.2–26.7	11.1–13.3	4.0–5.3	5.33–6.67	6.67
	lb/bu	2.0–2.2	1.11–1.33	0.56–0.67	0.20–0.27	0.27–0.33	0.33

* Soybeans, dry beans, forage legumes get most of their nitrogen from the air.

** Nutrient contents in harvested stover or straw are extremely variable due to variations in harvesting methods (cutting height, method of collection, timing of harvest, etc.). It is highly recommended that nutrient analyses of a representative subsample of the harvested material be conducted for more reliable estimates of nutrient removal.

Ranges of nutrient uptake and removal for yield levels typical of good growing conditions for field crops. Figures are based on Ontario field data where possible and are estimates. Actual uptake and removal will vary with yield, and nutrient concentrations will also vary with year, level of soil fertility and crop variety. Precise nutrient management planning would require analysis of each crop each year. Actual changes to soil fertility may differ from the amount removed by the crop. In some instances, weathering of soil materials and organic matter may compensate for part of the nutrient removal by crops. In other instances, nutrients may be chemically fixed by the soil or lost to leaching, and the loss of nutrients will exceed crop removal.

Table 7–10. Field crop nutrient removal in Ontario

LEGEND: — = Data not available

Crop	Unit	N*	P₂O₅	K₂O	Ca	Mg	S
Grains and oilseeds — stover or straw (based on dry weight) **							
corn stover	kg/t	8.0–10.6	2.1–6.4	17.4–20.0	3.5–13.4	2.5–8.6	1.3–1.7
	lb/ton	16.0–21.2	4.1–12.8	34.8–39.9	7.0–11.4	5.0–17.2	2.6–3.4
soybean stover	kg/t	8.0–23.0	1.0–4.4	8.7–19.0	15.0–17.3	4.1–8.6	3.1–6.5
	lb/ton	4.0–46.0	2.0–8.8	17.4–37.9	30.0–34.6	8.1–17.2	6.2–13.0
winter wheat straw	kg/t	4.4–9.6	1.0–4.9	12.0–23.2	1.6–10.4	0.4–7.1	2.7
	lb/ton	8.8–19.2	2.0–9.8	24.0–46.4	3.2–20.8	0.7	5.4
oat straw	kg/t	6.0	3.2	19.0	2.4	0.7	2.3
	lb/ton	12.0	6.4	37.9	4.8	1.3	4.5
winter rye straw	kg/t	6	6.1–8.2	6.3	—	0.3	1.0
	lb/ton	12.0	12.2–16.4	12.5	—	0.6	2.0
Forages (based on dry weight)							
corn silage	kg/t	10.8–15.0	4.6–6.8	8.3–15.2	1.6–3.1	1.1–1.9	0.8–1.0
	lb/ton	21.6–29.9	9.3–13.6	16.6–30.4	3.3–6.1	2.3–3.8	1.6–2.0
legume haylage	kg/t	26.6–36.8	5.3–7.9	22.4–35.5	11.3–17.7	1.9–3.6	1.9–2.0
	lb/ton	53.2–73.4	10.6–15.8	44.8–70.8	22.6–35.4	3.8–7.2	3.8–4.0
mixed haylage	kg/t	22.8–33.9	5.2–7.8	22.4–35.6	9.5–16.4	1.6–3.4	1.5–2.9
	lb/ton	45.6–67.6	10.4–15.6	44.8–71.0	19.0–32.8	3.2–6.8	3.0–5.8
grass haylage	kg/t	16.2–27.4	4.9–7.8	20.4–35.9	5.3–11.3	1.3–2.6	0.8
	lb/ton	32.3–54.8	9.8–15.5	40.8–71.8	10.5–22.5	2.5–5.3	1.6
legume hay, 1st cut	kg/t	22.3–33.1	5.2–8.0	20.6–35.1	10.1–15.4	2.1–3.4	1.9–2.7
	lb/ton	44.6–66.2	10.4–16.0	41.2–70.0	20.2–30.8	4.2–6.8	3.8–5.4
mixed hay, 1st cut	kg/t	17.2–27.4	5.0–7.2	17.0–29.8	8.2–13.5	1.8–3.0	1.3–2.1
	lb/ton	34.4–54.6	10.0–14.4	34.0–59.4	16.4–27.0	3.6–6.0	2.6–4.2
grass, 1st cut	kg/t	12.9–22.7	4.4–7.0	13.9–28.1	5.3–10.6	1.4–2.6	1.4–2.0
	lb/ton	25.8–45.3	8.8–14.0	27.8–56.0	10.5–21.3	2.8–5.3	2.8–4.0
mixed hay, 2nd cut	kg/t	25.4–35.9	5.7–7.8	19.7–31.9	11.4–17.0	2.3–3.8	1.8–2.8
	lb/ton	50.7–71.7	11.3–15.7	39.7–63.7	22.7–34.0	4.7–7.7	3.7–5.7

* Soybeans, dry beans, forage legumes get most of their nitrogen from the air.

** Nutrient contents in harvested stover or straw are extremely variable due to variations in harvesting methods (cutting height, method of collection, timing of harvest, etc.). It is highly recommended that nutrient analyses of a representative subsample of the harvested material be conducted for more reliable estimates of nutrient removal.

Ranges of nutrient uptake and removal for yield levels typical of good growing conditions for field crops. Figures are based on Ontario field data where possible and are estimates. Actual uptake and removal will vary with yield, and nutrient concentrations will also vary with year, level of soil fertility and crop variety. Precise nutrient management planning would require analysis of each crop each year. Actual changes to soil fertility may differ from the amount removed by the crop. In some instances, weathering of soil materials and organic matter may compensate for part of the nutrient removal by crops. In other instances, nutrients may be chemically fixed by the soil or lost to leaching, and the loss of nutrients will exceed crop removal.

Table 7–11. Horticultural crop nutrient uptake and removal Ontario
Ranges of nutrient uptake and removal for yield levels typical of good growing conditions for horticultural crops

LEGEND: — = Data not available

Crop	Uptake/ removal	N*	P_2O_5	K_2O	Ca	Mg	S
				kg/tonne (lb/ton)			
beans, green	uptake	17 (34)	5–12 (10–24)	10–20.4 (20–40.7)	— —	2.2 (4.3)	— —
	removal	2.9 (5.7)	0.5 (1)	5.7 (11.3)	— —	— —	— —
broccoli	uptake	16.6 (33.3)	1 (2)	20.6 (41.2)	— —	— —	— —
	removal	6 (12)	0.6 (1.3)	4.5 (9)	— —	— —	— —
cabbage	uptake	3–4.8 (6–9.6)	0.8–1.8 (1.6–3.6)	3.3–5.4 (6.5–10.8)	1.1–3.3 (2.2–6.6)	1.1 (2.2)	0.9–1.1 (1.8–2.2)
	removal	2.0–3.3 (4.0–6.6)	0.6–1.1 (1.2–2.2)	2.1–3.4 (4.2–6.8)	1.0–3.1 (2.0–6.2)	0.7 (1.4)	0.6–0.7 (1.2–1.4)
carrot	uptake	2.9 (5.8)	0.5 (1.0)	6.9 (13.8)	— —	— —	— —
	removal	1.6 (3.2)	0.4 (0.8)	4.0 (8.0)	— —	— —	— —
corn, sweet	uptake	12.9–15.6 (25.8–31.2)	1.7–5.3 (3.3–10.5)	8.8–15.1 (17.5–30.2)	— —	2.3 (4.5)	1.3 (2.5)
	removal	4.2 (8.3)	0.3 (0.7)	2.5 (5.0)	— —	— —	— —
onion	uptake	3–3.6 (6–7.3)	0.6–1.3 (1.3–2.7)	2.6–3.9 (5.3–7.8)	0.8 (1.5)	0.3 (0.5)	0.5–0.9 (1.0–1.8)
	removal	1.9 (3.8)	0.4 (0.8)	2.0–2.1 (4.0–4.3)	0.6 (1.2)	0.1–0.3 (0.2–0.5)	0.5–0.9 (1.0–1.8)
peas, green	uptake	43–65 (85–130)	5.5–14.0 (11–28)	20–42 (40–84)	— —	7.3 (14.5)	4 (8)
	removal	10 (20)	0.5 (1)	7.5 (15)	— —	— —	— —
potato	uptake	5.3–5.7 (10.7–11.3)	1.7–1.8 (3.3–3.7)	7.3–11.0 (14.7–22.0)	— —	1 (2)	0.5 (1)
	removal	2.1 (4.2)	0.4 (0.8)	3.6–4.2 (7.2–8.3)	0.08 (0.16)	0.17 (0.33)	0.17–0.20 (0.33–0.40)
sugar beets	uptake	4.2–4.8 (8.5–9.6)	0.7–1.5 (1.3–3.0)	8.8–9.2 (17.5–18.3)	— —	1.3 (2.7)	0.7–0.8 (1.4–1.6)
	removal	2.0–2.1 (4.0–4.2)	0.3–0.9 (0.5–1.8)	3.3–4.2 (6.5–8.3)	— —	— —	0.3 (0.6)

* Legumes such as beans and peas get much of their nitrogen from the air.

Table 7–11. Horticultural crop nutrient uptake and removal Ontario
Ranges of nutrient uptake and removal for yield levels typical of good growing conditions for horticultural crops

LEGEND: — = Data not available

Crop	Uptake/ removal	N*	P_2O_5	K_2O	Ca	Mg	S
		kg/tonne (lb/ton)					
tobacco	uptake	42–55 (84–110)	8.5–15 (17–30)	85.0–85.5 (170–171)	— —	9 (18)	7 (14)
	removal	28.0–37.5 (56–75)	2–3 (4–6)	52–60 (104–120)	37.5 (75)	8 (16)	6.5 (13)
tomato	uptake	2.9 (5.8)	1.1 (2.2)	5.8 (11.6)	— —	0.45 (0.9)	0.7 (1.4)
	removal	1.8–2.0 (3.6–4.0)	0.3 (0.6)	3.5–3.6 (7.0–7.2)	0.18–0.30 (0.35–0.60)	0.28–0.30 (0.55–0.60)	0.35 (0.7)
apple	uptake	4.2 (8.3)	1.9 (3.8)	7.5 (15)	— —	1 (2)	— —
grapes	uptake	4.3 (8.5)	1.5 (3)	6.7 (13.3)	— —	0.8 (1.5)	— —
peaches	uptake	1.7 (3.3)	0.7 (1.3)	2 (4)	0.36 (0.7)	— —	— —

* Legumes such as beans and peas get much of their nitrogen from the air.

Nutrient recommendations based on plant tissue analysis

Tissue, leaf or plant analysis can be used to:

- determine the nutrient needs of established perennial crops such as cane berries, tree fruit and grapes
- confirm the diagnosis of visual symptoms of unusual plant growth, so that remedies can be used immediately

In perennial crops, it is often preferable to use tissue analysis in conjunction with soil testing. Tissue analysis also helps show what nutrients are being taken up by the crop, as opposed to what is available in the soil. Occasional soil analysis from orchards and vineyards is often useful when done along with tissue analysis, particularly for monitoring pH levels. A tissue analysis may indicate a nutrient could be deficient or limiting, but it is not easy to make a fertilizer recommendation rate from a tissue analysis. Thus, tissue analyses can be used to adjust fertilizer application for the following growing season.

Used along with a soil test, tissue analysis can identify possible nutrient limitations or deficiencies. A tissue analysis may indicate that nutrients could be deficient or limiting but may not provide information in time for correction for annual crops in the current growing season.
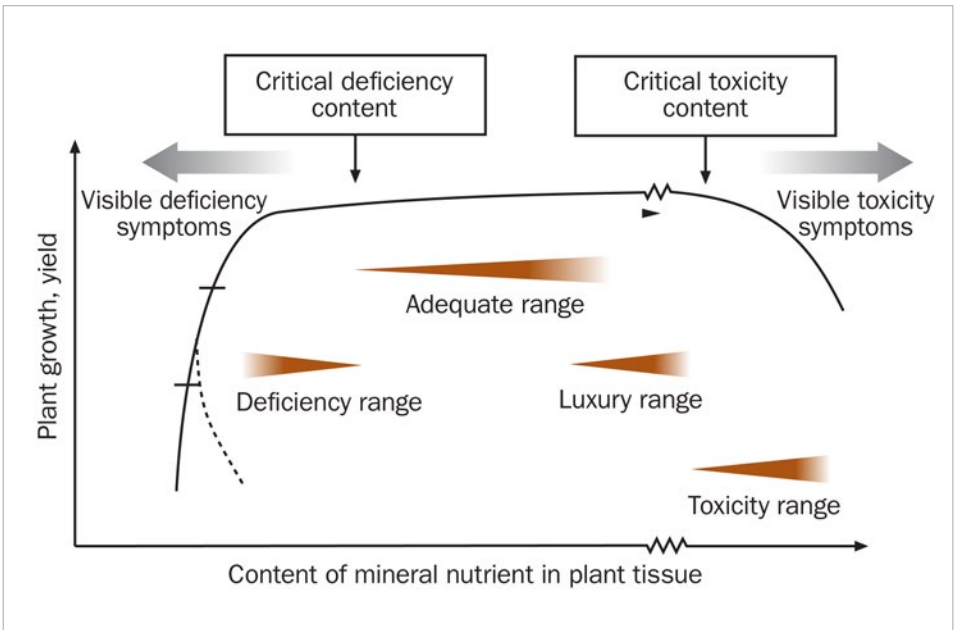
Figure 7–11. Relationship between plant nutrient content and growth yield of plants

Deficient, critical and sufficient concentrations

Plant analysis identifies a nutrient as being deficient when its concentration falls below a critical level for a given plant part for a given crop at a given stage of plant development. The concept of the critical level separating deficient and adequate ranges is illustrated in Figure 7–11.

In order to interpret the tissue analysis, the timing or stage of plant growth and the plant part being sampled are very important. For more details on sampling plant tissue, refer to Chapter 4.

OMAFRA crop recommendation and production guides list critical nutrient ranges for most crops grown in Ontario. Many publications on field and horticultural crops list critical

values. Most labs that do tissue analysis have their own set of critical values, developed from their own experience. It is important to closely follow the laboratory's instructions regarding plant part sampled, stage of plant development and sample handling.

When investigating crop growth peculiarities, if the time of sampling does not correspond to the stage of plant development for which there are established critical values, separately sample affected and unaffected areas for comparison.

Table 7–12 shows the probable causes for excessive or deficient levels of nutrients in plant tissue samples. Interpretations of these results are not as simple as simply looking at the numbers on the analytical report.

Table 7–12. Possible causes for variation in plant tissue nutrient levels

Nutrient	Excessive	Deficient
all nutrients	soil or dust contamination of the plant material can give rise to elevated values for many nutrients; similarly, recent foliar application of fertilizers will give elevated plant tissue values	inadequate supply of any nutrient from the soil will tend to produce low plant tissue levels
nitrogen	over-application of nitrogen, from commercial sources and or manure; high levels of soil organic matter; high rates of mineralization	low organic matter, soil compaction, dry soil conditions, water-logged conditions causing denitrification
phosphorus	high soil test value, low or deficient zinc, high rates of phosphorus nutrient application	low or high soil pH, soil compaction, drought, cold soils, root disease
potassium	high rates of application, high soil test level	excessive nitrogen, soil compaction, cold soils
magnesium	mature plant parts, over-application of magnesium fertilizer	low pH, high potassium availability, high ammonium-N levels
calcium	mature plant parts, diseased leaf, contamination of sample with soil **Note:** High calcium levels are rare.	leached sandy soil, high rates of potassium in low-CEC soils, high ammonium-N availability, low pH, inadequate rates of limestone
zinc	naturally high soil zinc, heavy application of swine manures, high levels of organic matter	high soil pH, high phosphorus application rates, eroded soil areas, low levels of soil organic matter
manganese	high nitrogen and phosphorus applications, low-pH, soil compaction, low oxygen root environment, contamination from sprays and dust	high soil pH, highly aerated soil, high organic matter
copper	high soil copper levels, spray materials (fungicides), soil splash up on leaves	high levels of soil organic matter, leached soil, high levels of zinc and manganese
iron	wet soil conditions, soil on leaves, zinc deficiency	excessive phosphorus, zinc, copper and manganese
boron	improper application rates, lowered soil pH	sandy leached soils, low levels of organic matter, dry sandy soils
sulphur	high application rates of sulphate-sulphur, foliar spray residues on leaves	excessive rates of nitrogen application or high mineralization rates from soil organic matter, leaching losses
molybdenum	high soil pH, foliar application residues	low soil pH, high levels of phosphorus, sulphur applications (ion antagonism at root)

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Diagnosis and recommendation integrated system (DRIS)

The DRIS was initially designed to apply to both soil and plant analysis. In North America it has been used more frequently for plant analysis.

The system relates complete sets of nutrient concentrations and ratios for a particular crop to those of crops grown under optimum conditions at the highest attainable yield levels. The values and ratios obtained from these crops are referred to as DRIS norms.

The DRIS approach applied to plant analysis places a relative ranking of the essential elements from the most to the least deficient. In some cases, this analysis has been found to be more sensitive than the critical, or sufficiency, level in identifying the need for higher levels of one or more nutrients. Because DRIS uses ratios of nutrients, dry matter dilution due to the maturing of the crop is minimized and the time of sampling has less influence on the test results.

Initially it was thought DRIS norms were applicable across wide areas. However, studies on major agronomic crops show that locally or regionally developed norms are more accurate in diagnosing deficiencies. While the DRIS has not yet become a completely reliable system for fertilizer recommendations, it provides the possibility of bringing together all the elements of plant nutrition and evaluating them simultaneously with yield level as part of the process. Providing that adequate calibration data become available, the DRIS approach may be used more often in the future.

Fertilizer recommendations: not a production prescription

No one table of recommendations can cover all situations. A recommendation is not a production prescription. The amounts recommended by any source may be adjusted using local experience and knowledge of the particular soils and financial conditions of the producer. It is more valid to make such an adjustment than to use the general recommendations.

The fertilizer retailer is often in a good position to know the peculiarities of the soils, owing to the geographic limitations of distribution from a fertilizer blending plant. For this reason, each retail outlet should have at least one experienced agronomist or Certified Crop Adviser qualified to make sound recommendations.

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8. Fertilizer Materials, Blending and Application

Fertilizer materials

No matter what fertilizer you apply, the materials you choose and the way you blend and apply them will have great impact on your fertilizer program. Most of the fertilizer applied in Ontario is in the granular form, but liquids and gases are also used. Each form is listed below and in Table 8–1 with its specific grade (% N-P_2O_5-K_2O by weight), chemical analysis, and handling and use characteristics. All fertilizer materials need to be handled in a safe and effective manner. Material Safety Data Sheets (MSDS) describe the characteristics of each material and are available at every point of sale for customers and employees to obtain.

Granular fertilizers generally have a higher analysis (nutrient content) than liquid fertilizers and are relatively less expensive. Their storage, handling and transport requirements differ from those of liquid or gaseous fertilizers. Granular materials can be blended to meet a wide range of crop requirements.

In general, liquid fertilizers are more expensive per unit of nutrient than granular fertilizers because of the extra weight and volume that must be transported, and, in some cases, the extra processing. This is balanced by the convenience of being able to pump it and the ease and accuracy of metering and placement.

In 2016, ammonium polyphosphate (10-34-0), a liquid, cost 84% more than the same amount of nutrient purchased as (granular) mono-ammonium phosphate. The difference is even greater for complete N-P-K fertilizers, where liquids may cost double the equivalent in granular fertilizer.

Nitrogen (N) sources

Urea (46-0-0)

- $CO(NH_2)_2$
- white
- manufactured from ammonia and carbon dioxide
- most commonly used fertilizer N source worldwide
- may contain small amounts (0.5%–1.5%) of biuret, about 0.3% conditioning agent (formaldehyde or methylene di-urea) and less than 0.5% moisture
- grades for foliar application should contain less biuret
- Urea converts to the ammonium form of N in the soil. The urease enzyme — present in soil, bacteria and crop residues — speeds the process. Surface-applied urea is subject to losses of ammonia gas. Losses increase with higher soil pH, greater crop residue cover and higher temperatures.

Ammonium nitrate (34-0-0)

- NH_4NO_3
- produced by combining ammonia with nitric acid
- may contain about 1% conditioning agent and 0.5% moisture
- more expensive per unit of N than urea
- no longer produced in Canada
- regulations apply to its transport (Transport of Dangerous Goods Class 5.1)
- needs to be kept away from oils and other flammable materials as it can form an explosive mixture
- more hygroscopic than urea and may deteriorate in storage during hot weather as crystal phase changes result in a breakdown of the prills

When applied to the soil, ammonium nitrate dissolves in the soil water and separates into ammonium and nitrate, both of which can be absorbed by plants. At low temperatures, it is available to plants slightly more quickly than urea, but under normal growing conditions there is no practical difference.

Calcium ammonium nitrate (27-0-0)

- uniform mixture of 80% ammonium nitrate and either calcitic or dolomitic limestone
- limestone reduces explosion hazard

When applied at equal weights of N, calcium ammonium nitrate is similar to ammonium nitrate. The lime included in the granules balances part of the acidity released by the N, so that it does not acidify the soil as quickly as ammonium nitrate does.

Urea-ammonium nitrate solution (UAN) (28-0-0 to 32-0-0)

- produced by dissolving urea and ammonium nitrate (50:50) in water
- 28-0-0 can salt out (precipitate out of solution) if the temperature drops below −18°C (0°F)
- more concentrated solution (32-0-0) is available but not often used in Ontario because the salting out temperature is 0°C
- due to its urea content, it is subject to loss as ammonia if applied to the soil surface
- herbicides and other pesticides are commonly added to UAN for broadcast application on the soil
- avoid application onto crop foliage because severe burning will result
- lends itself to side-dress applications

Urea-ammonium nitrate solution is the most commonly used liquid fertilizer in Ontario.

Anhydrous ammonia (82-0-0)

- NH_3
- manufactured by reacting natural gas with atmospheric N under high pressures and temperatures
- colourless, pungent gas at atmospheric pressure
- handled as a pressurized liquid: at −2°C, the pressure is the same as surrounding air; at 16°C, it is 655 kPa (95 psi).
- building block for all manufactured N fertilizers
- similar to urea and ammonium nitrate in its acidifying effect (1.8 lb $CaCO_3$ to neutralize acidity generated per lb of N supplied)

Anhydrous ammonia is applied directly by injecting it into the soil, where it vapourizes and dissolves in the soil moisture. To avoid vapour losses to the air, the anhydrous band must be placed deep enough in the soil that the injection slot closes over.

There is some concern that anhydrous ammonia is harmful to soil life. Within the injection band, high soil pH and hygroscopic conditions are severe enough to kill earthworms and other soil fauna and microflora, but this zone is relatively small and dissipates quickly. The population of soil organisms quickly recovers and is actually increased by the addition of N to the soil ecosystem.

Ammonium sulphate (21-0-0)

- $(NH_4)_2SO_4$
- white-to-brown crystalline industrial by-product obtained by neutralizing ammonia from coke ovens with recycled sulphuric acid, or from nylon manufacturing
- may contain about 0.5% moisture and minute amounts of nutrients such as K, calcium, copper, iron, manganese and zinc
- generally more expensive per unit of N than urea

Ammonium sulphate breaks down to ammonium and sulphate when dissolved in the soil water. It is useful for surface broadcast applications as there is less risk of ammonia volatilization. Depending on source, its form is granular or coarse powder.

Calcium nitrate (15-0-0)

- $Ca(NO_3)_2$
- expensive source of N
- used only where both calcium and N are required and soil acidification is undesirable
- contains N in nitrate form and water-soluble calcium
- highly hygroscopic; may liquefy completely when exposed to air with a relative humidity above 47%; store any broken bags in a tightly closed waterproof bag

The highly soluble nitrate-N and calcium are immediately available to the plant.

Potassium nitrate (12-0-44)

- KNO_3
- extracted from dry brine lakes (e.g., Dead Sea) or manufactured by reacting potassium chloride and nitric acid
- expensive source of N and K
- used mainly for horticultural crops, tobacco and hydroponics

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Those little puffs

Have you wondered about those little puffs of vapour behind the anhydrous applicator?

Many farmers worry they are losing large quantities of N fertilizer. In fact, most of what they are seeing is a fog created by the cold ammonia gas condensing water vapour. It has been estimated that each millilitre of ammonia can produce over a litre of mist. The average emission loss is only 4% and is less in good conditions.

Table 8–1. Common fertilizer ingredients

LEGEND: – = none   N/A = not available

Ingredient	Grade[1] (%)	Other nutrients[2]	Salt index[3]	CaCO₃ equivalent[4] (lb/lb)	Bulk density[5] (lb/ft³)	Bulk density[5] (kg/L)	Relative cost/unit nutrient[6]
Granular							
urea	46-0-0	–	74	1.8	50	0.80	1.00
ammonium nitrate	34-0-0	–	104	1.8	56	0.90	1.42
calcium ammonium nitrate	27-0-0	4%–6% Ca 0%–2% Mg	93	0.9	68	1.10	1.46
ammonium sulphate	21-0-0	24% S	88	3.6	68	1.10	1.41–2.04
calcium nitrate	15-0-0	19% Ca	65	-1.3 (B)	75	1.20	3.72
potassium nitrate	12-0-44	–	70	-1.9 (B)	75	1.20	2.54
sodium nitrate	16-0-0	–	100	-1.8 (B)	78	1.25	N/A
single superphosphate	0-20-0	20% Ca, 12% S	8	neutral	68	1.10	1.77
triple superphosphate	0-46-0	21% Ca	10	neutral	68	1.10	1.00
mono-ammonium phosphate	11-52-0	–	27	5.4	62	1.00	0.82
di-ammonium phosphate	18-46-0	–	29	3.6	62	1.00	0.81
muriate of potash (red)	0-0-60	45% Cl	115	neutral	70	1.10	1.00
muriate of potash (white)	0-0-62	46% Cl	116	neutral	75	1.20	1.00
potassium sulphate	0-0-50	18% S	43	neutral	75	1.20	2.34
sulphate of potash-magnesia	0-0-22	20% S 11% Mg	43	neutral	94	1.50	3.71

[1] Grade: guaranteed minimum percentage by weight of total N, available phosphoric acid (P_2O_5) and soluble potash (K_2O) in each fertilizer material.

[2] Nutrients other than N, P or K.

[3] Salt index: comparison of relative solubilities of fertilizer compounds with sodium nitrate (100) per weight of material. When applied too close to the seed or on the foliage, materials with a higher salt index are more likely to cause injury.

[4] CaCO₃ equivalent: pounds of lime required to neutralize the acid formed by 1 lb of the N supplied by the fertilizer material. "B" following the lime index indicates a basic (acid-neutralizing or alkaline) ingredient. **Note:** acid-forming effects can be up to twice as great as indicated, depending on plant uptake processes.

[5] Bulk density: expressed as pounds per cubic foot or kg/L. This is important since fertilizers are metered by volume rather than weight in spreaders or planting equipment.

[6] Relative cost/unit: based on 2006 prices of urea for N, triple superphosphate for P and muriate of potash for K.

Table 8–1. Common fertilizer ingredients

LEGEND: – = none   N/A = not available

Ingredient	Grade[1] (%)	Other nutrients[2]	Salt index[3]	CaCO$_3$ equivalent[4] (lb/lb)	Bulk density[5] (lb/ft^3)	Bulk density[5] (kg/L)	Relative cost/unit nutrient[6]
Liquid							
anhydrous ammonia	82-0-0	–	47	1.8	37	0.6	0.83
urea-ammonium nitrate (UAN)	28-0-0	–	63	1.8	80	1.28	1.10
	32-0-0	–	71	N/A	82	1.32	N/A
ammonium polyphosphate	10-34-0 11-37-0	–	20	3.6	87	1.40	1.27

[1] Grade: guaranteed minimum percentage by weight of total N, available phosphoric acid (P$_2$O$_5$) and soluble potash (K$_2$O) in each fertilizer material.

[2] Nutrients other than N, P or K.

[3] Salt index: comparison of relative solubilities of fertilizer compounds with sodium nitrate (100) per weight of material. When applied too close to the seed or on the foliage, materials with a higher salt index are more likely to cause injury.

[4] CaCO$_3$ equivalent: pounds of lime required to neutralize the acid formed by 1 lb of the N supplied by the fertilizer material. "B" following the lime index indicates a basic (acid-neutralizing or alkaline) ingredient. **Note:** acid-forming effects can be up to twice as great as indicated, depending on plant uptake processes.

[5] Bulk density: expressed as pounds per cubic foot or kg/L. This is important since fertilizers are metered by volume rather than weight in spreaders or planting equipment.

[6] Relative cost/unit: based on 2006 prices of urea for N, triple superphosphate for P and muriate of potash for K.

Phosphorus (P) sources

Single superphosphate (0-20-0)

- about one-half mono-calcium phosphate and one-half gypsum [Ca(H$_2$PO$_4$)$_2$•H$_2$O + CaSO$_4$•2H$_2$O]
- made by reacting phosphate rock with sulphuric acid
- usually contains 20% available phosphate, 12% sulphur and 20% calcium

The oldest commercial fertilizer, single superphosphate has been on the market since 1840 and is no longer handled by major fertilizer suppliers in Ontario. It has been largely replaced by mono-ammonium phosphate (MAP).

Triple superphosphate (0-46-0)

- mostly mono-calcium phosphate [Ca(H$_2$PO$_4$)$_2$•H$_2$O]
- made by reacting phosphate rock with phosphoric acid
- contains about 83% mono-calcium phosphate, 2% moisture, and a balance of mostly unreacted phosphate rock and other insoluble phosphates

Mono-calcium phosphate is an acidic salt that can break down urea fairly easily. Triple superphosphate should not be blended with urea. It is rarely available in Ontario, and there is only one North American manufacturer producing it, in the western U.S.

Mono-ammonium phosphate (MAP; 11-52-0)

- $NH_4H_2PO_4$
- produced by reacting anhydrous ammonia with phosphoric acid
- off-white-to-grey colour
- usually contains 85% pure chemical compound, 3%–5% di-ammonium phosphate, 1% moisture, and a balance of magnesium and other phosphates and sulphates
- economical source of N (10%–12.5%) and P (48%–52% P_2O_5)

Mono-ammonium phosphate is the P source of choice in Ontario because of its high nutrient concentration and relative crop safety in starter fertilizers. It's well-suited for use in starter bands.

Di-ammonium phosphate (DAP; 18-46-0)

- $(NH_4)_2HPO_4$
- produced by reacting anhydrous ammonia and phosphoric acid
- relatively low cost per unit
- light-to-dark-grey colour
- usually contains about 80% pure chemical compound, 10% mono-ammonium phosphate, 1%–2% moisture, and a balance of magnesium and other phosphates or sulphates
- may also contain a small amount of ammonium nitrate or urea added during manufacturing to bring the N content up to the guaranteed 18%
- nitrogen 100% water soluble; available phosphate usually 90% water soluble

Di-ammonium phosphate had been the main source of P for several decades because of its cost and high nutrient content. However, it is not always the most suitable choice because of the risk of ammonia injury when used in starter fertilizers, particularly in alkaline soils. Availability of DAP in Ontario is very limited, and it has been replaced by mono-ammonium phosphate (MAP).

Ammonium polyphosphate

- $(NH_4)_3HP_2O_7$
- liquid solution, 10-34-0 analysis (can also be 11-37-0)
- about 75% of the P is polyphosphate; 25% is orthophosphate
- made by reacting ammonia with pyrophosphoric acid, which is made by dehydrating orthophosphoric acid
- solution pH of 6, near neutral
- blends well with UAN

A 10-34-0 solution also blends well with micronutrients. For example, it can maintain 2% Zn in solution compared to 0.05% with phosphoric acid (H_3PO_4).

Rock phosphate

- sedimentary rock made up primarily of calcium fluorophosphate with impurities of iron, aluminum and magnesium
- raw material for production of P fertilizers
- sometimes promoted as a "natural" source of P
- none of the P is water-soluble

- citrate solubility of the P ranges from 5%–17%
- finely ground, it can supply sufficient plant-available P in low pH (acidic) soils when applied at 2 to 3 times the rates of superphosphates
- availability to plants is low-to-nil in neutral or alkaline soils

Potassium (K) sources

Muriate of potash (0-0-60 or 0-0-62)
- KCl (potassium chloride)
- most common and least expensive source of K
- contains chloride (47%), an essential plant nutrient needed for cell division, photosynthesis and disease suppression
- a small amount (less than 100 g/t) of an amine/oil anti-caking agent is often included in the shipped product
- red and white forms offer equal availability of the K to plants

Red muriate of potash (0-0-60)
- mined primarily in Saskatchewan, and some in New Brunswick
- contains about 97% potassium chloride (KCl)
- iron impurities are responsible for the colour; they do not affect solubility

White muriate of potash (0-0-62)
- obtained by crystallizing potassium chloride out of the solution mining liquor
- almost pure potassium chloride

Potassium sulphate (0-0-50-17S)
- K_2SO_4
- extracted from the brines of Great Salt Lake in Utah
- also contains 17% sulphur in the water-soluble form

Potassium sulphate, or sulphate of potash, has a lower salt index and is more expensive than muriate of potash. It is used mainly on crops sensitive to chloride, such as tobacco, potatoes, tree fruits and some vegetables.

Sulphate of potash-magnesia (0-0-22-10.5Mg-22S)
- potassium-magnesium sulphate $K_2SO_4 \bullet 2MgSO_4$
- mined from deposits in New Mexico
- commonly referred to as K-Mag and Sul-Po-Mag

Potassium-magnesium sulphate, or sulphate of potash-magnesia, has a higher cost per unit of K than the muriate form. It also contains 10.5% magnesium and 22% sulphur in water-soluble form and therefore readily available to plants. It is useful as a source of soluble magnesium in fields where lime is not required.

Table 8–2. Blended liquid fertilizers

Analyses	Weight/ US Gal (lb)	Weight/ Imp. Gal (lb)	Weight/ Litre (lb)	Imp. Gal/ Tonne	US Gal/ Tonne	Litre/ Tonne
8-25-3	11.11	13.35	2.94	165.1	198.4	749.9
6-18-6	10.69	12.85	2.83	171.6	206.2	779.0
3-11-11	10.45	12.55	2.76	175.7	211.0	798.8
9-9-9	10.49	12.60	2.77	175.0	210.2	795.9
7-7-7	10.41	12.5	2.75	176.4	211.8	801.7
6-24-6	11.07	13.30	2.93	165.8	199.2	752.4
9-18-9	11.07	13.30	2.92	165.8	199.2	755
5-10-15	10.7	12.85	2.83	171.6	206.0	799
2-10-15	10.62	12.75	2.81	172.9	207.6	784.6
10-34-0	11.6	14.0	3.09	157.0	188.5	715.8

1 Imperial gallon = 1.201 US gallons   1 US gallon = 3.785 litres

1 US gallon = 0.8326 Imperial gallons   1 Imperial gallon = 4.546 litres

Clear solutions
- wide range available of N-P and N-P-K fertilizers with neutral pH (see Table 8–2)
- based on ammonium polyphosphate (10-34-0)
- made by adding urea, aqua ammonia, phosphoric acid, potassium chloride or potassium hydroxide to the ammonium polyphosphate
- micronutrients can be added but must be in the chelated form
- all ingredients must be high quality, since impurities can lead to salting out or gelling of the fertilizer solution
- generally of high agronomic quality, although salt injury to seeds and roots becomes a concern with higher amounts of N and K
- most commonly used as starter fertilizer applied in the seed furrow
- reduces time and labour at planting because of low use rates and the ability to pump the material from nurse tanks into the planter
- equipment cost for planters can be reduced because separate fertilizer opener not required

Acid solutions
- combinations of phosphoric acid, sulphuric acid and urea
- micronutrients do not have to be added in chelated form

Acid solutions are not commonly used in Ontario because they are corrosive and expensive compared to granular fertilizers. These solutions are promoted on the basis that nutrients are more available at the low pH created in the fertilizer band, particularly in alkaline soils. Most soils are well enough buffered, however, that the acid addition has no effect on soil pH. These materials are equal to, but not better than, other fertilizer materials in nutrient availability.

Suspensions

- produced by mixing finely ground dry ingredients with water and a suspending agent such as clay
- can produce a complete fertilizer with a higher analysis than dissolved fertilizer
- mix needs agitation to keep it suspended and special handling and application equipment

Suspensions form an almost insignificant part of the Ontario fertilizer market. Although they were once popular in western Canada, they are in decline.

Secondary nutrient sources

Secondary nutrients are needed occasionally in Ontario soils. If required, they may be applied as part of a fertilizer blend or added as part of a lime application to correct soil acidity. Common sources for secondary and micronutrients are shown in Table 8–3.

Table 8–3. Common secondary and micronutrient sources

Nutrient	Source	Percentage nutrient	Other nutrients	Application soil	Application foliar
calcium (Ca)	calcitic limestone	22%–40%		yes	no
	dolomitic limestone	16%–22%	6%–13% Mg	yes	no
	gypsum ($CaSO_4 \cdot 2H_2O$)	23%	19% S	yes	no
	calcium chloride ($CaCl_2$)	36%	64% Cl	yes	yes
	calcium nitrate ($Ca(NO_3)_2$)	19%	15.5% N	yes	yes
	pelletized lime	16%–40%	0%–13% Mg	yes	no
	cement kiln dust	26%–32%	2%–9% K_2O	yes	no
magnesium (Mg)	dolomitic limestone	6%–13%	16%–22% Ca	yes	no
	Epsom salts ($MgSO_4$)	9%	13% S	yes	yes
	sulphate of potash magnesia	11%	22% K_2O; 20% S	yes	no
sulphur (S)	ammonium sulphate	24%	34% N	yes	no
	potassium sulphate	18%	50% K_2O	yes	no
	sulphate of potash magnesia	22%	22% K_2O; 11% Mg	yes	no
	calcium sulphate	19%	23% Ca	yes	no
	granular sulphur	90%	–	yes	no
boron (B)	various granular materials	12%–15%	–	yes	no
	Solubor™	20%	–	no	yes
copper (Cu)	copper sulphate	25%	–	yes	no
	copper chelates	5%–13%	–	no	no
manganese (Mn)	manganese sulphate	28%–32%	–	no	yes
	manganese chelates	5%–12%	–	no	yes
molybdenum (Mo)	sodium molybdate	39%	–	no	yes
zinc (Zn)	zinc sulphate	36%	–	yes	yes
	zinc oxysulphate	8%–36%	–	yes	no
	zinc chelates	9%–14%	–	no	yes

Calcium

Limestone (either calcitic or dolomitic) is the most common source of calcium. There are some quarries and cement manufacturers that offer limestone-based by-products that carry significant quantities of potassium (e.g., 3%– 9%), magnesium and sulphate-sulphur. Care must be taken to account for the differences in Agricultural Index and the additional nutrient content, which may or may not be required for a given field.

Limestone is used to increase the pH of acidic soils. To be effective, it must be finely ground. Limestone is available in powder form or in pellets made from finely ground limestone. The solubility of limestone drops quickly as soil pH increases.

In soils with neutral or alkaline pH, gypsum (calcium sulphate) is the preferred form of calcium because it is more soluble than lime. Gypsum has no effect on soil pH.

Calcium chloride or calcium nitrate are occasionally used as foliar sources of calcium.

Magnesium

Magnesium deficiency is most common in acidic soils. If dolomitic limestone is added to correct the acidity, it will also supply enough magnesium to correct the deficiency. The solubility of dolomitic limestone decreases as the soil pH increases, and it is therefore not appropriate for alkaline soils.

In neutral or alkaline soils, Epsom salts (magnesium sulphate) or sulphate of potash magnesia can be used for supplemental magnesium.

Sulphur

Sulphate-sulphur is present in a number of common fertilizer materials and can be included in a fertilizer blend in these ingredients. Most common are ammonium sulphate, potassium sulphate and sulphate of potash magnesia. Gypsum (calcium sulphate) can also be used as a sulphur source. Product availability, transportation costs and crop requirements for other nutrients will dictate which source of sulphur is most economical.

Granular elemental sulphur (90% S) can be another source. It will also acidify the soil. The sulphur must be oxidized to sulphate before it is available to the crop, which can take several months. Some of the intermediate products in the oxidation process can be toxic to crops; therefore, if high rates are required, they should be broadcast rather than banded.

Micronutrient sources

Since micronutrients are required and applied in relatively small quantities, even distribution during application is important. The main classes of micronutrient products are granules intended for mixing with granular fertilizers and liquids or soluble powders for foliar application. The most appropriate form for application will depend on the specific nutrient as well as the crop species and soil conditions.

Granular micronutrient products are blended with other fertilizer ingredients for broadcast application or use as a starter fertilizer. Compatibility with the other ingredients is important, both chemically and in granule size. Since many micronutrients are toxic to plants if over-applied, segregation of the fertilizer blends must be avoided.

Oxy-sulphates
- combinations of the oxide and sulphate forms of the micronutrient
- sulphates are much more soluble and available than the oxides
- oxides are much more stable in a blended product
- oxides are only slowly available to the crop

These products have been declining in popularity because of the inconsistency in plant availability and crop response.

Sulphates
- quite soluble
- tend to be hygroscopic and can cause problems with caking or clumping when mixed with other fertilizer ingredients

Despite these concerns, their consistent plant availability has made them popular in fertilizer blends.

Liquid and soluble micronutrients
These materials may be mixed with water and sprayed on crop foliage or mixed with liquid fertilizers for use as starters.

Chelates
- complex organic molecules that bind metallic ions held in soluble forms, which prevents them from reacting with other minerals to form insoluble compounds
- allows many of these nutrients to be mixed with liquid fertilizers without forming insoluble precipitates
- may increase the availability of the nutrients in soil
- most commonly used chelating agents are EDTA and DTPA
- other organic materials (humic acids, lignosulphonates, glucoheptonates) will form complexes with metallic ions but do not hold them as tightly as a true chelate

Chelates are considerably more expensive than other soluble forms of micronutrients. They should be used with care, since they can bind with minerals already in the soil and make the deficiency worse.

Water-soluble powders
- the least expensive form of micronutrients for foliar application and the most consistently reliable
- most require a sprayer with good agitation to keep material in solution
- sticker-spreader needed to get the nutrient through the cuticle and into the leaf

Dry dispersible powders
- powdered materials that are made for use in dry granular blend applications and are applied by the fertilizer retail blender

- the inclusion rate per tonne is set by the manufacturer to assure the correct application rate and reduce dust off
- excess dust can be created by exceeding the manufacturer's recommendations and over-mixing the blend
- the material clings by static forces to the granular fertilizer, which results in each individual granule receiving the micronutrient
- much more expensive on a nutrient basis than other dry granular material; however, improved performance at lower inclusion rates may justify use
- each granule in the blend is coated with the micronutrient for better application distribution

Liquid micronutrient coatings

- similar in concept to dry dispersible powders, some manufacturers have liquid materials in either a latex or oil-based formulation designed to be sprayed onto granular fertilizer
- these coatings are professionally applied by retail blenders and usually require a heating blanket on liquid totes during cool weather and specialized metering equipment for proper application
- since they are liquid there is no dust-off potential, but there are restrictions to inclusion rates applied per tonne
- on-farm trials are a good way to compare or confirm product performances

Materials to enhance fertilizer efficiency

Nitrogen

Most products designed to enhance the efficiency of N uptake delay the release of its mineral forms, ammonium and nitrate. A 2016 fertilizer use survey conducted by Stratus Ag Research found that 22% of Eastern Canadian corn producers used a nitrogen stabilizer of some form (Stratus Ag Research, 2016). The products fall into one or more of the following categories:

- **Slow or controlled-release fertilizers.** These are materials that contain N in a form that delays its availability for plant uptake and thus makes it available over a longer period of time, in comparison to the regular ammonium, nitrate or urea fertilizers. The delay in release can be attained by a variety of mechanisms, including polymer or sulphur coatings, occlusions, or incorporation into compounds that are either insoluble or require mineralization to release the N. Some products are available in a range of grades varying in release profiles. Note that each material is designed for a specific application and specific crop.
- **Urease inhibitors.** These are substances that inhibit the hydrolytic action on urea by the urease enzyme. An example is Agrotain which contains N-(n-butyl) thiophosphoric triamide (NBPT).
- **Nitrification inhibitors.** These are substances that inhibit the biological oxidation of ammonium to nitrate. Examples include

N-Serve (nitrapyrin) and DCD (dicyandiamide). Ammonium thiosulphate also inhibits nitrification to some extent.

- **Stabilized fertilizers.** A nitrogen stabilizer is a substance added to a fertilizer that extends the time the fertilizer remains in the urea or ammoniacal form. An example is SuperU, a urea fertilizer containing both NBPT (a urease inhibitor) and DCD (a nitrification inhibitor).

Research by Dr. Craig Drury of Agriculture and Agri-Food Canada (AAFC) at the Woodslee Research Farm in Essex County in 2013 and 2014 has demonstrated the efficacy of some of the products above. He has shown that the combined use of a urease and nitrification inhibitor with corn N fertilization reduces losses from both volatilization and nitrous oxide production (Drury et al, 2017). The benefit depends on the specific combination of management, soil and weather conditions. Generally, urease and nitrification inhibitors can help to:

- minimize the concentration of inorganic soil N that is susceptible to loss
- substitute for capital investment in specialized machinery for placement
- increase flexibility in timing of application
- reduce potential for losses due to volatilization
- capture more yield potential by reducing the risk of N loss
- reduce environmental loss through pathways such as leaching and denitrification

Controlling the release of nitrogen can have disadvantages if the use of these materials is not carefully planned. Most fertilizer materials are supplied in a soluble form to maximize plant availability. It is only in specific situations — when the amount applied exceeds what plants can take up within a reasonable time frame — that the above materials will enhance efficiency.

Phosphorus
Products designed to enhance efficiency of P uptake prevent the fixation of P by the soil. These may include organic or humic materials, and polymer coatings that reduce the rate of diffusion from the granule to the fixation sites in the soil. As an example, a grade of 11-52-0 mono-ammonium phosphate coated with maleic itaconic copolymer (AVAIL) has been marketed for more than 25 years in North America.

In certain soil conditions, slowing the release of phosphate could potentially reduce fixation reactions that make applied P unavailable. For instance, Garcia et al. (1997) found that urea phosphate or lignin-coated triple superphosphate increased soil P availability in a highly calcareous P-fixing soil, while uncoated superphosphate or di-ammonium phosphate did not. However, the timing of release is a critical factor for most starter fertilizers. Most field crops require available P release to the seedling within a few weeks from planting.

There are some products that inoculate the soil with micro-organisms that claim to make phosphorus and other nutrients more available. Recent introductions of *Penicillium bilaii, Bacillus amyloliquefaciens* and *Trichoderma virens* seed treatments are part of an emerging industry of biologicals. On-farm trials that determine how effective these products might be on your own farm are the best way to validate their performance.

Materials for organic production systems

Many of the materials listed above are not approved for use in organic production systems. According to the Canadian General Standards Board, substances used to improve the fertility of soils in organic production systems must be of plant, animal, microbial or mineral origin and may undergo the following processes: physical, enzymatic or microbial. Since most N, P and K fertilizers undergo some degree of chemical processing, they are considered not to be naturally occurring elements. Exceptions include some grades of rock phosphate, muriate of potash, potassium sulphate and sulphate of potash magnesia. For a detailed list of permitted substances, contact the Canadian General Standards Board.

Fertilizer blending

Blended fertilizers were available for much of 20th century, but the early forms left much to be desired. For many years, fertilizers were shipped to the farm as fine powders in paper bags. These powders tended to bridge in the drill boxes or cake if they got damp.

In the 1950s, mixed granulated fertilizers were introduced in Ontario. These materials incorporated the same raw materials into a multi-nutrient granule. The equipment to produce these mixed granules, however, was cumbersome and expensive, and mixed granulated fertilizers were soon supplanted by bulk blends.

Bulk blending is the act of mixing granular fertilizer ingredients to produce the desired ratio. In Ontario, these operations are generally carried out at retail blenders.

These operators make custom blends based on unique agronomic needs of individual fields. Custom blends, or customer formula fertilizers, are obtained by mixing granular fertilizer materials according to a formula calculated to suit the fertilization recommendation for a given field and crop.

Custom blends are efficient because they:

• provide the exact amount of nutrients required to grow the crop
• are less likely to absorb moisture and cake in storage
• minimize the cost of fertilization with high-analysis, filler-free materials

Limitations to blends

Bulk blends, and custom blends in particular, are subject to a few limitations. Applying low rates of high-analysis fertilizers requires the use of appropriate metering systems. Often air distribution systems are used to precisely apply the required rates.

For some applications, there are advantages to fertilizers that combine several nutrients in the same granule. Examples include starter fertilizers incorporating small amounts of micronutrients and home lawn fertilizers. These homogenized fertilizers spread all nutrients uniformly and are convenient to use. Their main limitation, however, is that their nutrient ratios are fixed, and thus it is difficult to match specific soil requirements.

Physical and chemical compatibility of blending materials

Fertilizer materials are generally compatible with each other as long as they remain dry.

There are some exceptions:

- Do not blend ammonium nitrate with urea. When these two are brought together, the mix is so hygroscopic that it turns into a soaking mess in minutes. Take precautions to avoid cross-contamination during storage and handling. Before mixing two blended fertilizers, check the ingredients to ensure you are not bringing ammonium nitrate and urea together.
- Do not blend single or triple superphosphate with urea. Superphosphates (0-20-0 or 0-46-0) may react with urea, especially if they are not dry and hard. When this reaction takes place, the urea is broken down and the mix becomes sticky.
- Spread blends containing a superphosphate and di-ammonium phosphate as soon as possible. Single or triple superphosphates may react with di-ammonium phosphate in the presence of moisture. The mix becomes sticky and eventually cakes.

DO NOT BLEND

- AMMONIUM NITRATE with UREA
- SUPERPHOSPHATE with UREA

Spread mixes containing micronutrients as soon as possible

Some micronutrient ingredients (particularly sulphates) may absorb moisture from the air.
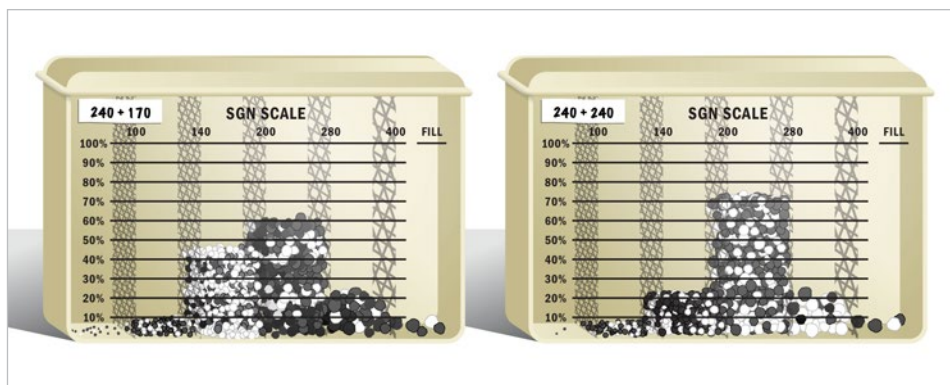
Figure 8–1. Testing for segregation

Consistent particle size critical

Consistent particle size is critical in mixing and applying bulk blends. If particle sizes of ingredients differ, the ingredients will segregate when they are dropped into a bin, with the largest particles at the outside of the pile and the finer materials in the centre. This can result in a large variation in the makeup of the fertilizer from one part of the pile to another.

Particle size also influences the spreading pattern of the fertilizer. Tests conducted by the Tennessee Valley Authority showed a range of spreading widths from 10.5 m (35 ft) for material with a 1.7 mm diameter, to 19.5 m (65 ft) for materials with a 3 mm diameter. If the materials in the blend are different sizes, the application of the different ingredients is not uniform.

The fertilizer blender should use materials with similar sizes. The Canadian Fertilizer Institute published the SGN System of Materials Identification in 1986.

SGN, or size guide number, is the average dimension of the fertilizer particles, measured in millimetres times 100. For example, SGN 280 means that half the fertilizer sample is retained on a testing sieve of 2.80 mm opening. SGN and the uniformity index, a measure of size uniformity, are the two characteristics used to simplify the selection of size-compatible materials.

Figure 8–1 shows the impact of mixing two materials of different sizes. A fertilizer blend made with the materials in the box labelled "SGN 240 + 170" will show significant segregation in the bin or fertilizer box, resulting in uneven application of the nutrients across the field.

There is no segregation in the box tagged 240 + 240. The box tagged 240 + 170, however, shows segregation between the white material SGN 170 and the grey material SGN 240.

Formula calculations

A custom blend is one formulated to meet the fertilization recommendation exactly. The formula is nothing more than a recipe calculated to use available materials to supply the desired plant nutrients.

The same calculations work with any combination of ingredients, but most fertilizer blenders have a limited range of ingredients. This normally includes an N source (46-0-0, 27-0-0, etc.), a P source (11-52-0, etc.) and a K source (0-0-60, 0-0-62, etc.).

The exact analyses of the ingredients may vary, depending on the source, making it important to know what ingredients are available. Some blenders also stock specialty ingredients for crops like tobacco.

The most important calculation is determining the amount of fertilizer required to provide each nutrient. Do this by using the proportion of each nutrient in the ingredient. (The proportion is the percentage divided by 100 — the decimal parts in 1 rather than the parts in 100. For example, 46% becomes 0.46.) Calculate the amount of ingredient required by dividing the amount of nutrient required by the proportion of nutrient in the ingredient. An example is shown in Worksheet A. A blank worksheet is found in Appendix A.

Calculating fertilizer blends that contain N and P is similar to calculating N-K or P-K blends, except you will want to take advantage of the savings possible with MAP or DAP. This adds a couple of steps to the process, because you will have to calculate the amount of ingredient to meet one requirement and then deduct the contribution of that ingredient from the other requirement (see Worksheet B and Appendix B).

Which requirement you calculate first depends on the ratio of N:P required and the choice of ammonium phosphate (MAP or DAP).

In general, fill the P requirement first in high-N fertilizers (fertilizers with an N:P ratio of 1:2 and higher). Fill the N requirement first in fertilizers with an N:P ratio of 1:4 and lower.

Computer software and smartphone apps are available that help facilitate blend calculations. Nutrient Management Planning software (go to ontario.ca/crops and search for AgriSuite Planning Tools) can be used to create crop nutrient plans using commonly available fertilizer blends and/or manure sources.

Worksheet A.
Example for N-K or P-K fertilizer blend

1. List materials on hand and grades.

Ingredient	Grade
urea	46-0-0
triple superphosphate	0-46-0
muriate of potash	0-0-60

2. Obtain nutrient requirement (kg/ha of N-P_2O_5-K_2O): **130-0-90**

3. Calculate ingredient required for each nutrient. Repeat for each nutrient:

Nutrient requirement ÷ proportion of nutrient = ingredient amount
130 ÷ 0.46 = 283

Nutrient requirement ÷ proportion of nutrient = ingredient amount
90 ÷ 0.60 = 150

4. Add weights of materials and calculate nutrients provided.

Material	Weight	N	P_2O_5	K_2O
Urea	283 kg	130	0	0
KCl	150 kg	0	0	90
Total	**433 kg**	**130**	**0**	**90**

The total weight of the blend at this point is the application rate. The units will be the same as the initial nutrient requirements.

5. Calculate the total amount of fertilizer required.

Application rate   x size of field   = total weight of fertilizer

433 kg/ha   x **20 ha**   = **8,660 kg**

6. Adjust material weights to give formula in kilograms per tonne.

Divide the weights of the individual materials by the total weight and multiply by 1,000.

Material	Weight	N	P_2O_5	K_2O
Urea	654 kg	301	0	0
KCl	346 kg	0	0	208
Total	**1,000 kg**	**301**	**0**	**208**
Grade (divide total NPK by 10)	—	30.1	0	20.8

Blank worksheets to copy and use are in Appendix A.

Worksheet B.
Example for NPK fertilizer blend

1. List materials on hand and grades.

Ingredient	Grade
Urea	46-0-0
Mono-ammonium phosphate (MAP)	11-52-0
Triple superphosphate	0-46-0
Muriate of potash (KCl)	0-0-60

2. Obtain nutrient requirement (or desired ratio or grade): **90-90-110 lb/acre**

3. Calculate ingredient (MAP) required for either N (for high P ratios) or P (for high N ratios).

nutrient requirement ÷ proportion of nutrient = amount of MAP (lb/acre)

90 ÷ 0.52 = 173

4. Calculate contribution of ingredient to other nutrient.

ingredient required x proportion of nutrient = contribution   **173 x 0.11 = 19**

5. Deduct contribution from requirement to determine the residual nutrient requirement .

(**Note:** if contribution is greater than requirement, you calculated the wrong nutrient first. Return to step 3.)

Requirement – contribution = residual requirement   **90 – 19 = 71**

6. Determine amount of ingredient to provide residual requirement (N source or P source).

residual requirement ÷ proportion of nutrient = ingredient amount

71 ÷ 0.46 = 154

7. Determine amount of muriate of potash to meet K requirement.

K nutrient requirement ÷ proportion of nutrient = ingredient amount

110 ÷ 0.60 = 183

8. Calculate any ingredients needed for any other micronutrients in the same way.

9. Add weights of materials and calculate nutrients provided.

Material	Weight	N	P_2O_5	K_2O
MAP	173	19	90	0
Urea	154	71	0	0
Potash	183	0	0	110
Total	**510**	**90**	**90**	**110**

The total weight of the blend at this point is the application rate. The units will be the same as the initial nutrient requirements.

10. Calculate the total amount of fertilizer required.

application rate   x size of field   = total weight of fertilizer
510 lb/acre   x **40 acres**   = **20,400 lb (9,251 kg)**

11. Adjust material weights to give formula in kilograms per tonne.

Divide the weights of the individual materials by the total weight (in the table from step 9) and multiply by 1,000.

Material	Weight (kg)	N	P_2O_5	K_2O
MAP	339	37	176	0
urea	302	139	0	0
potash	359	0	0	215
Total	**1,000**	**176**	**176**	**215**
Grade (divide total NPK by 10)	—	17.6	17.6	21.5

Now you can calculate the price of the fertilizer.

A blank chart for you to copy and use is in Appendix B.

Legalities

The Canadian Food Inspection Agency monitors and controls fertilizers and supplements sold in or imported into Canada. The purpose of the *Fertilizers Act* and Regulations is to ensure that fertilizer and supplement products are safe, efficacious and accurately represented in the marketplace.

Most fertilizer and supplement products are regulated; however, not all of these products require registration. Micronutrient products, fertilizer-pesticide products and supplements not found in Schedule II of the *Fertilizers Act* and Regulations (such as plant growth regulators, soil conditioners, wetting agents, microbial inoculants, etc.) require registration before they can be legally imported into and/or sold in Canada.

All products must be safe for plants, animals, humans and the environment. They must be effective, and they must be properly labelled. The minimum required information that must appear on a fertilizer or supplement product label is the name, grade (if any), brand (if any), name and address of the manufacturer or registrant, lot number (if any), registration number (where applicable), guaranteed analysis, directions for use (where applicable), product weight and appropriate cautionary statements. Some specialty fertilizer products and supplements will require additional information to appear on the label. In addition, the guarantees displayed on the product label must be met, as all products are subject to monitoring and inspection.

Many fertilizer manufacturers and blend producers are part of the Canadian Fertilizer Quality Assurance Program (CFQAP). Under this voluntary program, participants take their own samples and send them to accredited labs that submit the analyses to the Canadian Food Inspection Agency. The results are tabulated, and each manufacturer or blend plant that submits the minimum number of required samples is given a performance rating. The ratings are published annually in the Canadian Fertilizer Quality Assurance Report, which is distributed widely. A customer can ask for a supplier's CFQAP rating.

For more information, contact the Fertilizer Section, Canadian Food Inspection Agency, www.inspection.gc.ca.

All fertilizers must be properly labelled, whether they are registered or not. Information that appears on the label must include the name, grade, guaranteed minimum analysis, manufacturer, packager and product weight. Specific types of products need more information. The guarantees on a label must be met, and all products are subject to monitoring and inspection.

Fertilizer application

The aim of any fertilizer program is to get the nutrient into the crop plants where it will be used to improve yield and quality of the crop. Fertilizer that isn't placed where the roots can reach it when the crop needs it won't do the job.

Fertilizer placement is a compromise between applying the fertilizer in optimum concentrations precisely where and when the plant needs it and the practical considerations of the time and equipment available for applying the fertilizer. If you are considering a more costly fertilizer application system, there should be advantages in increased crop yield or reduced fertilizer cost that compensate.

The best placement for a particular nutrient (or combination) depends on how mobile the nutrient is in the soil, the concentration required by crop plants, how toxic the nutrient is at high concentrations, the soil texture and moisture status, and the crop being fertilized.

Crop safety

Plant tissue is sensitive to injury from high salt concentrations (osmotic pressure) or free ammonia, both of which can be produced by too much fertilizer in too small a volume of soil.

Plant symptoms

The symptoms of fertilizer burn are reduced root growth and blackened or discoloured areas on the roots, as

if they were burned. Injury will be most severe with seedlings because young tissues are more sensitive, larger proportions of the plant tissue are affected by any injury, there is less reserve for re-growth following injury, and there is less opportunity for the plant to grow around the area of high concentration.

Concentration is key

The key factor in fertilizer injury is concentration rather than the total amount applied. Banded fertilizers are much more likely to cause injury than broadcast fertilizers.

If fertilizer is applied with a corn planter in a 2.5 cm band (1 in.) in rows 0.75 m (30 in.) apart, the concentration within the band is 30 times what it would have been if the fertilizer had been broadcast over the whole area. Also, the distribution along the row is not always even — as a result, fertilizer rates can be much higher at some points.

The concentration can be diluted as the fertilizer diffuses out of the band, but the amount of dilution depends on the texture and moisture content of the soil. Moist soils cause greater dilution. We commonly see fertilizer burn in dry springs and on coarse-textured, well-drained soils. Since coarse-textured soils with low organic matter also have less surface area to react with and adsorb fertilizer, the concentration in the soil solution will remain higher than in clay soils.

Proximity to plant

The risk of injury also increases with the proximity of the seed or transplant to the fertilizer band. With the fertilizer too close, there is little opportunity for dilution by the soil water. There is also little or no chance for the roots to grow beyond the zone of concentration. Nitrogen and potassium in particular can be harmful to seedlings and to seed germination. Cold soils, which slow root growth, can magnify these effects.

When a fertilizer is banded with the seed, the safe rate of nutrients is much less than that of fertilizer banded 5 cm to the side and 5 cm below the seed. Even at recommended rates, seed-applied fertilizer will slow germination and emergence slightly, as the salt effect slows the absorption of water. Applying fertilizer with seed is not appropriate for all crops.

Types of injury

Salt injury occurs when the concentration of ions in the soil solution is greater than the concentration within the plant. When this happens, water is pulled across the cell membranes and out of the root. The root tissues are injured by desiccation, as if they had been singed by heated air.

Any soluble compound in a high enough concentration will cause salt injury. The greater the solubility of a fertilizer, the greater the potential to cause salt injury. The acids and hydroxides are somewhat less likely

to cause injury, but these ingredients as used in fertilizer manufacture are combined into other soluble compounds before application.

Ammonia injury occurs when there is free ammonia in the soil solution. Normally, this compound would be dissolved as the ammonium ion, but with high concentrations and particularly with alkaline conditions, some of the ammonium will be released as ammonia. This could occur with applications of anhydrous ammonia or high rates of liquid manure, or if urea or di-ammonium phosphate (DAP, 18-46-0) is banded near the row. The symptoms of ammonia injury are similar to salt injury, and they often happen together.

Crop susceptibility
Not every crop is equally sensitive to fertilizer injury. In general, grasses (monocots) are much less susceptible than broadleaf crops (dicots). Within the grasses, cereals are more tolerant of high banded fertilizer rates than corn.

Among the broadleaf crops, soybeans and edible beans are more susceptible than forage legumes or canola, but they are all much more sensitive than corn.

In general, seeded vegetables are quite sensitive to fertilizer injury.

Application methods

Broadcast
Broadcast fertilizer application is by far the fastest and least expensive method. The fertilizer is spread evenly over the soil surface and then incorporated into the soil for most field crops. This gives the greatest possible dilution, which minimizes the risk of fertilizer burn. Broadcast application also maximizes the contact between the fertilizer and the soil, which results in faster immobilization reactions than with banding.

Fertilizer burn can still occur on very sandy soils with low organic matter. High rates of urea and potash spread on these soils can cause seedling injury under dry conditions, especially if combined with banded or seed-applied fertilizer.

Whether a granular fertilizer is spread by a pull-type or self-propelled spreader, there are two types of delivery systems: spinners and pneumatic (airstream). Either will do a good job if properly operated and maintained.

Spinner spreaders
Spinner spreaders use one or two rapidly spinning disks with paddles to throw the fertilizer granules out from the spreader. A consistent granule size is important because smaller particles do not travel as far and they spread out in an uneven pattern. Windy conditions can also distort the spread pattern, as does a buildup of fertilizer on the distributor

or the paddles. Frequent cleaning is necessary, but the areas needing cleaning are easily accessible.

Spinner-type spreaders are relatively simple mechanically and relatively inexpensive. The power requirements are modest, so that any tractor capable of pulling the spreader has lots of power for the spinners. These are the most popular types of spreaders for rental units because of their low cost, generally trouble-free operation and ease of repair in the field.

Pneumatic spreaders

Pneumatic spreaders use a high-velocity airstream to carry the granules through a boom to distributors spaced about 1.7 m (5 ft) apart. These spreaders have a higher power requirement because the fan that creates the airstream runs at high speeds. These spreaders are also more complicated because of the moving parts in the fan and the metering system that distributes the fertilizer evenly to each of the boom sections.

However, the metering can be more precise than with the spinner-type spreaders, and the mixing action of the airstream allows the addition of small quantities of granular herbicides or micronutrients in the field.

Because the distributors are relatively close together, these spreaders are not affected by wind as much as the spinner type. The self-propelled units often have a wider spread pattern

than spinner spreaders, allowing greater throughput from the same power unit. Plugging is not a frequent problem because of the high velocity of the airstream, but the spreader does need to be monitored in humid conditions or when using damp materials.

The pneumatic spreader is relatively expensive and complicated and thus not generally suitable for an individual; it has, however, taken over the largest part of the market for custom application.

Tru-Spread system

The Tru-Spread system uses a screw conveyor to deliver granular fertilizer across the width of a boom and drop it through openings on 17.5 cm (7 in.) spacing. These machines are also quite accurate and unaffected by wind.

Spraying equipment

Most broadcast fertilizer is in granular form, but a sizeable quantity of liquid N solution is soil-applied on winter wheat. Small quantities are applied by broadcast as a herbicide carrier for corn.

The spread with this equipment is usually even, although there is the chance of drift in windy conditions. Some field sprayers do not perform well with liquid fertilizers because they are not designed to handle large volumes or are not protected against corrosive fertilizer materials.

Variable-rate fertilizer

The simplest variable-rate applicators are conventional spreaders of any type fitted with a global positioning system (GPS) receiver and a link to the controller. This allows the unit to variably apply one material or blend. This system may require multiple passes over the field to meet the fertilizer requirements. However, the equipment is less expensive than the multi-bin variable-rate unit. Having to do a number of passes slows application and may lead to increased soil compaction.

Multi-material variable-rate applicator units have multiple bins, and the discharge from each can be controlled individually. This allows the application rate of multiple materials to be varied in a single pass over the field.

Variable-rate application of lime can be done using a lime applicator equipped with a GPS receiver and a variable rate controller. Or, application zones within the field can be mapped and flagged and specific rates applied to each with a conventional lime spreader by dead reckoning.

Banding

Banding is applying fertilizer in a band beside and below the seed in the case of row crops or with the seed of cereals. A common practice on corn is to apply a starter band of dry fertilizer 5 cm (2 in.) beside and 5 cm (2 in.) below seeding depth. A common error is the placement of fertilizer at a 5 cm (2 in.) depth from the surface of the soil. The correct positioning is 5 cm (2 in.) below seed depth. If the seed is planted 5 cm (2 in.) deep, the starter band should be set for a 10 cm (4 in.) depth.

Banding requires fertilizer boxes and metering systems on the planter or drill and an extra opener on planters to place the fertilizer into the soil. This can require extra power to pull the planter, and the time to fill the fertilizer boxes slows the planting. The advantage is that the fertilizer is located at a high concentration where the roots of the seedlings will intercept it. This is particularly important for P, which is required early in the growth of many crops.

It is important to take care with banded fertilizer, since the high concentration also increases the risk of fertilizer burn. The rates of N and K must be limited, particularly where urea or di-ammonium phosphate is the N source. Band pH may also influence availability of other nutrients in the soil — see sidebar entitled "Soil pH in Starter Fertilizer Bands" in Chapter 3.

Planting equipment must also be set properly to place the fertilizer the right distance from the seed. If the fertilizer openers shift too close to the seed row, the risk of burn increases. If the openers shift away from the row, the seedlings may not be able to intercept the fertilizer early enough.

Metering equipment for banded fertilizer is fairly simple, with a delivery

auger in the bottom of the fertilizer boxes dropping the fertilizer through an adjustable gate. The rate can be varied with the speed of the auger, the size of the gate opening or the pitch of the auger flighting. The alignment of the delivery auger must be checked carefully. If the auger is shifted to one side, it can deliver 50% more fertilizer to one side of the box than to the other.

Pop-up

Pop-up is the term for fertilizer applied with the seed of row crops, even though it actually delays germination slightly. This method has the advantage of producing relatively large yield responses in corn (up to 0.5 t/ha (8 bu/acre) in one study) with low rates of fertilizer, even at higher soil test levels where response from banded or broadcast fertilizer would not be expected. This method also gives a consistent increase in seedling vigour.

Because of the close proximity of the fertilizer to the seed, this method has a higher risk of injury than any other. You must adhere to the maximum safe rates (see Table 8-6), and the equipment must be calibrated to apply the fertilizer evenly. Pulses in fertilizer application can easily result in wavy crop growth as some areas receive higher-than-required concentrations of fertilizer while others don't get enough.

Liquid fertilizers are most commonly used for seed application because they can be metered precisely and handled easily. To avoid pulses, the fertilizer should be delivered to the

seed openers under pressure and metered through an orifice. Care must be taken that the fertilizer delivery tube is centred in the seed opener. Liquid fertilizer dribbling onto the opener disks will result in mud buildup and plugging.

Side-dressing

Side-dressing is the application of fertilizer, primarily N, between the rows of growing crops. This applies the N closer to the time when the crop needs it, which can increase the efficiency of N use. It also minimizes the risk of nitrate leaching on sandy soils or of denitrification on poorly drained soils.

In corn, the most common forms of side-dressed fertilizer are anhydrous ammonia and UAN solution.

Anhydrous ammonia is attractive because of its low cost per unit of N, and on the clay soils of southwestern Ontario it has also provided a yield advantage over other forms of N. It must be injected deep enough into the soil so that the injection slot seals over, otherwise the losses to the atmosphere will be too high. The power requirements and application costs are higher for anhydrous, and it must be handled carefully to be safe.

UAN solutions do not need to be injected deep into the soil, making the power requirements for application modest. In high-residue situations, the solution must be placed below the surface residue layer to prevent volatilization losses of ammonia. The cost for UAN solution is relatively high,

but safety and ease of handling have made it a popular choice.

In high-residue situations, injector knives can catch on and drag residue. To prevent this, no-till applicators are equipped with coulters to cut the residue and improve penetration into firm ground. Another approach is the spoke-wheel injector, which pokes the N solution into the soil with minimal disturbance of the residue. These work quite well, but the initial cost is higher than for other side-dress equipment.

Granular fertilizers are used for side-dressing vegetable crops and tobacco but are not as common in corn.

Deep banding
Some farmers have experimented with banding P and K fertilizers 15–20 cm (6–8 in.) below the row, especially in no-till and strip-till situations where the soil is firm. This may increase the availability of fertilizers under dry conditions and protect them from immobilization reactions. Limited Ontario trials, however, have not shown a yield response to deep banding. It may be useful in some situations.

Foliar
Foliar fertilizer can be an excellent supplement to soil-applied nutrients. It can correct deficiencies quickly and is not susceptible to tie-up in the soil. There is a chance the nutrient will be washed off or the carrier will dry up before the nutrient is absorbed. The use of a spreader-sticker may increase absorption of the fertilizer through the cuticle.

Limited quantities can be applied to the leaf before the tissue is damaged. Therefore, deficiencies of micronutrients, where plants only require a few grams per hectare, are corrected more easily than those of macronutrients. Foliar application of manganese, for example, is the most effective way to correct manganese deficiencies.

Be sure to check pesticide labels before mixing foliar nutrients with any pesticide spray. In particular, manganese and glyphosate are known to antagonize each other's effectiveness.

Foliar application of urea has been successful in many crops. Urea-N can be applied to leaves at much higher concentrations than P or K. The grade chosen should be for feed or foliar uses, since it is lower in biuret, a by-product that can harm plant tissue. There is little research that supports maximum safe rates, but results from some experiments suggest that a single foliar urea application should not exceed 22 kg/ha (20 lb/acre) of N, and the concentration in the spray should be less than 2%.

Even though urea is the nutrient most rapidly absorbed by leaves, it often takes many applications to get enough N into the plant to make a difference. For this reason, foliar application of macronutrients tends to be economical more often in high-value horticultural crops than in common field crops.

Transplant starters

Starter solutions are water-soluble or liquid fertilizers that provide a source of fertilizer surrounding the root ball. These solutions always include P, which is important for root development, and may also include N and K.

Transplanted stock will benefit from readily available nutrients to encourage new root growth and overcome transplanting shock. Transplants receive starter fertilizer via the transplant water or are fed a starter before going to the field.

In using starter fertilizer at transplanting, the objective is to gain the benefits of early growth but avoid plant injury. Fortunately, the primary nutrient of interest in a starter — phosphorus — is fairly safe. Nitrogen and potassium salts can pose more of a risk. Including micronutrients in a starter solution increases the potential toxicity to the transplants. Different brands or batches of starter with the same fertilizer analysis can vary in salt levels, depending on the ingredients used to formulate them.

Be aware that the salt level of the transplant solution can vary through the day, as the tanks are refilled. Fertilizer concentration can also pulse up and down when using a metering system.

Salt levels (electrical conductivity or EC) are often expressed based on a certain fertilizer concentration, such as 1.5 L in 100 L of water. Table 8–4, below, shows a comparison of several starter fertilizers that were tested by former OMAFRA Vegetable Specialist, Janice LeBoeuf.

Table 8–4. Comparison of the electrical conductivity (EC) of 1.5% and 2.5% starter solutions and nutrient content of the fertilizer concentrate

Fertilizer[1]	EC (mS/cm) 1.5%	EC (mS/cm) 2.5%	g/L or g/kg of fertilizer concentrate			
			N	P_2O_5	K_2O	N + K_2O
3-18-18	7.31	12.01	41	244	244	285
9-18-9	7.42	11.86	117	234	117	234
6-24-6	7.84	13.32	82	328	82	164
6-24-6	8.34	13.12	82	328	82	164
10-31-4 IBA & PHCA	10.12	16.16	131	407	52	184
10-34-0	10.22	15.16	131	446	0	131
10-50-10 (dry soluble)	10.80	16.81	100	500	100	200
Water	0.00	0.00	0	0	0	0

[1] EC for a sample of a particular batch of each formulation. Fertilizer products of the same analysis can vary greatly in salt levels. Always test your own solution with an EC meter.

Look for a starter that will give you an adequate rate of phosphorus at a low EC and an acceptable price (notice how you need twice as much of low-analysis products to deliver phosphorus levels equivalent to a 1.5% solution of 10-34-0). Remember, the presence of some ammonium nitrogen provides a benefit, but potassium and micronutrients are not particularly beneficial in a starter and can increase the risk of damage.

Fertigation

Fertigation is a method of applying water and nutrients through a drip irrigation system. It can be used to increase the yield and quality of many vegetable crops.

A stock solution of soluble (greenhouse grade) fertilizer is dissolved in a tank and introduced through a valve into the irrigation system either by suction or pressure. The fertilizer solution should be fed through the system slowly. After the fertilizer has passed through the system, continue to irrigate to flush the system.

DO NOT mix fertilizers containing calcium, phosphates or sulphates as these can precipitate out and plug emitters.

Broadcast all of the phosphate requirement and approximately 30%–50% of the nitrogen and potash requirement prior to planting. The remainder should be injected through the drip irrigation system. Use soil tests to determine phosphate and potash requirements. Table 8–5 outlines recommended application rates for tomatoes, peppers and vine crops.

Table 8–5. Nitrogen and potash injection schedules

Growth stage	Rate of N and K_2O to inject per week (kg/ha)		
	vine crops[1]	peppers	tomatoes
transplanting to fruit set	5	3–5	2.5
fruit sizing to harvest	10	7–10	5
harvest	5	3–5	2.5

[1] Cucumbers, melons, summer squash

Combining methods

The choice of starter fertilizer will depend on the crop to be grown, the mineral fertilizer requirements and the equipment available. It is often as efficient to apply part of the fertilizer as a starter and broadcast the rest as it is to apply all the fertilizer through the planter or drill. The advantages to splitting the fertilizer application are savings in time and labour and less risk of fertilizer injury to the seedling. The recent interest in strip tillage provides another alternative to fertilizer placement and timing.

Deduct applications of starter fertilizer and side-dressed fertilizer from the total mineral requirement. Any balance remaining should be broadcast. If only tiny numbers remain, you may want to consider adjusting the rates of one of the other nutrient sources, ignoring the small residuals or planning a fertilizer application that will meet multi-year requirements (for P and K only).

Fertilizer worksheet

Once you have established the crop requirements, you need to determine how the required nutrients are to be supplied. Economics and environmental concerns dictate that we make the best possible use of all sources of nutrients. This includes organic forms of nutrients, either already on the farm or imported, as well as mineral fertilizers.

Maximum safe rates of nutrients

Maximum safe rates of any nutrient source should be observed to avoid injury to the crop. The rates listed in Table 8–6 may cause symptoms of injury or retardation of growth in up to 10% of all cases. Use lower rates where possible. Since fertilizer injury can occur when the concentration of fertilizer is too high, uneven application can cause intermittent problems even though the average rate is low enough to be safe.

Dilution has a large influence on what rates are safe. Injury is most common when the weather is dry and in coarse-textured soils with low organic matter.

Narrower rows will increase the safe rate per hectare, because the same amount of fertilizer is spread over a greater length of row.

Proper equipment maintenance is important to prevent fertilizer injury. If the fertilizer opener moves closer to the seed, fertilizer burn will occur at rates that would have been safe otherwise.

Fertilizer source and placement

Use on-farm nutrient sources first as they will be applied to farm fields anyway, and base application rates on meeting crop N or P requirements.

Many farmers find it beneficial to split nutrient requirements between organic and mineral sources, providing some insurance against variability in manure applications. Off-farm organic nutrient sources such as sewage biosolids and municipal compost can also be considered.

Commercial fertilizers are used to supply the crop requirements not available from other nutrient sources. Apply commercial fertilizers as close as possible to when the crop requires the nutrients and as close as possible to the plant.

Table 8–6.	Maximum safe rates of nutrients in fertilizer						
LEGEND: NR = not recommended – = no data							
		N kg/ha			N + K$_2$O + S kg/ha		
		Row space:			Row space:		
		75 cm	38 cm	18 cm	75 cm	38 cm	18 cm
		30 in.	15 in.	7 in.	30 in.	15 in.	7 in.
Banded 5 cm to the side x 5 cm (2 in. x 2 in.) below seed							
corn[1]	urea	40	–	–	79	–	–
	other fertilizers	52	–	–	117	–	–
soybean[2], pea, dry beans	ammonium sulphate	30	60	–	NR	NR	–
	other fertilizers	NR	NR	–	90	180	–
with the seed[3]							
corn	other fertilizers	NR	NR	–	10	20	–
winter wheat, triticale, barley	other fertilizers	–	–	15	–	–	40
spring oat, barley, wheat	urea	–	NR	10	–	–	30
	other fertilizer — sand	–	NR	35	–	–	55
	other fertilizer — clay	–	–	45	–	–	70
canola	ammonium sulphate — sand	–	–	22	–	–	11
	ammonium sulphate — clay	–	–	22	–	–	33
broadcast, strip till							
corn	urea	200	–	–	250	–	–
100 kg/ha = 90 lb/acre							

[1] At higher rates, band at least 15 cm (6 in.) from seed. At row widths other than 75 cm, the rate may be adjusted to provide the same maximum concentration in the row (e.g., in a 50 cm (20 in.) row, the safe rate = 75/50 x 52 = 78 kg/ha (70 lb/acre) N).

[2] Significant amounts of nitrogen inhibit nodulation and are not recommended.

[3] Urea with the seed is not recommended for corn, soybean or winter wheat.

Fertilizer recommendations and application rate calculation

Worksheet C is an example of a worksheet used to calculate the rate of fertilizer application. (See Appendix C for a blank version to copy.)

Enter the N, P$_2$O$_5$ and K$_2$O requirements on the top line. Deduct the available nutrients from legumes, manure or other organic sources to determine the amount of mineral fertilizer needed to meet the total requirements.

Either metric or imperial units can be used in this worksheet.

Worksheet C.
Fertilizer application calculations

Crop to be grown: corn

Previous crop: barley with red clover

Manure applied (type, amount): solid dairy manure (10 tons/acre), spring incorporated

Other organic nutrient sources: none

Starter fertilizer (rate, analysis): (140 lb/acre) 8-32-16

Supplemental N (rate, analysis): none

Requirements	N	P_2O_5	K_2O
Requirements — kg/ha (lb/acre)[1]	157 (140)	50 (45)	81 (72)
less legumes	45 (40)	0	0
less manure	34 (30)	34 (30)	157 (140)
less other organic amendment	0	0	0
Total mineral fertilizer requirements	78 (70)	17 (15)	0
less starter fertilizer	12 (11)	49 (44)	25 (22)
less side-dressed fertilizer	0	0	0
Total broadcast fertilizer requirements	66 (59)	0	0

[1] Requirements as total crop need. Check whether recommendations are already adjusted for legumes and manure credits.

In this example, the total broadcast fertilizer required is 59 lb N/acre, or 128 lb/acre of urea. The starter fertilizer application could also have been reduced.

If a more complex blend is required, it could be calculated using the Fertilizer Blend Worksheet, p. 200.

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Appendices

Appendix A.
Fertilizer Blend Worksheet: sample for N-K or P-K blend

1. List materials on hand and grades.

Ingredient	Grade

2. Determine nutrient requirement (or desired ratio or grade). _____

3. Calculate ingredient required for each nutrient. Repeat for each nutrient.

   Nutrient requirement ÷ proportion of nutrient = ingredient amount

   _____ ÷ _____ = _____

   _____ ÷ _____ = _____

   _____ ÷ _____ = _____

4. Add weights of materials and calculate nutrients provided.

Material	Weight	N	P_2O_5	K_2O
Total				

   The total weight of the blend at this point is the application rate. The units will be the same as the initial nutrient requirements.

5. Calculate the total amount of fertilizer required.

   Application rate   x   size of field   = total weight of fertilizer

   _____   x   _____   = _____

6. Adjust material weights to give formula in kilograms per tonne.

   Divide the weights of the individual materials by the total weight and multiplying by 1,000.

Material	Weight	N	P_2O_5	K_2O
Total				
Grade (divide total NPK by 10)				

Appendix B.
Fertilizer Blend Worksheet: sample for NPK blend

1. List materials on hand and grades

Ingredient	Grade

2. Determine nutrient requirement (or desired ratio or grade) _____

3. Calculate ingredient (DAP or MAP) required for either N (for high P ratios) or P (for high N ratios)

Nutrient requirement ÷ proportion of nutrient = ingredient amount

_____ ÷ _____ = _____

_____ ÷ _____ = _____

4. Calculate contribution of ingredient to other nutrient

Ingredient required x proportion of nutrient = contribution

_____ x _____ = _____

5. Deduct contribution from requirement to determine the residual nutrient requirement. (**Note:** if contribution is greater than requirement, you calculated the wrong nutrient first. Return to step 3)

Requirement – contribution = residual requirement

_____ – _____ = _____

6. Determine amount of ingredient to provide residual requirement (N source or P source)

Residual nutrient requirement ÷ proportion of nutrient = ingredient amount

_____ ÷ _____ = _____

7. Determine amount of potash to meet K requirement

K nutrient requirement ÷ proportion of nutrient = ingredient amount

_____ ÷ _____ = _____

8. Calculate any ingredients needed for any other micronutrients in the same way.

9. Add weights of materials and calculate nutrients provided.

Material	Weight	N	P_2O_5	K_2O
MAP				
urea				
potash				
Total				

The total weight of the blend at this point is the application rate. The units will be the same as the initial nutrient requirements.

10. Calculate the total amount of fertilizer required.

Application rate   x   size of field   =   total weight of fertilizer

_____   x   _____   =   _____

11. Adjust material weights to give formula in kilograms per tonne.

Divide the weights of the individual materials by the total weight and multiply by 1,000.

Material	Weight	N	P_2O_5	K_2O
MAP				
urea				
potash				
Total				
Grade (divide total NPK by 10)				

Now you can calculate the price of the fertilizer.

Appendix C.
Fertilizer Application Calculations Worksheet

Crop to be grown _____

Previous crop _____

Manure applied (type, amount) _____

Other organic nutrient sources_____

Starter fertilizer (rate, analysis) _____

Supplemental N (rate, analysis) _____

	N	P_2O_5	K_2O
Requirements — kg/ha (lb/acre)			
less legumes			
less manure			
less other organic amendment			
Total mineral fertilizer requirements			
less starter fertilizer			
less side-dressed fertilizer			
Total broadcast fertilizer requirements			

Appendix D.
Conversions and equivalents

Metric to Imperial

litres per hectare x 0.09	=	gallons per acre
litres per hectare x 0.36	=	quarts per acre
litres per hectare x 0.71	=	pints per acre
millilitres per hectare x 0.015	=	fluid ounces per acre
grams per hectare x 0.015	=	ounces per acre
kilograms per hectare x 0.89	=	pounds per acre
tonnes per hectare x 0.45	=	tons per acre

Imperial to Metric

gallons per acre x 11.23	=	litres per hectare (L/ha)
quarts per acre x 2.8	=	litres per hectare (L/ha)
pints per acre x 1.4	=	litres per hectare (L/ha)
fluid ounces per acre x 70	=	millilitres per hectare (mL/ha)
tons per acre x 2.24	=	tonnes per hectare (t/ha)
pounds per acre x 1.12	=	kilograms per hectare (kg/ha)
ounces per acre x 70	=	grams per hectare (g/ha)

Liquid Equivalents

litres/hectare		gallons/acre
50	=	5
100	=	10
150	=	15
200	=	20
250	=	25
300	=	30

Dry Weight Equivalents

grams/hectare		ounces/acre
100	=	1½
200	=	3
300	=	4½
500	=	7
700	=	10

kilograms/hectare		pounds/acre
1.1	=	1
1.5	=	1¼
2.0	=	1¾
2.5	=	2¼
3.25	=	3
4.0	=	3½
5.0	=	4½
6.0	=	5¼
7.5	=	6¾
9.0	=	8
11.0	=	10
13.0	=	11½
15.0	=	13½

Imperial to Metric (approximate)

Length

inch	=	2.54 cm
foot	=	0.30 m
yard	=	0.91 m
mile	=	1.61 km

Area

square foot	=	0.09 m²
square yard	=	0.84 m²
acre	=	0.40 ha

Volume (dry)

cubic yard	=	0.76 m³
bushel	=	36.37 L

Volume (liquid)

fluid ounce (Imp.)	=	28.41 mL
pint (Imp.)	=	0.57 L
gallon (Imp.)	=	4.54 L
gallon (U.S.)	=	3.79 L

Pressure

pound per square inch	=	6.90 kPa

Weight

ounce	=	28.35 g
pound	=	453.6 g
ton	=	0.91 tonne

Temperature

°C	=	(°F - 32) x ⅝
°F	=	(°C x ⅑) + 32

Metric to Imperial (approximate)

Length

millimetre (mm)	=	0.04 inch
centimetre (cm)	=	0.40 inch
metre (m)	=	39.40 inches
metre (m)	=	3.28 feet
metre (m)	=	1.09 yards
kilometre (km)	=	0.62 mile

Area

square centimetre (cm^2)	=	0.61 cubic inch
square metre (m^2)	=	10.77 square feet
square metre (m^2)	=	1.20 square yards
square kilometre (km^2)	=	0.39 square mile
hectare (ha)	=	107,636 square feet
hectare (ha)	=	2.5 acres

Volume (liquid)

millilitre (mL)	=	0.035 fluid ounce
litre (L)	=	1.76 pints
litre (L)	=	0.88 quart
litre (L)	=	0.22 gallon (Imp.)
litre (L)	=	0.26 gallon (U.S.)

Volume (dry)

cubic centimetre (cm^3)	=	0.061 cubic inch
cubic metre (m^3)	=	1.31 cubic yards
cubic metre (m^3)	=	35.31 cubic feet
1000 cubic metre (m^3)	=	0.81 acre-foot
hectolitre (hL)	=	2.8 bushels

Weight

gram (g)	=	0.035 ounce
kilogram (kg)	=	2.21 pounds
tonne (t)	=	1.10 short tons
tonne (t)	=	2,205 pounds

Speed

metre per second	=	3.28 feet per second
metre per second	=	2.24 miles per hour
metre per hour	=	0.62 mile per hour

Pressure

kilopascal (kPa)	=	0.15 pounds/square inch

Glossary

Acid: A solution with an excess of hydrogen ions (H^+). This solution will have a pH reading below 7.

Acre furrow-slice: The amount of topsoil contained in an area of 1 acre to a depth of 6 in. The weight of this volume of soil is about 2,000,000 lb.

Adsorb: To stick to the surface of something, as opposed to being absorbed into something. Nutrient ions are generally adsorbed on the surface of clay particles.

Aerobic: In the presence of oxygen (air).

Alkaline: A solution with an excess of hydroxyl ions (OH^-). This solution will have a pH reading above 7.

Allelopathic: The negative effect of some plant residues on the growth or vigour of the following crop.

Anaerobic: In the absence of oxygen. In soils, generally occurs when the soil is waterlogged.

Anion (AN-eye-on): A negatively charged ion, produced by the dissociation of an acid or a salt when dissolved in water (e.g., $KCl \rightarrow K^+$, a cation, + Cl^-, an anion). Common anions in the soil of importance for crop production include nitrate (NO_3^-), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), and chloride (Cl^-).

Apparent specific gravity: See bulk density.

Arbuscular mycorrhizal fungi (AMF): Symbiotic fungi that colonize roots of many crop species, effectively extending the root system and increasing the absorption of nutrients, especially phosphorus. The word mycorrhizae comes from Latin *mycos* for fungus and *rhizae* for root.

Atomic Absorption Spectrometry: An analytical technique where an extract is broken down to individual elements in a flame, and then a light beam passing through the flame measures the concentration of each element by determining the absorption of specific wavelengths.

Auto Analyzer: A machine that automates the repetitive tasks of chemical analysis. In most soil and plant tissue analysis, the concentration of an element is determined from the intensity of a colour formed when mixed with specific compounds.

Available phosphate: In a fertilizer, the sum of the water soluble and the citrate soluble phosphate, expressed as phosphorous pentoxide. (P_2O_5).

Biosolids: Organic materials from industrial or municipal sources that are suitable for application to agricultural land. This includes a wide range of materials, from sewage sludge to paper waste.

Buffer pH: A measure of how much lime is required to neutralize the acidity in a particular soil.

Bulk density: Sometimes referred to as apparent specific gravity. A measure of the weight of a material in a given volume. In soil, bulk density is an indication of how compact the soil is. In fertilizer application, bulk density is important for setting application rates, since spreaders meter the fertilizer by volume rather than weight.

Calcareous: A soil containing calcium carbonate in the mineral form. Calcareous soils have a high pH and are very well buffered against changes in soil pH.

Calibration: The process of determining the most economic fertilizer application rates for a particular soil test value with a specific soil extraction.

Cation (CAT-eye-on): A positively charged ion, produced by the dissociation of an acid or a salt when dissolved in water (e.g., KCl $\rightarrow$ K^+, a cation, + Cl^-, an anion). Cations are commonly held in the soil by electrostatic attraction to negative charges on soil particles and organic matter. Common cations in the soil of importance for crop production are calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), hydrogen (H^+) iron ($Fe^{2+ \text{ or } 3+}$) and ammonium (NH_4^+).

Cation exchange: The continuous movement of positively charged ions (cations) between the soil solution and the surfaces of clay minerals and organic matter. This process results in an equilibrium between ions in solution and adsorbed ions. Adding to or taking ions away from the solution upsets this equilibrium, causing an exchange of ions until a new equilibrium is established.

Chelate (KEY-late): A complex organic molecule that can surround a metal ion and bind to it in several places, keeping the ion in solution and protecting it from reactions that could precipitate it as an insoluble compound. Chelates are used as carriers for some micronutrient fertilizers and as extractants for determining the amount of available micronutrient in the soil.

Chelating: The process of combining a metal ion with a chelate.

Chlorosis: Discolouration of plant tissue caused by a loss of chlorophyll. It typically shows as a yellow colour, but may range from pale green to almost white.

Coefficient: A number describing the relation between two other numbers or objects.

Colloids: Very small particles (less than 0.002 mm diameter) of clay or organic matter. Colloids carry a negative charge and are responsible for most of the nutrient-holding capacity of the soil.

Complex: To combine with a single metal ion at several different places, as with a chelate.

Correlated: Related to one another. For example, an increase in crop yield could be correlated to the amount of fertilizer added.

Denitrification: The conversion of nitrate (NO_3^-) to nitrogen gas (N_2) or nitrogen oxides (NO_x) by bacteria. This occurs under conditions of low oxygen and can result in considerable loss of available nitrogen to the atmosphere.

Desorb: To remove an ion from the surface it was adsorbed to. Usually accomplished by adding an excess of ions, which desorb the others from the clay surfaces.

DTPA (diethylenetriaminepentaacetic acid): A chelate used as a soil test extractant for zinc and other micronutrients and as a carrier for micronutrient fertilizers.

EDTA (ethylenediaminetetraacetic acid): A chelate used as a soil test extractant for zinc and other micronutrients and as a carrier for micronutrient fertilizers.

Equilibrium: Many chemical reactions can operate in both directions, so that in the end there is a mixture of the initial reactants and the final products in balance. The most common example of this type of reaction in soil is the adsorption of cations onto negatively charged soil particles. Some cations always remain in solution, and these are in balance, or equilibrium, with the cations held on the soil particles. There is a constant movement of cations between the solution and the soil particles, but the average concentrations do not change.

Extractant: A solution used in soil fertility testing to extract nutrients from the soil in proportion to the amount available to plants growing in that soil. No single extractant is appropriate for all nutrients or for all soil types.

Fixation: 1. The reduction of atmospheric nitrogen, which is not available to plants, to ammonium by microbial action. 2. The tie-up of potassium between the layers of some clay minerals (vermiculite and smectite), rendering it unavailable or slowly available to plants.

Grade: The percentage content of total nitrogen (N), available phosphate (P_2O_5) and soluble potash (K_2O) stated in that sequence as hyphenated numbers arranged horizontally and including zero if applicable. The grade of urea 46% nitrogen is 46-0-0. The grade represents minimum guarantees in whole numbers for materials and mixes. The grade of a custom blend (customer formula fertilizers), however, can be stated in percentage to the second decimal e.g., 19.25-19.21-19.27.

Guaranteed analysis: Also referred to as guarantees, should be described as guaranteed minimum analysis, except for chlorine (in tobacco fertilizers) where the maximum percentage must be guaranteed. Guarantees are expressed in terms of the chemical element, except for available phosphate (P_2O_5) and soluble potash (K_2O).

Hygroscopic: Attracting and absorbing water out of the atmosphere. Many fertilizer ingredients are hygroscopic and will cake because of the moisture they absorb when exposed to the atmosphere.

ICP: Inductively Coupled Plasma Emission Spectrometry.

Immobilization: The temporary or permanent unavailability of nutrients due to their incorporation into microbial tissue and organic matter. Temporary immobilization of nitrogen can occur if organic materials with a high carbon content are added to the soil.

Ion: An atom or molecule carrying an electrical charge, either positive (cation) or negative (anion). Most are formed by the dissociation of acids or salts when dissolved in water (e.g., $KCl \rightarrow K^+$, a cation, + Cl^-, an anion).

Labile: Held loosely by soil particles and able to move easily into soil solution.

Leaching: The movement of ions down through the soil and eventually into groundwater, with the movement of water through the soil. Leaching occurs only when there is a net downward movement of water (usually late fall to spring) and ions present in the soil solution. Nitrates, sulphates and chlorides are the ions most susceptible to leaching.

Lodging: Crops that lean over or lie flat on the ground because of stalk breakage or inadequate roots. Cereals may lodge because of excess nitrogen.

M: Abbreviation for mole. One mole is the number of molecules with a weight in grams equivalent to their atomic weights. In other words, one mole of hydrogen (atomic weight = 1) weighs one gram. A one molar solution (1M) contains one mole of a compound dissolved in one litre of water.

Macropore flow: the rapid movement of water through preferential pathways in the soil, e.g., cracks and earthworm channels

Midrib: A prominent, strengthened vein along the midline of a leaf.

Mineralization: The release of nutrients from organic matter as it is broken down by microbial activity.

Mitscherlich equation: One form of equation that is used to describe the response of crop yield to added fertilizer or to soil test. It never reaches a maximum value.

N-P-K: Denotes the grade guarantees. In formulation calculations it is common usage to use the phosphorus symbol (P) to mean available phosphate (P_2O_5) and the potassium symbol (K) to mean soluble potash (K_2O).

Petiole: The stalk that attaches the leaf blade to the stem.

pH: A measurement of the acidity or alkalinity of a solution. The pH scale is from 0 to 14. A pH of 7 is neutral. Values below 7 are acid and values above 7 are alkaline. Most soils fall in a range from pH 5 to 8.

Phosphorus Index: An indicator of the risk of surface water enrichment with P from runoff from agricultural land. It takes into account proximity to water, land management and erosion potential as well as P soil test and fertilization to assess risk.

Phloem: Interconnected hollow cells (vascular tissue) extending from the leaves through the stems to the roots and fruits. Water and dissolved nutrients can move in both directions in the phloem. This is the pathway for redistributing sugars and proteins within the plant, as well as mobile nutrients.

Potash: In the fertilizer industry, the word potash is used to mean either K_2O (potassium oxide), to measure the potassium content, to refer to KCl (muriate of potash), or to identify the fertilizer material.

Prill: A small granule of urea or ammonium nitrate. The name is derived from the method of producing the granule.

Quadratic equation: A form of equation used to describe the response of crop yield to added fertilizer. It reaches a maximum value and then begins to drop off as the fertilizer rate is increased.

Quadratic plateau equation: A form of equation used to describe the response of crop yield to added fertilizer. It is similar to the quadratic equation, but remains level upon reaching its maximum value.

Salt index: An index of the relative solubilities of different fertilizer ingredients, by total weight. There is no critical level, but the higher the salt index, the more risk of injury to seeds or roots when the fertilizer is in contact with these plant parts. The index is expressed in relation to sodium nitrate, which is given a value of 100.

Sodic: A soil with the majority of the cation exchange complex occupied by sodium. These soils are characterized by large shrinking and swelling and very poor structural stability when wet.

Soluble potash: That portion of the potash, expressed as potassium oxide (K_2O), that is soluble in aqueous ammonium oxalate, aqueous ammonium citrate, or water, according to an applicable AOAC international method.

Suspension: A mixture of finely ground solid material and water or a solution, which is agitated to keep the solid material suspended in the liquid. Higher concentrations of fertilizer materials can be carried in a suspension than in a true solution.

Tilth: The structure and friability of the soil; the ease of producing a desirable seedbed from the soil.

Volatilization: The loss of a vapour, usually ammonia, to the air from a solid material that has been applied to the soil surface.

Xylem: Hollow tubes extending from the roots to the leaves and fruiting bodies of a plant. Water and dissolved nutrients flow only up the xylem. Most nutrients entering plants travel through the xylem.

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Nutrient Deficiencies

Nitrogen Deficiency

- Yellowing from leaf tip along midrib
- N is mobile in plants, so symptoms appear on lower leaves first
- Indicates N losses, tie up or under-fertilization

See page 23.

Corn, Bruce County

Potassium Deficiency

- Symptoms appear on lower, older leaves: yellowing or white spots (alfalfa) along leaf margins
- Caused by low soil test or poor root growth (disease, compaction, poor drainage, etc.)

See page 33.

Alfalfa, Bruce County

Soybeans, Wellington County

Sulphur Deficiency

- Sulphur deficiency present in the right side of the photo
- Chlorosis or yellowing occurs in youngest leaves first due to poor mobility of sulphur within plants

See page 41.

Winter Wheat, Niagara Region

Response to Phosphorus

Winter Wheat, Kent County

Source: Dr. Dave Hooker, University of Guelph, Ridgetown

- Soil test phosphorus: 7 ppm (Olsen)
- Photo: April 13, 2016 (wheat seeded on October 5th, 2015)
- 42 kg/ha P_2O_5 applied in furrow (R), no P applied (L)
- Yield: 112 bushels/acre (with P) vs. 86 bushels/acre (without P)

See page 30.

Internal Calcium Deficiency

(Blossom End Rot)

- Low mobility in plant tissues
- Deficiency caused by moisture deficit or high transpiration demand during fruit set — not usually a lack of calcium in the soil or roots
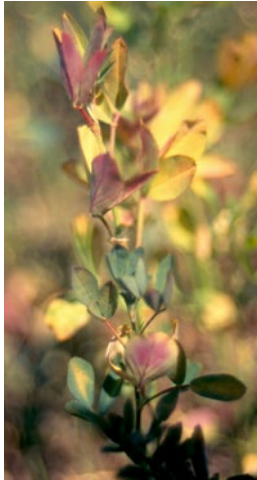
See page 35.

Peppers and Tomatoes, Kent County

Boron Deficiency

- Deficiency symptoms include shortened internodes, leaf discolouration and poor flowering and seed set
- Most common on light-textured soils in dry conditions

See page 45.

Alfalfa, Kent County

Manganese Deficiency

- Manganese has low mobility in both soil and plant tissue
- Deficiency symptoms can include stunting, interveinal chlorosis
- Most commonly seen on high pH soils, muck soils and eroded soils

See page 44.

Processing Peas, Kent County

Soybeans, Kent County

Source: Dale Cowan, CCA-ON

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