A3588

Management of Wisconsin Soils

Fifth Edition

UW Extension

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CONTENTS

"If you are thinking a year ahead, sow seed. If you are thinking 10 years ahead, plant a tree. If you are thinking 100 years ahead, educate the people."

Old Chinese saying

Introduction

People look at soils differently. People may view soil in the home as a source of "dirt" or as a good medium for growing house plants. Construction engineers look at soil in terms of its ability to support a building or highway. But agriculturalists look at soil in terms of its ability to support the growth of plants. Obviously, this is its most important function because the soil ultimately supports nearly all plant and animal life.

Soil appears to be simply an inert mixture of different-sized particles. But this certainly is not the case. Living organisms by the billions, decaying and residual organic matter, a wide variety of minerals, and air and water interact to form a dynamic and exceedingly complex biological, physical and chemical system. For example, a teaspoon of soil may contain as many microorganisms as there are people on the earth. This same teaspoon of soil contains more chemical atoms than there are drops of water in Lake Superior and Lake Michigan combined!

The various chemical, physical, and biological processes taking place in the soil are complex and sometimes not easily understood. But for farmers and land managers to make wise decisions in the future, they must understand these processes. In this age of rapid technological change, we need to know why things happen—knowing only what to do is often inadequate. Both grain and livestock farmers need to produce crops efficiently in order to succeed economically. And to produce crops efficiently, they must understand and use good soil management practices.

Growth of a colony of organisms, whether microbes, higher plants, animals, or people, is limited ultimately by exhaustion of the food supply or toxic accumulation of wastes. As the world population continues to grow, agriculturalists will be challenged as never before to increase production while managing wastes so as to recycle nutrients without polluting water supplies.

Good soil management is a key factor in maintaining the quality of our water resources. Protecting our surface water supplies requires that we follow a good soil and water conservation program. Runoff water and soil erosion losses account for much of the nitrogen and phosphorus entering our lakes and streams from rural areas. To protect groundwater we must develop nutrient management programs that support productive cropping systems and simultaneously reduce leaching of nutrients. If we are interested in agricultural sustainability and environmental protection, we must develop a conservation ethic and truly become "stewards of the soil."

Emmett E. Schulte
Leo M. Walsh

CHAPTER 1

Soil formation and classification

"Soil is a living entity: the crucible of life, a seething foundry in which matter and energy are in constant flux and life is continually created and destroyed."

D. Hillel, Out of the Earth, *1991*

What is soil?

Soil is the upper layer of earth which may be tilled and cultivated. More specifically, soils are the unconsolidated (loose) inorganic and organic materials on the surface of the earth which support the growth of plants. Weathered rocks and minerals make up the inorganic fraction of the soil and can supply all essential plant nutrients except nitrogen. Virtually all of the nitrogen, as well as a portion of several other essential plant nutrients, is stored in the organic matter.

Soil formation

Soils are formed from many kinds of materials exposed on the land surface known as parent materials. Physical and chemical weathering processes gradually change rocks, glacial deposits, and wind or water deposits into soil over long periods of time. These processes are influenced by variations in climate, plants and animals, and topography.

Factors of soil formation

Parent material, climate, living organisms, topography, and time are the five factors of soil formation. Some would include humans as a sixth factor, for our activities can markedly change the formation of many soils. The type of soil developed depends on the amount of time a parent material in a specific topography is exposed to the effects of climate and vegetation.

Parent materials that make up Wisconsin's soils are (1) bedrock weathered in place, (2) deposits left by glaciers, (3) materials deposited by wind or water, and (4) decaying plant material.

The bedrock geology of an area often directly or indirectly influences soil formation. Soils in the west central and central parts of the state are the result of direct influence of bedrock. In these areas the weathering of the sandstone bedrock left predominately sandy soils. The bedrock has indirectly influenced those soils formed in glacial till. In northern and north central Wisconsin the glacial till is acid because the till was derived from the weathering of acidic granitic rock in northern Wisconsin; whereas, calcareous glacial till was developed in the southern and eastern parts of the state where the predominant bedrock is limestone. The map, *Bedrock Geology of Wisconsin,* shows the location of the different kinds of bedrock throughout the state. See the back side of the map for additional information on Wisconsin bedrock.

Glacial deposits and the action of glaciers in altering the landscape have profoundly influenced the formation of most soils in Wisconsin. Many soils are formed partially or entirely out of glacial "drift" or till. In these areas the soils have taken on many of the physical and chemical characteristics of the till. Acid soils are formed from acid till; stony soils are formed from stony till; red-colored soils are formed from red-colored till, etc. The *Ice Age Deposits of Wisconsin* map shows the glacial deposits in Wisconsin. The back side contains additional information on the ice age in Wisconsin.

Materials deposited by wind and water have been important in the formation of many soils in the state. The wind-blown or aeolian silts (loess) are quite deep in the unglaciated area in western and southwestern Wisconsin. A silt cap of more than 4 feet is common near the Mississippi River. The silt cap or loess becomes progressively thinner as one moves in a northeasterly direction. Little, if any, silt cap exists on the soils in the eastern and northeastern parts of the state. Soils with a deep silt cap are very productive because they are usually well-drained and store relatively large quantities of available water. Also, they are generally easy to work and free from stones.

Alluvial soils have been formed as a result of materials being deposited by water. These soils are commonly found on stream terraces and range from silty to very sandy, and from well-drained to very poorly drained.

Decaying plant material in bogs and low-lying areas is the parent material of organic soils. The lack of oxygen in these saturated soils prevents decomposition, allowing organic material to accumulate. Generally, organic soils contain at least 20% of organic matter (by weight), and this organic layer is more than 1 foot thick. Organic soils occupy approximately 7.5% of Wisconsin's surface and are often referred to as mucks or peats. Mucks are more highly decomposed than peats to the extent that the kind of plants from which they formed is not easily identified. Mineral soils contain less than 20% organic matter.

Climate is defined as weather as it exists over a long period of time. Climate changes with time, and soils often reflect the effects of past climates.

Precipitation and temperature changes both help form soil. Water from rain and melting snow dissolves some soil minerals. Freezing and thawing break rocks and large soil particles into smaller pieces.

High temperatures and high levels of precipitation often speed weathering. The effect of climate can be seen best by comparing soils over large areas. For instance, the more intensive weathering in southeastern United States has resulted in the development of extensive areas of brick-red colored soil containing relatively low amounts of organic matter and high levels of oxidized iron. In contrast, most soils in the Midwest contain much more organic matter and lower amounts of oxidized iron. Soils in the northern Great Plains differ from soils in the north central region mainly because they developed in a drier climate. Soils formed in drier climates typically have a relatively high pH and more plant nutrients due to less leaching.

Even within Wisconsin there is enough climatic difference from the north to the south to produce noticeable variation in the soils. Northern Wisconsin's cooler climate slows decomposition of organic matter on the surface of the soil. This slowly decomposing organic matter produces organic substances that promote leaching of minerals and nutrients from the soil. Northern Wisconsin soils are, therefore, more leached and tend to be less fertile than those further south.

Climate also influences the kinds of plants and animals that will grow in and on the soil. For instance, under natural conditions grasses and shrubs grow on soils where the climate is relatively dry while trees tend to grow in the more humid climates.

Living organisms, plants and animals, play an important role in soil formation. Plants extract nutrients from the subsoil as they grow. These nutrients are subsequently deposited on the soil surface when the plants die. Soil differences frequently can be related to the type of plants grown on them over long periods of time. In parts of southern Wisconsin, tall prairie grasses growing on soil produced a thick black layer of surface soil high in humus. Much of this humus came from the decay of grass roots. Trees, on the other hand, deposit their leaves, needles and twigs on the top of the soil, and tree roots do not die each year as most grass roots do. Therefore, most forest soils do not have thick black surface layers.

Fire has also played an important role in determining the native vegetation growing on our soils. For example, in southern Wisconsin the prairies burned frequently. Fire prevented the development of forests; thus, in these areas only a few large oak trees growing in fields of grass survived.

Bacteria and fungi, which are microscopic plants, are a vital part of the soil. They decompose organic matter and produce materials that bind soil particles together in aggregates, and they help make certain nutrients available for plants.

Animals have a lot to do with soil formation. Earthworms burrow through the soil making large holes that improve both water and air movement in the soil. They also consume large amounts of dead organic matter and often carry plant material from the surface down several inches into the soil. This hastens decomposition of organic matter and tends to thicken the dark surface soil. Other small animals living in the soil also eat and partially decompose organic matter from leaves, grass blades, and other plant materials.

Humans have had an extremely important effect on soil formation—both beneficial and destructive. They can cause erosion, compaction and depletion of essential nutrients, or they can improve the physical and chemical conditions in soil by using sound tillage practices and by adding lime, fertilizer, manure, and crop residues.

Topography refers to the lay of the land—the patterns of hills, valleys, and plains. It strongly influences water flow across and through soils, and this has a major influence on soil formation. For instance, soils may be very shallow or "thin" where slopes are steep and serious erosion has occurred. In the eastern part of the state the topography has been strongly influenced by the glaciers. Many low-lying soils—peats and mucks, for example—occur in bogs and poorly drained depressions. Topography becomes especially important when soils are farmed. Steep slopes require excellent soil conservation practices, while low-lands and depressional areas need surface or tile drainage for optimum crop production.

Time, measured in thousands of years, is the final element in soil development. Most Wisconsin soils have formed since the glaciers retreated. With the exception of southwestern Wisconsin, most of the state has been covered by glaciers within the last 30,000 years, and much of the eastern, central and northern parts of the state were covered by ice or water within the last 8,000 to 15,000 years. Because of leaching and the weathering process, older soils tend to be less fertile than soils of relatively recent origin.

Soil-forming processes

Many complex physical, biological, and chemical transformations occur in soils. Any set of events that intimately affects the soil in which it operates is a soil-forming process. There are many soil-forming processes active in soil. Only the more important processes will be discussed here. Not all processes are active in every soil. Some processes predominate in one soil, others in another soil. The terms defined below identify several of the more important soil-forming processes.

decomposition—breakdown of a mineral or organic matter into its components.

eluviation—downward movement of solid material, usually clay particles, within a soil profile.

erosion—loss of material from the surface layer of soil by the action of water or wind.

gleization—reduction of iron under waterlogged soil conditions, giving subsoils a blue-grey color.

humification—transformation of raw organic matter into humus.

illuviation—the accumulation of fine soil particles which move from upper layers of soil to the subsoil.

laterization—chemical migration of silica out of the soil profile and concentration of oxides and hydroxides of iron and aluminum. Occurs in tropical regions.

leaching—movement of soluble material through the soil in percolating water.

mineralization—conversion of organic compounds into inorganic elements.

salinization—accumulation of soluble salts (usually sulfates or chlorides of calcium, magnesium, potassium and sodium). Usually found in semi-arid regions.

More than one soil-forming process can be active simultaneously or sequentially. It is the net effect of the active processes that give a soil its unique characteristics.

Weathering

Weathering transforms parent materials in the process of soil formation. This weathering may be physical, chemical, or both. Chemical weathering is not very significant in large rocks because there is relatively little surface area exposed. Physical weathering is more important.

Physical weathering involves natural forces that break rocks into smaller pieces. These forces include temperature, wind, water, ice, and plant roots. Rapid temperature changes can cause rocks to crack. Rocks are made up of two or more minerals, each mineral expanding and contracting differently in response to temperature changes. Some early pioneers built fires on large rocks, then doused them with cold water to break them into smaller rocks that could be hauled away.

Wind strong enough to carry sand particles can sandblast rock surfaces. Moving water, especially that carrying sediment, is also abrasive. Pebbles on the bottom of a stream tend to be rounded or smooth as a result of the tumbling action of the water. Water freezing in cracks and crevices also causes disintegration by expansion. In Wisconsin, glacial activity broke rocks into smaller fragments and ground some rocks to silt-sized particles. Plant roots growing into cracks in rocks can also cause cracking and breaking.

Chemical weathering becomes significant once physical weathering reduces parent materials to the size of sand or smaller particles. The most important chemical reactions are solution, hydration, hydrolysis, decomposition, and complexation.

Solution refers to the dissolving of a solid in a liquid. Water is the liquid in soils and is considered a universal solvent. Every solid is soluble in water to some extent. Most rocks and minerals are negligibly soluble. Most chloride and nitrate salts are highly soluble; whereas many phosphate compounds are only slightly soluble. When the solubility of a dissolved substance is exceeded, it precipitates or solidifies and drops out of solution. For example, when hard water is heated, calcium carbonate precipitates to form lime on the walls of a teakettle. Also, some dissolved materials may be adsorbed or attached onto the surfaces of existing soil particles.

Hydration is the addition of water to a substance. For example, the addition of water to dry calcium sulfate ($CaSO_4$) results in gypsum ($CaSO_4•2H_2O$), with two water molecules bound to each calcium sulfate molecule.

Hydrolysis is a form of decomposition in which the hydrogen-hydroxyl (H-OH) bond in water is split, and the resulting ions combine with a reactant. For example, feldspar ($KAlSi_3O_8$) and water (H_2O) react to form silicic acid ($HAlSi_3O_8$) and potassium hydroxide (KOH).

Decomposition involves the breakdown of a substance into its component parts. Organic matter, for example, is broken down into carbon dioxide and nutrients which can be recycled for new plant growth.

Oxidation, a form of decomposition, is the combination of oxygen with a substance, as in burning. Organic matter decomposes (oxidizes) in soils. Also, some elements such as nitrogen, sulfur, iron, and manganese undergo oxidation in well-aerated soils. Under waterlogged conditions, reduction—the reverse of oxidation—can occur. Under these conditions, the removal of part of the oxygen from iron and manganese oxides makes them more soluble, allowing them to be leached.

Complexation refers to the surrounding of metallic ions by groups of anions or neutral molecules. Ammonia, for example, forms a complex with copper by surrounding a copper ion with four ammonia molecules. Organic molecules can form complexes with metallic ions. Some large organic molecules form two or more bonds with the same metallic ions. These are known as *chelates* (Greek: *chele* = claw). Some chelates, such as ZnEDTA, make good fertilizers because they prevent precipitation of the metallic ion, keeping it more available to plants. In chemical weathering, chelates help make the metals in rocks and minerals slightly more soluble.

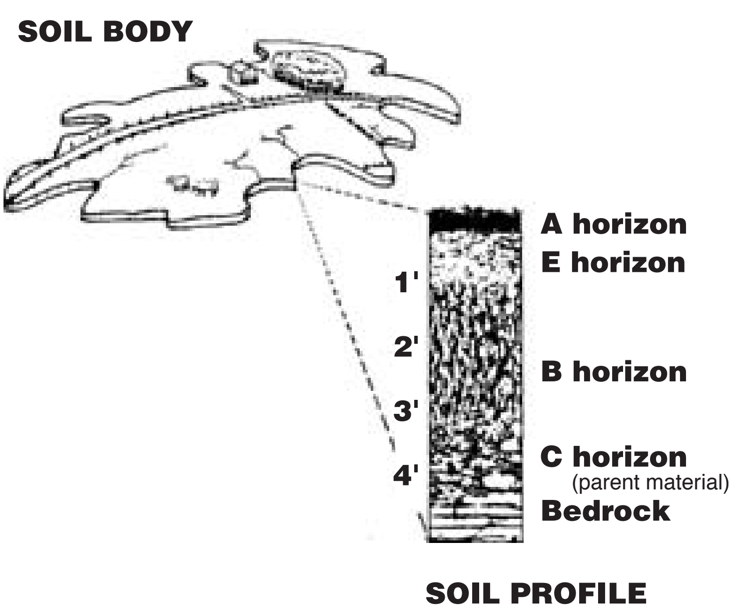


Figure 1-1. Relationship of soil horizons and profile to soil body.
Source: F.D. Hole, UW-Madison.

Soil classification

The factors and processes of soil formation discussed above have produced many kinds of soil in Wisconsin. Soils vary considerably from place to place, sometimes even within a small field. Soils are classified in a manner similarly to how plants and animals are classified. Instead of genus and species, however, the lowest or most specific unit of soil classification is the soil series. Higher levels of classification include the family, subgroup, great group, suborder, and order. The classification system implies that one soil differs from another sufficiently to make classification meaningful.

Soil horizons

A body of soil is three-dimensional (figure 1-1). The depth is the lower limit to which native perennial plant

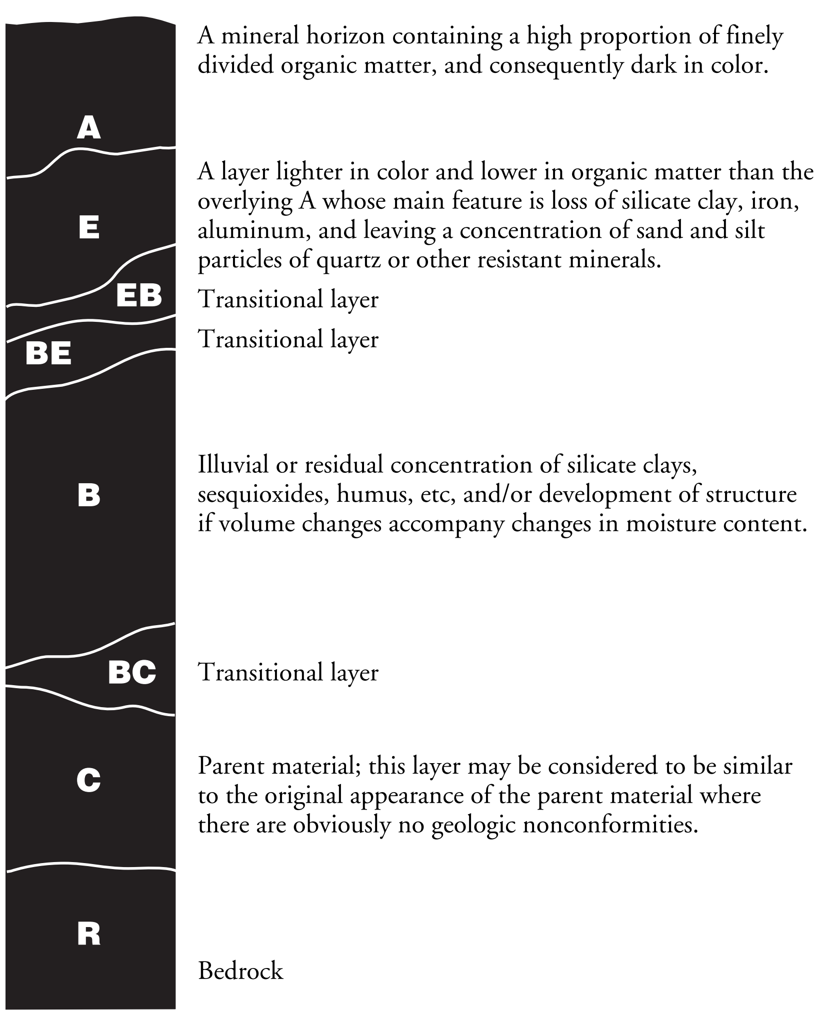


Figure 1-2. A hypothetical profile for a cultivated soil with all master horizons and some transitional horizons. The thickness of the horizons varies as indicated. *Adapted from Foth, 1988.*

roots extend. In Wisconsin, soil depth usually ranges from 1 foot in shallow soils over bedrock to about 7 feet. The surface area may be less than an acre to more than 100 acres. Usually we view only the soil surface or the depth to which the soil is tilled. In ditches and along road cuts one can see the vertical dimension. A vertical section of soil is called a soil profile. This profile typically has distinct layers called *horizons*. Horizons are the result of various soil-forming processes occurring in a particular soil.

Accumulation of organic matter under prairie, for example, results in dark-colored surface soil. In contrast, soils formed under forests are much lighter in color. Regardless of original vegetation, the downward movement of clay and iron oxides results in the formation of subsoil horizons that are more dense than the surface soil. The depths at which the different horizons occur depends on the intensity of the predominant soil-forming factors acting on a particular soil.

Soil scientists designate horizons alphabetically: A for the surface layers, B for subsoil, C for parent material, E for eluvial (loss of clay, iron, or aluminum), and R (sometimes D) for bedrock. These horizons may be subdivided. The horizon sequence typical for a cultivated soil is presented in figure 1-2. The kind and arrangement of soil horizons is used as a basis for soil classification.

Soil name

The name of a soil is a combination of its series and type. The series is a geographical name taken from the area in which the soil was first described and mapped. The type is the textural class (e.g., sandy loam, silty clay loam, clay). Thus, we have such soil names as Fayette silt loam, Plainfield sand, and Kewaunee silty clay loam. The same soil type can be found in neighboring states (Fayette, for example, is named after Fayette, Iowa). In all, there are more than 730 soil names recognized in Wisconsin and more than 20,000 in the United States and affiliated territories. Nevertheless, these soils can be grouped together into several major soil regions. The map on the following page, *Soil Regions of Wisconsin,* shows the locations of these major soil regions. The soils in each of the major soil regions are described in general terms on the back side of the map.

Soil maps and mapping reports

The following map shows the areas of the state that have roughly the same kinds of soils. However, to find out what soils occur on a small tract of land—such as a farm—a much more detailed soil map is necessary.

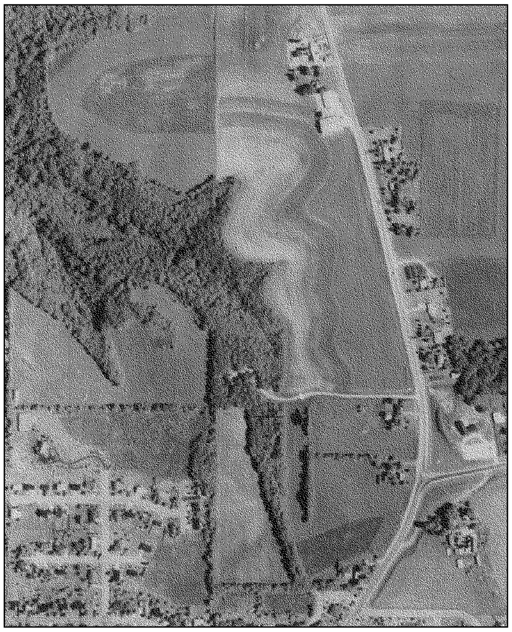


Figure 1-3. Aerial photograph used for detailed mapping of a 160-acre tract of land.

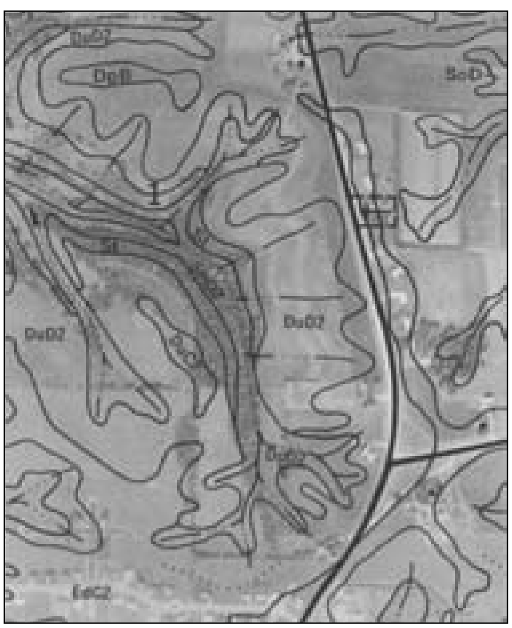


Figure 1-4. Detailed soil map drawn on the aerial photograph. Symbols indicate soil type, slope, and degree of erosion. For example, DuD2 means a Dunbarton silt loam (Du) on a slope of 12 to 20% (D) and a moderate degree of erosion (2). *(NRCS photo)*

The Natural Resources Conservation Service (NRCS) makes detailed maps to assist farmers in developing soil and water conservation plans. A detailed soil map, drawn on an aerial photograph, is a very important part of a soil and water conservation plan. It shows the extent of erosion, the need for and possibilities of drainage, and gives an indication of what yields can be expected from the soils shown on the map. The NRCS also suggests soil and crop management practices to keep soil loss at or below tolerable levels. Figures 1-3 and 1-4 show an aerial photograph used for mapping and the detailed soil map drawn from the photograph.

NRCS publishes soil maps and detailed reports for each county. Upon request, NRCS and other conservation agencies can prepare individual farm plans using the county soil survey report. Soil survey reports can often be obtained free from senators or congressional representatives from Wisconsin. They may also be purchased from county land conservation departments or NRCS offices. Many libraries also have a copy of the local survey report. The soil survey provides much useful information in addition to the detailed soil maps. Use and management of the soils for different purposes is explained. Expected yields of crops are given for each soil, as is information on woodland management and productivity. Engineering properties and suitability for recreation and wildlife are listed. History, geology, climate, topography, soil formation, and more are also included.

Soil factors affecting management

Soil slope

Slope has a great deal of influence on soil management and crop production. Three important characteristics are steepness, length, and direction.

Cultivated land with a slope of greater than 2% is usually subject to erosion. The velocity and amount of the collecting runoff water increases with steepness or length of the slope. A larger quantity of water moving at a greater speed has much more energy to carry soil away. If sloping soils are not properly managed, serious erosion can occur. Runoff water coming from a steep to gentle slope undergoes an abrupt decrease in velocity. The sudden change of speed allows sediment to drop out of the water.

Extremely long slopes (300 to 500 feet) concentrate a great deal of water near the bottom. These long slopes often need to be broken up by the use of terraces, diversions, and strip cropping. Short, choppy slopes present management challenges. The uneven surface makes it difficult to install soil conservation practices on them and crops may mature unevenly. Short irregular slopes may require a drainage system and soil conserving practices on the same field.

The direction that a slope faces, or aspect, can also influence plant growth. In the northern hemisphere, south- and west-facing slopes are generally warmer and drier than north- and east-facing slopes. This temperature and moisture difference can affect both agricultural crops and trees.

Soil depth

The depth of soil favorable for root development is more important now than it has been in the past. This is because better production and management practices are increasing yields year by year. As a result, water more often becomes the factor which limits yields. Plants growing in deep soil will have a greater volume of soil from which to extract water than will plants growing in soil with a restricted root zone.

Soils with 4 to 5 feet of medium-textured subsoil will provide the best conditions for plant roots. Poor soil conditions such as very dense, heavy subsoils, claypans and plow pans, very high acidity, and excessive wetness will restrict root growth. In most cases, only excessive wetness, which can often be overcome by proper drainage, can be corrected economically. Sometimes crop growth can be improved on soils with unfavorable subsoils by liming and fertilizing the surface soils adequately.

Soil drainage

Drainage is often essential to good soil management. Successful use of some of the most productive land in Wisconsin is dependent upon proper drainage. Agricultural drainage is the removal of excess water by artificial means from the soil profile to enhance agricultural production, or more specifically, the removal of excess gravitational water from the soil.

Surface drainage systems (usually referred to as “land forming”) are designed primarily to remove surface water that has not entered the soil profile. This is done by shaping the slope of the land to allow excess water to flow slowly to a system of shallow field waterways which empty into larger drainage systems.

Open-ditch drainage systems are very effective on flat, low-lying soils such as peats and mucks that are normally saturated to near the surface. Such soils frequently have seepage zones and springy areas that require tiling as well as ditching. However, because of regulations to protect wetlands, a permit must be obtained from the Department of Natural Resources (DNR) before any new or improved drainage systems can be installed in wetland soils.

Tile drainage removes excess water from the soil through a continuous line of tile or plastic tubing. Tiling is designed to keep the water table below the root zones of plants. The excess water enters through tile joints or holes in the plastic tubes and flows out by gravity. Water will enter a tile line only when the soil around the tile becomes saturated.

Tiling is highly effective on peats, mucks, and other soils that are normally saturated to near the surface. These soils frequently have seepage zones and springy areas that make tiling an absolute must. Some mineral soil types, especially those with deep, fine-textured subsoils such as the red clays, have been tiled satisfactorily. On some soils “land-forming” will increase the efficiency of tile. Soils with impervious layers in the subsoil and most wet sandy soils are unsuited to tiling. Such soils occur mainly in central and north-central Wisconsin.

Land capability classes

Land capability classes are practical groupings of soil limitations based on such characteristics as erosion hazard, droughtiness, wetness, stoniness, and response to management. Soil maps prepared by NRCS farm planners are colored to show different land capability classes. Each color on the soil map indicates one of eight land capability classes. These classes reflect the land's relative suitability for crops, grazing, forestry, and wildlife. For a summary of the limitations and the recommended management practices, see table 1-1.

Land classes are designated using roman numerals I through VIII. The classes are divided into subclasses and units. Subclasses are designated by letters and numbers. The letter "e" stands for an erosion hazard, "w" for a wetness hazard, and "s" for a permanent soil limitation such as shallow depth and/or droughtiness.

Class I land has the widest range of use with the least risk of being damaged. It is level or nearly level, well-drained, and productive. Land in this class can be cultivated with almost no risk of erosion and will remain productive if managed with normal care. This class is colored green on soil maps.

Class II land can be cultivated regularly, but certain physical conditions give it more limitations than Class I land. Some Class II land may be gently sloping so it will need moderate erosion control. Other soils in this class may be slightly droughty, slightly wet, or somewhat limited in depth. This class is colored yellow on soil maps.

Class III land can be cropped regularly but has a narrower range of safe alternative uses than Class I or II land. This land usually requires extensive use of conservation practices to control erosion or provide drainage. This class is colored red on soil maps.

Class IV soils should be cultivated only occasionally or under very careful management. Generally, it is best adapted for pastures or forests. This class is colored blue on soil maps.

Class V land is not suited to ordinary cultivation because it is too wet or too stony, or because the growing season is too short. It can produce good pasture and trees. This class is white.

Class VI or VII land use is severely limited because of erosion hazards. Some kind of permanent cover should be kept on these soils. With very special management, including elaborate soil and water conservation practices, improved pastures can in some instances be established by renovation. Class VI is colored orange, and Class VII is colored brown.

Class VIII land is not suited to economic crops. Usually it is very severely eroded or is extremely sandy, wet, arid, rough, steep, or stony. Much of it is valuable for wildlife food and cover, for watershed protection, or for recreation. Class VIII land is colored purple.

These capability classes, as summarized in table 1-1, indicate the limitations of land and the hazards associated with its use for agriculture and forestry. Land use recommendations in soil and water conservation plans take these hazards into account and are based primarily upon the needs for erosion control and good water management rather than upon practices such as fertilizer application and weed control.

Table 1-1. Description of land capability classes and the conservation practices needed for each.

Land capability class (degree of limitations)	Map color	Conservation practices (organized by subclass)[a]
Suited for cultivation		
I Few limitations. Very good land from every standpoint.	Green	Practice good soil and crop management.
II Moderate limitations or risks of damage when used for crops.	Yellow	**e** Use contour strip cropping, terraces, grass waterways, and conservation tillage. **w** Protect from flooding, use drainage. **s** Maintain good soil structure.
III Moderate to severe risk of damage or limitations. Regular cultivation possible if limitations are observed.	Red	**e** Use contour strip cropping, grass waterways, terraces, diversions, and conservation tillage. **w** Install surface and/or tile drainage, diversions. **s** Practice moisture conservation, control wind erosion, and irrigate.
IV Severe limitations. Can be cultivated with special management.	Blue	**e** Use contour strip cropping, grass waterways, diversions, terraces and conservation tillage, or manage as permanent pasture or woodland. **w** Protect from flooding, use surface drainage. **s** Practice moisture conservation and control wind erosion.
Not suited for cultivation		
V Too wet or stony for cultivation.	White	Grazing, forestry, recreation
VI Too steep, stony, wet, or droughty. Moderate limitations for grazing. or forestry	Orange	Grazing, forestry, recreation
VII Very steep, rough, wet, or sandy. Severe limitations for grazing or forestry.	Brown	Grazing, forestry, recreation
VIII Extremely rough, swampy, etc.	Purple	Wildlife, watershed protection, or recreation

[a] *Abbreviations:* **e**=*erosion hazard;*
w=*wetness hazard;*
s=*permanent soil limitation such as shallow depth and/or droughtiness.*

Questions

1. The soils of southwestern Wisconsin are considerably older than those of northeastern Wisconsin. Explain why.

2. Why are the soils of north-central Wisconsin consistently more acid than the red clay soils in eastern Wisconsin?

3. What are aeolian deposits, and what is their importance in terms of the soils in Wisconsin?

4. The parent materials having the most effect on the soils of Wisconsin are the bedrock, glacial deposits, and aeolian deposits. Explain what effect, if any, each of these parent materials have had on the soils in your local area.

5. What are alluvial soils? Name some important areas of alluvial soils in Wisconsin, elsewhere in the United States, and in other countries.

6. Why are soils developed from sandstone inherently less fertile than soils developed from limestone?

7. In southwestern Wisconsin, prairie soils developed on the broad, flat hilltops while forested soils predominate on the hillsides and in the valleys. Explain why.

8. What is the difference between physical weathering and chemical weathering?

9. Explain how “horizons” form in soil.What is the difference between the A and B horizons in a soil?

10. How are soils named? Give an example of a soil name and explain the meaning of each part of the name. How can you find out the names of soils on a particular farm and the yields of crops that these soils are capable of producing?

11. A soil map in a soil and water conservation plan shows a field with some land in Land Capability Subclass IIIe and some in Subclass IIIw. What land use practices would apply to these land subclasses?

CHAPTER 2

Physical properties of soil

There is a widespread popular acceptance of the importance of the physical properties of soil to plant growth, but a large proportion of the statements commonly made on this subject are vague, qualitative and frequently unsupported by factual evidence."

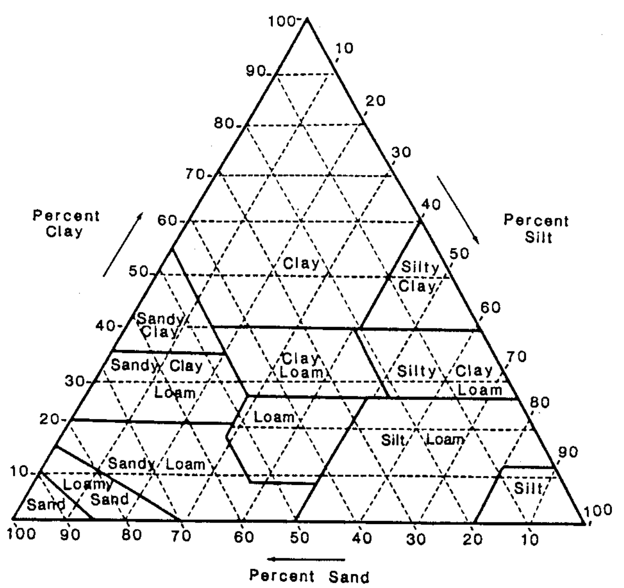
B.T. Shaw, Soil Physical Conditions and Plant Growth, *1952*

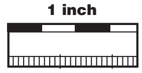
Spectacular advances in the use of fertilizers, pesticides, and other agricultural chemicals since the 1950s have placed a great deal of emphasis on agricultural chemistry. In the process, the importance of the physical properties of soils and their effects on plant growth have often been overlooked. For example, heavier equipment makes soil compaction an increasing problem. Also, few people understand the physical forces that control water retention and movement in soils. As a result, water is frequently the most mismanaged of all growth factors.

Texture

In its broadest sense, soil texture refers to the "feel" of the soil; that is, its coarseness or fineness. Soils are often referred to as being coarse-textured, medium-textured, or fine-textured. More specifically, soil texture is defined as the relative proportion of sand, silt, and clay in the soil. The textural triangle in figure 2-1 shows the ranges in the percentage of sand, silt, and clay associated with different textural classifications. A soil containing equal percentages (33.3%) of sand, silt, and clay would be classified as a clay loam,

Figure 2-1. Ranges in sand, silt, and clay for the different textural classes.





Size range in millimeters (mean diameter)

75 2 1 .5 .25 .1 .05 .02 .005 .002 .0002 .0008

GRAVEL	SAND					SILT			CLAY		
	very coarse	coarse	medium	fine	very fine	coarse	medium	fine	coarse	medium	fine

not as a loam which many would guess. There is a tremendous difference in size between sand, silt, and clay particles. This is shown on the scale on the bottom of figure 2-1 and in the illustration of relative sizes presented in figure 2-2.

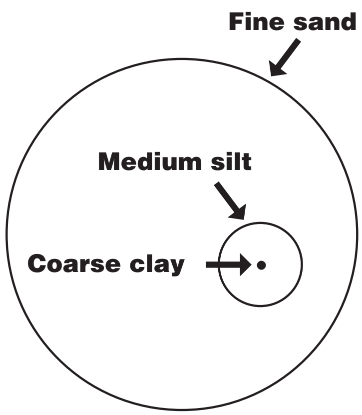


Figure 2-2. Relative sizes of fine sand, medium silt, and coarse clay particles enlarged 500 times. Coarse sand is about 1/25 of an inch or 1 millimeter in diameter.

Another way of visualizing the size of various soil particles is to look at their rate of sedimentation, or the rate at which they settle out of a suspension. If soils are dispersed by shaking them in water with a dispersing agent, the sand-sized particles will settle out of the suspension in about 40 seconds. The silt-sized particles will settle out in approximately 7 hours. Because of their extremely small size, most clay particles will remain in suspension for a very long period of time.

Importance of soil texture

Soil texture is important because it affects physical and chemical properties that influence crop growth. Soil structure, organic matter, aeration, bulk density, tilth, water movement and storage, weathering of minerals, and nutrient supply are all influenced directly or indirectly by soil texture. Clay soil may be termed "heavy"—even though it weighs less per cubic foot than a sandy soil—because it is harder to pull a tillage implement through clayey soil than through silty or sandy soil.

Soil texture has a substantial effect on the growth of crops. Sandy soils have large pores that hold little water and are, therefore, droughty. Wind erosion is also a serious problem on these soils when they are bare. Some plant nutrients rapidly leach through sandy soils. Clay soils are often hard to work up into a good seedbed. Water often moves through clay soils very slowly, making them excessively wet. Medium-textured soils, which are between sandy and clayey soils, are usually the best suited for crop production.

The amount of surface area that soil particles have is very important. Surface area determines the amount of available water and plant nutrients that a soil can hold. Clay particles, being extremely small, have a very high surface area in proportion to their volume. These particles are usually broad and flat, like flakes of mica. Most of them are composed of millions of thin layers, each separated by layers of water. The internal surface along these layers is much larger than the outside surface. In fact, an acre of clay 7 inches deep has a surface area equivalent to 25,000,000 acres (table 2-1). It is this vast surface area that causes a small amount of clay to have such a great effect on both the physical and the chemical properties of soils. The clay in most soils accounts for the bulk of the surface area that holds plant nutrients.

Table 2-1. Properties of sand, silt, and clay-sized soil particles.

Particle sizes	Physical properties	Surface area of soil particles in an acre plowed 7 inches deep
Coarse sand	Loose, non-sticky, gritty	500 acres
Fine & very fine sand	Loose, not sticky	5,000 acres
Coarse, medium, fine silts	Smooth and floury, slightly sticky	50,000 acres
Coarse, medium, fine clay	Sticky and plastic when wet; hard and cohesive when dry	25,000,000 acres[a]

[a] *Includes both external surfaces and surfaces between crystal plates.*

Determining soil texture by feel

A precise determination of soil texture requires laboratory analysis. For most practical purposes, the texture can be estimated accurately enough by hand texturing. In a mineral soil, the feel of the soil when rubbed between the thumb and forefinger is dependent primarily on the relative amount of sand, silt, and clay. While soils rarely consist entirely of one particle size range, learning the characteristic feel of each particle size helps in identifying the different size fractions (table 2-2). Mastering this method requires knowing how each soil texture feels. However, moisture and organic matter can change the feel of the different size fractions and thus the soil itself. For example, clay moistened to the consistency of workable putty feels like smooth satin, while dry clay feels rough and gritty. Organic matter makes clay feel less sticky and sand feel less gritty. Organic matter is also an important coloring agent in soil; however, soil color is not an indicator of texture.

Table 2-2. Textural properties of mineral soils.

Soil class	Feel and appearance of soil[a]: Dry soil	Moist soil
Sand	Loose single grains that feel gritty. Squeezed in the hand the soil mass falls apart when the pressure is released.	Squeezed in the hand it forms a cast or mold that crumbles when touched. Does not form a ribbon.
Sandy loam	Aggregates are easily crushed; very faint velvety feeling initially but as rubbing is continued the gritty feeling of sand soon dominates.	Forms a cast requiring careful handling to keep it from breaking. Does not form a ribbon.
Loam	Moderate pressure crushes aggregates; clods can be quite firm. Pulverized loam has a velvety feel that becomes gritty with continued rubbing.	Cast can be handled quite freely without breaking. Very slight tendency to ribbon. Rubbed surface is rough.
Silt loam	Aggregates are firm but may be crushed under moderate pressure. Clods are firm to hard. Smooth, flour-like feel dominates when soil is pulverized.	Cast can be freely handled without breaking. Slight tendency to ribbon with rubbed surface having a broken or rippled appearance.
Clay loam	Very firm aggregates and hard clods are difficult to crush by hand. Pulverized clay loam feels somewhat gritty due to the harshness of the tiny remaining aggregates.	Cast can bear much handling without breaking. Pinched between the thumb and forefinger it forms a ribbon. The ribbon's surface tends to feel slightly gritty when dampened and rubbed. Soil is plastic, sticky, and puddles easily.
Clay	Aggregates are hard and clods are extremely hard to crush by hand. Pulverized clay has a gritty texture due to the harshness of numerous very small aggregates.	Casts can bear considerable handling without breaking. Forms a flexible ribbon and retains its plasticity when elongated. Rubbed very smooth, surface has a satin feeling. Sticky when wet and easily puddled.

[a] *The properties described for the clayey soils refer to those found in the temperate regions.*

Structure

The arrangement of primary soil particles (sand, silt, clay) into aggregates of definite shape is known as soil structure. Soil structure affects water movement into and through soil, root penetration, porosity or aeration, and bulk density. In all soils other than sands, soil particles tend to stick together. The pieces that are formed are called structural aggregates or peds (figure 2-3). The major materials cementing soil particles together into peds are clay, organic matter, various bacterial gums, iron and aluminum oxides, silica, and lime. Root hairs and fungal mycelia also help stabilize soil aggregates.

Some soils, such as sands, have no structure and are described as single-grained. Another kind of structureless soil is one in which the structure has been physically destroyed or puddled when wet. The soil in the rut of a tractor that has been stuck in the mud is an example of such a structureless or massive soil.

Granular soils work up easily into a good seedbed. This is particularly true when the granules are well-cemented together and are fine. Many surface soils in Wisconsin were originally granular. Intensive row cropping, poor management, and erosion have destroyed much of this granular structure. The impact of raindrops can also break down aggregates near the soil surface. Moreover, the use of heavy equipment and excessive tillage when the soil is too wet can destroy soil structure. With modern four-wheel-drive tractors, fields can be tilled when they are too wet. The resulting compaction stunts crop growth by reducing aeration, restricting root growth, and inducing nutrient deficiencies. Plant roots will tend to grow horizontally when they encounter a compacted layer of soil.

In a Wisconsin study on a Plano silt loam, researchers compacted the soil by driving a loaded tractor with a 14-ton axle weight over plots in the spring before planting. Corn yields on the compacted plots were reduced from 129 bu/a to 98 bu/a the first year and from 167 to 156 bu/a the second year (table 2-3). Alfalfa yields were reduced by 0.97 and 0.81 ton/a in the first and second year, respectively.

When surface soils have been poorly managed, the natural aggregates in the surface soils are destroyed and large, hard, irregularly shaped clods are formed. Restoring good soil structure involves growing sod crops such as native grasses and grass-legume mixtures, returning barnyard manure and crop residues to the soil, controlling erosion, and minimizing tillage and traffic over the field with heavy equipment. The expansion and contraction caused by wetting and drying or freezing and thawing in Wisconsin winters will also help to restore soil structure. If excessively heavy loads cause deep compaction, freezing and thawing might not suffice to undo the damage, and deep chiseling or subsoiling may be needed.

Many subsoils in Wisconsin have blocky or prismatic structure. Both of these kinds of peds aid the movement

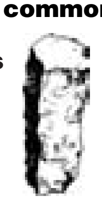
Table 2-3. Effect of soil compaction on the yield of alfalfa and corn in Plano silt loam at Arlington, WI.

Compaction (axle weight)	Alfalfa Year 1	Alfalfa Year 2	Corn Year 1	Corn Year 2
tons	ton/a		bu/a	
Less than 5	2.27	4.13	129	167
14	1.30	3.32	98	156

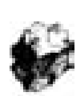
Source: Wolkowski, R.P., and L.G. Bundy. 1990. Proc. 1990 Fert., Aglime & Pest Mgmt. Conf. 29:29-37. Wolkowski, R.P., and L.G. Bundy. 1992. New Horizons in Soil Sci. No. 3; Dept., of Soil Sci., UW-Madison.

Figure 2-3. The most common shapes for peds.

prisms or columns
six-sided and columnar shapes

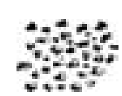


blocks
roughly cubical shapes



plates
long, broad, and flat shapes

granules
roughly spherical shapes found in the A horizon



Adapted from Soil Survey Manual, *USDA Handbook No.18, 1951, p.227.*

of water, air, and plant roots through the subsoil.

Platy structure is the least desirable. Water and roots have to go back and forth to get between the plates, slowing their downward movement. Platy structure occurs naturally in some soils. It can also be created by farming. Use of the moldboard plow when the soil is too wet and plowing at the same depth year after year tend to create a platy structure (plow pan) just below the plowed layer of surface soil. Plow pans can be eliminated by varying the depth of plowing occasionally, by using a chisel plow or subsoiler, and by not working the soil when it is too wet.

Sometimes farmers attempt to improve poorly drained, tight subsoils by deep tillage. Deep tillage may provide some temporary benefit, but it won't give long-term improvement on soils that have drainage problems or in cases where improper management is not corrected.

Organic matter

The organic portion of the soil is extremely important. It stores plant nutrients and improves the water-holding capacity of soil. On the surface as a mulch, organic matter shades the soil and reduces the harmful effect of raindrop impact on soil structure. Organic matter improves soils for the growth of plants by promoting soil aggregation, thus improving soil structure and tilth.

The plants and animals living in soil feed on organic matter. Frequent additions of fresh organic matter are needed to maintain large and vigorous populations of bacteria, earthworms and other soil organisms. Organic matter also helps soil retain plant nutrients. This is most noticeable in sandy soils but is important in all soils. While adding fresh organic matter is very beneficial, it does not significantly increase the residual organic matter or humus content. For example, the incorporation of 6,000 pounds of crop residues into the soil results in about 90% of this dry matter returned to the air as carbon dioxide through microbial respiration or reduced to simple chemical salts and water. Only 600 pounds will remain as stable organic matter or humus. Since the soils of Wisconsin commonly contain 30,000 to 80,000 pounds/acre of organic matter (1.5 to 4.0%), adding a few hundred pounds per acre will have very little effect on the total organic matter content. It is not possible to quickly change the organic matter content of the soil in the same way that the content of available phosphorus or potassium can be modified by fertilization. Some typical organic matter contents of the plow layers of various kinds of Wisconsin soils are given in table 2-4.

Soils tend to have a natural equilibrium level of organic matter. This level is regulated mainly by soil temperature, moisture, aeration, pH,

Table 2-4. Approximate amounts of organic matter in various Wisconsin soils.

Soil color and texture	Approximate % organic matter
Light- and dark-colored loamy sands	0.4 – 1.2
Light-colored sandy loam	1.2 – 2.0
Dark-colored sandy loams and light-colored silt loams and loams	2.0 – 3.5
Moderately dark and dark-colored silt loams, loams and clay loams	3.5 – 5.5
Imperfectly drained soils	5.5 – 9.0
Poorly drained and very poorly drained soils	9.0 – 20.0
Peats and mucks	> 20.0

carbon:nitrogen ratio, and nutrient supply. These factors influence the microbial process that decomposes organic matter. Organic matter accumulates in swamps and poorly drained soils because aeration is restricted. It also accumulates in arctic soils, as in Alaska, because accumulation during the short growing season exceeds decomposition during the rest of the year.

Tillage accelerates organic matter decomposition by aerating the soil. A 30-year study of the effect of tillage on organic carbon in a Wooster silt loam soil in Ohio showed that organic matter decreased by 64% after 30 years of continuous corn (table 2-5.). The drop in organic matter was proportional to the number of years in corn, although there was some loss (37%) even with continuous oats or wheat. Some tillage is involved in seeding these crops. With good soil management and returning crop residues to the soil, organic matter can be maintained or slightly increased. For example, corn was grown continuously on Plano silt loam at Arlington, WI, since 1958. At that time the organic matter varied from 3.0 to 3.5%. In 1990, as a result of incorporation of the corn stover, the organic matter content had increased to 3.5 to 4.0%.

Mineral matter

Many kinds of minerals occur in soils. A mineral is a naturally occurring inorganic substance whose chemical composition varies only within prescribed limits and which has definite physical properties. Some of these minerals contribute little to plant growth. Others provide the main sources of many plant nutrients. Primary minerals are formed by the solidification of molten magma within the earth's interior. Secondary minerals are formed from pre-existing minerals by weathering.

Silicate minerals make up about 80% of the earth's crust (table 2-6). In this group, the most abundant class of minerals are the framework silicates, typified by feldspar and quartz. Quartz is silicon dioxide, a combination of silicon and oxygen (SiO_2), the two most abundant elements on earth. Quartz contains no plant nutrients. Feldspars contain potassium, calcium, magnesium, copper, iron, manganese, and zinc. The ferromagnesium silicates are high in iron and magnesium. The layer silicates are usually found in the clay fraction of soil, although mica can be found in large pieces several inches across in rocks. (A rock is a complex combination of two or more minerals.)

Oxides of iron, manganese, aluminum, and magnesium are commonly found in the clay fraction of

Table 2-5. Decrease in soil organic matter in a Wooster silt loam after 30 years under several cropping systems.

Cropping system	Organic carbon	Organic matter	Decrease in organic matter
	%	%	%
Initial	2.04	3.52	—
Continuous corn	0.74	1.28	64
Continuous oats or wheat	1.28	2.22	37
Corn-wheat-clover	1.16	2.00	43
Corn-oats-wheat-clover-timothy	1.55	2.67	24

Source: Salter and Greene, 1933. J. Amer. Soc. Agron., 25:622–23.

soils. They are important sources of magnesium, boron, copper, iron, manganese, molybdenum, and zinc. Some of these nutrients are adsorbed (bonded) onto the surfaces of these oxides.

Dolomite is the predominant carbonate mineral found in Wisconsin; dolomitic limestone is the rock formation quarried for use as aglime. It is a source of both calcium and magnesium. Apatite is the original source of native phosphorus in soils. Wisconsin soils have no native sources of gypsum (calcium sulfate).

The kinds of minerals in Wisconsin soils vary somewhat from place to place throughout the state. They also vary greatly among the different particle sizes in each soil. Sand and coarse silt particles are mostly quartz, a colorless mineral which contains no elements essential for plants. Medium and fine silt often contain significant amounts of feldspars and micas in addition to quartz. These minerals contain potassium, iron, zinc, copper, magnesium, manganese, and other elements essential for plants.

Some essential plant nutrients such as potassium and magnesium are structural components inside clay particles, but clay minerals also hold these and other essential elements in an available form on their surfaces by means of an electrical charge. This is one reason why clay is a very important part of the soil.

Table 2-6. Minerals common in Wisconsin soils.

Class of mineral[a]	Examples	Associated plant nutrients
Silicates (80% of earth's crust)		
Ferromagnesium (16%)	Amphibole	Calcium, magnesium, iron, boron
	Pyroxene	Calcium, magnesium, iron
	Olivine	Iron, magnesium
Framework (60%)	Feldspar	Potassium, magnesium, copper, zinc, manganese
	Quartz	None
Layer silicates (4%)	Montmorillonite	Calcium, potassium, magnesium
	Vermiculite	Calcium, potassium, magnesium
	Mica	Potassium, magnesium, iron, manganese
	Kaolinite	Calcium, potassium, magnesium
Oxides of aluminum, iron, magnesium, and manganese (13%)	Hematite	Iron, trace element impurities
	Goethite	Iron, trace element impurities
	Limonite	Iron, trace element impurities
	Magnetite	Iron, trace element impurities
	Gibbsite	Trace element impurities
	Pyrolusite	Manganese, trace element impurities
	Brucite	Magnesium, trace element impurities
Carbonates (<5)	Dolomite	Calcium, magnesium
	Calcite	Calcium
Other (trace)	Apatite	Phosphorus
	Tourmaline	Boron

[a] *The percentages indicate the approximate amount of each of the minerals in soil.*

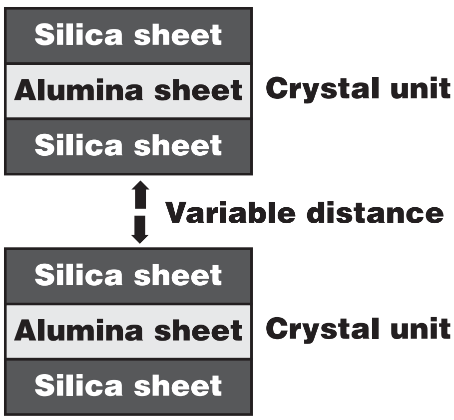


Figure 2-4. Schematic representation of montmorillonite, a common layer silicate mineral.

As previously mentioned, clay particles are layer-like crystals, with each layer separated by water. The exact kind of clay mineral found in soils depends upon the degree and length of weathering. Montmorillonite, the dominant clay mineral in Wisconsin soils, is composed of crystal units containing a layer of alumina sandwiched between two layers of silica (figure 2-4). Water separates each crystal unit. The changing water content causes the clay to swell when the soil is wet and shrink or contract when the soil is dry. Collapse of the crystal units of the clay particles is, in part, responsible for the cracking of soil during dry weather.

Bulk density

Bulk density is the dry weight of a given volume of soil. The bulk density of water is 62.4 pounds per cubic foot or 1.0 grams per cubic centimeter. Mineral soils have a bulk density heavier than water, but most organic soils are lighter than water. Bulk density is inversely proportional to pore space (table 2-7). That is, the greater the soil bulk density, the lesser the soil pore space.

Tilth

Tilth is a description of the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration. It is a descriptive term that is difficult to quantify.

Table 2-7. Relationship between soil texture, bulk density, and pore space.

Soil texture	Bulk density	Pore space
	g/cc	%
Sand	1.6	39
Loam	1.3	50
Silt loam	1.2	54
Clay	1.1	58
Muck	0.9–1.1	Variable
Peat	0.7–1.0	Variable

Color

Soil color is determined mainly by the iron and organic matter in soil and the oxidation state of the iron. Soil minerals are mostly whitish to grayish in color when the iron and organic matter are removed. Humus and iron oxide are the principal pigments in soil, and like paint, a little goes a long way. Color bears little relationship to soil fertility, although it may give some useful clues to the nature of soils. A black or dark soil usually is high in organic matter. Yet a peat with 60% organic matter will not be as dark as a muck with only 30% organic matter because the peat is less decomposed. The reddish soils of eastern Wisconsin are red because of the presence of iron oxide coatings. This pigment coats the silt, clay, and humus and masks the dark pigmentation of the latter.

Highly oxidized iron oxide is red. Iron that's been exposed to both water and oxygen, called *hydrated iron oxide*, is yellowish. Iron in an oxygen-scarce environment (such as waterlogged soils), called *reduced iron oxide*, is blue-gray. Thus, when a wet mineral soil is drained and cultivated, the subsoil will have a blue-gray color. In time, with tillage and good drainage, the reduced iron slowly oxidizes, and the color turns yellowish-brown. Many tropical soils are brick-red because intense weathering results in accumulation of iron oxides. The pinkish-red soils of eastern Wisconsin are young; the iron oxide was removed from iron deposits by glacial activity and ground and mixed with the parent material that formed these soils. Soils that are subjected to alternate periods of wet and dry conditions often have reddish-yellow mottles in the subsoil because the oxidation and reduction of iron oxide is a slow process. While the color of a soil gives some clues to its organic matter content and state of iron oxidation, it is not a reliable indicator of soil fertility.

Temperature

The temperature of the soil is important for both root growth and microbial activity. Little microbial activity occurs below 45°F or above 90°F. A temperature difference of only a few degrees can be important when a crop is near the threshold temperature required for growth. For example, the difference in early season vigor between corn planted with conventional tillage and that planted no-till has been attributed to slightly cooler soil (2° to 4°F) under no-till.

Although we cannot control the weather, some management practices will affect soil temperature. It takes five times as many calories to heat a pound of water than it does to heat a pound of dry soil. Consequently, wet soils remain cold much longer than well-drained soils. Proper drainage, therefore, will facilitate soil warming in the spring. Also, surface residue shades the soil from direct solar radiation and tends to keep the surface soil moist. At 4 inches deep, soil temperatures of fields with substantial surface residue typically are a few degrees cooler than under bare soil. However, the advantage of a warmer soil must be weighed against the erosion potential of a bare soil.

North slopes are cooler than south slopes (in the northern hemisphere). Sometimes the difference is great enough to result in differences in cropping and native vegetation. In southern Wisconsin, for example, apples are often grown on northern slopes because the temperature fluctuates less, lessening the risks of premature bloom and subsequent frost damage.

Questions

1. What is meant by the texture of a soil? How is soil texture measured? Which soil texture offers ideal growth conditions for plants? Why?

2. The percentages of sand, silt, and clay are given below for several soils. What would be the textural classification of each of these soils?

	sand	silt	clay
		%	
a.	65	25	10
b.	50	20	30
c.	40	40	20
d.	30	40	30
e.	15	50	35

3. Why is soil structure important? What are some factors that contribute to the breakdown of soil structure?

4. How can the structure and tilth of a soil be maintained when the land is cropped to continuous corn?

5. Why is a sandy soil that weighs 100 pounds per cubic foot easier to plow than a silty clay loam that weighs only 72 pounds per cubic foot?

6. Explain why tilling silty or clayey soils when they are too wet reduces crop yields.

7. Discuss five reasons why organic matter is an important component of soil.

8. It is much easier to lose organic matter from soil than to increase soil organic matter. Why?

9. Why do cracks form in silt loam soils during periods of drought but not in sandy soils?

10. What can you tell about a soil from its color?

11. Why do dry soils warm up faster than wet soils?

CHAPTER

3

Soil water

"In a majority of seasons, deficiency of moisture [is] a marked limiting factor of yield."

F.H. King, The Soil, *1895*

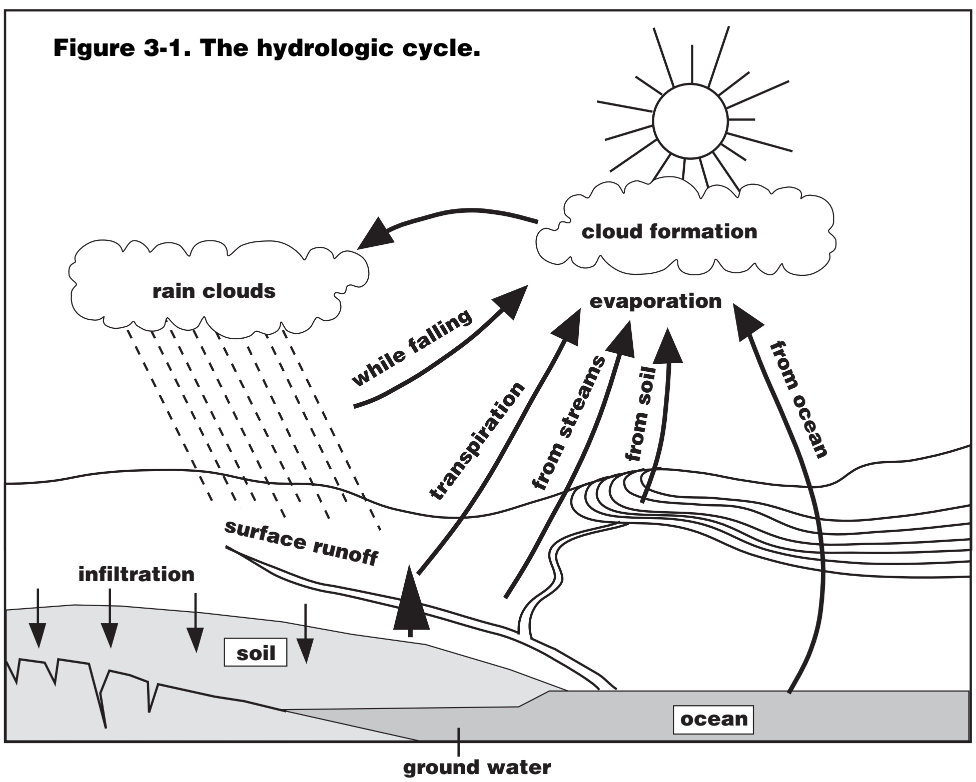
Water is the most limiting factor affecting plant growth throughout much of the world. The amount and frequency of rainfall received during the growing season is as important as the total annual precipitation. Wisconsin receives an average of 31 inches of precipitation annually, with about two-thirds coming during the growing season.

Water is the plant's source of hydrogen, which is incorporated into carbohydrates by photosynthesis. It serves as the medium in which nutrients are taken up and distributed within the plant and through which materials that have been synthesized within the plant are translocated. In fact, all of the biochemical reactions within the plant and the chemical reactions of the soil take place in an aqueous system. However, all of these functions demand only a very small percentage of the water absorbed by plants; most of the water is lost to the atmosphere by transpiration.

Hydrologic cycle

The cycling of water from the atmosphere to the ground and back again is known as the hydrologic cycle (figure 3-1). Water travels along one of many paths before returning to the

Figure 3-1. The hydrologic cycle.



Source: Reproduced by permission of Deere & Co.

atmosphere through evaporation. It may remain on the earth's surface, infiltrate the soil, or run off into swamps, streams, lakes, or reservoirs. Water entering the soil may be stored in the soil, used by plants, or continue moving downward through the vadose (unsaturated) zone to the groundwater. Groundwater moves laterally to lakes, springs, streams, and rivers where it eventually returns to the surface. Water at the surface of soil or water bodies evaporates and returns to the atmosphere where it may form clouds and eventually return to the surface as precipitation.

Evapotranspiration (ET)

Evapotranspiration is a combination of water loss from evaporation of the soil surface plus transpiration from plants. It is estimated that roughly two-thirds of Wisconsin's 31-inch average annual precipitation returns to the atmosphere through evapotranspiration. The remainder either percolates through the soil profile to the water table or runs off the land surface.

The amount of water lost from the soil by evaporation depends on many factors, including soil moisture, temperature, vegetation, and soil texture. On moist soil, heat determines the amount of evaporation. Wet soils stay cold longer in the spring because it takes more heat to warm the water in soil pores than it does to warm the air or soil particles. However, when the soil surface is dry, evaporation also depends on the rate of water movement through capillary flow to the surface, not on heat alone. Fine-textured soils have greater capillary movement than sands or peats, so they lose more water by evaporation.

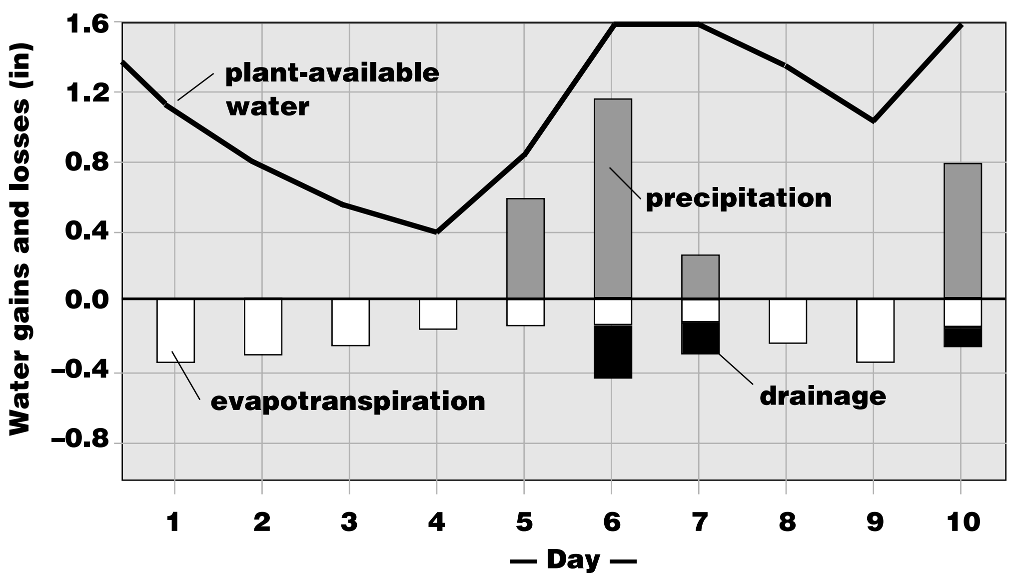
Transpiration is the process of plants pulling water from the soil through their roots to replace the water that is lost by evaporation from their leaves. The amount of water plants can transpire depends on length of growing season, plant density, depth of rooting, rainfall distribution, temperature, and humidity. Early in the season, the amount of water lost by transpiration depends on the amount of leaf surface exposed. When the soil is reasonably wet and the sun is shining there is a steady flow of water into roots, up the plant stem, and into the leaves. Increasing the plant population beyond that required to form a closed canopy does not increase transpiration. Once the soil is completely shaded by vegetation, most of the water loss is by transpiration rather than evaporation from the soil surface. Depth of rooting is important because it determines how much water is available. Deep-rooted plants continue transpiring after shallow-rooted plants wilt for lack of moisture. Rainfall distribution determines the amount of time the exposed surface soil is wet, and it influences the depth of rooting. Longer periods of time between rains result in deeper rooting. Table 3-1 compares amounts of evapotranspiration from different kinds of vegetation over a year and over the length of their growing season.

Figure 3-2 depicts a soil water budget for a crop grown on a sandy loam soil. The graph shows how the amount of stored soil water changes daily with evapotranpiration, drainage, and rainfall. At the start of day 1 all of the gravitational water has drained away and the available water is at 1.4 inches, nearly its maximum (1.6 inches in this example). Daily evaporation removes some water from the storage (0.12 to 0.32 inches), as is easily seen on days 1 through 4. Rain on day 5 refills the available water, and because it is cloudy only a small amount evaporates. On day 6, however, it rains too much for the soil to hold, and after the 1.6 inches of available water capacity is saturated, the remainder drains. Because the soil was completely saturated on day 6, much of the day 7 rain also drains. During the rain-free period of days 8 and 9 evaporation again steadily depletes the available water. Another rain on day 10 refills the soil's reserve for available water.

Table 3-1. Evapotranspiration losses of water as affected by various uses of land in Wisconsin.

Land use	Growing season	— Evapotranspiration (inches) — Annual	Growing season
Water (lake or stream)	—	29–32	—
Forest	April–October	26–29	26–29
Alfalfa-bromegrass	April–September	22–26	19–23
Corn	mid-May–September	18–22	11–15
Grain (with seeding)	April–June	18–22	9–13
Bluegrass	April–June	12–18	10–16
Bare soil	—	12–18	—

Figure 3-2. A soil water budget for a crop growing in a sandy loam soil.



Water-use efficiency

The amount of water (from the soil, precipitation, and irrigation) needed to produce dry matter is known as water-use efficiency and varies depending on the crop. For instance, corn requires less water to produce a ton of dry matter than does alfalfa. The difference is due to the fact that alfalfa uses water from April until the first killing frost in the fall; whereas corn has a shorter period of growth.

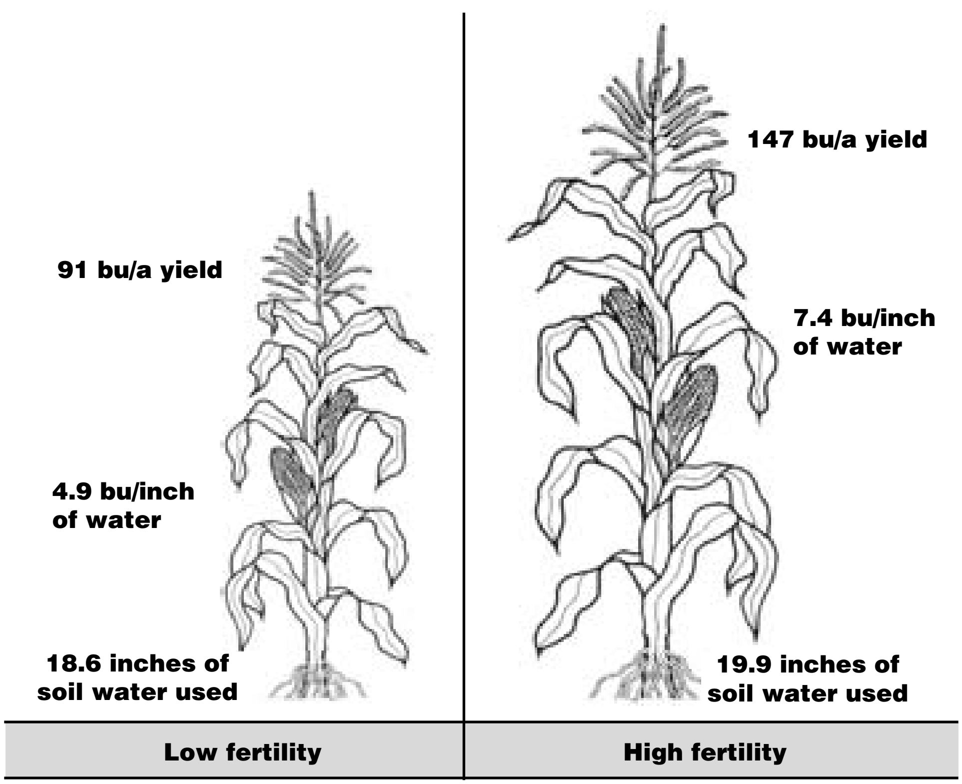
Factors limiting plant growth, such as poor soil fertility, markedly lower a plant's water-use efficiency. That is, plants subjected to these conditions require more water to produce a given amount of dry matter. Improving soil fertility to produce optimum crop yields also gives the highest water-use efficiency (figure 3-3). The more-vigorous root system of plants in a well-fertilized soil enables the plants to extract more water and nutrients from the soil than can plants in a soil of lower fertility.

How water is held in soil

Gravity moves soil water downward. However, the attractive forces between water molecules and soil particles (adhesion), and between one water molecule and another (cohesion) counteract the gravitational force. Water is attracted to the surface of soil particles and held there by adhesion in thin films around each particle. This water is bound so tightly that plants cannot extract it. It can be removed by heating. Water molecules are polar; that is, each molecule has a negative side and a positive side. This polarity makes the molecules stick together by *cohesion*.

The size of the space between soil particles (soil pores) determines whether water will remain in the soil or continue to move downward. If the soil pores are small enough, adhesion and cohesion work together to hold the water in place. If the pores are too large, as in sand, the cohesive force is not great enough to hold the water molecules together, and the water drains.

Figure 3-3. Fertilization and water-use efficiency.



Source: Adapted from Potash & Phosphate Institute.

Forms of soil water

Plant growth requires soils containing water and air. On a volume basis, "ideal" soils should have about 50% pore space and 50% solids. The ideal composition of a surface soil in good physical condition would be about 25% air, 25% water, 45% mineral matter and 5% organic matter (figure 3-4). The percentages of water and air will fluctuate considerably, and lack of either water or air will severely limit plant growth.

Sandy soils have few pores but these pores are relatively large. Medium-textured soils such as loams and silt loams and well-structured clay soils have both large and small pores. Poorly structured clay soils have many very small pores. When water fills all of the pores, silty and clayey soils hold more total water than sandy soils simply because they have so many more pores.

When all soil pores are filled with water, the soil is said to be saturated. The excess water, often called gravitational water, drains from the large pores within a few days due to the force of gravity. Only excess water (that which cannot be held in the large soil pores) drains out of the soil profile; this drainage takes place much faster in sandy or well-aggregated soils than in clayey or poorly aggregated soils.

Once the gravitational water drains away, the soil is at *field moisture capacity*. At this point, water is held in the small pores and as a thin film on soil particles, while the large soil pores contain air. At field moisture capacity, plant roots can absorb approximately half of the water in the soil. The water films become thinner as water evaporates or is taken up by plants. Eventually the water films become so thin and are so tightly held by the soil particles that the plant roots can no longer remove enough water to replace that lost by transpiration. Without additional water, the plant will wilt and eventually die. The amount of water in the soil at this point is called the *permanent wilting percentage*. *Available water*, then, is the amount of moisture held in the soil between field moisture capacity and permanent wilting percentage. Water is held in soil much as it is in a sponge. If a sponge is saturated with water, a certain amount will drain by gravity. The water remaining in the sponge is analogous to field moisture capacity. If you wring out the sponge, more water, analogous to available water, will be released; but there will be some water left that cannot be wrung out (permanent wilting percentage).

The amount of water available to plants depends on the soil texture. The smaller the soil pores, the more tightly the water is held. That is why a clay loam contains slightly less available water than a silt loam. As shown in

Figure 3-4. Typical volume composition of the surface layer (A horizon) of a silt loam soil. The percentages of air and water vary considerably, as the soil pores are filled with either air or water.

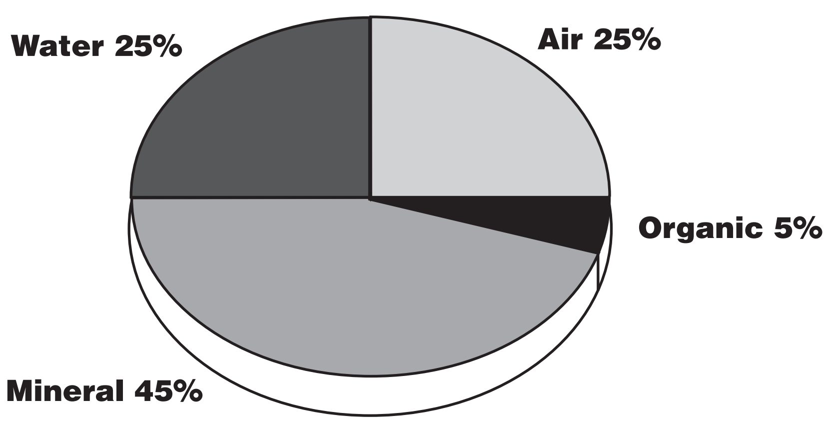
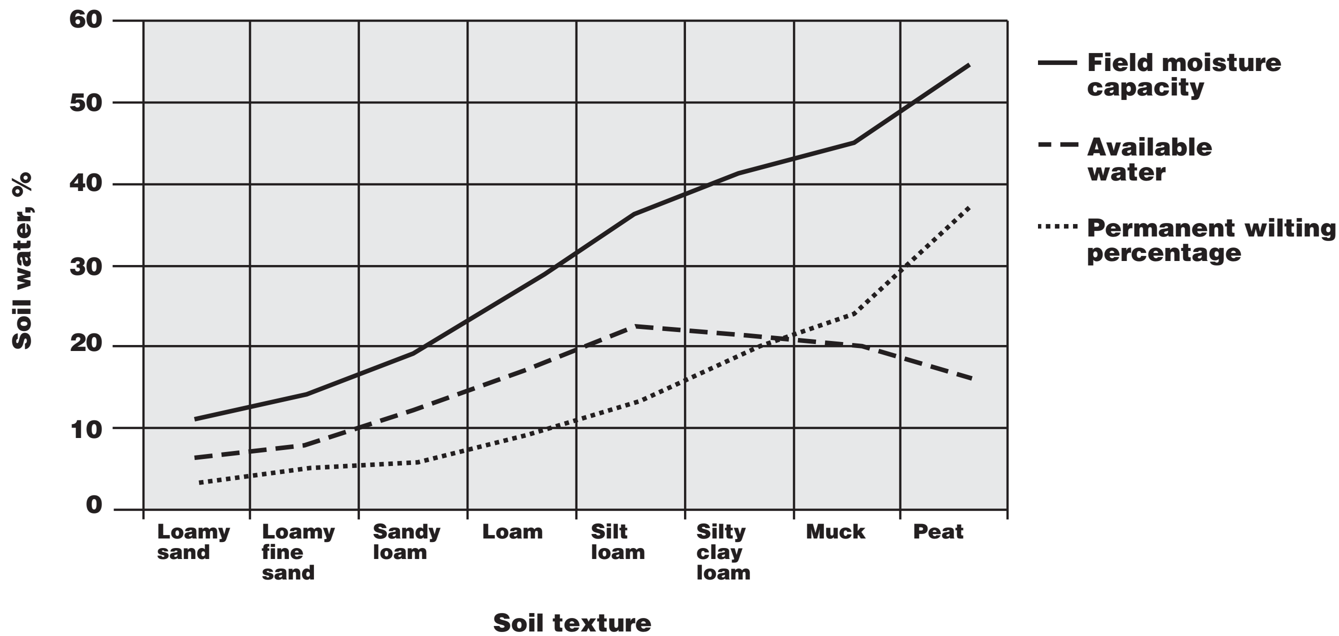


Figure 3-5. Water availability relative to soil texture.



Source: Potash & Phosphate Institute.

figure 3-5, a silty clay loam holds about the same amount of water as a silt loam, but it holds the water more tightly so slightly less is available to crops. (Silty clay loams hold 2.6 inches of available water per foot compared to 2.8 inches for a silt loam.)

Poorly drained soils hold excess water in the soil pores, sometimes almost permanently, either because internal drainage is impeded by clay layers or hardpans or because the soil is situated in a low area in the landscape. When there is too much water, not enough pore space remains for good exchange of carbon dioxide and oxygen between soil air and the external atmosphere. Carbon dioxide accumulates and the oxygen supply diminishes as plant roots and microorganisms respire. This combination—insufficient oxygen and excess carbon dioxide—impairs root growth and absorption of plant nutrients. Most plants suffer permanent damage and yields are severely reduced if a soil is ponded for more than 1 to 3 days in the growing season.

Water movement in soil

Water molecules try to equalize moisture tension, or even out the soil moisture. Water moves to areas where the moisture content is lowest (highest moisture tension). For example, water absorption by plants reduces the amount of water near the roots, raising the moisture tension in that part of the soil. Water moves toward the roots by capillary action to equalize the tension. Unlike gravitational water, which only moves downward, capillary water can move in any direction. If the water table is within 40 inches of the soil surface, capillary rise of water can supply a significant percentage of the crop's moisture requirement.

Layering of different soil textures impedes water movement through soils. If a layer of fine-textured soil lies above a coarser layer (such as silt over sand), the fine pores in the upper layer will hold moisture from the lower layer until the upper layer becomes saturated. Only then will moisture move downward by gravity. This situation is known as a *perched water table*. The coarser lower layer does not have enough fine capillaries to "pull" moisture from the fine upper layer.

When the reverse occurs—a layer of coarser-textured soil over a finer-textured soil, such as a loam over a clay—another type of perched water table is formed. In this example, water moves fairly fast through the loam, but very slowly through the clay. As a result, water again accumulates in the upper layer.

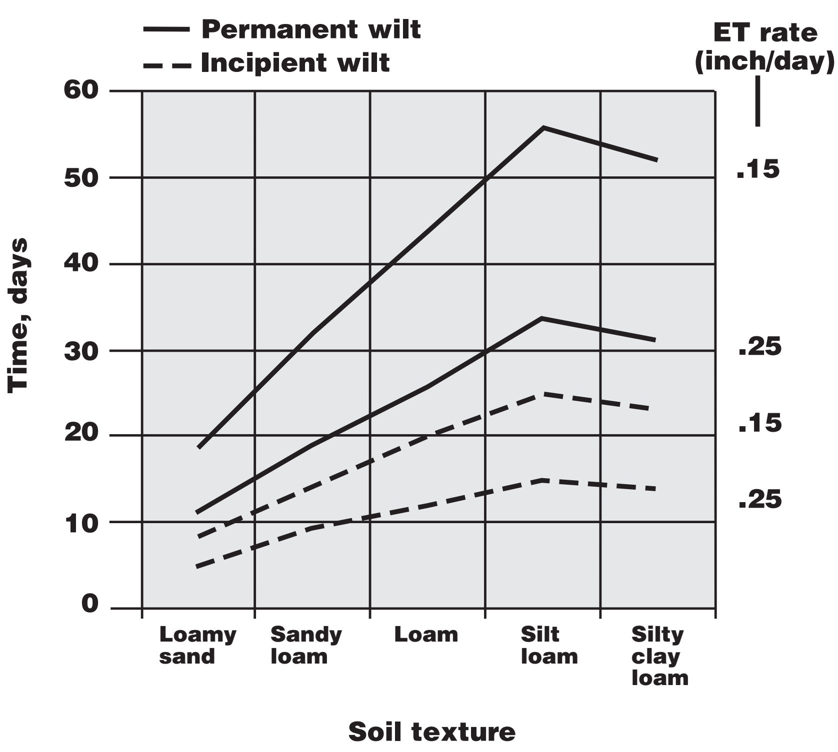
Irrigation scheduling

Most crops could benefit from additional water during parts of the growing season. Even so, economics and the availability of water limit irrigation in Wisconsin mainly to sandy soils.

How often should a soil be irrigated if it doesn't rain? The answer depends on the amount of available water stored in the soil, the rooting depth of the crop and rate of evapotranspiration. On a hot summer day, the rate of evapotranspiration is about 0.25 inches of water per day. Over the growing season, the average rate is about 0.15 inches per day. Figure 3-6 shows an example of how long plants growing in different soil textures take to reach the permanent wilting point.

Crops begin to wilt (incipient wilt) when about 45% of the available water has been depleted. This first happens in the early afternoon on warm, bright days after several days without rain, but the plants recover when the rate of evapotranspiration drops toward evening and overnight. Nevertheless, the stomata (leaf pores) close when the plant wilts. As a result, carbon dioxide can no longer enter the leaves, and photosynthesis and other growth processes slow down. To prevent damage and to maximize crop production, irrigation should begin as soon as plants start to wilt—long before they've reached the permanent wilting point.

Figure 3-6. Time required at different rates of evapotranspiration (ET) for plants to begin wilting and to reach permanent wilt with the soil initially at field moisture capacity (rooting depth, 3 ft).



Excess water from over-irrigation is not only wasteful, it can also leach nitrates and other nutrients as well as pesticides into the groundwater. A good irrigation scheduling program lessens these problems by evaluating different factors to determine the timing and amount of water needed. These factors include the water-holding capacity of the soil, stage of growth of the crop, evapotranspiration, and water supplied through rainfall and previous irrigations.

Irrigation scheduling tools can be as simple as a notebook or as intricate as a computer software program. Both approaches track the various water use factors described above and calculate irrigation needs. When the calculations show that the available water supply is low, irrigation water should be applied to restore soil water back to desired levels. Reasonably accurate evapotranspiration values are critical to any irrigation scheduling system. Evapotranspiration estimates for crop production areas in Wisconsin and Minnesota can be viewed by accessing the Wisconsin-Minnesota Cooperative Extension agricultural weather page at www.soils.wisc.edu/wimnext/et/wimnet.html. An example of a checkbook-style irrigation scheduling method from the University of Minnesota–Extension Service can be found at www.extension.umn.edu/distribution/cropsystems/DC1322.html.

Questions

1. Approximately two-thirds of the rainfall received in Wisconsin is returned to the atmosphere by way of evapotranspiration. What useful purpose(s) does evapotranspiration serve? What would happen if only one-third of the rainfall received returned to the air by evapotranspiration?

2. Why is less water lost by evapotranspiration from land cropped to corn than from forested land?

3. Explain why a well-fertilized crop uses less water to produce a pound of dry matter than does a crop on an infertile soil.

4. A farmer has a field containing three kinds of soil: (a) a uniform loamy sand several feet deep, (b) a silt loam several feet deep and (c) a clay several feet deep. Identify where in the field you'd expect to see the following characteristics:

a. Plants showing the first signs of water shortage.

b. Plants showing deficiency symptoms of nitrogen and potassium if no fertilizer was used.

c. Soil that works up into a fine granular seedbed most readily.

d. Water ponding after a heavy rain.

5. Define the following:

a. field moisture capacity

b. permanent wilting percentage

c. available water

d. gravitational water

e. evapotranspiration

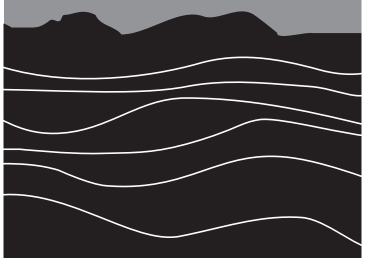
6. Corn sometimes curls in mid-afternoon due to moisture stress but recovers by the next morning even though there was no rain or dew. Explain.

7. A farmer has difficulty establishing alfalfa on a soil containing 8.0% organic matter while the same crop grows very well on another soil containing 3.0% organic matter. What is the most likely reason for the poor alfalfa growth and survival on the soil containing high organic matter?

8. What is a perched water table? Under what conditions is a perched water table possible?

9. If corn is growing on a silt loam soil 3 feet deep which contains 2 inches of available water per foot of soil, and if 0.15 inches of water is lost per day by evapotranspiration, about how many days can this crop grow without rain before showing incipient wilt? Permanent wilt?

CHAPTER 4



Tillage

"But Nature neither plows, harrows, nor hoes her fields, and yet where water is abundant and the temperature right, the grasses thrive, the flowers bloom and fruit, and tree and shrub vie with one another for occupancy of the whole surface of the earth."

F.H King, The Soil, *1895*

Soil scientists have long appreciated the physical effect of tillage. F.H. King, UW Professor of Agricultural Physics, in his book *The Soil*, published in 1895, gives us an insight that many have overlooked to this day when he stated:

> *When we reflect upon Nature's methods, we see plainly that they are quite different from those adopted by thrifty husbandry. In the first place, by Nature's methods, not one seed in many hundreds ever germinates and comes to maturity, but in farming no such chances can be taken. In the second place, by Nature's methods, almost all fields bear a mixed vegetation, …but in agriculture certain crops must occupy the field for the season to the exclusion of all others, and in these…(fields) we find the chief needs for, and the great importance of, good (soil) tilth...*

Purpose of tillage

The main purposes of tillage are to prepare a seedbed, prepare a rootbed, eliminate competing vegetation, and manage previous crop residue. The seedbed is that small volume of soil in the immediate vicinity of the germinating seed; whereas the rootbed is the much larger volume of soil in which roots develop. Tillage loosens and aerates the soil if done at the proper moisture stage. Over-aggressive soil preparation can hurt crop production and accelerate erosion by destroying soil structure. Depending upon the previous crop it may be advantageous to incorporate or move some crop residue so that the soil will warm more quickly in the spring. Tillage to manage crop residue following corn is common, whereas residue may not be a consideration where a crop is planted after soybean.

Ideal conditions for a rootbed are considerably different than for a seedbed. A field serves as a rootbed throughout 95% of the growing season, so the primary emphasis should be on rootbed preparation. A good seedbed requires fine, grain-like soil aggregates that will be in firm contact with the seed. This ensures good moisture movement to the seeds to speed germination. However, a good rootbed requires a loose and porous soil with some residue being maintained on the soil surface. Such a soil improves root growth and absorbs water rapidly, reducing runoff and erosion. Hence, only the seedbed area should be thoroughly tilled and compacted. Preparing the entire field as a seedbed for row crops wastes time and money.

Kinds of tillage

Tillage systems are sometimes defined according to their objective (reduced, conventional, conservation) or according to the principal tillage implement employed (moldboard plow, chisel plow, no-till). Another way to define a tillage system is by describing the amount of crop residue left following tillage. Measurements are made after planting since any manipulation of the soil, no matter how slight, will affect residue coverage. The Conservation Technology Information Center at Purdue University conducts an annual "Crop Residue Management Survey" for the United States. This survey defines three types of tillage:

1. Conventional tillage = <15% residue;
2. Reduced tillage = 15–30% residue; and,
3. Conservation tillage = >30% residue.

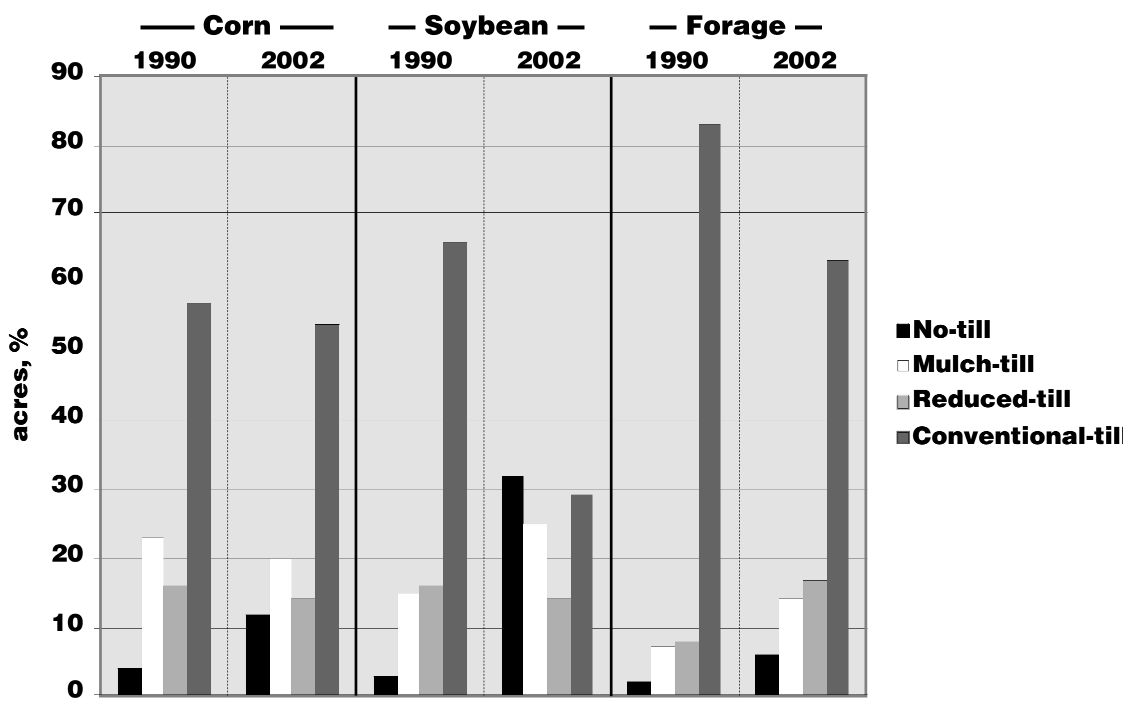
Conservation tillage is further broken down into no-till or mulch-till. The latter being full width tillage leaving at least 30% residue. Tillage practices have changed in the past decade because of improvements in pest management, hybrid and variety tolerance, and tillage implements. Figure 4-1 shows the changes in tillage systems in Wisconsin between 1990 and 2002. There are still numerous acres that have less than 15% residue, but many of these are likely first-year corn following soybean where any tillage will bury a substantial amount of residue. The greatest change in residue management over this period has been in soybean where in 2002 nearly 60% of the crop was grown in a conservation tillage system.

Conventional tillage

Conventional tillage is commonly conducted with a moldboard plow (primary tillage) followed by one or more passes with a secondary tillage implement, such as a disk, field cultivator or springtooth harrow. Primary tillage is the initial, major soil manipulation operation intended to loosen soil and manage crop residue, either by burial or movement away from the future row area. Secondary tillage is intended to create a seedbed that is suitable for planting.

Primary tillage in a conventional system uses a moldboard plow, which greatly benefits the soil when used properly. It lifts, turns, aerates, and loosens the soil and incorporates organic matter. Moldboard plowing does not compact the soil when used properly and is one of the few implements that can move soil uphill. However, if a soil is plowed at the same depth every year, a plow

Figure 4-1. Changes in Wisconsin tillage systems, 1990–2002.



Source: Conservation Technology Information Center (CTIC) residue management survey, 2002.

sole or compacted zone just below the plow layer can develop. This layer can impede root growth and water movement through the soil.

Fall plowing should be limited to fine-textured, non-erosive soils. Spring plowing may be unsatisfactory on these soils. Freezing and thawing, wetting and drying, and rain need time to break down clay lumps. In addition, a good job of plowing high-clay soils in the fall can improve drainage in the plow layer temporarily, which could permit earlier spring tillage and planting.

A 6- to 8-inch depth is sufficient when plowing well-drained and well-aerated soils. In contrast, deeper plowing may benefit soils with naturally tight layers or soils packed by vehicle traffic. Before undertaking deep plowing, consider the following points:

- Ordinary 16-inch plows will not turn a good furrow if operated more than 8 inches deep.
- Deep plowing is not practical in rocky soils.
- If the subsoil is acid, deep plowing will require a larger application of lime to neutralize the furrow slice.
- Draft (power) requirements increase greatly.
- Plowing well-managed soils deeper than 8 inches generally does not improve yields.

Moldboard plowing's primary disadvantage is that it leaves insufficient surface residue—often less than 5%. This results in soil surface sealing (crusting), less infiltration, more runoff, and greater problems with soil erosion than in conservation tillage systems that maintain 30% or more residue cover.

Secondary tillage in a conventional system usually involves use of a tandem disk, field cultivator, spring-tooth harrow, or combination implement to smooth the soil surface. Weather, soil and crop type, and implement used all play a role in determining when secondary tillage should occur. Lumps and clods break up most easily when the soil is slightly moist (table 4-1). Working the soil when it is at the proper moisture content and incorporating organic matter maintains or even improves soil tilth. Tilth describes the physical condition of soil—how easy it is to till, its fitness as a seedbed, and how suited it is for seedling emergence and root penetration. Good tilth is essential for good plant growth. It improves drainage, increases water storage capacity, and decreases the danger of soil crusting or packing.

Care must be taken not to over-till the soil. Both disks and spring-tooth harrows have a tendency to separate larger clods from fine particles rather than mix all particle sizes uniformly throughout the tilled layer. The fine particles accumulate near the bottom of the operating depth of the tool. Tandem disks, due to their weight, pack the soil below the cutting depth more than any other secondary implement. Many modern planters are designed to plant in rough ground.

Conservation tillage

The Natural Resources Conservation Service (NRCS) defines conservation tillage as "any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce soil erosion by water." Conservation tillage is designed to increase infiltration and reduce water runoff and erosion by maintaining soil surface residue which

Table 4-1. The effects of tillage on the tilth of soil at various moisture levels.

Soil moisture	Appearance	Effect
Dry	Dusty, usually hard.	Tilth building impossible.
Moist	Crumbly, not pliable and not slick, forms weak ball.	Moisture lubricates and softens clods. Tilth building easy.
Slightly wet	Moist soil forms pliable, sticky ball.	Soil packing likely; tilth building impossible.
Muddy	Water oozes from ball.	You are stuck!

absorbs the energy of raindrops and impedes overland flow. In addition to soil conservation, this system conserves moisture, energy, labor, equipment, and stored carbon to reduce the emission of CO_2, a greenhouse gas. Conservation tillage implements include the no-till planter, ridge-till planter, strip-tillage tools and planter attachments, and various mulch tillage implements.

The amount of residue remaining after tillage depends on the previous crop, soil conditions, tractor speed, depth of tillage, and the tillage implement. Approximately 80 to 95% of the soil surface will be covered with residue in the spring following corn harvest assuming that the residue is well distributed by the combine. Table 4-2 shows the different amounts of corn residue cover following different conservation tillage methods. Two passes with the same implement do not bury twice as much residue as a single pass because the second pass brings some residue back to the surface. In fact, a tandem disk followed by a field cultivator leaves more residue (32%) than two passes with a tandem disk (23%). Nevertheless, avoid tilling more than necessary. Shredding stalks prior to tillage will lower residue coverage because the smaller-sized material is more easily covered by soil. One study showed that stalk shredding followed by chisel plowing resulted in 42% residue, whereas 58% residue was left on the surface when stalks were not shredded.

Residue on the surface keeps the soil wetter and cooler than bare soil. Although the temperature difference between bare and residue-covered soil is only a few degrees, it is enough to delay early growth of crops. Corn planted in plots with substantial surface residue typically germinates 4 to 7 days later than corn planted in moldboard-plowed plots.

The slightly higher moisture levels in residue-covered fields are a definite advantage in dry years but a disadvantage in cool, wet years. The higher moisture plus higher bulk density under reduced tillage means there are fewer large pores and more water-filled pores. Thus, aeration is reduced. Table 4-3 shows how tillage affects surface residue, soil temperature at 2 inches, and soil moisture. The moisture differences persisted throughout the growing season, but temperature differences were slight after a complete canopy covered the soil.

Table 4-2. Corn residue cover following various tillage methods on farms in southern Wisconsin.

Tillage implement(s)	Average cover	Expected range
	%	%
No-till	70	65–80
Chisel plow	37	30–70
Chisel plow and field cultivator	34	30–65
Chisel plow and soil finisher	31	25–50
Chisel plow and tandem disk	27	20–40
Chisel plow and field cultivator (two passes)	30	25–50
Chisel plow and tandem disk (two passes)	23	15–35
Chisel plow, tandem disk, and field cultivator	32	25–50

Source: Adapted from Enlow et al. Proc. 1992 Fert., Aglime & Pest Mgmt. Conf. 31:136–144.

Table 4-3. Effect of tillage on residue cover, soil temperature at 2 inches, and soil moisture (Lancaster, WI, 1979).

Tillage system	Residue cover	— Soil temperature —			— Soil moisture —	
		May 25	May 28	May 30	May 28	May 30
	%	— °F —			— % water by weight —	
Moldboard plow	5	67.8	75.6	78.1	19.3	17.4
Chisel plow	26	66.2	73.6	77.0	19.7	18.2
No-till	60	63.3	69.3	72.7	20.6	19.2

Source: Moncrief, J.F. and Schulte, E.E. 1980. Proc. 1980 Fert., Aglime, and Pest Mgmt Conf. 19:134–144.

There has been some concern about the stratification of nutrients and organic matter in conservation tillage systems. Some advocate the use of a moldboard plow every 5 to 10 years to redistribute nutrients and organic matter, to incorporate lime and fertilizer, and to aerate the soil. However, long-term tillage studies in Minnesota indicate that after about 4 years the soil bulk density decreases while the size of the pores and aggregates increase in conservation tillage systems. These changes result from the buildup of earthworm and burrowing insect populations, which aerate the soil and incorporate organic matter. Hence, it is doubtful that periodic use of the moldboard plow is necessary or even desirable. If the surface soil acidifies, some tillage to incorporate lime is advisable. (See chapter 6.)

No-till means that crops are planted in untilled fields using special planters or drills designed to cut through crop residue. This technique uses a disk or knife opener to insert the seed, while a second opener is used to apply row fertilizer. Residue from the previous crop is sometimes chopped, but this is not necessary for well-designed equipment. In fact, drills and planters often perform better when the residue is standing and attached to the soil. Chopped residue sometimes forms a wet mat which is more difficult to penetrate. Herbicides are used to control weeds and to kill the previous crop if it was a perennial (e.g., a forage legume). The use of glyphosate-resistant crops has increased the adoption of high-residue systems due to the ease of weed control.

Ridge-till systems have row crops planted on the ridges formed during cultivation of the previous crop. Residue covers the soil until planting. During planting, residue on the ridge is removed or falls into the valleys between ridges. This leaves 40 to 65% of the soil surface covered with residue, although it is not distributed uniformly. The bare soil in the ridge warms up faster in the spring than the covered soil between rows. The ridges should be 6 to 8 inches higher than the valleys, with round or flat tops to facilitate planting the following year. The ridge-till cultivator reforms the ridges flattened during planting and removes weeds between rows.

Strip-till systems have row crops planted on the small ridges formed following harvest of the previous crop either in the fall or the following spring. A variation of this method is known as row-clearing. Row clearing is most often accomplished with planter attachments mounted ahead of the seeding unit. These are designed to move residue from the future row area using finger coulters, disks, or brushes. Similar to ridge-till, this system leaves 40 to 65% surface residue, that may not be distributed uniformly. The bare soil in the cleared strip warms up faster in the spring than the covered soil between rows. These smaller ridges should be 2 to 4 inches higher than the valleys. Fertilizer is often banded-applied during tillage to replace the need for starter fertilizer applied with the planter.

Mulch till systems use a variety of tillage implements, including the chisel plow, offset disk, tandem disk, field cultivator, and soil finisher. The tool that is selected depends somewhat on the nature of the existing crop residue.

The chisel plow is the most commonly used of these implements in Wisconsin. The chisel plow, disks, and field cultivator may be used alone or in combination with each other. Soil finishers are commonly used in combination with a chisel plow or disk to incorporate herbicides.

One pass with a chisel plow leaves 30 to 70% of corn residue on the soil surface; however, the actual amount remaining is greatly influenced by the type of point used on the plow. See table 4-4 for a comparison of three chisel types and their effect on residue. Twisted shovels bury more residue than do straight shanks or sweeps. In heavy or wet residue, light disking or stalk shredding is sometimes used to reduce clogging. Most units have coulters or disks mounted ahead of the chisels for this purpose. Chisel plowing in the fall loosens the soil and may provide better erosion control over winter. Some additional tillage is often needed to prepare a good seedbed in the spring. Another advantage of using a disk, field cultivator, or combination implement in the spring is that they incorporate some of the fertilizer and pesticides on fields chiseled in the fall.

Offset disks have long been used in the Great Plains for primary tillage, but they're not very popular in Wisconsin. An offset disk uses large blades (22 inches or more) for deep tillage. It buries considerable residue, leaving only 5 to 40% on the surface. As a result, it usually does not leave enough residue to qualify as conservation tillage for compliance with government soil conservation programs. On wet fields, the offset disk can compact the soil beneath the blades.

A tandem disk used in a single pass to prepare a seedbed following chisel plowing leaves 20 to 40% of the surface covered with residue; two passes leave 15 to 35%. Sometimes a soil finisher is attached behind the disk to smooth the field and prepare it for planting by making a single pass.

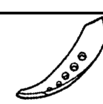
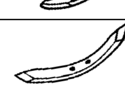
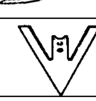
To increase surface residue and ensure compliance with soil conservation programs, follow these recommendations:

- Replace twisted shovels with points or sweeps.
- Limit tandem disking to a single pass.
- Replace tandem disks with implements equipped with sweeps (field cultivator, soil finisher)
- Avoid shredding crop residue. Use equipment that can handle corn stover without shredding.

Comparison of tillage systems

Different tillage implements are compared in table 4-5. What works well on one farm under a given set of conditions might not work as well on another farm with different management and conditions. For each system, evaluate differences in soil conservation, as well as cost of equipment, pesticide, fuel, and labor requirements. Tables 4-6 and 4-7 estimate fuel and labor requirements for five tillage and planting systems.

Table 4-4. Effect of implement shape on surface residue following fall chisel plowing (one pass).

Tool	Residue cover (%)
3-inch concave twisted shovel 	53
2-inch chisel point 	60
16-inch medium crown sweep 	66

Source: Johnson, R.R. 1988. Soil Sci. Soc. Amer. J. 53:237–243. Reprinted with permission of the Soil Science Society of America, Inc., Madison, WI.

Table 4-5. Typical tillage field operations.

System	Typical field operations	Major advantages	Major disadvantages
Moldboard plow	Fall or spring plow; one or two spring diskings or field cultivations; plant; cultivate.	Suited to most soil and management conditions. Suitable for poorly drained soils. Excellent incorporation. Soils warm up early.	Excessive soil erosion. High soil moisture loss. Must be timed carefully. Highest fuel and labor costs.
Chisel plow	Fall chisel; one or two spring diskings or field cultivations; plant; cultivate.	Less erosion potential than fall plow or fall disk. Well adapted to all soils, including those that are poorly drained. Good to excellent incorporation.	Multiple passes cause excessive soil erosion and moisture loss. In heavy residues, may need to shred stalks to keep chisels from clogging.
Disk	Fall or spring disk; spring disk and/or field cultivate; plant; cultivate.	Less erosion than from cleanly tilled systems. Well adapted for lighter to medium textured, well-drained soils. Good to excellent incorporation.	Multiple passes cause excessive soil erosion and moisture loss. Disking wet fields compacts soils.
No-till	Spray; plant into undisturbed surface; postemergent spray as necessary.	Maximum erosion control. Soil moisture conservation. Lowest fuel and labor costs.	No incorporation. Increases dependence on herbicides. Not well suited for poorly drained soils.
Ridge-till	Shred stalks; plant on ridges; cultivate for weed control and to rebuild ridges.	Excellent erosion control on contour fields. Well adapted to all soils. Ridges warm up and dry out quickly. Low fuel and labor costs.	No incorporation. May be difficult to create and maintain ridges. Not well suited to narrow-row corn or soybeans.
Strip-till	Fall strip-till; spray; plant row crops on cleared strips; post-emergent sprays as needed.	Clears residue from row area to allow preplant soil warming and drying. Injection of nutrients directly into row area. Well suited for poorly drained soils.	Cost of preplant operation. Strips may dry too much, crust, or erode without residue. Potential for nitrogen fertilizer losses.

Source: Reeder et al., 2000. Reproduced with permission from Conservation Tillage Systems and Management, MWPS-45, 2nd edition, Midwest Plan Service, Ames, IA 50011-3080.

Table 4-6. Typical diesel fuel requirements for various tillage and planting systems.

Operation	Fuel use, gal/a				
	Moldboard	Chisel	Disk	No-till/Strip-till	Ridge-till
Chop stalks					0.55
Moldboard plow	2.25				
Chisel plow		1.05			
Fertilize, knife	0.60	0.60	0.60	0.60	0.60
Disk	1.48[a]	0.74	1.48[a]		
Plant	0.52	0.52	0.52	0.60	0.68
Cultivate	0.43	0.43	0.43		0.86[a]
Spray				0.23[a]	
Total	5.28	3.34	3.03	1.43	2.69

[a] *Two passes.*

Source: Reeder et al., 2000. Reproduced with permission from Conservation Tillage Systems and Management*, MWPS-45, 2nd edition, Midwest Plan Service, Ames, IA 50011-3080.*

Table 4-7. Typical labor requirements for various tillage and planting systems.

Operation	Labor, hr/a[a]				
	Moldboard	Chisel	Disk	No-till/Strip-till	Ridge-till
Chop stalks					0.17
Moldboard plow	0.38				
Chisel plow		0.21			
Fertilize, knife	0.13	0.13	0.13	0.13	0.13
Disk	0.32[b]	0.16	0.32[b]		
Plant	0.21	0.21	0.21	0.25	0.25
Cultivate	0.18	0.18	0.18		0.36[b]
Spray				0.11[b]	
Total	1.22	0.89	0.84	0.49	0.91

[a] *Hours per acre assumes 100 hp tractor and matching equipment for average soil conditions.*

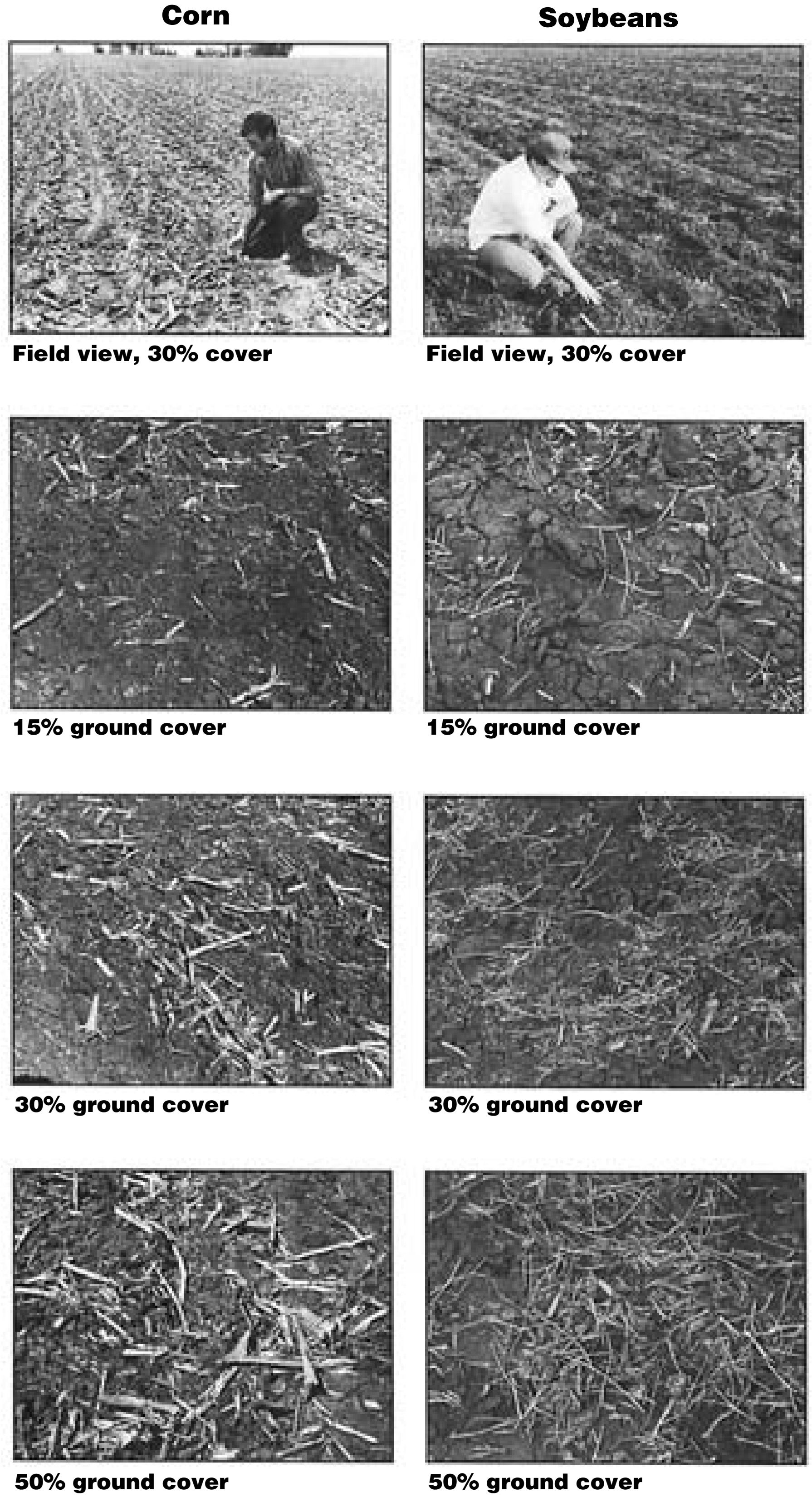
[b] *Two passes.*

Source: Reeder et al., 2000. Reproduced with permission from Conservation Tillage Systems and Management, MWPS-45, 2nd edition, Midwest Plan Service, Ames, IA 50011-3080.

Estimating residue cover

With experience, the amount of crop residue on the soil surface can be approximated by inspection. Figure 4-2 shows how 15, 30, and 50% corn and soybean residue cover appear. A more exact measurement can be made by the line-transect method. This procedure involves stretching a line diagonal to the crop rows and recording whether or not residue intersects the line at specified points. The line can be a wire cable with tabs attached at fixed spacings, a knotted rope, or a tape measure. It should be 100 feet long with markings at 1-foot intervals or 50 feet long with markings every 6 inches. Anchor both ends of the line. Walk along the line and look straight down at each recording point (tab, knot, etc.). Record the number of points that are directly over a piece of residue. Always look at the same side of the line and avoid moving the line while counting. Stones should not be counted, but manure should be counted as residue. The number of intersections with residue out of the 100 recording points is the percent residue cover. Repeat the procedure at five randomly selected locations in the field, and take the average of the five results. For more details, see Extension publication *Estimating Residue Using the Line-Transect Method* (A3533).

Figure 4-2. Appearance of soil with different amounts of corn or soybean residue. *Photos courtesy USDA Natural Resources Conservation Service.*



Soil crusting

Raindrop impact on bare soil dislodges individual sand, silt, clay, and organic matter particles from soil aggregates. When pools of water develop, the sand settles to the bottom, the silt rests on top of the sand, and the clay on top of the silt—if it is not carried away with organic matter particles in the runoff water. When the water dries, a surface crust about ¼-inch thick is formed. This crust can prevent seedling emergence, reduce air exchange, limit water infiltration, and increase water runoff.

Crop residue on the surface retards crust formation by absorbing the energy of the raindrop and limiting the amount of dislodged soil particles. Coarse, sandy soils do not form crusts, nor do well-granulated clays. Most clayey soils will shrink enough on drying to break up crusts. Sandy loam and silt loam soils low in organic matter seem to produce the densest and thickest crusts. Sometimes these crusts can be broken up with a rotary hoe.

Soil compaction

Compacted soil reduces water infiltration at the surface and decreases permeability at lower levels, reduces aeration, and physically restricts plant shoot emergence and root development. Three forces compact soil: gravity, rain, and traffic. If the soil surface is bare, raindrop impact tends to dislodge silt and clay particles from aggregates at the surface. The silt and clay get washed into larger pores, increasing the bulk density of the soil. Residue on the surface protects soil structure from this effect of raindrop impact.

Moisture is usually the determining factor in compaction. Before doing any field work, check soil moisture, not only at the surface but to the depth of tillage and immediately below. The most serious damage occurs when tillage, planting, cultivating, or harvesting operations are done when the soil is wet. For example, in one study on a clay loam soil, three passes with a tractor packed the plow layer to the same bulk density as the subsoil.

It is a good practice to return as much fresh organic matter (crop residue, manure) to the soil as possible. All soil compaction problems become more severe as organic matter is depleted. Humus (decomposing organic matter) acts as a cementing material to give stability to soil aggregates, thus maintaining soil structure.

Most compaction is the result of wheel traffic. Large rubber tires cause less surface compaction than small tires because of their larger “footprint.” Radial-ply tires have a larger footprint than bias-ply tires. Depth of compaction depends on the total load on the tire. Deep compaction is not affected by slippage of a driving tire, but it is increased by liquid in the tire and wheel weights. Wheel weights should be removed when they are not needed for traction.

Another way to reduce compaction is to control traffic. All vehicle and implement wheels are spaced to run centered between rows. Many tillage, planting, spraying, and harvesting operations can use the same tracks. In continuous row crops, this system works well with ridge-till, strip-till, and no-till where the same tracks are used year after year. Traffic, and therefore compaction, is confined to a small percentage of the soil between rows. Compaction is thereby managed, not eliminated.

A common management response to compaction is subsoiling or deep tillage. Recent research showed that the type of subsoiler that is used can influence yield. A straight-shanked subsoiler following either corn or soybean was found to increase crop yield when compared to a more aggressive subsoiler that lifted and shattered the entire soil volume. Researchers have noted that intensive subsoiling destroys the bearing strength and natural channels in the soil such that it can be recompacted to a worse condition. Before subsoiling, compaction should be diagnosed. The most common tool is a cone penetrometer that is pushed into the soil at a constant rate. Be sure to note both the intensity and depth of the resistance. Subsoiling points should run 1 to 2 inches below the compacted layer. Be sure to take penetrometer measurements in affected and unaffected areas because the resistance to penetration is relative to the moisture content of the soil.

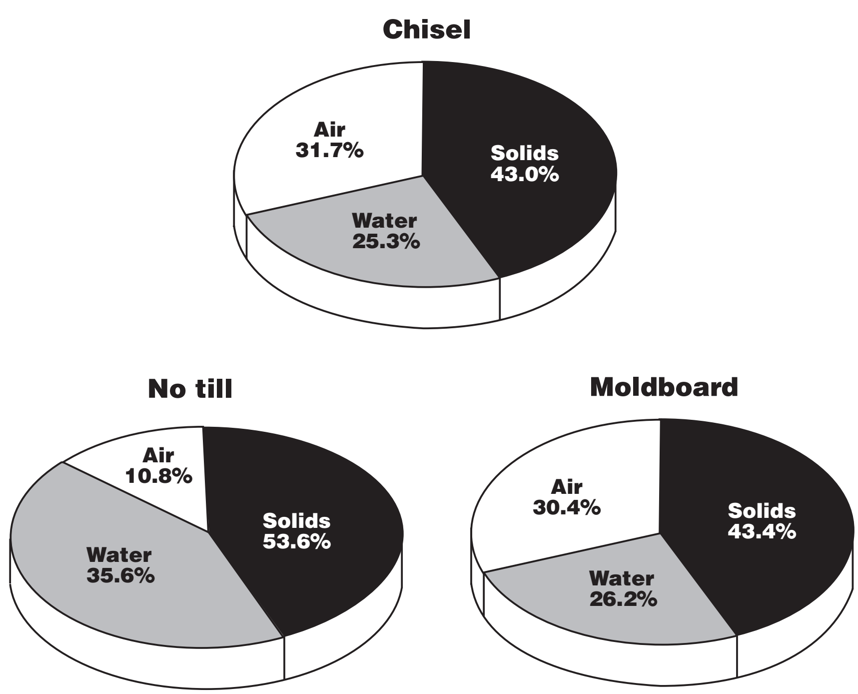
Effect of tillage on nutrient availability

Wisconsin research shows that tillage has little influence on phosphorus (P) availability, but it strongly influences the availability of nitrogen (N) and potassium (K). Nutrient availability is linked to tillage because of changes in soil moisture and air space. Reduced tillage increases moisture and reduces air space. Figure 4-3 shows how various tillage systems affect moisture content and air space.

For nitrogen, reduced air space provides conditions conducive to the conversion of nitrate-nitrogen to atmospheric nitrogen (denitrification) resulting in less plant-available nitrogen. Studies of seven soils across the U.S. have shown a much higher population of denitrifying microorganisms in no-till plots compared to moldboard-plowed plots. Wisconsin research shows that, in wet years, nitrogen is less available in no-till plots compared to moldboard or chisel-plowed plots. However, in dry years the no-till plots had better yields than moldboard or chisel-plowed plots.

Reduced air space also plays a role in potassium availability. The concentration of potassium in plant root cells is about 2,000 times higher than the concentration of potassium in the soil solution. Plants must exert energy to take in potassium against this high concentration gradient. This energy comes from respiration of sugars translocated to the roots from the leaves where it was manufactured. Respiration requires oxygen, so when aeration is reduced, the plant has less energy to extract potassium (and other nutrients).

Figure 4-3. Influence of tillage on soil bulk density and pore space occupied by air or water (upper 3 inches of soil).

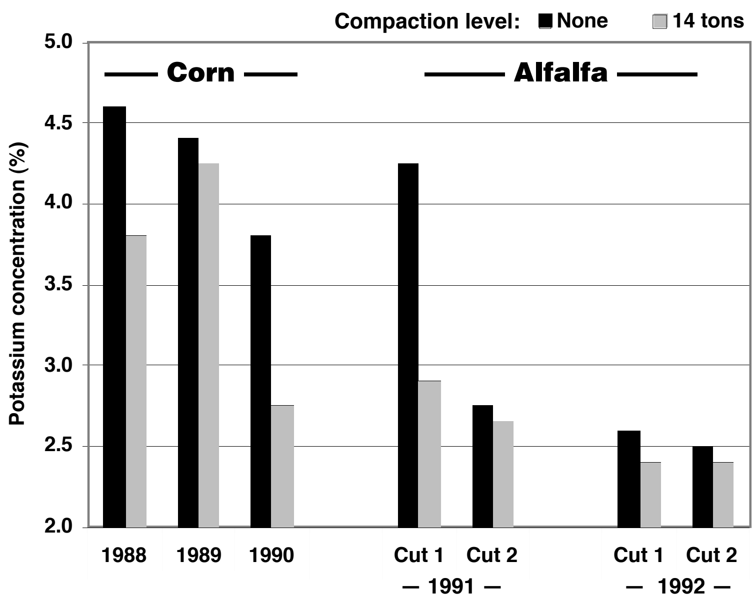


Adapted from Moncrief, J.F. 1981. Ph.D thesis, UW-Madison.

Compacting a Plano silt loam using a payloader with a 14-ton axle weight reduced the concentration of potassium in whole corn plants at the eight-leaf stage and in alfalfa at harvest (figure 4-4). The reduction in potassium concentration resulted in reduced yields of both crops.

Potassium is less readily available under reduced tillage than in conventionally tilled fields. The best way to correct potassium deficiency is to include potassium in row (starter) fertilizer and ensure that soil test potassium is in the optimum range.

Figure 4-4. Effect of soil compaction on potassium concentrations in corn (eighth leaf stage) and alfalfa.



Source: Wolkowski, R.P. and L.G. Bundy. 1992. New Horizons in Soil Science. *No. 3, Dept. of Soil Sci., UW-Madison.*

Questions

1. One reason for tilling the soil is to remove vegetation that competes with crops. With herbicides that reason is no longer of primary importance. Discuss other reasons for tillage, as well as disadvantages of tillage.

2. Under what conditions should soils be plowed deeper than 8 inches? Why is deep plowing not ordinarily recommended?

3. What percent residue cover is needed to meet the requirements of a conservation plan that calls for residue management?

4. Describe a method of measuring soil residue cover.

5. What kinds of soil are most prone to crusting? What can be done to reduce crust formation on these soils?

6. Why is soil compaction becoming an increasing problem in Wisconsin? What can be done to minimize soil compaction?

7. The soil in no-till fields usually contains somewhat more moisture than soil in plowed fields. Under what conditions is the extra moisture an advantage? A disadvantage?

8. A tillage trial comparing no-till with moldboard plowing is conducted on a field of corn. The no-till corn shows potassium deficiency; the conventional tillage does not. Explain why.

CHAPTER 5

Soil and water conservation

"The nation that destroys its soil destroys itself. The soil is indispensable. Heedless wastage of the wealth which nature has stored in the soil cannot long continue without the effects being felt by every member of society."

Henry A. Wallace,
U.S. Secretary of Agriculture, 1936

Soil erosion affects everyone, and we all contribute to the problem. Erosion occurs at construction sites, along roadsides, in parks and forests, along stream banks, on hiking trails and bicycle paths, and on agricultural land. It scars the landscape, causes siltation in drainage ways, sewers, reservoirs and lakes, degrades water quality, and reduces soil productivity. The Natural Resources Conservation Service (NRCS) estimates in its 2001 national resources inventory that the nation's cropland is losing 1.8 billion tons of topsoil per year. Average erosion rates are estimated to be 2.7 tons per acre per year from water (sheet and rill) erosion and 2.1 tons per acre per year from wind erosion. Soil erosion by water is a natural process that occurs whenever rain falls on sloping land. Erosion produced the sediment that gave rise to the fertile delta soils of the great rivers of the world long before people began to till the soil. But human activities have often accelerated erosion beyond acceptable limits.

Organic matter and clay erode more easily than silt and sand because the particles are lighter or smaller and are more easily suspended in runoff water. These particles hold more available nutrients than sand or silt. Hence, the most fertile part of the soil is lost. In one study using conventional tillage, the organic matter, total nitrogen, and available phosphorus in eroded sediments were about 33% higher than the soil from which they came. Exchangeable potassium was more than six times higher. With conservation tillage, phosphorus and potassium tend to be concentrated on the soil surface. As a result, the concentration of these nutrients in runoff and sediments is often higher as well. Even so, the total loss of phosphorus and potassium is less from conservation tillage fields because these systems reduce sediment loss.

Most soil conservationists feel that erosion cannot be stopped; it can only be controlled. Soil loss from sheet and rill erosion is estimated through the use of the Revised Universal Soil Loss Equation 2 (RUSLE2) software model. The RUSLE2 model is the latest in a series of predictive tools (including USLE and RUSLE) for estimating long-term, average annual soil loss caused by rainfall. Model inputs include slope length and steepness, rainfall factors (intensity and duration), soil erodibility, cropping practices, and presence of soil conservation practices for a given field. Results are compared to tolerable soil loss (T) values. Values for "T" are defined for a given soil as the soil loss rate that is, in theory, equal to the rate of soil formation. Hence, at T, equilibrium between soil loss and gain is reached. T values typically range from 3 to 5 tons per acre per year for most crop, pasture, and forest lands. On western rangeland, T values are typically much lower (2 tons per acre per year) because soil formation in arid and semi-arid climates is much slower than in more humid environments. Comparing predicted soil loss estimates from RUSLE2 to soil T values allows conservation planners to develop management plans for effective erosion control. Conservation efforts should be concentrated on the soils with the greatest erosion potential.

Runoff and erosion

Water erosion is a three-step process that involves detachment, transport, and deposition of soil particles. Erosion begins when raindrops or running water detach soil particles for aggregates and flowing water passes over the soil and carries some of it away. Sand, silt, and coarse clay particles are deposited when water movement slows sufficiently, but fine clay can be suspended and carried off to surface water.

Water erosion may be divided into four basic categories:

1) Splash—raindrop impact on the soil surface breaks soil aggregates into particles that can then be carried by running water (figure 5-1).

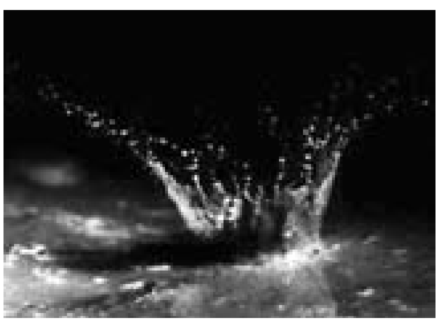
2) Interrill/sheet—continuous splash erosion causes interrill erosion; water moving across the soil carries thin sheets of soil downhill. Interrill erosion is usually slow and imperceptible, so its occurrence is not recognized immediately.

3) Rill —water moving across the soil surface cuts many small channels or ditches, usually only a few inches wide and deep (figure 5-2).

4) Gully—water flows through one channel long enough to cut large gullies. This is the most dramatic type of erosion and receives the most notice, but the other types can remove just as much soil. *Ephemeral* gullies are small channels that can be filled by normal tillage, but are likely to reform again in the same location. *Classical* gullies are channels too wide and deep to be obliterated with normal tillage operations (figure 5-3).

The obvious solution to water erosion is to control water movement. The erosive power of water is dictated by the volume and velocity of water

Figure 5-1. Raindrop splash.



Source: USDA-NRCS

Figure 5-2. Rill erosion.

Source: USDA-NRCS

Figure 5-3. Gully erosion.

Source: USDA-NRCS

moving over the soil surface. The greater the volume and velocity, the greater the amount of sediment that can be carried by runoff. Slowing the water allows more time for it to soak in rather than run off and reduces its capacity to carry sediment. Furthermore, in a dry year the additional water held in the soil can make the difference between a good and poor crop. An extra inch of stored moisture during a drought period will give a significantly better crop yield.

Source: USDA-NRCS

Factors influencing erosion

The most important factors influencing erosion are the intensity and duration of rainfall, the erodibility of the soil, length of slope, slope angle, soil cover, and erosion control practices.

A light steady rain that falls slower than it's absorbed by the soil causes very little erosion. Most erosion is caused by heavy rains and by rapid melting of snow when the soil begins to thaw. Erosive rain storms occur most often in late spring or summer. Erosion control practices must be designed for these intense storms and rapid snow melts. An inch of rain over an acre weighs 226,000 pounds and carries considerable energy when flowing over the landscape. A raindrop strikes the soil surface at a velocity of 20 mph. This is enough force to splash soil as much as 2 feet high and 5 feet away from the point of impact.

Some soils erode more easily than others. The composition of the soil, particularly the soil structure, makes a big difference in the ease with which rainfall can detach particles and get them moving with running water. Organic matter is very important in holding aggregates together and stabilizing them against erosion.

The steepness and length of slope are extremely important. Water on a level field has much more time to soak in than water on a steep slope. Doubling the steepness more than doubles the amount of soil loss. Soil loss increases rapidly as slope length increases up to about 400 feet, then more gradual increases in erosion occur at longer slope lengths. However, slopes that are nearly level are not immune to soil erosion. A long, relatively flat slope with a lot of water flowing over it can transport as much sediment as a steep slope having only a little runoff.

Soil cover varies in its effectiveness to reduce raindrop impact and soil loss. Vegetation or residue that covers the soil during intense storms is more effective than land use that leaves the soil exposed during critical times. Forage legumes and grasses are more effective than row crops because part of the soil surface under row crops is bare from the time the soil is tilled until a complete canopy covers the surface. This means the soil is bare when many intense rainstorms occur.

Soil and water conservation practices

Conservation practices help growers retain the soils' productivity while making the best use of resources (land, labor, and capital). This section describes the most commonly used soil conservation practices. Erosion and runoff control practices range from changes in agricultural land management (such as crop rotation, conservation tillage, contour tillage, strip cropping, and cover crops) to the installation of structural practices such as terraces, diversions, and waterways.

Crop rotation

Crop rotation is the practice of growing different crops in recurring succession on the same field. Perennial forage crops provide year-round soil coverage and, therefore, greatly reduce erosion compared to row crops. By combining conserving practices, such as terraces or contour strips with conservation tillage, rotations can often be used with more corn and small grain and less forage. These more intensive rotations are usually more profitable on cash crop farms and those with hog or beef enterprises.

Corn grown in rotation with alfalfa, soybeans, or other crops typically out-performs continuous corn. As shown in table 5-1, the maximum yield of continuous corn was 141 bushels/acre when 200 pounds/acre of nitrogen was applied. In contrast, first-year corn following alfalfa yielded 157 bushels/acre with no added nitrogen. Legumes in the rotation provide more than just nitrogen. The improved productivity (added yield) that occurs with rotated corn as compared to continuous corn is sometimes referred to as the "rotation effect." Rotations help break the life cycles of insects and diseases that build up in monocropping.

Another recent adaptation of crop rotations is the practice of keeping hilly fields in permanent alfalfa and grass and growing corn and soybeans on nearly level fields. Corn can be grown for grain on such fields for several years with no damage to soil structure if conservation tillage is used. If recommended amounts of lime and fertilizer are applied and if weeds, insects and disease are controlled, high yields can be maintained. County Land Conservation Department (LCD) personnel and NRCS conservationists can help farmers develop a cropping system that best fits their farming program and land.

Conservation tillage

Any tillage practice that leaves residue on the soil surface aids in soil and water conservation. Conservation or mulch tillage systems can be defined as those that result in the least amount of tillage necessary to provide a good seedbed. They can also be defined as restricting the number of cultural operations to those that are properly timed and are essential to produce an ideal seedbed and rootbed. Generally, those systems that leave at least 30% residue cover are considered to be conservation tillage. See chapter 4 for additional information on conservation tillage systems.

Contour tillage

Contour tillage follows the shape of the land to till and plant. The effectiveness of contour tillage is dependent largely on the ridges produced by tillage implements. By cutting across the natural flow of runoff water, contour tillage builds small impediments to flow that reduce the speed and amount of runoff, which in turn reduces soil loss.

Contour tillage is most effective at reducing soil loss on slopes below 8%. On steeper slopes, ridges lose their ability to hold and retard water flow. Contour tillage on slopes of 3 to 8% reduces soil loss by 50% compared to up-and-down-slope tillage.

Slope length also influences the effectiveness of contour tillage. There is a limit to the length of slope that can be contoured without supplementary practices. Runoff from the upper part of the slope combines with runoff from the lower part. The additional water on the lower part of the slope increases the rate of erosion. Most of the severe cutting from water erosion occurs on

Table 5-1. Effect of alfalfa or soybeans on the yield of corn grown on a Rozetta silt loam soil (Lancaster, WI), 1995–2004.

	Cropping sequence			
Nitrogen applied	**Continuous corn**	**Second-year corn after alfalfa**	**First-year corn after alfalfa**	**First-year corn after soybean**
lb/a	Corn yield, bu/a			
0	57	96	157	102
50	88	130	167	134
100	128	145	170	157
200	141	155	173	164

the lower parts of the field where running water will have the most energy. On 3 to 8% slopes longer than 300 feet, contour tillage needs to be augmented with terraces or other conservation practices to prevent erosion.

Strip cropping

Strip cropping is the practice of growing row or grain crops in alternate contour strips with sod crops (grasses or legumes). The grass strips should cover at least 20% of the field. The dense sod cover slows runoff and holds any soil carried from the clean-tilled crop.

Certain conservation measures improve the effectiveness of strip cropping. Contour tillage, an integral part of strip cropping, helps control erosion. Grass waterways are essential to carry concentrated runoff. On long slopes, diversions or terraces are essential to redirect and remove excess runoff slowly and to prevent gullies. Unfortunately, many fields do not have an adequate system of grass waterways as these are often removed by tillage or herbicide application.

Cover crops

Cover crops provide interim protection to the soil between regular cropping intervals. They protect the soil surface from the impact of raindrops and wind erosion, add organic matter, and minimize loss of nutrients by leaching. Water is absorbed more readily because the pore space on the surface of the soil is kept open. Thus, cover crops aid in the conservation of water, in the control of wind and water erosion, weed control, and the maintenance of soil productivity. Several crops can be used for cover crops, among them rye, oats, wheat, barley, domestic ryegrass, hairy vetch, and sweet-clover.

Cover crops on sandy soils, especially irrigated sands, help reduce early spring wind erosion. They are also extremely beneficial when the principal crop is harvested early. Cover crops, such as winter rye, are being used following the harvest of corn for silage. This crop actively grows until early winter and then initiates regrowth in early spring. It is important that it be managed by herbicide or clipping the following season to prevent competition with the succeeding crop.

Terraces and diversions

Terraces and diversions, when properly installed and maintained, are very effective mechanical practices for controlling erosion. Recent modifications have made them even more effective and easier to use.

Formerly, irregular terraces left many hard-to-handle point rows (areas of planter overlap due to field boundaries that are not square) in the field. But the use of parallel terraces has substantially reduced the acreage of point rows. The second modification is the construction of terraces that use drainage tiles to remove excess water. Alternatively, the terraces may be graded or sloped towards one end, and excess water is removed via a grass waterway. Graded terraces that use grass waterways are cheaper to construct than those that use tile drainage, but they require more maintenance.

Surface drainage is required for some poorly drained soils that cannot be tiled, such as those in north central Wisconsin. The soil landscape is smoothed with a large land leveler between shallow, graded terraces. This system allows excess water to run off the land slowly to the terrace, and then into a surface outlet. Erosion is minimized by slowing the water and directing the flow.

Diversions are similar to terraces but do not have standard spacings. Each diversion handles runoff from its drainage area. Diversions are effective under the following conditions:

- to reduce slope length on long slopes, making strip cropping more effective,
- to protect gullied areas,
- to divert surface water away from low-lying lands, and
- to divert water away from barnyards, buildings, and roadways.

Grass waterways

Grass waterways are wide, shallow, vegetated channels. They are usually designed to carry peak runoff following severe rainstorms. A plow, grader, bulldozer, or scraper can be used to shape the channels.

Functional grass waterways require well-established, “heavy-duty” vegetative cover. The sod grown in the water course needs special care during establishment to help it withstand the added hazard of flowing water. Avoid any practices that would hurt the quality or quantity of the grass in the waterway, such as using it as a farm road. Also, use herbicides very carefully near grass waterways; otherwise, runoff water can carry the herbicide into the waterway and kill the grass. Only conscientious management and maintenance will keep this important conservation structure operating effectively.

Buffer/filter strips

Buffer or filter strips are areas of grass or other vegetation planted either in a field or along a field edge, often near a stream or other surface water feature. These act like the silt fences that are commonly placed around construction sites. As runoff flows through the filter strip, its velocity is slowed by the vegetation and sediment drops out of the runoff. Water volume moving across the slope decreases as runoff infiltrates reducing the sediment load.

A contour buffer strip is typically 12 to 15 feet wide and is planted in the upland on the contour between contour strips. Normally, a cool-season grass such as timothy or bromegrass is used. This grassy forage can be harvested occasionally for hay.

Riparian filter strips are planted near bodies of surface water and are typically 50 to 60 feet wide. Their major function is to remove sediment, but they also serve to stabilize stream banks and provide habitat for wildlife. While some are planted to a cool-season grass, native warm-season grasses such as switchgrass are more effective because they have stiffer stems and remain erect when dormant. They also produce more vegetation and can absorb larger quantities of nutrients.

The use of buffer strips can be controversial because they are typically installed in the tillable portion of a field and, subsequently, remove land from production. Filter strips should not be used as roads to outlying fields and need to be clipped occasionally to eliminate undesirable vegetation, remove excess nutrients from the riparian area, and maintain the vigor of the plants. Cutting is often done in mid-summer to protect the nests of grassland birds. Riparian filter strips serve as a "last line of defense" for the protection of surface water and should be used in conjunction with the other upland conservation practices described in this section.

Wind erosion

Wind, like water, can cause erosion. In addition to removing topsoil, wind erosion can damage young seedlings by a sandblasting effect. Airborne particles contribute to air pollution, poor visibility, and allergies.

For wind to lift and move a soil particle, the wind must be stronger than the forces holding the particle to the ground (gravity and adhesion). Clay and silt-sized particles may be lifted high in the air and carried great distances (figure 5-4). Silt from the Great Plains and glacial floodplains in the Mississippi River valley was carried eastward across much of Wisconsin following the glaciers that receded thousands of years ago. Roughly two-thirds of the state is still covered by this loess or wind-blown silt. The great dust storms of the 1930s were a result of wind erosion. Beautiful sunsets are caused by different wavelengths of visible light being reflected from dust in the atmosphere.

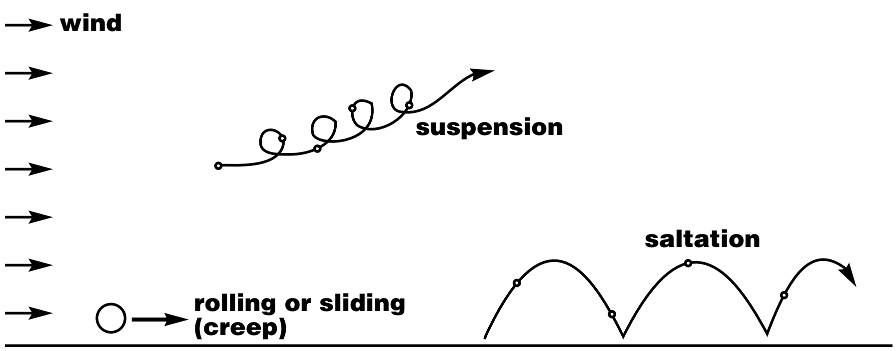
Coarse sand grains are too heavy to be lifted by most winds, but they can be rolled short distances and "creep" along the soil surface (figure 5-5). Most soil is moved by a process known as *saltation* which lifts and bounces particles along. In another type of wind erosion, *suspension,* wind blowing over soil surfaces exerts a lifting force like that on an airplane wing as it flies through the air. Once airborne, the soil is moved along with the wind for some distance and then lifted again.

Wind erosion is influenced by the erodibility of the soil, climate (wind velocity and duration, soil moisture, etc.), field roughness, field length and orientation to wind, and the amount of vegetative cover. Long-term, average, annual soil losses from wind erosion are estimated by the Wind Erosion Equation (WEQ) model which includes all these parameters. The most serious wind erosion problem in Wisconsin is in the Central Sands area where windbreaks have been removed to make way for quarter-section center-pivot irrigation systems. Wind erosion

Figure 5-4. Wind erosion.

Source: USDA-NRCS

Fig. 5.5. Types of soil movement by wind.



is most severe on bare, dry soil. Cover crops and windbreaks should be used in areas prone to this type of erosion.

There are chemicals available to spray onto soils prone to wind erosion that create a short-lived crust to help control erosion. However, they are costly and, once applied, cannot be disturbed by tillage. If applied early in the spring, they will not protect the crop after tillage and planting. If applied after planting, the soil is not protected early.

The best way to prevent wind erosion is by keeping the soil covered as much as possible and by tilling as little as possible. To do this, cover crops can be sown into standing crops or planted after harvest and allowed to grow until the next crop is planted in spring. Cover crops can be killed using a herbicide, and the crop can be no-till planted in the spring. The residue from the cover crop continues to reduce wind erosion and protect the soil. An additional benefit is that the cover crop takes up nitrogen that might otherwise leach over winter. This nitrogen is released gradually as the cover crop decomposes.

Tillage translocation

Another type of soil movement that is often overlooked is tillage translocation, or the movement of soil by the action of various tillage operations. It is not difficult to visualize tillage translocation. When an implement is moving upslope and then downslope, or across a steep slope, it is expected that there will be a net movement of soil in the downslope direction. Tillage translocation has a leveling effect and it is likely that eroded knolls within fields are caused, in part, by this mechanism. When combined with the effects of water erosion, a significant amount of soil can be moved within the field. Actual sediment loss from the field is minimal, however, because physical boundaries such as fences, roads, and ditches can stop the movement of soil from tillage translocation. Speed and intensity of tillage operations contribute to the effects of tillage translocation. Over long periods of time tillage translocation will reduce productivity in upper portions of a field though the loss of nutrients, organic matter, and topsoil.

Conservation incentives

The greatest incentive to practicing soil conservation should be a moral one, a conviction that one has a responsibility to take the best possible care of soil that has been entrusted to us so that future generations may continue to reap the benefits derived from productive soil. Secondly, farmers who live on the land they till take pride in managing it well and passing it on to future generations in a more productive condition than when they acquired it. Soil stewardship along with economic benefits become yardsticks by which some managerial decisions are made.

Several federal, state, and county agencies provide farmers with information and technical and financial assistance to implement soil conservation practices. Federal agencies include the Natural Resources Conservation Service (NRCS) and the Farm Service Agency (FSA). Wisconsin agencies include the Department of Agriculture, Trade and Consumer Protection (DATCP) and the Department of Natural Resources (DNR). These agencies work closely with county Land Conservation Departments (LCDs) and the county Land Conservation Committees (LCCs) that supervise the LCDs.

The county LCDs provide planning, financial, and technical assistance to private landowners and local units of government for soil and water conservation practices. The DATCP administers the conservation provisions of the Farmland Preservation Program. They also support soil conservation programs at the county and state level, and provide cost-sharing to participants. The DNR administers Wisconsin non-point source water pollution abatement programs, which are implemented locally by LCDs in selected watersheds. University of Wisconsin-Extension and other institutions within the university system conduct educational programs and do research in support of soil and water conservation programs.

The NRCS assigns full-time professional technicians to Wisconsin counties to assist LCDs in developing and carrying out conservation programs. These specialists assist landowners in developing resource conservation plans. They provide specifications, standards, and guidelines for selection, design, layout, installation, and maintenance of management practices and engineering measures to control runoff, soil erosion, and sedimentation. They also help plan and design animal waste management systems. The FSA administers federally funded programs which provide cost sharing and incentive payments to farmers to encourage the use of practices that will reduce soil erosion and water pollution.

Questions

1. Apart from the loss of precious topsoil, why is soil erosion undesirable?
2. How much soil loss is permissible?
3. Describe four different kinds of water erosion. Which causes the greatest soil loss in your area?
4. Name three factors that affect soil erosion. Explain the importance of each factor.
5. Explain how a surface mulch of crop residues reduces soil erosion.
6. If all rainfall could be held on the soil long enough to eliminate runoff, soil erosion by water would be eliminated as well. Why is this not practical?
7. What soil conservation measures can be used to counteract the effects of long, steep slopes on soil erosion?
8. "Water conservation equals soil conservation." Explain.
9. Under what conditions might wind erosion be a problem? How can it be reduced?
10. List each federal, state, and county agency involved in conservation programs. What role does each play?

CHAPTER

6

Soil acidity and liming

"So without question, the most important single chemical characteristic of a soil as regards its suitability for plant growth is its reaction or pH status."

Emil Truog,
Mineral Nutrition of Plants, *1951*

The late Professor Emil Truog once remarked that if you could have but one soil test run on a field, that test should be pH. Soil acidity, which is determined by measuring soil pH, reduces productivity of all crops and eliminates the possibility of growing acid-sensitive crops. Aglime added to acid soils raises the pH by neutralizing soil acidity. On the other hand, lowering the pH of alkaline soils is seldom required and usually is not practical on a large scale.

Soil pH

Soil pH, a measure of acidity or alkalinity, affects many chemical and biological reactions taking place in the soil. Before discussing these reactions, it is necessary to understand what the pH measurement means and the chemical nature of acids and bases.

Stated simply, an acid is a substance with an excess of hydrogen ions (H^+), and a base is a substance with an excess of hydroxyl ions (OH^-). A common example of an acid is sulfuric acid (the solution in car batteries). Sodium hydroxide (lye) is an example of a base. When sulfuric acid is mixed with water, the following reaction occurs (in chemical equations the symbol HOH is often used for water instead of H_2O):

$$H_2SO_4 + HOH \longleftrightarrow 3H^+ + SO_4^{=} + OH^-$$

sulfuric acid, water, hydrogen ion, sulfate ion, hydroxyl ion

Sulfuric acid ionizes (dissolves) completely; that is, it goes to the right in the reaction above. It is a strong acid because it contains more hydrogen ions (H^+) than hydroxyl ions (OH^-).

When lye (sodium hydroxide) is mixed with water, it ionizes, forming excess hydroxyl ions. This results in a strongly alkaline or basic solution:

$$NaOH + HOH \longleftrightarrow Na^+ + H^+ + 2OH^-$$

sodium hydroxide, water, sodium ion, hydrogen ion, hydroxyl ion

Pure water contains an equal amount of hydrogen and hydroxyl ions and, therefore, is neutral.

$$HOH \longleftrightarrow H^+ + OH^-$$

The concentration of hydrogen ions in pure water has been found to be 0.0000001 moles per liter of water (1 mole = 1.008 grams of H^+). The pH scale is a convenient way to express such small numbers. The pH is defined as the logarithm of the reciprocal of the hydrogen ion concentration (pH = log $1/H^+$). For example, the concentration of 0.0000001 moles of hydrogen per liter of water is converted into a pH of 7 as follows:

pH = log 1 / 0.0000001
= log 10,000,000
(reciprocal number)
= 7

Table 6-1. Hydrogen and hydroxyl concentrations and interpretations at common pH levels.

H^+ concentration	OH^- concentration	pH	Interpretation
——— moles/liter ———			
0.00000001	0.000001	8	strongly alkaline
0.0000001	0.0000001	7	neutral
0.000001	0.00000001	6	slightly acid
0.00001	0.000000001	5	strongly acid
0.0001	0.0000000001	4	extremely acid

The concentration of hydrogen and hydroxyl ions at pH levels commonly observed in Wisconsin soils is presented in table 6-1. Note that as acidity *increases*, the pH number *decreases*. Another important point is that for each one unit change in the pH value, there is a 10-fold change in the concentration of hydrogen ions. For instance, when the pH decreases from 5.0 to 4.0, the concentration of hydrogen ions increases 10 times from 0.00001 to 0.0001 moles/liter.

Importance of soil pH

Soil pH is important because it affects both chemical and biological reactions, including the following:

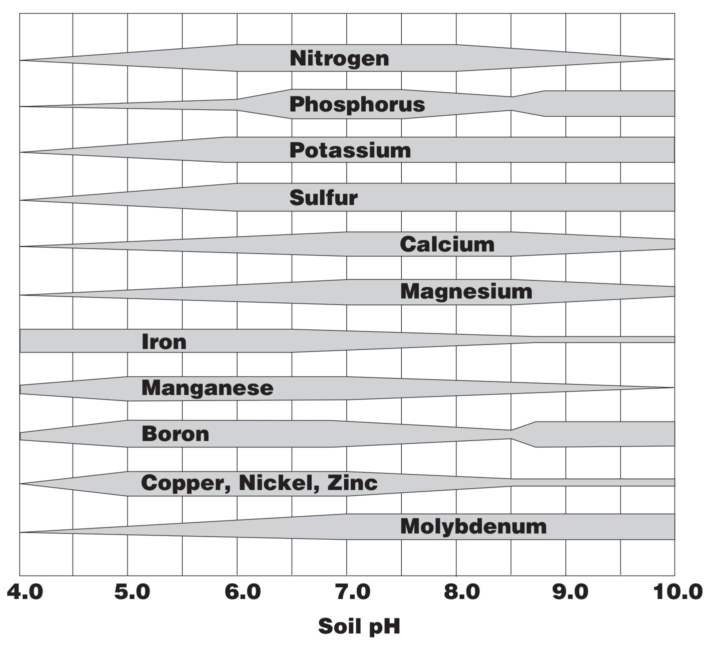
- availability of most of the essential nutrients,
- activity of microorganisms,
- ability of soil to hold positively charged nutrients (cations),
- solubility of non-essential elements, including heavy metals, and
- performance of some herbicides.

The soil pH directly affects the availability of some nutrients, but it often indirectly affects nutrient availability through its influence on microbial activity. The relationship between soil pH and nutrient availability is illustrated in figure 6-1. In this graph, the wider the bar, the greater the relative availability of the nutrient.

The effect of pH on nitrogen availability is due mainly to its influence on microbial activity. Nitrogen in soil is stored in humus or organic matter and becomes available as microorganisms decompose the organic matter. The optimum pH for most soil microorganisms is pH 6.0 to 7.5. Also, *Rhizobium* bacteria are most active in converting atmospheric nitrogen into plant-usable nitrogen in this pH range. The *Rhizobium* bacteria associated with alfalfa are most active at pH 6.8 and higher. Nitrogen fixation by *Rhizobia* associated with other legumes, such as red clover and birdsfoot trefoil, is less dependent on pH.

Phosphorus is most available between pH 6.5 and 7.5. Below pH 6.0, phosphorus reacts with iron and aluminum oxides to form insoluble phosphates. Above pH 7.0, phosphorus reacts with calcium compounds to form insoluble calcium phosphates. The influence of pH on the availability of potassium, calcium, and magnesium is due principally to competition between these cations (positively charged ions) and hydrogen ions for exchange sites. (For more details about chemical reactions, see chapter 8.) In

Figure 6-1. Relationship between soil pH and nutrient availability. The width of the bar represents relative nutrient availability.



addition, calcium and magnesium are added when dolomitic lime is applied.

Sulfur availability is related to pH in much the same way as is nitrogen availability. In acid soils, most of the sulfur is a component of soil organic matter. It becomes available as microorganisms decompose or mineralize organic matter. In some alkaline soils, sulfur accumulates as sulfate salts. The solubility of these salts is not greatly affected by pH. Sulfate-sulfur ($SO_4^{=}$-S) is usually not held by the clay minerals in soils. However, under very acid conditions (pH less than 5.5), clays can retain fairly substantial amounts of sulfate sulfur. This can be an important source of sulfur in areas where the subsoils are fine-textured and strongly acid, such as north-central Wisconsin.

Manganese, zinc, iron, and nickel availability decreases as soil pH increases because of the formation of insoluble hydroxides of these metals. The availability of boron and copper also decrease as pH increases. Boron becomes more strongly adsorbed in an insoluble form by organic matter and clay as the pH increases above 6.5. Similarly, copper is strongly bound by soil organic matter.

Unlike most of the other micronutrients, the availability of molybdenum increases as pH increases. Liming alone is often sufficient to overcome molybdenum deficiency. Chlorine exists in soil as a soluble salt and is unaffected by pH.

As noted earlier, soil pH influences the activity of microorganisms. Fungi do well in acid soils; bacteria generally thrive best at pH 6.0 to 7.5; and actinomycetes usually reproduce most rapidly in alkaline soils. (See chapter 7 for a description of microorganisms.) These are generalizations; some species of these organisms do better outside of these ranges. Some plant diseases can be controlled by controlling soil pH. Potato scab, for example, is controlled by maintaining soil pH at 5.3 or below. In contrast, club root disease of cabbage and cauliflower can be controlled by growing these crops in a soil with a pH of 7.2 or above.

The cation exchange capacity (CEC) of soil (to be discussed in chapter 8) increases as soil pH increases due to the removal of hydrogen ions from potential cation exchange sites on clay minerals and organic matter. Increasing the pH of Wisconsin soils by one full pH unit increases the CEC of its organic fraction by about 25% and the clay fraction by 8%. Overall, soil CEC increases by about 12% for each unit increase in pH.

How soils become acidic

Soils are acidic because of one or more of the following reasons:

- acidic parent material
- bases removed by leaching
- bases removed by crops
- use of acid-forming fertilizers
- carbonic acid from microbial and plant respiration
- acid rain
- oxidation of sulfide
- organic acids secreted by plant roots

Acid parent material

Some soils were formed from acidic parent material, such as granitic till, and have always been acid. Soils in north-central Wisconsin (as shown on the soil map in chapter 1) are examples of such soils.

Leaching of basic cations

Some soils were originally neutral or alkaline, but over thousands of years they have become acid due to leaching of basic cations (calcium, magnesium, potassium, sodium). When soluble anions are leached, such as nitrates and chlorides, an equivalent amount of cations, such as calcium and magnesium, must leach as well in order to maintain electro-chemical neutrality.

Crop removal of basic cations

Harvesting crops also acidifies soils by removing cations. If the harvested

Table 6-2. Amount of pure calcium carbonate ($CaCO_3$) needed to replace the basic cations in several crops.

Crop	Yield	$CaCO_3$ equivalent of excess basic cations
Corn grain	150 bu/a	20 lb/a
Corn silage	8 ton/a	200 lb/a
Oats	75 bu/a	5 lb/a
Soybean	45 bu/a	95 lb/a
Alfalfa	4 ton/a	515 lb/a

Source: Pierre, W.H., and W.L. Banwart, 1973, Agron. J. 65: 91–96. Reproduced with permission from the American Society of Agronomy, Inc., Madison, WI.

portion contains more cations (calcium, magnesium, potassium, sodium) than anions (phosphate, sulfate, nitrate, chloride), then there will be a net loss of basic cations from the soil. Leguminous crops (alfalfa, soybeans) remove more basic cations than cereals. Harvesting corn for silage removes more basic cations than harvesting it for grain. Table 6-2 lists the amount of pure calcium carbonate ($CaCO_3$) that would be required to replace harvested cations and prevent an increase in soil acidity.

Acid-forming fertilizers

Another significant means by which soils become acidic is through the use of fertilizers containing ammonium nitrogen. Ammonium accounts for half of the nitrogen in ammonium nitrate, three-quarters of the nitrogen in urea-ammonium nitrate (UAN) solutions, and all of the nitrogen in ammonium sulfate, diammonium phosphate, monoammonium phosphate, anhydrous ammonia, and urea. Some nitrogen carriers, such as anhydrous ammonia and urea, raise soil pH temporarily. But, their long-term effect is to lower the pH because the ammonium form of nitrogen is converted ultimately to the nitrate form by soil bacteria, with the production of hydrogen ions, as shown below:

$$2NH_4^+ + 3O_2 \longrightarrow 2NO_2^- + 2H_2O + 4H^+$$

ammonium, oxygen, nitrite, water, hydrogen

$$2NO_2^- + O_2 \longrightarrow 2NO_3^-$$

nitrite, oxygen, nitrate

The effect of nitrogen fertilization on the pH of a Plano silt loam soil is presented in table 6-3. The pH drop would be even greater in a soil with less clay and organic matter, or in the surface of a no-tilled soil. When 200 pounds of nitrogen per acre was applied each year for 5 years (1,000 pounds total), the pH dropped from 6.11 to 5.68. To raise the pH back to 6.11 would have required 2.7 tons per acre (5,400 pounds) of aglime (equivalent to 5.4 pounds of aglime per 1 pound of nitrogen). In this example, nitrogen was applied as ammonium nitrate. Thus, half of the nitrogen was applied as ammonium and half as nitrate. Therefore, 10.8 pounds of aglime would have been needed to neutralize the acidity produced by 1 pound of ammonium nitrogen.

Carbonic acid

Displacement of calcium, magnesium, potassium, and sodium from soil exchange sites is due, in part, to the hydrogen ion derived from carbonic acid (H_2CO_3) present in the soil solution. The amount of carbonic acid present depends on the amount of carbon dioxide (CO_2) in the soil atmosphere (pore spaces). The source of carbon dioxide in soil is that released from plant roots due to respiration, that given off by soil microorganisms during the decomposition of organic matter, and a small amount directly from the atmosphere. The concentration of carbon dioxide in the soil is often 10 to 100 times that found in the atmosphere.

The carbon dioxide in soil air readily reacts with water to form carbonic acid:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3$$

carbon dioxide, water, carbonic acid

The carbonic acid in turn ionizes to form the acidic hydrogen ion and the bicarbonate ion (HCO_3^-):

$$H_2CO_3 \longleftrightarrow H^+ + HCO_3^-$$

carbonic acid, hydrogen ion, bicarbonate ion

Table 6-3. The effect of nitrogen fertilizer application on the pH of Plano silt loam (Arlington, WI).

Nitrogen applied each year for 5 years[a]	Soil pH after 5 years	Aglime needed to return soil pH to 6.1
lb/a		ton/a
0	6.11	0.00
40	6.10	0.31
80	6.02	0.65
120	5.98	0.96
160	5.81	2.03
200	5.68	2.72

[a] *Nitrogen was applied as ammonium nitrate and incorporated by plowing to a depth of 7 inches.*
Source: Walsh, L.M. 1965. Proc. Wis. Fert. and Aglime Conf.

The hydrogen ion readily reacts with soil particles to displace adsorbed calcium (and other cations) to the soil solution. The result is that hydrogen ions are preferentially adsorbed by the soil, making it more acid, and calcium bicarbonate [$Ca(HCO_3)_2$] is formed. This is a moderately soluble salt which can be leached from the soil.

Acid rain

Acid rain contributes to soil acidity, although the effect is small compared to other sources of acidity. The pH of rainwater in equilibrium with carbon dioxide from the atmosphere is about 5.6. Rain more acid than this is considered acid rain. The sources of this additional acidity are sulfur dioxide (SO_2) from the burning of fuel and volcanic activity; oxidation of hydrogen sulfide (H_2S) from pulp mills, swamps, and oceans; and nitrous and nitric oxides from thunderstorms and emissions, from internal combustion engines, and from conversion of soil nitrate.

Oxidation of sulfides

Under prolonged water-logged conditions, as in a marsh, sulfur is reduced to hydrogen sulfide (H_2S). If there is reduced iron (Fe^{++}) present, it will react with hydrogen sulfide to form a precipitate of iron sulfide (FeS or pyrite). If the swamp is drained, the iron sulfide will slowly oxidize to iron oxide (rust) and sulfuric acid. In some cases, the pH will drop by two to three full units if these soils are drained, so the cost of liming may be prohibitive and should be considered before attempting to farm these soils.

Figure 6-2. Active and reserve acidity in soil compared with a poultry watering fountain.

Nature of soil acidity

Soil acidity is comprised of active and reserve acidity. Active acidity refers to the free hydrogen ions (H^+) present in the soil solution. Reserve acidity arises from neutralizable hydrogen ions (H^+) and aluminum chemically bound to organic matter and clay particles. The reserve acidity accounts for virtually all the acidity in soil. In fact, less than 5 ounces of limestone per acre would be required to completely neutralize the active acidity in a soil with a pH of 5.5.

Although active and reserve acidity are separable by definition, they are interrelated through chemical equilibrium. Thus, neutralization of acidity contained in the soil solution (active acidity) triggers the release of more hydrogen ions from soil particles (reserve acidity) to replenish the acidity of the soil solution. When a soil is limed, this cycle is repeated continuously until the liming material is completely consumed in the neutralization reaction or until the reserve acidity has been neutralized and the pH is raised.

The concept of an interacting reserve and active acidity is quite simple and can be compared to a poultry drinking fountain (figure 6-2). The fountain may contain several gallons of water (comparable to reserve acidity) even though only a few cups of water (comparable to active acidity) are accessible at any one time. The level of accessible water in the drinking trough cannot be reduced significantly until the reserve is depleted. Similarly, the active acidity in soil solution cannot be neutralized by lime until the reserve acidity is depleted.

Aluminum ions (Al^{+++}) in soil are another source of acidity at low pH levels (below 5.2). Aluminum is not an essential element, but it is taken up by plants if it is present in the soil solution. In very acid soils, it can be present in toxic concentrations. Excess aluminum interferes with cell division in plant roots, decreases root respiration, increases cell wall rigidity, interferes with certain enzymes involved in the deposition of polysacharides in cell walls, and interferes with the uptake of calcium, magnesium, phosphorus, and water by plants. Most Wisconsin soils do not contain large amounts of aluminum ions.

Optimum pH for crops

Most crops have a range in pH in which they grow best. In general, leguminous crops do better at a pH above 6.3. Research in Wisconsin indicates that the most economical pH for alfalfa is 6.8. The pH for which lime recommendations are made for Wisconsin crops is shown in table 6-4. Because most crops in Wisconsin are grown in rotation, the soil should be limed to the optimum pH for the most acid-sensitive crop in the rotation. These optimum pH values are based on research from lime plots in Wisconsin where data are available or from information in the literature under conditions as close as possible to

Table 6-4. Optimum pH for Wisconsin crops growing in mineral and organic soils.

Common name	Lime recommendation — Target pH — Mineral	Organic	Common name	Lime recommendation — Target pH — Mineral	Organic
Alfalfa	6.8	—	Pea, canning	6.0	5.6
Alfalfa seeding	6.8	—	Pea (chick, field, cow)	6.0	5.6
Asparagus	6.0	5.6	Pepper	6.0	5.6
Barley	6.6	5.6	Popcorn	6.0	5.6
Bean, dry (kidney, navy)	6.0	5.6	Potato	5.2/6.0	5.2/5.6
Bean, lima	6.0	5.6	Pumpkin	6.0	5.6
Beet, table	6.0	5.6	Reed canarygrass	6.0	5.6
Brassica, forage	6.0	5.6	Red clover	6.3	5.6
Broccoli	6.0	5.6	Rye	5.6	5.4
Brussels sprout	6.0	5.6	Snapbean	6.8	5.6
Buckwheat	5.6	5.4	Sod	6.0	5.6
Cabbage	6.0	5.6	Sorghum, grain	5.6	5.4
Canola	5.8	5.6	Sorghum-sudan forage	5.6	5.4
Carrot	5.8	5.6	Soybean	6.3	5.6
Cauliflower	6.0	5.6	Spinach	6.0	5.6
Celery	6.0	5.6	Squash	6.0	5.6
Corn, grain	6.0	5.6	Sunflower	6.0	5.6
Corn, silage	6.0	5.6	Tobacco	5.8	5.6
Corn, sweet	6.0	5.6	Tomato	6.0	5.6
Cucumber	5.8	5.6	Trefoil, birdsfoot	6.0	5.6
Flax	6.0	5.6	Triticale	6.0	5.6
Ginseng	—	—	Truck crops	6.0	5.6
Lettuce	5.8	5.6	Vetch, crown, hairy	6.0	5.6
Lupin	6.3	5.6	Wheat	6.0	5.6
Melon	5.8	5.6	Miscellaneous	—	—
Millet	5.6	5.4	Apple[c]	6.0	—
Mint, oil	—	5.6	Blueberry	4.5	4.5
Oat	5.8	5.6	Cherry[c]	6.0	—
Oatlage[a]	6.8	—	Cranberry	4.5	4.5
Oat–pea–forage[a]	6.8	—	Raspberry	6.0	5.6
Onion	5.6	5.4	Strawberry	6.0	5.6
Pasture, unimproved	6.0	5.6	CRP, alfalfa	6.6	—
Pasture, managed[b]	6.0	5.6	CRP, red clover	6.3	5.6
Pasture, legume–grass	6.0	—	CRP, grass	5.6	5.4

— = no data available
[a] *Assumes alfalfa underseeding.*
[b] *Includes bromegrass, fescue, orchardgrass, ryegrass, and timothy.*
[c] *Lime recommendations for apples and cherries apply only to preplant tests. Adjustment of pH is impractical once an orchard is established.*

Wisconsin's soils. Organic soils are not limed above pH 5.6 because the amount of lime needed would be uneconomical and aluminum and manganese toxicity are not problems in organic soils.

Liming acid soils

Acid soils can be neutralized by the addition of aglime. Soils should be limed to the optimum pH for the crop in the rotation having the highest pH requirement. Thus, in a corn-oats-alfalfa rotation, lime needs should be based on alfalfa, but in a corn-soybean rotation, liming for soybeans to pH of 6.3 is adequate.

Benefits of liming

Liming to raise soil pH benefits both biological and chemical reactions in the soil:

- It increases yields.
- It improves the availability of nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and molybdenum.
- It increases nitrogen fixation of leguminous crops, which increases protein content.
- It reduces the toxicity of aluminum, manganese, and heavy metals.
- It creates a favorable environment for microorganisms to break down crop residue and recycle plant nutrients.
- It adds calcium and magnesium, both essential nutrients.
- It improves the performance of some herbicides.

Table 6-5. Increases in yield and protein concentration of alfalfa due to liming an acid Withee silt loam soil (Marshfield, WI).

pH	Dry matter yield (2 cuts)	Protein concentration	Protein yield
	ton/a	%	lb/a
5.4	1.35	16.2	437
6.0	2.59	18.9	977
6.9	2.66	20.1	1069

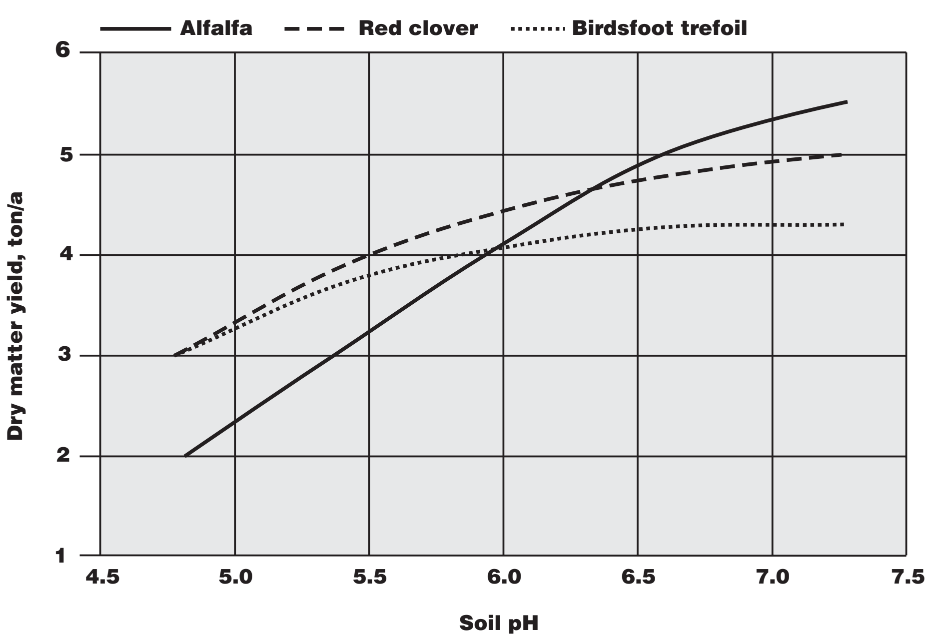
Source: Schulte, E.E. 1983. Unpublished data.

Liming acid soils markedly improves the yield of most crops, especially alfalfa. Liming increases the protein content of leguminous crops by providing a more favorable environment for nitrogen fixation by *Rhizobium* bacteria in their root nodules. Liming an acid (pH 5.4) Withee silt loam soil to pH 6.9 nearly doubled the dry matter yield (table 6-5) while increasing the protein concentration from 16.2% to 20.1%. As a result, protein yield increased 145%.

Figure 6-3 shows the differences in yields for alfalfa, red clover, and birdsfoot trefoil relative to soil pH. All three crops responded to liming, but alfalfa gave the greatest response. Although red clover and birdsfoot trefoil perform fairly well on strongly acid soils (pH 4.8 to 5.2), liming increased their yields as well. In addition to improving yield, liming to pH 6.0 markedly increases both establishment and survival of alfalfa (figure 6-4).

Corn does not always respond to increasing pH. Response is most likely

Figure 6-3. Effect of soil pH on the dry matter yield of four cuttings of legume forages grown in Withee silt loam (Marshfield, WI).



Source: Schulte et al. 1981. Proc. 1981 Fert., Aglime & Pest Mgmt Conf. 20:77–85.

Figure 6-4. Effect of soil pH on establishment and persistence of alfalfa in Withee silt loam (Marshfield, WI).
Adapted from Proc. 1981 Fert., Aglime & Pest Mgmt Conf. 20:77–85.

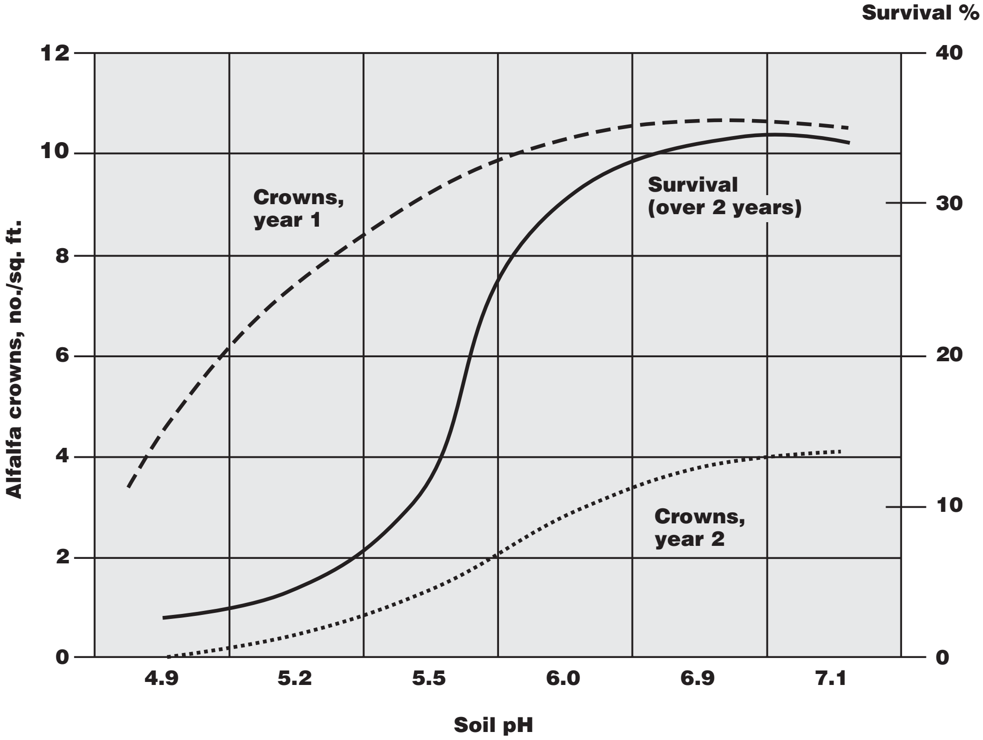
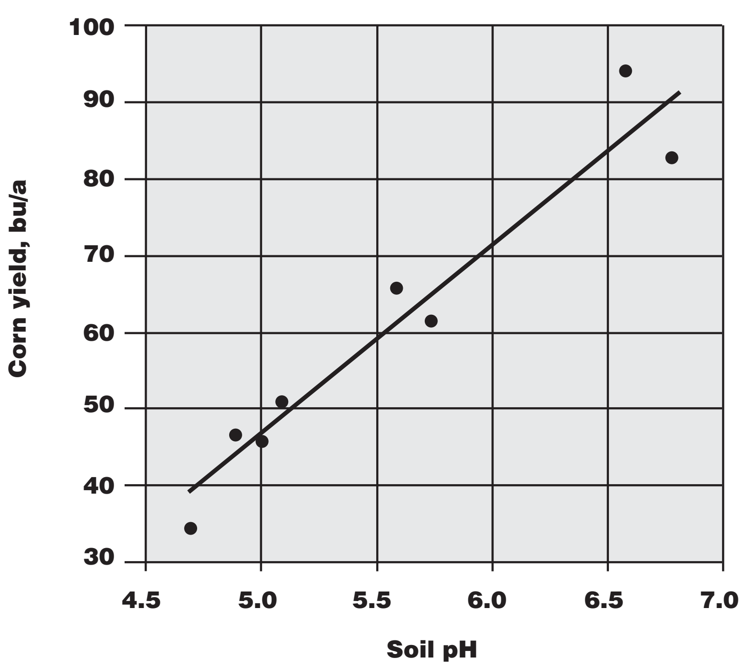


Figure 6-5. Effect of soil pH on the yield of second-year corn following alfalfa grown in Withee silt loam (Marshfield, WI).
Source: Schulte, E.E. 1983. Unpublished data.



to occur in areas where soil acidity can cause a manganese toxicity and in areas where the acidity ties up marginal levels of available phosphorus. Corn yields can also be influenced by the indirect effects of soil pH. For example, in a continuation of the study represented in figure 6-4, the alfalfa was plowed down, and the field was planted to corn the next 2 years. In the second year of corn, yields were improved substantially as the pH increased. As shown in figure 6-5, yields were increased about 21 bushels per acre for every unit increase in pH. The herbicide used on these plots was more effective as the soil pH increased, as a result, some of the yield increase was due to improved weed control. Also, the improved yield and survival of alfalfa at the higher pH levels (figures 6-3 and 6-4) probably resulted in more carry-over organic nitrogen being released during the second year of corn. Additional research has shown that corn matures more quickly when soil is adequately limed.

Other crops also respond to lime. In soybean, the protein concentration increased as well as the yield where lime was applied (figure 6-6), and on snapbeans grown on a Plainfield loamy sand at Hancock the yield more than tripled as the soil pH increased from 5.1 to 7.2 (figure 6-7). Part of the snapbean yield increase was attributed to the effect of pH on root rot organisms. These organisms markedly reduced the stand when grown in very acid soils.

Liming reduces toxic concentrations of manganese, aluminum, and iron that are possible at low pH. The concentration of manganese in alfalfa tissue dropped from 950 ppm at pH 4.9 to 61 ppm at pH 7.1 (figure 6-8). The

Figure 6-6. Effect of soil pH on soybean yield and protein (Marshfield, WI). *Source: Gritton et al., 1985. Proc. 1985. Fert., Aglime & Pest Mgmt. Conf. 24:43–48.*

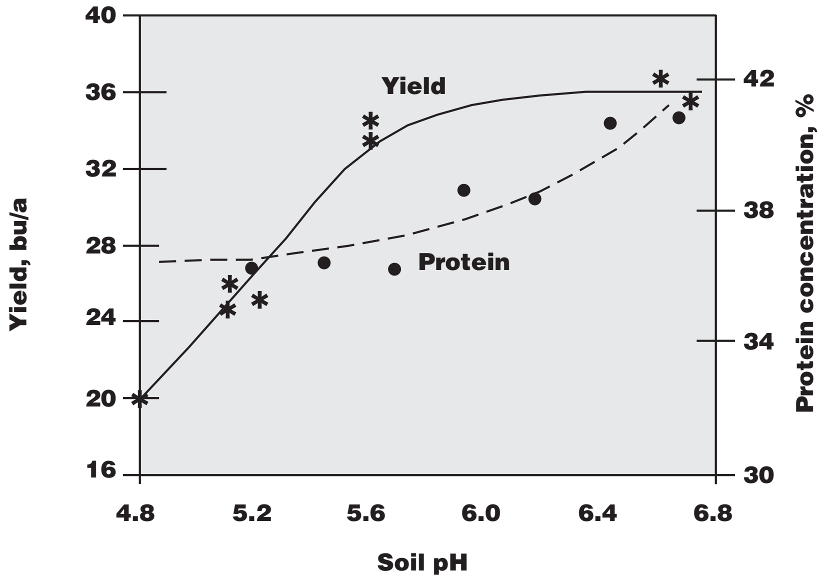


Figure 6-7. Relationship between soil pH, snapbean yield, and root rot (Hancock, WI). *Source: Schulte, E.E. 1987. Proc. Processing Crops Conf. Dept. of Hort., UW-Madison.*

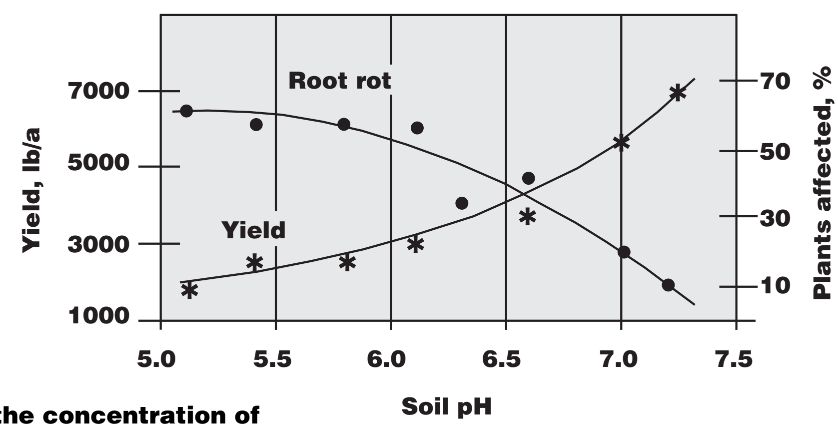
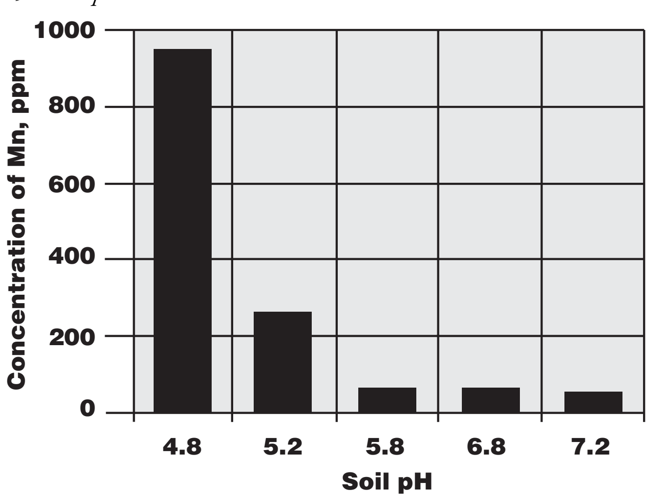


Figure 6-8. The influence of soil pH on the concentration of manganese in alfalfa tissue (Marshfield, WI). *Source: Schulte, E.E. 1982. Unpublished data.*



concentrations of iron and aluminum did not decrease as dramatically, but both were less than one-half of the level observed at pH 4.9.

Liming materials

A liming material in the broadest sense is anything that neutralizes excess hydrogen ions and raises the soil pH. As such, it must be a base. There is a popular misconception that any calcium compound is a liming material. While it is true that most common liming materials contain calcium, not all calcium compounds are liming materials.

Gypsum ($CaSO_4$), for example, is not a liming material. Gypsum is a salt of calcium hydroxide [$Ca(OH)_2$] and sulfuric acid (H_2SO_4). Adding gypsum to soil will actually lower soil pH slightly (about 0.3 pH unit) because the calcium ions (Ca^{++}) will force some hydrogen (H^+) ions held on the surface of soil particles into soil solution.

Table 6-6 is a list of liming materials used to raise soil pH, along with their calcium carbonate ($CaCO_3$) equivalent. The calcium carbonate equivalent of a liming material is a measure of the amount of acid a given weight of the material will neutralize compared to pure calcium carbonate. It is expressed as a percent, with pure calcium carbonate being 100%.

Limestone deposits in this state were laid down 100 to 400 million years ago, when much of Wisconsin was covered by a shallow sea. The most common and least expensive liming material in Wisconsin is dolomitic limestone. It contains calcium and magnesium in roughly the proportions needed by most crops. In states where calcitic lime (calcium carbonate) is the principal liming material, magnesium deficiency is a potential problem. Some agri-businesses have suggested that calcitic lime should be used in Wisconsin because soils are already high in magnesium. Research has not shown this to be true. See chapter 9 for a discussion on calcium to magnesium ratios.

Hydrated lime and air-slaked lime are made by heating dolomitic or calcitic limestone in a furnace to drive off the carbon dioxide. Hydrated lime is burnt lime reacted with water to form calcium hydroxide [$Ca(OH)_2$]. Upon reaction with carbon dioxide from the air, hydrated lime will form air-slaked lime, a mixture of calcium hydroxide and calcium carbonate. Hydrated and air-slaked lime are very soluble compared to dolomitic limestone, so it's possible to overlime with these materials, especially in sandy soils.

Marl is a mixture of calcareous shells and mud deposited in wetlands where mollusks were active when these soils were formed. The composition

Table 6-6. Liming materials and their calcium carbonate ($CaCO_3$) equivalent.

Liming material	Neutralizing agent	$CaCO_3$ equivalent of pure material (%)
Dolomitic limestone	$CaCO_3{\bullet}MgCO_3$	110–118
Paper mill lime sludge	Mainly $CaCO_3$	*
Marl	Mainly $CaCO_3$	variable
Calcitic limestone	$CaCO_3$	100
Water treatment lime waste	$CaCO_3$	variable
Wood ash	K_2CO_3, $CaCO_3$, $MgCO_3$	20–90
Fly ash	CaO, $Ca(OH)_2$, $CaCO_3$	variable
Hydrated lime	$Ca(OH)_2$	135
Air-slaked lime	$Ca(OH)_2 + CaCO_3$	100–135

* *According to the Wisconsin Lime Law, 1 cubic yard of papermill lime sludge is equivalent to 1 ton of aglime having a neutralizing index of 60–69.*

depends on the amount of silt and clay mixed with the shells.

Papermill lime sludge is a byproduct of the paper industry. Finely ground lime is used in the papermaking process. The lime is recovered from storage pits where excess moisture drains away. It is handled and spread while still moist. Since the moisture content varies, it is sold and applied on a volume basis with 1 cubic yard of papermill lime sludge equivalent to 1 ton of aglime having a neutralizing index of 60–69.

Wood ash was one of the first liming materials used. In addition to carbonates, it contains a significant amount of potash (5 to 30%). The composition depends on the tree species and temperature of combustion. Some potassium, chlorine, and sulfur vaporize at high temperatures. Analysis of wood ashes from 14 fireplaces in Madison showed calcium carbonate equivalents ranging from 27 to 93% and potash (K_2O) concentrations from 4.6 to 16.3%. If a high-potash wood ash (e.g., 10%) were applied at a normal rate for a liming material (e.g., 4 tons per acre), the potash addition would be 800 pounds per acre. Thus, wood ash should be applied on the basis of its potash content, not primarily as a liming material.

Fly ash is the ash from the exhaust stream of coal-burning plants. It is estimated that the United States produces 100 million tons of fly ash annually. Ash from coal containing lime will also contain lime. Western coals tend to be relatively high in lime, whereas southern coals are low. Fly ash is made up of silt-sized particles. Because of its fine size, fly ash reacts quickly, but it is difficult to spread. Some fly ash can be moistened to improve spreadability, but others set up like concrete when moistened. In fact, most of the fly ash generated by the Columbia Power Facility near Portage, Wisconsin is sold as a cement replacer. In addition to its liming potential, fly ash contains significant amounts of boron, sulfur, and molybdenum. Alfalfa has relatively high requirements for these three nutrients, making fly ash ideally suited for alfalfa production—if the spreading problem could be resolved.

Kiln dust is a byproduct of the cement industry, having a calcium carbonate equivalent of 40 to 100%. Like fly ash, the fine particles make spreadability a problem.

Various municipal water treatment plants use lime to purify water. Adding slaked lime to the water raises the pH above 11, high enough to kill pathogens. Waste lime and other by-products from treatment plants have variable compositions, so they need to be tested before use.

How much lime to apply

The amount of lime needed to raise soil pH to a given level depends on the quality of the liming material and the lime requirement of the soil.

Lime quality is judged by how effectively it raises soil pH to a desirable level within 3 years. Two properties of lime govern its quality:

- purity (% $CaCO_3$ equivalent)
- fineness (particle size)

The time required to neutralize an acid soil depends largely on the size of the lime particles. Particle size is measured using mesh screens: the larger the mesh number, the smaller the particle that can pass through it. As shown in table 6-7, particle sizes between 8 and 20 mesh are 20% as effective as particles smaller than 60-mesh. It takes 5 tons of 8- to 20-mesh aglime to make the same pH change as 1 ton of less than 60-mesh material. To give a sense of particle sizes, a window screen is 12- to 14-mesh. So particles fitting through a 60-mesh screen would be about one-fifth the size of the space in a window screen.

Since purity and fineness are the primary factors in determining limestone quality, its relative effectiveness in changing soil pH can be reduced to a single numerical figure. This figure is called the neutralizing index (NI). A smaller number indicates a less efficient liming material. The NI

Table 6-7. Lime effectiveness over 3-year period.

	Particle size (mesh)			
	Coarser than 8	8–20	20–60	Finer than 60
	% of lime reacted			
Percent effectiveness	0	20	60	100

for most Wisconsin aglime ranges in value from 40 to over 100 and is calculated using the following equation:

NI = [(% 8–20 mesh x 0.2) + (% 20–60 mesh x 0.6) + (% less than 60 mesh x 1.0)] x % $CaCO_3$ equivalent.

Two examples follow:

Example I: Lime A (95% calcium carbonate equivalent).

Screen size	Screen analysis		Effectiveness factor		
	%				
greater than 8 mesh	10.0	x	0.0	=	0.0
8 to 20 mesh	30.0	x	0.2	=	6.0
20 to 60 mesh	25.0	x	0.6	=	15.0
less than 60 mesh	35.0	x	1.0	=	35.0
			Total	=	56.0

NI = 56.0 x 95% = 53.2

Example 2: Lime B (90% calcium carbonate equivalent).

Screen size	Screen analysis		Effectiveness factor		
	%				
greater than 8 mesh	5.0	x	0.0	=	0.0
8 to 20 mesh	25.0	x	0.2	=	5.0
20 to 60 mesh	20.0	x	0.6	=	12.0
less than 60 mesh	50.0	x	1.0	=	50.0
			Total	=	67.0

NI = 67.0 x 90% = 60.3

When comparing the relative soil neutralizing ability of the two lime materials in the examples above, lime A (NI = 53.2) is less efficient than lime B (NI = 60.3) even though lime A has a higher calcium carbonate equivalent than lime B (95% vs. 90%). Therefore, it would take more of lime A to raise the soil pH to the desired level in the same period of time.

Lime recommendations need to be adjusted to account for differences in lime quality. Use the aglime conversion data in table 6-8 to determine how much to apply. For example, if you receive a recommendation from a soil test report for 4.0 ton/a of 60–69 aglime, you would need 4.7 ton/a of 50–59 lime, or 3.5 ton/a of 70–79 lime. Usually the price of lime increases as the neutralizing index increases because more energy is required to grind limestone finer. The cost of 4.7 tons of 50–59 lime, for example, may be the same or less than 4.0 tons of 60–69 lime. The 50–59 lime will give the same soil pH as the 60–69 and—because it has larger particles—will continue to neutralize soil acidity beyond 3 years.

Lime requirement in Wisconsin soil testing labs is calculated from estimates of reserve acidity, using soil organic matter and buffer pH. Organic matter is estimated by loss of weight when a soil sample is heated to 360°C. The buffer pH is a measurement of how much the soil reduces the pH of a solution that is buffered at pH 7.5. (Reserve acidity lowers the pH of the soil-buffer mixture.) The pH of the soil in water (water pH or active acidity) is also measured to determine whether aglime is needed in the first place and, if so, how much the soil pH must be raised for the crops to be grown. An accurate lime recommendation cannot

Table 6-8. Aglime conversion table for different neutralizing index zones.

Lime recommendation[a]	Zones of lime quality according to neutralizing index values 40–49	50–59	60–69	70–79	80–89	90–99	100–109+
(ton/a)	ton/a lime to apply						
1	1.4	1.2	1.0	0.9	0.8	0.7	0.6
2	2.9	2.4	2.0	1.7	1.5	1.4	1.2
3	4.3	3.5	3.0	2.6	2.3	2.1	1.9
4	5.8	4.7	4.0	3.5	3.1	2.7	2.5
5	7.2	5.9	5.0	4.3	3.8	3.4	3.1
6	8.7	7.1	6.0	5.2	4.6	4.1	3.7
7	10.1	8.3	7.0	6.1	5.4	4.8	4.3
8	11.6	9.5	8.0	6.9	6.1	5.5	5.0
9	13.0	10.6	9.0	7.8	6.9	6.2	5.6
10	14.4	11.8	10.0	8.7	7.6	6.8	6.2

[a] *Soil test recommendations are made for lime having a neutralizing index zone of 60–69. To convert a recommendation to a liming material with a different grade, read across the table to the appropriate column.*

be made with a water pH measurement alone because it only measures the active acidity. Water pH does not measure reserve acidity; that is, the hydrogen bonded to clay and organic matter.

The lime requirement is calculated using loss of weight on heating to 360°C, buffer pH, and water pH. As an example, the amount of aglime (NI of 60–69) needed to raise the water pH from 5.8 to 6.3 in a soil with a weight loss upon heating of 3.3% and a buffer pH of 6.0 would be as follows:

More explanation of how the lime requirement is calculated for several target pH levels is given in Extension publication *Soil Test Recommendations for Field, Vegetable and Fruit Crops* (A2809).

Standard recommendations are based on liming the soil to a depth of 7 inches or less. If tillage is deeper than 7 inches, more lime will be needed to neutralize the entire tilled layer. To calculate how much more lime to add, use the appropriate multiplier (table 6-9) to adjust the formula.

Table 6-9. Multipliers used to adjust lime recommendations based on tillage depth.

Tillage depth (inches)	Multiplier
<7.1	1.00
7.1–8.0	1.15
8.1–9.0	1.31
>9.0	1.46

Lime required = 1.75 [1.20(6.3 – soil pH)(% weight loss) + 0.030 (buffer pH)]

= 1.75 [1.20(6.3–5.8)(3.3) + 0.030(6.0)]

= 1.75 [1.98 + 0.18] = 4 ton/a

When to apply aglime

The proper time to apply aglime is determined by five factors: the crops to be grown, tillage method, lime particle size, soil type, and convenience.

Crops to be grown. In Wisconsin, soil is limed to the optimum pH for the most sensitive crop in the rotation. Because lime reacts very slowly with soil acids, it should be applied at least 1 year (preferably longer) before seeding alfalfa or other legumes. In many cases, the best time to apply lime is when the crop rotation is coming out of alfalfa. This provides more time for reaction and may result in two or three remixings of the lime with the soil. The pH will then be raised to the desired level by the time the rotation is returned to alfalfa.

Aglime applied immediately before seeding a legume may not benefit the new seeding. This may result in a poor stand and reduced forage yield and quality, particularly if the soil is initially quite acid. Topdressing the stand after it is established may serve as a stopgap measure but is not as effective as neutralizing the entire plow layer.

Method of tillage. Where lime incorporation is not possible, such as in no-till grass-legume pastures, apply as fine a grade as possible at least 1 year before the seeding.

Lime particle size. Wisconsin aglimes have coarse as well as fine particles which react with soil acids at different rates. The mesh rating indicates the particle size of the lime: the smaller the mesh number, the coarser the aglime. Table 6-10 shows that finer (60–100 mesh) aglime particles result in a higher soil pH than coarser sizes over similar time periods. Fine particles begin neutralizing acids immediately, while coarser particles continue the process after fine particles have dissolved. Consequently, coarse aglime must be applied further in advance than fine aglime to achieve the same pH change.

Coarse aglime must be applied at somewhat higher rates but is usually less expensive per ton than fine lime. In addition, it may not be necessary to relime as often where some coarse lime is used. When comparing prices, be sure to evaluate materials on the basis of amounts of lime needed to achieve similar effectiveness.

Table 6-10. Soil pH when treated with three particle sizes of aglime (Arlington, WI)[a].

Time (months)	Particle size (mesh) 8–20	40–60	60–100
	soil pH		
1	5.00	5.35	5.43
12	5.65	5.96	6.19
24	5.91	6.33	6.37
36	6.30	6.54	6.65

[a] *Original soil pH = 4.6; Plano silt loam.*

Soil. Aglime can be applied any time the soils are physically fit and spreading equipment doesn't damage soils or crops. Sample your soils every 4 years to determine whether lime is needed. If required, apply aglime, disk, and plow it under well in advance of seeding. Lime's effectiveness begins when it is incorporated into the soil. If possible, don't apply aglime where wind or water erosion will remove it before it can be incorporated.

Soils can be limed in the summer, even prior to harvest of another cutting or two of forage. At that time, the soil is in excellent condition to bear the weight of a lime spreader. Soils with high buffering capacities (high clay and/or high organic matter content) should be limed more in advance of the sensitive crop than coarser-textured soils. These soils require more redistribution of lime particles to neutralize the entire plow layer.

Convenience. Fall and summer may be the most convenient times for applying aglime. In the spring, long waits for aglime can occur, there may be weight limitations on the roads, or the soil may be too wet to spread the aglime before it is time to plant. These problems can be avoided by applying aglime on cropland in the fall or on hay fields in summer. Lime is not lost by leaching, and it will have more time to neutralize soil acids.

Other factors to consider

Unlike fertilizer, aglime may not promote increased plant growth immediately after application. This doesn't mean aglime is not needed—it simply takes effect more slowly. Also unlike fertilizer, once a soil is limed adequately, it may remain that way for several years without additional aglime applications. In fact, once a pH of 6.5

to 7.0 is achieved, it is often 5 to 10 years before an application of lime is required again. The reasons for this are the low solubility of limestone, the slow dissolution of larger lime particles applied in prior applications, and the use of barn lime. Dairy farmers often add some lime to their soils as barn lime mixed with the manure. This contribution, along with the coarse, slowly dissolving limestone particles previously applied, tends to maintain the soil pH over several years.

Neutralizing soil acidity only occurs in the solution surrounding each limestone particle because aglime is too insoluble to dissolve completely. The rate of the neutralization reaction depends on how fast hydrogen ions can move toward the lime particle, how fast calcium and bicarbonate ions can move away from the lime particle, and the number of lime particles in a given volume of soil. In other words, the finer the particles and the more evenly they're distributed throughout the soil, the faster the lime will react. If lime is mixed thoroughly with the soil, the soil pH will rise within a few weeks after liming. After that the pH increases very slowly until another tillage operation redistributes the lime particles, bringing them into contact with more acid soil. Therefore, it is important to incorporate any needed lime thoroughly before switching to a reduced tillage system.

In some instances, application of the recommended amount of lime will not completely neutralize an acid soil. This problem is commonly caused by poor incorporation or by not allowing enough time for the lime to react. Another reason why a soil might still be acid after applying lime is deep plowing. The standard lime recommendations are calculated for a 7-inch plow layer. Thus, when a soil is plowed deeper than 7 inches, proportionally more lime will be required.

Correcting soil alkalinity

Except in small-scale plantings (home gardens) and special crops, it is not economically feasible to lower the pH of an alkaline soil. For field crops the cost of the treatment will usually exceed the value of any yield increases.

Occasionally, however, the pH of the soil should be lowered for certain special crops. Blueberries and some ornamentals need high levels of iron and manganese so they must be grown on very acid soils. Also, soil acidity reduces the scab problem on potatoes. Elemental sulfur is the most commonly used material to lower the soil pH, but it must be oxidized by bacteria in order to cause this change. The reaction which increases soil acidity is as follows:

$$2S + 3O_2 + 2H_2O \longrightarrow 4H^+ + 2SO_4^=$$

sulfur, oxygen, water, hydrogen ion, sulfate ion

Table 6-11 shows how much sulfur is required to lower the pH of a medium-textured soil.

Since bacterial action is required, the pH change occurs slowly. Apply no more than 500 pounds of sulfur per acre at any one time. Test the soil between each application to make sure the pH is not lowered more than desired.

At soil pH levels above 7.5, free calcium carbonate is usually found in Wisconsin soils. If free calcium carbonate is present, it probably will not be feasible to acidify the soil because very large amounts of sulfur would be required.

Aluminum and iron sulfates can also be used to acidify soils in lawns or gardens. Unlike elemental sulfur, their effect is immediate. It requires about six times more of these materials to

Table 6-11. Approximate amount of finely ground elemental sulfur needed to increase soil acidity (lower pH).

Desired change in pH	Soil organic matter content (%) 0.5–2.0	2.0–4.0	4.0–6.0	6.0–8.0	8.0–10.0	>10.0
	amount of sulfur needed, lb/a					
0.25	250	750	1200	1700	2300	2100
0.5	500	1500	2500	3500	4600	5500
1.0	1000	3000	5000	7000	9200	11000

change the pH as compared to sulfur. Because too much aluminum and iron can be toxic to plants, do not apply more than 50 pounds per 1,000 square feet.

Acid peat moss usually has a pH of 4.5 or less and is a good material to mix with lawn or garden soils to make them more acid. It also adds organic matter. It is convenient to use on small garden areas and for potting soil. It may make up one-fourth the volume of potting soil, depending on the pH of the soil with which it is mixed and the pH requirement of the plants to be grown, On gardens, apply 1 to 2 inches on the surface and spade or rototill to mix it in.

As noted previously, fertilizers containing ammonium nitrogen are acid-forming. Ammonium sulfate is the most acidifying per pound of nitrogen applied. Ammonium sulfate (21-0-0) is the best nitrogen fertilizer for maintaining an acid soil, as with blueberries, cranberries, and hydrangeas.

Questions

1. What influence does soil pH have on chemical and biolgical reactions?

2. List several ways by which soils become acid.

3. What is the difference between active acidity and reserve acidity? Which of these forms is measured when the soil is analyzed for its pH in water?

4. Is lime requirement more closely associated with the active acidity or the reserve acidity? Explain.

5. List several benefits of liming.

6. Explain why calcium carbonate ($CaCO_3$) will neutralize soil acidity but calcium sulfate ($CaSO_4$) will not.

7. A soil test recommendation calls for 4 ton/a of 60–69 aglime. How much 40–49 aglime would be required? 70–79 aglime? 90–99 aglime?

8. An aglime vendor had samples of two of products tested, with the following results:

Screen size (mesh)	Screen analysis A	B
	—%—	
less than 8	5.0	2.0
8–20	20.4	4.5
20–60	57.3	25.6
greater than 60	17.3	67.9
$CaCO_3$ equivalence	98.0	93.0

What is the neutralizing index of each product? If it costs $12/ton to spread product A and $15/ton to spread product B, which is the better buy?

9. Assume that two different liming materials have a neutralizing index of 60–69 and 90–99 and that the cost of these materials is $9.00/ton and $18.00/ton, respectively. Which material is the better buy?

10. When a field is to be limed in April and seeded in May, lime with a neutralizing index of 90–99 or 100–109 is recommended rather than lime with an index of 60–69. Why?

11. How many tons of lime would be required to raise the pH of the following soils to 6.3? (Use the formula given on page 61.)

Soil[a]	Water pH	Buffer pH	Weight loss (%)
Plano	6.0	6.6	4.0
Fayette	5.8	6.7	1.5
Tama	5.8	6.0	3.5

[a] *Assume that all soils are plowed at a depth of 7 inches.*

12. Assume that a field has a pH of 5.2 and is being cropped in a corn-oats-alfalfa-alfalfa-alfalfa rotation. When would be the best time to lime this field? Why?

13. When an acid soil is limed in April and seeded in May, the new alfalfa seeding sometimes fails to survive due to soil acidity. Explain how this can happen.

14. Under what conditions would you recommend that the pH of a soil should be lowered from 7.3 to 4.5? How would you accomplish this?

CHAPTER 7

Biological properties of soil

"The series of biophysical and biochemical processes that follow [weathering] ultimately reorganize the initially haphazard mineral constituents into a distinct, internally ordered, living natural body. This final metamorphosis is brought about by the activity and the accumulated organic products of myriad microscopic and macroscopic plants and animals which coinhabit the soil as an integrated community."

Daniel J. Hillel, Out of the Earth, *1991*

Fertile soils are biologically active. This means they support the growth of a wide variety of microscopic plants and soil animals, as well as terrestrial plants. Most soil organisms are beneficial, but some can cause plant disease or physical damage to the soil (e.g., excessive burrowing by rodents). Soil organisms range in size from microscopic, single-celled plants to large burrowing animals. Immense numbers of organisms live in fertile soils. A gram of such soil, for example, can contain more than 500 million microorganisms.

Another important characteristic of a biologically active soil is the cycling of carbon and several plant nutrients, such as nitrogen, phosphorus and sulfur, through plants and soil-dwelling animals. These chemical elements are in constant flux: they cycle from decaying organic residue, to actively growing plants and animals, and back again to decomposing organic matter.

The information presented in this chapter is concerned with animals or microscopic plants living within the soil. Other chapters deal with the growth of crops and native plants.

For organisms to grow and multiply in the soil, they must have favorable environmental conditions. An environment that favors growth in one group of organisms may limit growth in another group. Some crops rely on interactions with organisms for optimum production. When environmental conditions limit growth of these beneficial organisms, crop yields can suffer. Factors favoring biological activity include the following:

- Food supply—soil organic matter and plant residues supply food and energy for most soil organisms. Terrestrial plants obtain energy from the sun but depend on the soil for nutrients.
- Favorable temperature—each organism has an optimum temperature range, above or below which its activity diminishes.
- Aeration—most organisms in cropped soils require adequate aeration to supply oxygen.
- Favorable moisture—all organisms require water. If soil is too dry, growth slows, and some organisms may die. If soil is too wet, aeration is reduced.
- Favorable pH—Each organism has an optimum pH range in which it functions best. Some prefer acid soils, but most do best in neutral or slightly alkaline soils.
- Absence of toxic substances—soil must be free of toxic substances for organisms to thrive. Some organisms produce toxins to help them compete with other organisms. People also introduce potentially toxic substances such as pesticides, heavy metals, salts and gases. Some are added deliberately, others inadvertently.

Soil fauna

Fauna refers to animals, including insects, as opposed to flora or plant life. The main groups include arthropods, mollusks, earthworms, protozoa, nematodes, and mammals.

Arthropods

These invertebrate organisms include insects, spiders, and crustaceans. Arthropods have a jointed body and limbs and a hard (chitinous) shell. Microscopic forms important in soils include springtails and mites—both of which feed on fungi. Some mites also feed on other soil animals.

Larger arthropods include wood lice, centipedes, millipedes, beetles and other insects, and spiders. Wood lice feed on decaying plant material and are active in soil too dry for earthworms. Centipedes are predators on other soil fauna. Millipedes feed on decaying litter, although some feed on roots of living plants. A wide range of insects inhabit soil. Most insects burrow, an activity that often improves aeration and water infiltration. Some are more important in the larval stages. Wireworms, for example, are the larval form of certain beetles and feed on plant roots. Ants feed on green vegetation, other fauna, and some species feed on seeds. In tropical and subtropical soils, termites are prominent in consuming dead plant remains. Some species are notorious for building huge mounds and destroying timber in buildings.

Mollusks

Important soil mollusks include slugs and snails. Slugs feed on dead or damaged vegetation. Some feed on succulent fruits and vegetables growing on or near the soil surface. A few species of snails help to decompose plant matter by digesting cellulose, the material that makes up cell walls of plants.

Earthworms

Earthworms are very important in mixing soil and incorporating dead or decaying plant remains. They have a voracious appetite, consuming as much as 80 times their body weight of food per day. Their burrowing activity improves aeration, water infiltration, and drainage. They are most numerous in undisturbed areas such as no-till corn fields, pastures, and deciduous forests where there is an abundant supply of litter and burrows are not disrupted by tillage. Some 1 to 1.5 million earthworms per acre were found in two productive Danish forest soils. Collectively, they weighed in at 1500 to 1750 pounds per acre. In an English apple orchard, an average of 15.5 earthworm burrows per square yard were found. This was estimated to be equivalent to one 1.4-inch drainage pipe per square yard.

Protozoa

Protozoa are microscopic one-celled animals abundant in soils. Most protozoa feed on soil fauna such as bacteria and other protozoa. Some bacteria apparently have a symbiotic relationship with predatory protozoa. Soil protozoa live in the film of water surrounding soil particles. Protozoa have different ways of surviving dry periods: most form cysts while others go into a state of suspended animation. They revive quickly when moisture returns.

Nematodes

Nematodes or eelworms are microscopic worms. Many species parasitize plant roots. Not all nematodes are parasites: some free-living species feed on bacteria, protozoa, and other nematodes.

Mammals

Mammals burrow into soil for shelter, mixing soil and promoting aeration. They influence a relatively small portion of the total root zone. Some feed on plant roots or eat seeds, damaging crops. Mammals of importance in soil include badgers, chipmunks, gophers, ground squirrels, mice, moles, prairie dogs, rabbits, shrews, and voles.

Soil flora

Four principal groups of microscopic plants in soil are the algae, bacteria, actinomycetes, and fungi.

Algae

Algae are the most numerous and widely distributed of green plants, excluding flowering plants. These multicellular organisms are found in fresh water, sea water, on land, in hot springs, and on arctic snows. They are the primary food of aquatic animals. Most species are photosynthetic, producing food from carbon dioxide (CO_2) with energy from light. Therefore, they are important only near the soil surface where light is adequate. They are of greater significance in aquatic environments such as rice paddies and swamps. A gram of fertile soil contains 1,000 to 500,000 algae.

Bacteria

Bacteria are one-celled organisms and occur in a wide variety of species. Fertile soils may contain over 500 million bacteria per gram (400 pounds per acre). They are active in organic matter decomposition and mineral transformations. Bacterial populations increase rapidly when food (fresh organic residues) is available, then decline as the supply runs out.

Actinomycetes

Actinomycetes are one-celled, filamentous organisms. Most species thrive between pH 6.0 and 7.5. Actinomycetes give freshly plowed soil its characteristic earthy odor. A gram of fertile soil may contain as many as 15 million actinomycetes (500 pounds per acre). Some species are pathogenic to plants and animals. Potato scab, for example, is caused by a species of actinomycete but can be controlled by keeping the soil pH below 5.3. Tuberculosis is an example of a human disease caused by an actinomycete.

Fungi

Fungi (yeasts, molds, mushrooms) are multicellular, filamentous organisms capable of vigorous development, especially in acid soil. There can be as many as 1 million fungi per gram of fertile soil, weighing about 1000 pounds per acre. This diverse group of organisms fills many niches in the ecosystem. The hairlike projections or filaments of fungi help hold soil aggregates together. Fungi secrete organic compounds which aid in the extraction of nutrients from rocks and organic matter. Some fungi produce antibiotics and other compounds useful as pharmaceuticals. Penicillin, for example, was isolated from soil fungi at the University of Wisconsin in the 1940s.

A lichen is a complex plant consisting of a fungus and an algae growing together symbiotically. The alga synthesizes carbohydrates from carbon dioxide (CO_2) by photosynthesis and, in return for the carbon, the fungus extracts nutrients from the growth medium, which may be rock, bark, or soil.

Mycorrhiza are fungi that infect plant roots. Mycorrhizal fungi are associated with nearly all plants. But, plants with fine roots or root hairs, such as grasses, are not nearly as dependent on mycorrhiza as those with tap roots, such as many trees. Most of these relationships are symbiotic—the host plant provides soluble carbohydrates to the root fungus, and the latter aids the host in nutrient uptake, especially phosphorus. Mycorrhiza can be thought of as an extension of the plant's root system. Mycorrhizal plants are sometimes more drought tolerant, and they also protect the plant from plant pathogens and nematodes.

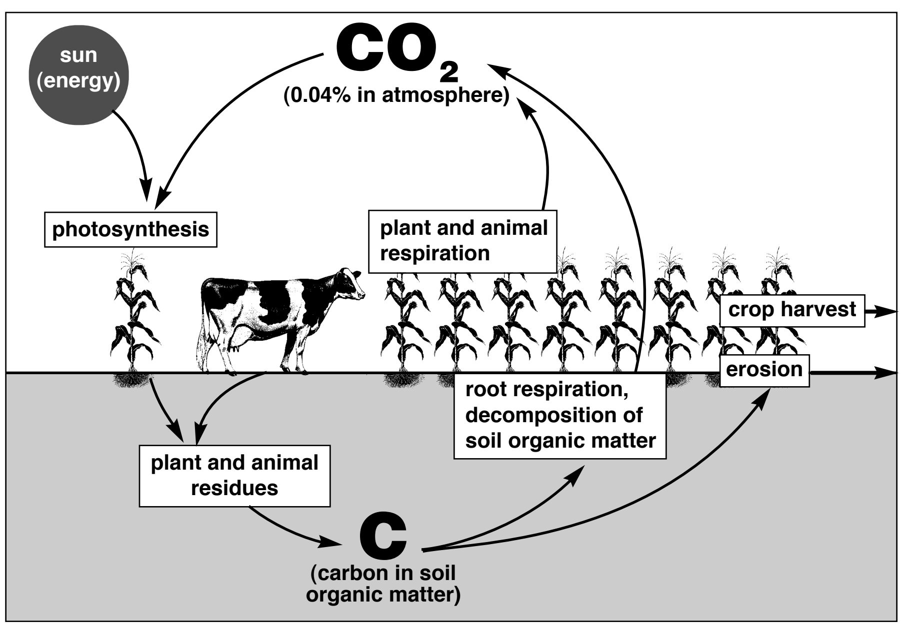
There are two general types of mycorrhiza. In one type, the small roots of the host plant are completely encased in a sheath of fungal tissue. Filaments of fungal tissue extend outward into the soil like root hairs. Other filaments penetrate the outer cells of the plant roots. This type is common on forest trees in temperate regions. In the other type, there is no external sheath of fungal tissue. Fungal filaments are partly external and partly within or between the root cells of the host plant. This type is found on many plant species, including grasses.

Carbon cycle

All organisms—including people and animals—require food for energy and carbon for building body tissue. For most, the same food serves both purposes. Green plants, however, use different sources of food for these two purposes. They obtain carbon from carbon dioxide (CO_2) and energy from sunlight. Most other organisms obtain carbon by eating green plants or eating animals that have eaten these plants. Some of the food is "burned" to provide energy. Only about 20% of the carbon in food is converted to cellular tissue; the rest is respired as carbon dioxide.

A simplified carbon cycle is shown in figure 7-1. The carbon in atmospheric carbon dioxide is incorporated into plant tissue by photosynthesis. Plants may be consumed by animals or returned to

Figure 7-1. The carbon cycle in soil.



the soil as residue. If eaten, most of the carbon is returned to the atmosphere as carbon dioxide via animal respiration or to the soil as animal waste. A small percentage is retained in milk and animal tissue. That carbon returns to the cycle when the animal products are eaten by another animal. If the animal dies, most of the carbon incorporated into its tissue returns to the atmosphere as the carcass decomposes.

The smaller animals and microorganisms that cause decomposition also give off carbon dioxide in respiration and retain some carbon in their cells. The respired carbon dioxide returns to the atmosphere where it can be recycled into new plant growth.

Microorganisms constantly produce carbon dioxide. Since it's heavier than air, the concentration of carbon dioxide below ground is about 10 times higher than it is above ground. Some of this carbon dioxide dissolves in soil moisture to form carbonic acid. If the concentration of carbonic acid and soluble calcium are high enough, calcium carbonate ($CaCO_3$) may precipitate, removing the carbon dioxide from the cycle.

Unlike most chemical solubilities, the solubility of carbon dioxide in water decreases as the temperature increases. (That is one reason for keeping carbonated beverages cold.) The ocean is a vast reservoir of dissolved carbon dioxide and inorganic ions such as calcium (Ca^{++}) and magnesium (Mg^{++}). In cold ocean water, carbon dioxide solubility is very high. When warm currents lower the solubility level of calcium and magnesium carbonate, these materials precipitate to form limestone. Other reservoirs of carbon include coal deposits, petroleum, organic soils, and forests.

Oxygen requirements

All organisms must respire; that is, they must use some source of energy to support their growth and development. Aerobic organisms require free oxygen (O_2). A good example of aerobic respiration is the breakdown of glucose, a simple sugar, into carbon dioxide and water, with the release of energy:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy (673 kcal)}$$

glucose oxygen carbon dioxide water

Anaerobic organisms can respire only in the absence of oxygen (O_2), but much less energy is obtained as compared to aerobic respiration. Alcohol, for example, is the result of an anaerobic process. The chemical reaction below shows the fermentation of sugar to produce alcohol. This reaction produces only 21 kcal of energy, as compared to 673 kcal for the aerobic reaction.

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2 + \text{energy (21 kcal)}$$

glucose ethanol carbon dioxide

Symbiotic relationships

The term symbiosis describes the relationship between two organisms living in close association, usually to the mutual benefit of each. A well-known example is the association of *Rhizobium* bacteria with roots of leguminous plants. The bacteria infect the roots, and the roots encapsulate the bacteria in growths called nodules. Within these nodules, the *Rhizobia* convert nitrogen gas from the atmosphere into organic nitrogen for the host plant. In exchange, the host plant provides the bacteria with organic carbon and mineral nutrients. Researchers estimate that *Rhizobia* annually fix as much as 300 pounds of nitrogen per acre.

Role of microorganisms in nutrient transformations

Soil organisms break down organic matter, releasing the nutrients for use by growing plants. Macroorganisms, such as earthworms, are important in the initial decomposition process, digesting large particles and secreting products which microorganisms decompose further. Ultimately, nutrients are returned to their inorganic state, the form taken up by plants. Conversion of organic forms of nutrients to inorganic is termed *mineralization*.

In addition to mineralization of organic matter, soil microorganisms are involved in many nutrient transformation reactions. Most reactions involving nitrogen, for example, are mediated by microorganisms. Transformations of phosphorus, iron, manganese, and sulfur are also influenced by microorganisms. These reactions are discussed in chapter 9.

Plant roots

Roots extract plant nutrients and water from soil. At the same time, they secrete carbon dioxide and organic compounds that serve as food for microorganisms. When the roots die, they become food for soil flora and fauna. After a dead root has decayed, the root channel becomes a conduit for air, water, and new roots. Thus, plant roots help shape the biological properties of soil.

Soil microbiologists have observed that larger numbers and types of bacteria, fungi, and other organisms are found around plant roots than in the surrounding soil. This zone of soil near plant roots is known as the *rhizosphere*. Table 7-2 shows the distribution of several microorganisms with distances from the root surface. In this study, the rhizosphere extended to 18 mm (0.7 inch) from the root.

High populations of microorganisms in the rhizosphere are due to a greater supply of readily available organic material. This material ranges from decaying roots to organic exudates (leakage) from healthy roots. Organic compounds identified in root exudates include sugars, amino acids, organic acids, and enzymes. For example, wheat exudes 2.6 to 22.5 mg of carbon per plant during the first 2 months of growth. Carbon is a component of one of the organic compounds previously noted. The root zone immediately behind the root tip appears to be the major source of exudates.

Microorganisms in the rhizosphere seem to have some influence on nutrient availability, but their effect is still under study. Most of the past research has concentrated on pathogenic organisms in the rhizosphere. In Russia a seed inoculant (*Azotobacter chroococcum*) to improve nutrient availability has been only marginally successful. While microorganisms in the rhizosphere appear to increase crop yields, the connection is not fully understood. More study is needed.

Table 7-2. Microorganisms in the rhizosphere of 18-day-old blue lupine seedlings.

Distance from root	Bacteria	Streptomycetes	Fungi
mm	—— 1000s per gram of dry soil ——		
0	159,000	46,700	355
0–3	49,000	15,500	176
3–6	38,000	11,400	170
9–12	37,400	11,800	130
15–18	34,170	10,100	117

From Papovigas, G.C. and C.B. Davey. 1961. In E.W. Carson (ed.), 1971. The Plant Root and Its Environment, *p. 157. Charlottesville. Univ. Press of Virginia. Reprinted by permission of the University Press of Virginia.*

Questions

1. What benefits result from the decomposition of crop residue and animal wastes?
2. List six factors favoring biological activity in soil.
3. Name ten species of fauna that you have observed in soil.
4. Name at least three useful purposes served by earthworms.
5. In leguminous crops such as alfalfa, the crop benefits from its association with *Rhizobium* bacteria by receiving organic nitrogen fixed from atmospheric nitrogen by the bacteria. How do the bacteria benefit from this mutual association?
6. Why are alfalfa, soybean, and other leguminous plant seeds usually inoculated? What is in the inoculant that is beneficial to these crops, and how does it work?
7. A culture of photosynthetic blue-green algae is sold for application to soil. The seller claims that adding these algae will reduce the need for fertilizer. Would you buy this product? Why?
8. What are mycorrhiza? How do they benefit plants?
9. Define mineralization. Why is it necessary?
10. Organic soils (mucks and peats) subside when they are drained and farmed. Mineral soils do not subside. Explain why this difference occurs.

CHAPTER 8

Soil chemistry and plant nutrition

"Each seed joined the earth, entered into some mysterious partnership with soil, water, air and sun and began to grow and become part of the living land."

Ben Logan, The Land Remembers, *1975*

Essential plant nutrients

Green plants have the unique ability to make everything they need to sustain growth from water, light, air, and an adequate supply of 17 essential elements. Lack of any one of these elements will hinder growth. Plants get carbon, hydrogen, and oxygen from air and water. The remaining 14 elements come from the soil (although they also receive small amounts of nitrogen and sulfur from the atmosphere). Table 8-1 lists all of the essential elements, the forms taken up by plants, their primary source, their approximate concentration in plants, and amounts in soil.

A plant nutrient is considered essential when a deficiency of the element makes it impossible for the plant to complete its life cycle, when the deficiency cannot be corrected by substituting another element, and when the element is needed by a wide variety of species from many different plant families.

Of the 14 essential elements available from the soil, six—nitrogen, phosphorus, potassium, calcium, magnesium, sulfur—are required in relatively large amounts. Nitrogen, phosphorus, and potassium are the most commonly deficient nutrients and are sometimes referred to as the *primary nutrients*. Calcium, magnesium, and sulfur are often added incidentally in lime, commercial fertilizers, or livestock manure and are not often deficient in soil. They are called *secondary nutrients*. The remaining elements—boron, chlorine, copper, iron, manganese, molybdenum, nickel, and zinc—are needed by plants in very small quantities, hence they are called *micronutrients* or *trace elements*.

The terms primary, secondary, and micro or trace have nothing to do with the importance of a nutrient in crop production. The lack of any one will reduce crop yield. This concept is stated in the *Law of the Minimum*, which says that the growth of a plant will be limited by the nutrient present in the least amount relative to its requirement.

Carbon, hydrogen, and oxygen together make up approximately 94% of the dry weight of plants, yet they are rarely deficient. Sometimes a lack of oxygen in poorly drained soils limits yields, but this is remedied by drainage, not by adding oxygen. Rapidly growing greenhouse crops sometimes respond to an atmosphere enriched with carbon dioxide, but adding carbon dioxide to a field has never proven to be economically beneficial. Most of soil fertility, therefore, deals with the 14 remaining elements which make up approximately 6% of the dry weight of plants.

Table 8-1. The essential elements

Element and symbol	Form taken up by plants[a]	Major source	Concentration in plants	— Nutrient content of a fertile silt loam — Total	Available	Amount in soil solution
				ppm		
Structural nutrients						
Carbon (C)	Carbon dioxide (CO_2)	Atmosphere	45%	—	—	—
Oxygen (O)	Air (O_2) Water (H_2O)	Atmosphere, water	43%	—	—	—
Hydrogen (H)	Water (H_2O)	Water	6%	—	—	—
Primary nutrients						
Nitrogen (N)	Nitrate (NO_3^-) Ammonium (NH_4^+)	Organic matter, atmosphere	1–6%	2000	5–100	1–50
Phosphorus (P)	Phosphate ($H_2PO_4^-$, $HPO_4^=$)	Soil minerals, organic matter	0.05–1.0%	1000	20–50	0.01–0.10
Potassium (K)	Potassium (K^+)	Soil minerals	0.3–6.0%	20000	100–150	5–15
Secondary nutrients						
Calcium (Ca)	Calcium (Ca^{++})	Soil minerals	0.1–3.0%	5000	1000–3000	10–100
Magnesium (Mg)	Magnesium (Mg^{++})	Soil minerals	0.05–1.0%	4000	100–1000	5–50
Sulfur (S)	Sulfate ($SO_4^=$)	Organic matter, precipitation	0.05–1.5%	1000	10–20	1–10
Micronutrients						
Boron (B)	Borate ($H_2BO_3^-$)	Organic matter	2–75 ppm	50	2–10	trace
Manganese (Mn)	Manganese (Mn^{++})	Soil minerals	5–500 ppm	1000	10–20	trace
Zinc (Zn)	Zinc (Zn^{++})	Soil minerals, organic matter	5–100 ppm	50	3–25	trace
Copper (Cu)	Copper (Cu^{++})	Soil minerals, organic matter	2–50 ppm	50	No reliable test	trace
Iron (Fe)	Iron (Fe^{++}, Fe^{+++})	Soil minerals, organic matter	10–1000 ppm	25000	No reliable test	trace
Molybdenum (Mo)	Molybdate ($MoO_4^=$)	Soil minerals	0.01–10.0 ppm	1	No reliable test	trace
Chlorine (Cl)	Chloride (Cl^-)	Precipitation	0.05–3.0%	100	No reliable test	trace
Nickel (Ni)	Nickel (Ni^{++})	Soil minerals	0.1–10.0 ppm	<50	No reliable test	trace

[a] *Other forms of many of these nutrients are present in the soil. This list includes only forms that can be used by plants.*

Non-essential elements

An essential plant nutrient is one that is required for life, whereas a non-essential plant nutrient can increase crop yield, but its absence will not cause the plant to die. Enhancing, or beneficial, non-essential elements can compensate for toxic effects of other elements or may replace mineral nutrients in some other function. Examples of non-essential elements include aluminum, cadmium, cobalt, lead, mercury, selenium, silicon, and sodium.

Beneficial elements have not been deemed essential for all plants but may be essential for some. The distinction between beneficial and essential is often difficult in the case of some trace elements. Cobalt for instance is essential for nitrogen fixation in legumes. Silicon, deposited in cell walls, has been found to improve heat and drought tolerance and increase resistance to insects and fungal infections. Silicon, acting as a beneficial element, can help compensate for toxic levels of manganese, iron, phosphorus, and aluminum as well as zinc deficiency. A more holistic approach to plant nutrition would not be limited to nutrients essential to survival but would include mineral elements at levels beneficial for optimum growth. The list of essential elements may well increase in the future to include nutrients that are currently considered non-essential.

Some non-essential elements can become toxic to plants, animals, and humans at high concentrations. Further discussion on the toxicity potential of non-essential elements can be found in chapter 11.

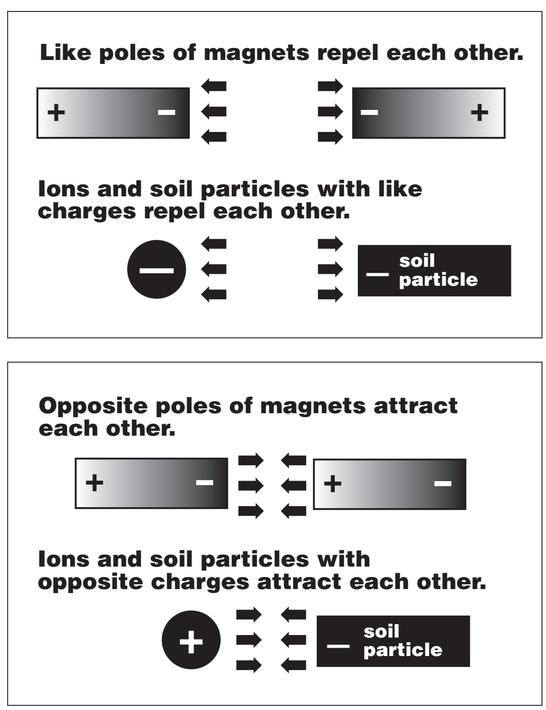
Properties of chemical elements, atoms, ions, and salts

Chemical elements are substances that ordinarily cannot be decomposed or changed into simpler substances. Nitrogen, phosphorus, and potassium are all chemical elements. An atom is the smallest particle of an element which has the physical and chemical characteristics of that element. Atoms are electrically neutral. However, many atoms gain or lose electrons (negatively charged particles) and become electrically charged *ions*. If an atom or group of atoms loses one or more electrons, it becomes a positively charged ion called a *cation*. If an atom or group of atoms gains one or more electrons, it becomes a negatively charged ion called an *anion*.

Ions with the same charge repel one another; ions with opposite charges attract one another to form a chemical bond. This is very similar to the way like poles of magnets repel each other, while opposite poles of magnets attract each other. This relationship is shown in figure 8-1. The compounds formed by the chemical bonds between positive and negative ions are termed *salts*. If these salts have a definite crystalline structure, they are called *minerals*.

There is always an attraction between positively and negatively charged ions. However, the intensity of the attraction depends on the ions. For some salts this attraction is overcome by interaction with water molecules. As a result, these salts dissolve easily and readily go into the soil solution. These salts are described as being soluble. Potassium chloride (KCl) and

Figure 8-1. Attractive and repulsive forces between chemical ions and soil particles are similar to the forces which repel or attract the opposite or like poles of bar magnets.



ammonium nitrate (NH_4NO_3) are examples of soluble salts. In other cases, the intensity of the attractive forces between ions is too strong to be overcome by the action of water. As a result, these salts dissolve in the soil solution only slightly and are described as being sparingly soluble or relatively insoluble. Examples of relatively insoluble salts include calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), which make up dolomitic limestone. Most oxides, such as ferric oxide (Fe_2O_3) and the silicate minerals which make up the skeleton of the soil, are very insoluble.

Most plant nutrients in commercial fertilizer are in the form of moderately to very soluble salts. These salts dissolve rapidly in soil water to form ions which frequently react with other ions or mineral surfaces in soil to form less soluble compounds. Therefore, the solubility of a fertilizer before application often bears little relationship to the solubility of the new compound formed after the fertilizer reacts with the soil.

If a nutrient remains very soluble after reacting with the soil, as is the case with nitrate (NO_3^-) salts, it is dissolved completely in the soil water and plants are able to take it up easily. However, it can also be leached more easily than less soluble salts. On the other hand, if the nutrient forms a very stable or insoluble compound, as is the case with most phosphates ($H_2PO_4^-$), only a very small amount of the nutrient remains in soil solution. The amount of phosphate in solution or in an available form depends on the amount of stable phosphates present. As plants extract the nutrient from the soil solution, more dissolves from the stable form. Consequently, the stable or "fixed" form of phosphorus acts as a nutrient reservoir.

Sources of plant nutrients in the soil

Soil solution

Only small amounts of essential plant nutrients are found in soil solution at any one time. Even on the most fertile soils, plants would quickly die if they had to depend on only the quantity of nutrients in the soil solution. Under actual conditions plants do remove nutrients from the solution. As these nutrients are removed from solution, soil reserves release more nutrients. Hence, the concentrations of plant nutrients in soil solution tend to remain constant.

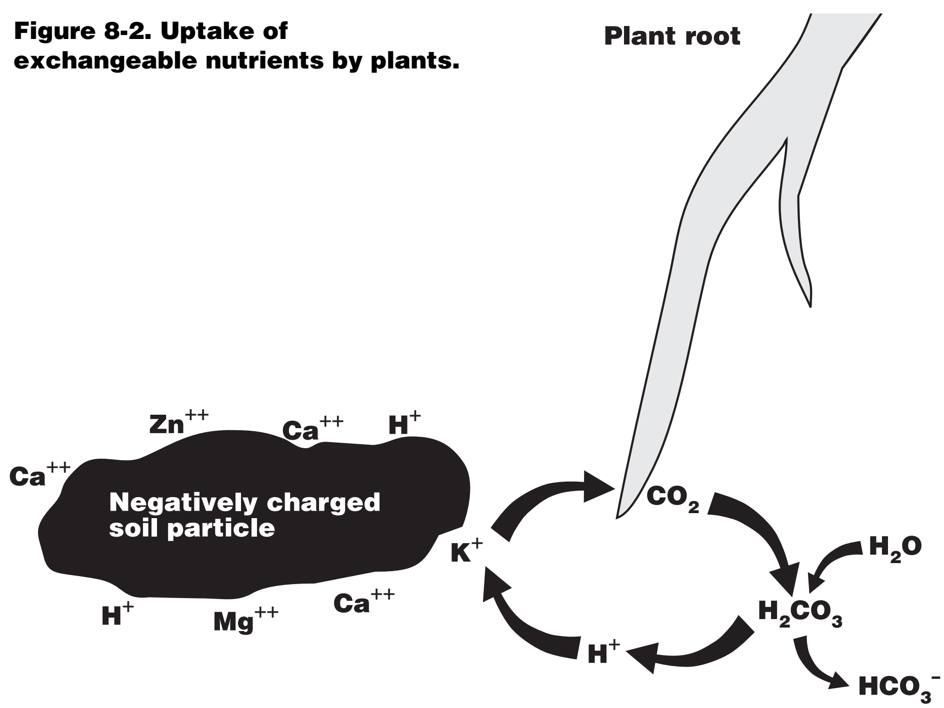
Since some nutrients exist in soil in a water soluble form, they are found primarily in soil solution. These include nitrate (NO_3^-), sulfate ($SO_4^=$), borate ($H_2BO_3^-$), and chloride (Cl^-). All of these nutrients are negatively charged and could be leached below the plant root zone, especially on sandy soils.

Exchange sites on clay and organic matter

The clay and organic matter particles contained in soil exhibit a negative electrical charge which is a result of the way the component ions making up these particles are linked together. Since opposite charges attract, the negatively charged clay and organic matter particles attract and hold positively charged plant nutrients, such as ammonium (NH_4^+), potassium (K^+), and calcium (Ca^{++}). Positively charged plant nutrients attracted to the negative charges on the soil particles are called exchangeable. See table 8-1 for a listing of the electrical charges of plant nutrients.

Exchangeable nutrients are held against leaching but can easily be taken up by plant roots. In this process an ion on a soil particle is exchanged for an ion in the soil solution. Figure 8-2 illustrates the process. In this example, a potassium ion moves from the soil particle to the plant root. The root simultaneously excretes carbon dioxide

Figure 8-2. Uptake of exchangeable nutrients by plants.



(CO_2) into the soil solution as part of respiration. The carbon dioxide reacts with water (H_2O) to form carbonic acid (H_2CO_3), an unstable compound which splits into a hydrogen ion (H^+) and a bicarbonate ion (HCO_3^-). The hydrogen ion moves to the negatively charged surface of the soil particle to replace the potassium ion. Thus, one positively charged ion is exchanged for another positively charged ion. If a calcium ion (Ca^{++}) had been exchanged instead of potassium, two hydrogen ions would be required because the calcium ion fills two negative charges on the soil particle.

Exchangeable nutrients are a very important reservoir of plant nutrients in soil. Nearly all of the ammonium, potassium, calcium, and magnesium used by plants comes from the exchangeable form. Exchangeable nutrients are readily available to plants and, at the same time, are essentially non-leachable. Soils cannot hold an unlimited quantity of positively charged ions. The amount of cations a soil can hold can be measured and is known as the *cation exchange capacity* (CEC). Silty and clayey soils, for instance, will hold anywhere from 3 to 10 times more positively charged ions than sandy soils. However, even the sands have sufficient “exchange capacity” to hold all of the positively charged plant nutrients needed by plants in an available but relatively non-leachable form.

Complexed or chelated nutrients

Certain types of positively charged ions are held very tightly by the organic matter—much more tightly than exchangeable ions are held. They are said to be complexed or chelated. Copper (Cu^{++}) and zinc (Zn^{++}) are two nutrients that are usually held as chelates. As noted in chapter 1, the name chelate comes from the Greek word *chele* meaning claw. This term is quite descriptive as the positively charged ions are literally held in the center of a negatively charged claw.

Decomposition of organic matter

In addition to holding available plant nutrients in an exchangeable form, organic matter supplies previously unavailable nutrients when it is decomposed. Crop residues, manure, and other organic materials contain considerable amounts of nitrogen, phosphorus, and sulfur and are a good source of most micronutrients, particularly boron (table 8-1). Organic matter is an important reservoir of these nutrients, but organic forms of nutrients generally cannot be used by plants. In order to change or mineralize these nutrients from an organic form (unavailable) to an inorganic form (available), the organic matter must be decomposed by soil microorganisms.

Soil microorganisms are microscopic living organisms which are very sensitive to their environment. In general, organic matter decomposition is hastened when:

- The soil temperature is 75° to 90°F. (Microbial activity is very slow at temperatures below 50°F and decreases above 90°F.)
- Moderate, but not excessive amounts of soil moisture are present.
- The soil pH is above 6.0.
- The soil is well-aerated. (Decomposition is much slower in waterlogged soils because of a lack of oxygen.)

In Wisconsin, organic matter may decompose slowly in the spring because many of our soils remain cool and wet. Therefore, the reserves of nitrogen and phosphorus often are not released fast enough to take care of the early growth of a spring-seeded crop. For this reason starter fertilizer is nearly always recommended for corn and other row crops even on fertile soils that could otherwise supply sufficient plant nutrients.

Low-solubility compounds

Some plant nutrients react with ions in the soil to form extremely stable compounds. These compounds have very low solubilities in water. Plant nutrients which form this type of compound are phosphorus ($H_2PO_4^-$), molybdate ($MoO_4^=$), iron (Fe^{+++}) and, in calcareous soils, manganese (Mn^{++}). Because of the low solubilities of these compounds, the concentrations of these nutrients in soil solution are very low. Even though it is quite insoluble, the surface of a stable compound does act as a nutrient reservoir. When plants remove a nutrient like phosphate from soil solution, some of the phosphate on the surface of the stable phosphate compound will dissolve. Thus, the concentration of phosphate in solution tends to remain constant. Because of the low concentrations in the soil solution, leaching is rarely a problem with these nutrients.

Soil rocks and minerals

Large amounts of many plant nutrients are found in soil rocks and minerals. However, these nutrients are considered to be unavailable because they are released much too slowly to support plant growth. Good evidence for this is the fact that a soil low in available potassium (less than 100 ppm) may contain as much as 20,000 ppm of total potassium (table 8-1).

What constitutes a fertile soil

A fertile soil is one that has sufficient reserves to maintain a high enough concentration of nutrients in soil solution to permit optimum plant growth throughout the growing season. An infertile soil cannot maintain a sufficient concentration of plant nutrients in the soil solution, reducing plant growth and, consequently, crop yields. For example, the nutrient reservoir in sandy soils is often quite small because these soils contain very little clay or organic matter as compared to silty soils. This is one reason why sandy soils are often less fertile than silty soils.

Questions

1. List the 17 essential elements and the form each is taken in by plants. Why are these elements said to be essential?
2. Soil fertility deals mainly with 14 nutrients that make up only 5 to 10% of the dry weight of plants. The other three essential nutrients are mostly ignored. Explain.
3. Define the following:
   a. atom
   b. element
   c. anion
   d. cation
   e. acid
   f. base
   g. salt
   h. mineral
4. Which primary nutrient—nitrogen, phosphorus, or potassium—could be leached below the root zone if applied in the fall?
5. Why do potassium or ammonium leach less easily than nitrate? Why do nitrates leach from soil whereas phosphates don't, even though both are negatively charged ions?
6. Which essential element can be taken up by plant roots both as an anion and as a cation?
7. Describe the types of soils and the conditions under which potassium may leach into the subsoil.
8. What is the significance of cation exchange capacity in soil? How can the cation exchange capacity of a soil be increased?
9. The top 7 inches of soil in an acre may contain as much as 4,000 lb of nitrogen, 2,000 lb of phosphorus, and 40,000 lb of potassium, yet the field requires addition of these nutrients to obtain good yields. Why?
10. A sandy soil in central Wisconsin and a silt loam in southern Wisconsin both test high in available phosphorus and potassium. If these soils are cropped and fertilizer is not applied, which soil will become depleted of its fertility first? Why?
11. Farmers in Wisconsin usually get response to starter fertilizer on corn even when the soil tests high in phosphorus and potassium. Farmers in central Illinois seldom get response to starter fertilizer on high testing soils. What is the reason for this difference?

CHAPTER 9

Soil and fertilizer sources of plant nutrients

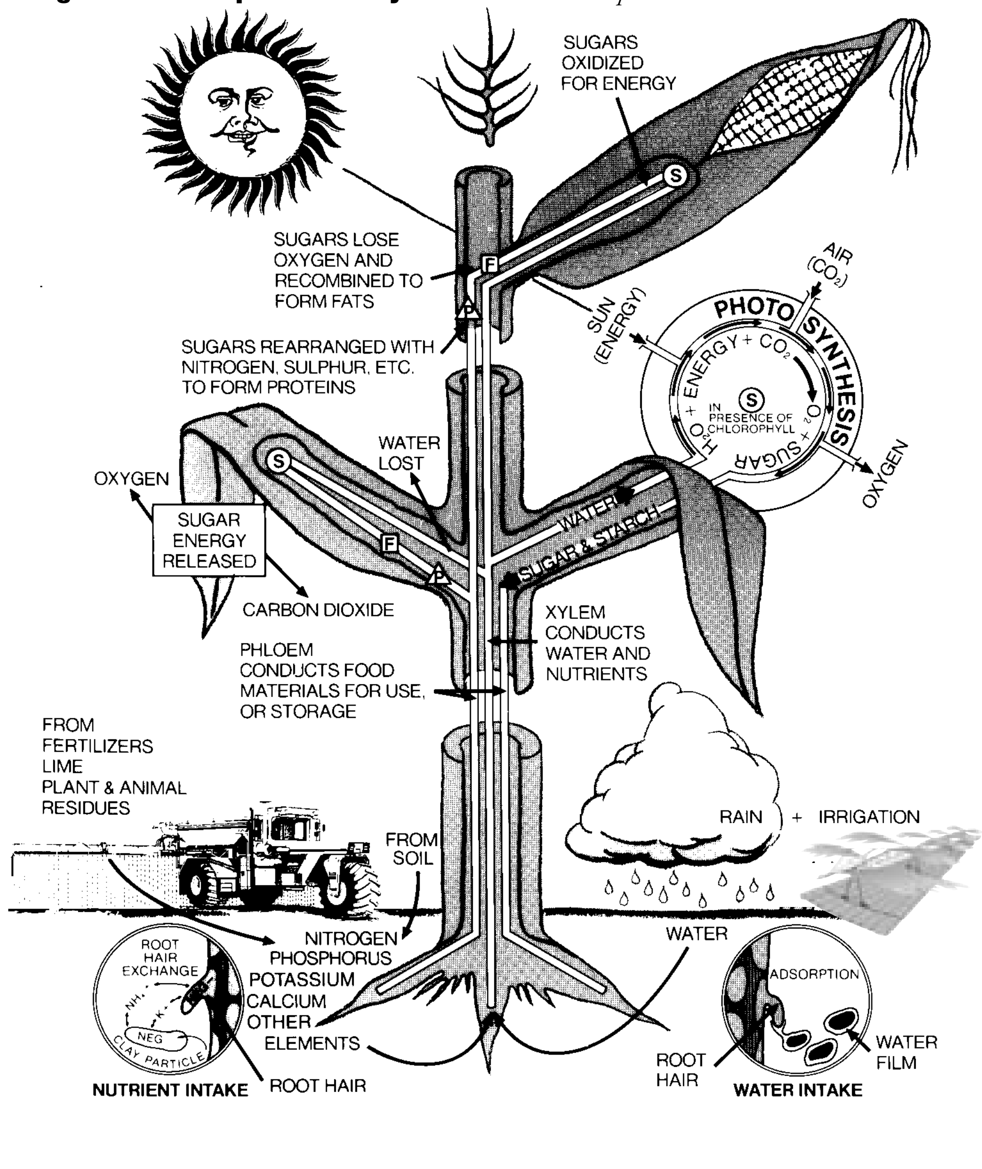
"…whoever could make two ears of corn or two blades of grass grow upon a spot of ground where only one grew before, would deserve better of mankind, and do more essential service to his country, than the whole race of politicians put together."

Jonathan Swift, Gulliver's Travels, *1726*

The plant is a marvelous factory (figure 9-1). It combines carbon dioxide (CO_2) from the air with water from the soil to make sugar in the leaves, using solar energy to drive the system. With nutrients taken up from the soil, sugar is then converted to starch, protein, vitamins, oil, and numerous other products. The leaves give off oxygen (O_2), and water evaporating from leaf surfaces cools the plant on hot days.

To keep this factory operating at capacity, the raw materials—soil nutrients—must be supplied at rates equal to plant needs. This chapter describes each of the nutrients.

Figure 9-1. The plant factory. *Source: Potash & Phosphate Institute.*



Nitrogen

The atmosphere contains about 78% nitrogen gas (N_2). This is the equivalent of more than 30,000 tons per acre. However, most plants cannot use nitrogen as it exists in the atmosphere. It must first be converted through biological or chemical fixation.

Biological fixation. *Rhizobia* and other bacteria that live in the roots of legumes take nitrogen from the air and fix it in a form that plants can use. This mutually beneficial relationship between microorganisms and plants is called symbiosis.

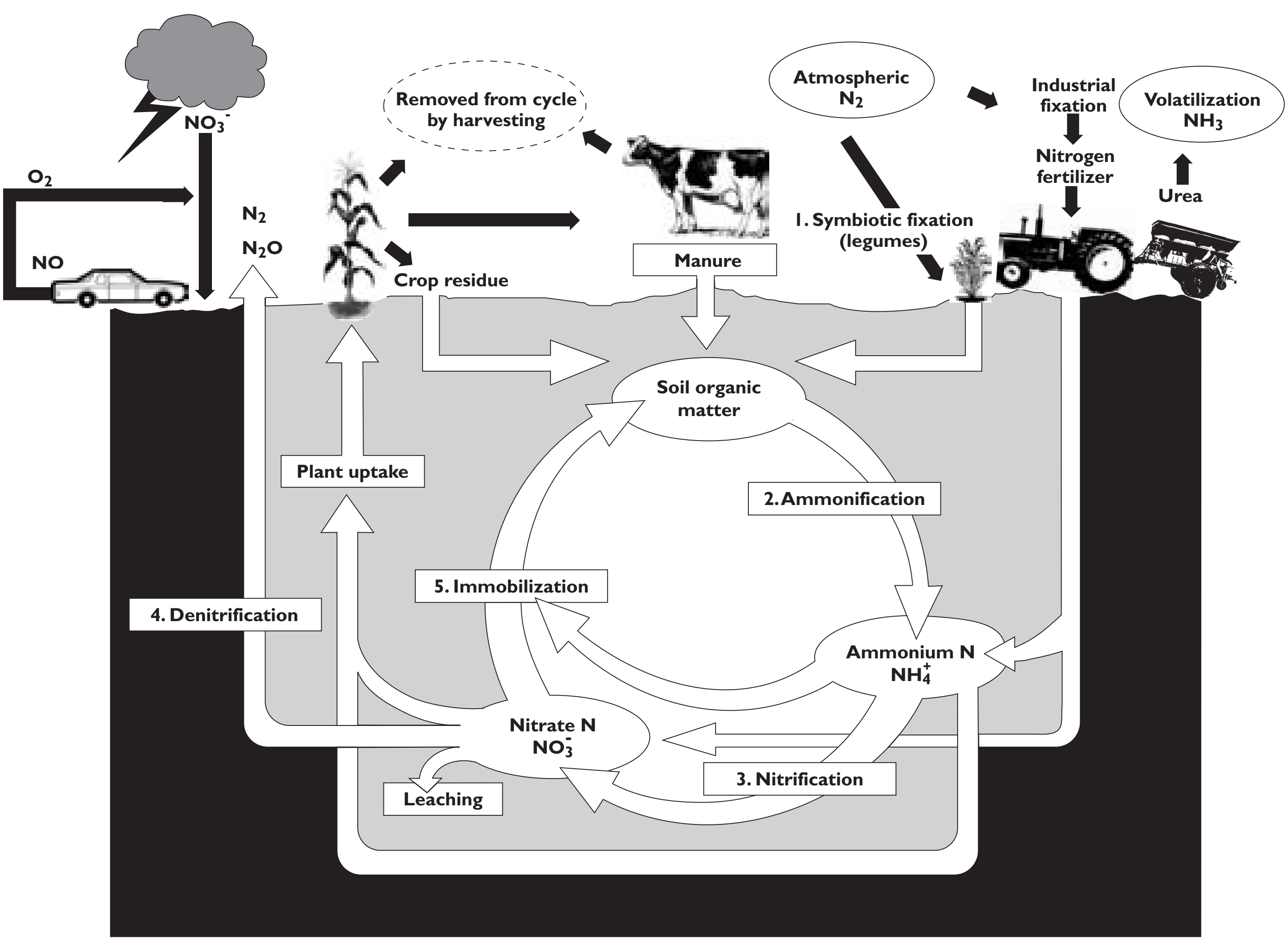
Chemical fixation. In the manufacture of chemical nitrogen fertilizer, atmospheric nitrogen (N_2) is combined with hydrogen (H_2) from natural gas, under heat and pressure in the presence of a catalyst, to form ammonia (NH_3). Ammonia can be sold for direct application, or it can be used to manufacture other forms of nitrogen fertilizer such as ammonium nitrate (NH_4NO_3) or urea ($CO(NH_2)_2$).

Function in plants

Nitrogen is a major constituent of protein. Plants contain 5 to 25% protein and protein contains 16 to 18% nitrogen. Nitrogen is also found in substantial amounts in chlorophyll, nucleic acids, enzymes, and many other cellular compounds.

Nitrogen is mobile within the plant. When deficiency occurs nitrogen moves or translocates from the lower leaves to the upper leaves. As a result, the lower leaves first show the characteristic yellowing. On corn, the yellowing starts at the leaf tip and proceeds up the midrib of the leaf.

Figure 9-2. The nitrogen cycle.



Reactions in soils

Nitrogen exists in many different forms. Several physical, chemical, and biological processes affect its availability to plants. Collectively, these transformations make up the nitrogen cycle, illustrated in figure 9-2.

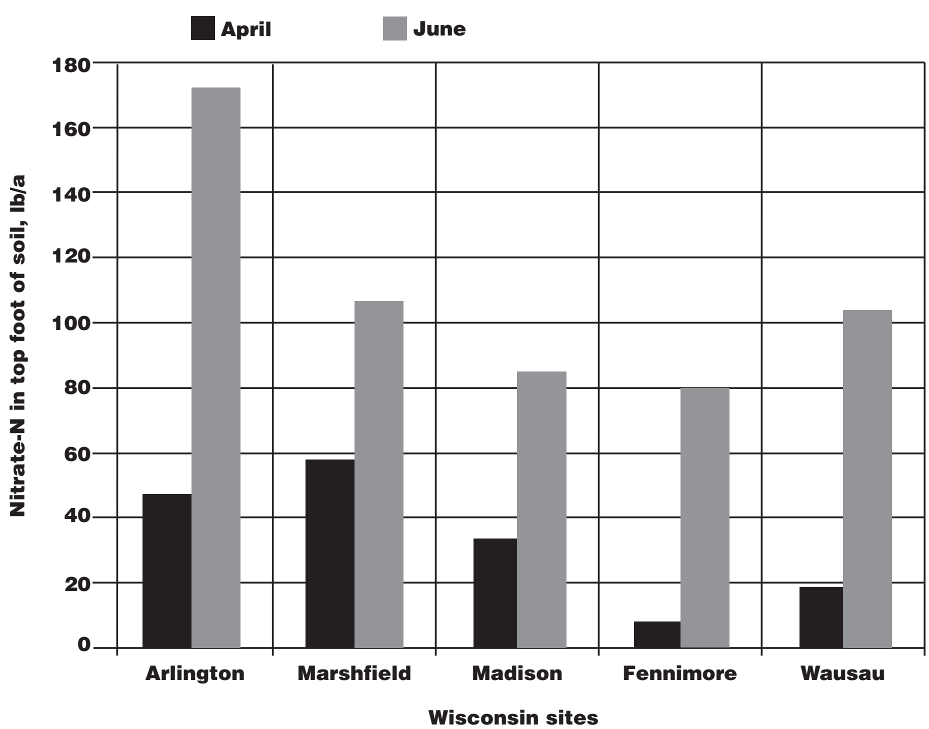
Soil often contains 2,000 to 6,000 pounds of organic nitrogen per acre in the top 7 inches of soil (about 2 million pounds), but almost all of this nitrogen is combined in stable organic matter (humus) which decomposes very slowly and is largely unavailable to plants. Research has shown that mineral soils in Wisconsin will supply only about 25 to 75 pounds of available nitrogen per acre annually. Available nitrogen can be estimated based on the organic matter content of the soil. About 5% of the organic matter is nitrogen. Only 1 to 3% of the organic nitrogen is mineralized (made available) annually. For example, if a soil contains 2% organic matter with a nitrogen content of 5%, and if the organic nitrogen mineralizes at a rate of 2% per year, this soil would release annually 40 pounds of available nitrogen per acre. (2% x 2,000,000 lb/a x 5% O.M. x 2% of N mineralized = 0.02 x 2,000,000 x 0.05 x 0.02 = 40 lb/a nitrogen).

Symbiotic fixation of nitrogen occurs when legumes such as alfalfa, clovers, soybeans, birdsfoot trefoil, beans, or peas are included in a cropping system. (Reaction 1 in figure 9-2.) Each legume requires association with a specific *Rhizobium* bacteria to fix atmospheric nitrogen. As long as the proper bacteria are present in the soil, nitrogen-fixing nodules will form in the roots of these plants as they grow. These bacteria are often added to the soil as an inoculant, usually by coating the seed at planting time.

Leguminous plants, like all other plants, need nitrogen for growth. If there is an abundance of plant-available nitrogen already in the soil (from manure or residual fertilizer, for example), a legume will use the soil-available nitrogen before expending energy for the *rhizobia*-fixed nitrogen. When soil nitrogen is low, however, the legume uses *rhizobia*-fixed nitrogen for its growth. No matter what its source, nitrogen is incorporated throughout all parts of the plant; it is not concentrated only in the root nodules. The amount of nitrogen contained in the above-ground plant parts is about equal to that found in the roots.

Legumes can store substantial amounts of nitrogen. For example, in the fall following a late-summer harvest, alfalfa contains 130 to 230 pounds of nitrogen per acre. When legumes decompose, the stored nitrogen is gradually mineralized or released in a plant-usable form and becomes available to the next crop. Figure 9-3 shows the levels of nitrate-nitrogen (NO_3^--N) in the soil profile of several fields of first-year corn following alfalfa. The amount present depends on the density of the previous alfalfa stand, soil texture, and height of plants prior to killing the stand, either by tillage, herbicide, or winter-kill. Alfalfa residue often supplies all of the nitrogen needed by first-year corn. The suggested reduction in the application of fertilizer nitrogen following various

Figure 9-3. Soil nitrate-nitrogen (NO_3^--N) levels where no nitrogen fertilizer has been applied to corn following alfalfa.



Source: Bundy et al., 1997. Using Legumes as a Nitrogen Source. *University of Wisconsin-Extension publication A3517.*

leguminous crops is given in table 9-1. Additional information on the crediting the nitrogen supplied by legume crops can be found in Extension publication *Using Legumes as a Nitrogen Source* (A3517).

Ammonification is the mineralization process by which certain soil microorganisms change organic nitrogen into ammonium ions (NH_4^+). (Reaction 2 in figure 9-2.) Ammonium nitrogen is available to plants but it is not lost by leaching. The positively charged ammonium ions are held in exchangeable form by the negatively charged particles of clay minerals and soil organic matter. Environmental conditions enhancing ammonification include soil temperatures of 50° to 85°F, good aeration (well-drained soils), and a pH of 5 to 8.

Nitrification is the process by which ammonium-nitrogen (NH_4^+-N) is changed to nitrate-nitrogen (NO_3^--N) by soil bacteria. (See reaction 3 in figure 9-2.) Nitrate ions (NO_3^-) are readily available to plants, but they are negatively charged and remain in soil solution. Therefore, they may be leached below the root zone with water as it percolates through the soil.

Nitrification occurs rapidly under conditions of good aeration, warm soil temperatures (60° to 85°F), and appropriate soil pH (6.5 to 7.0). When soil conditions are favorable, most of the ammonium form of nitrogen commonly found in dry or liquid fertilizer will be changed to the nitrate form within 1 to 2 weeks of application. With anhydrous ammonia, nitrification is much slower because the very high pH in the vicinity of the ammonia band will markedly restrict the activity of nitrifying bacteria. Within 2 to 6 weeks the pH in the ammonia band will return to its original level, and nitrification will proceed.

Denitrification is the process by which anaerobic (absence of oxygen) soil bacteria change available nitrate-nitrogen into unavailable atmospheric nitrogen (reaction 4 in figure 9-2). This process occurs primarily in poorly aerated, waterlogged soils. But, even in well-drained soils, some denitrification can occur inside dense soil clods that drain very slowly. For denitrification to

Table 9-1. Nitrogen credits for previous legume crops.

Legume crop	Nitrogen credit (lb/a)	Exceptions
Forages		
First-year credit:		
Alfalfa	190 for a good stand[a] 160 for a fair stand[a] 130 for a poor stand[a]	Reduce credit by 50 lb/a N on sandy soils.[b] Reduce credit by 40 lb/a N if plant regrowth was less than 6–10 inches before tillage or plant death.
Birdsfoot trefoil, red clover	Use 80% of alfalfa credit	Same as alfalfa.
Second-year credit:		
Fair or good stand	50	No credit on sandy soils[b]
Green manure crops		
Alfalfa Red clover Sweet clover	60–100 50–80 80–120	Use 40 lb/a N credit if field has less than 6 inches of growth before tillage. Reduce credit by 50 lb/a N on sandy soils.[b]
Soybean	40	No credit on sandy soils[b]
Leguminous vegetable crops		
Pea, lima, snap bean	20	No credit on sandy soils[b]

[a] *A good stand of alfalfa (>70% alfalfa) has more than 4 plants per square foot; a fair stand (30–70% alfalfa) has 1.5–4 plants per square foot; and a poor stand of alfalfa (<30% alfalfa) has fewer than 1.5 plants per square foot.*

[b] *Sands and loamy sands.*

Source: L.G. Bundy. 1998. Understanding Plant Nutrients: Soil and Applied Nitrogen. *University of Wisconsin-Extension publication A2519.*

occur, readily decomposable organic matter must be present as a source of energy. Because of this energy requirement, little denitrification occurs deep in the subsoil or in groundwater.

Denitrification takes place very rapidly. If water stands on the soil for only 2 to 3 days during the growing season, most of the nitrate-nitrogen will be lost by denitrification. Applications of nitrogen should be delayed as long as possible on soils that often become waterlogged in the spring. Also, use of a nitrification inhibitor—a material that slows down the nitrification process—can be beneficial when preplant nitrogen is applied to soils that tend to be temporarily waterlogged.

Immobilization is the conversion of mineral forms of nitrogen to unavailable organic forms. (See reaction 5 in figure 9-2.) For example, incorporating carbon-rich crop residues, such as straw or corn stalks, stimulates microbial activity. Available nitrogen is then converted into microbial protein and will remain unavailable until the crop residue decomposes. When the microbes die, the nitrogen is again released in an available form. Under ideal weather conditions, release of immobilized nitrogen will begin about 1 month after incorporation of the organic matter.

The addition of nitrogen fertilizer may hasten residue decomposition, but most well-managed soils contain enough nitrogen to break down crop residues. The factor limiting decomposition of residues is usually the size of the residue pieces rather than the amount of nitrogen present. Small particles decompose much more rapidly than large particles. To speed decomposition, crop residues can be chopped or shredded. Crop residues need about 20 pounds of nitrogen per ton of dry matter to satisfy the requirements of the microorganisms decomposing the residue. For example, 3 tons of corn stalks would require 60 pounds of nitrogen. Such a nitrogen application would be recommended if these low-nitrogen residues cause temporary nitrogen deficiencies to occur, especially when the crop to be grown needs additional nitrogen. However, because of the expense and environmental concerns, nitrogen should not be applied for the sole purpose of speeding up decomposition. Soil test recommendations take residue conditions into consideration. The nitrogen needed to decompose the residue is built into the calculation of the nitrogen rate.

In addition to nitrogen losses due to biological transformations such as denitrification and immobilization, nitrogen can be removed from the crop root zone by leaching and volatilization.

Leaching is the movement of plant nutrients in the soil solution below the root zone. Leaching of nitrate-nitrogen can be very serious crop production and water quality problems, especially on sandy soils.

Since coarse-textured soils retain only about 1 inch of water per foot of soil, relatively small amounts of rain or irrigation water can readily move nitrate below the root zone. Well-drained silty and clayey soils, however, commonly hold 2.5 to 3 inches of water per foot of soil, so very rapid leaching on these soils occurs only when rainfall is abnormally high or nitrogen is over-applied. When rainfall is normal or below normal, leaching is not a problem on silty or clayey soils during the growing season because nitrate seldom moves downward more than 2 feet.

Ammonium-nitrogen is held in an exchangeable form on soil particles and does not leach below the root zone. Nitrate-nitrogen is not held by soil particles and can be leached below the root zone. But, this does not necessarily mean that ammonium-nitrogen will be more effective than nitrate-nitrogen. Ammonium-nitrogen quickly changes to nitrate-nitrogen under optimum soil conditions. As a result, nitrogen loss through leaching can occur even where nitrogen is initially applied as ammonium.

On sandy soils where excessive leaching often occurs, ammonium-containing nitrogen fertilizers (e.g., urea, anhydrous ammonia, ammonium sulfate) sometimes do better than nitrate-containing nitrogen fertilizers (e.g., ammonium nitrate). This difference appears when substantial rainfall occurs shortly after application. In this case the ammonium nitrogen would not yet be nitrified and would not be leached as easily as nitrate. Organic sources of nitrogen are especially beneficial on sandy soils because they serve as a reservoir of nitrogen that is slowly released during the growing season.

Volatilization is the conversion of usable nitrogen to ammonia gas. Direct loss of ammonia as a gas can occur when anhydrous ammonia is injected into soils that are too wet or too dry so that the vapor escapes before the soil seals behind the applicator knives. Volatilization can also take place when materials containing urea (manure and other organic wastes; fertilizers such as urea, 28% nitrogen solutions, and some mixed fertilizers) are applied to the soil surface and are not incorporated (table 9-2). Immediate incorporation of these materials eliminates volatilization losses. Rainfall (as little as 0.2 inch) within 2 days after surface application of urea-containing materials will greatly reduce or eliminate volatilization. Very little ammonia loss will occur when ammonium nitrate, ammonium sulfate, or ammonium phosphate are surface-applied on acid or neutral soils. When the soil pH is above 8.0 some loss of ammonia can occur from these materials, so they should be incorporated when applied on alkaline soils.

Sources of nitrogen

In addition to organic matter contributions, nitrogen is also supplied to soil and plants by commercial fertilizers, manure and other organic byproducts, legumes, and precipitation.

Nitrogen fertilizers. Many different chemical and physical forms of nitrogen fertilizer are available. If properly applied, the various forms are equally effective, although one form may have an advantage over another under certain conditions. Table 9-3 lists the general characteristics of the important fertilizer sources of nitrogen. The most widely used nitrogen fertilizer sources are discussed below.

Anhydrous ammonia has the highest concentration of nitrogen (82%). It is stored under pressure as a liquid but turns to a gas when the pressure is released. The drop in pressure cools the surrounding air when anhydrous ammonia is released. The puffs of "steam" observed when injector knives are raised is a result of moisture condensing in the cooled air. Anhydrous ammonia is very caustic and considered to be a hazardous material. A container of water must always be available when working with this gas in case eyes or mucous membranes are exposed to the vapors.

UAN (urea-ammonium nitrate) or pressureless nitrogen solutions are made by mixing roughly equal amounts of ammonium nitrate and urea in water to form a fertilizer containing 28% or 32% nitrogen. Since the nitrogen in urea quickly converts to ammonium when applied to the soil, these nitrogen solutions provide three-quarters of the nitrogen as ammonium and one-quarter as nitrate.

Urea has the highest nitrogen concentration of any dry nitrogen fertilizer (45% N). It reacts with moisture to form ammonium carbonate, an unstable salt that decomposes into ammonia (gas), carbon dioxide, and water. Consequently, urea and solutions containing urea must be incorporated by rain, tillage, or injection to minimize loss. Urea volatilizes more rapidly when surface residue prevents it from contacting the soil and in high temperature, high pH, and dry weather.

Table 9-2. Effect of ammonia volatilization from surface-applied nitrogen fertilizers on the yields of corn and grass pasture.

Crop	Nitrogen source[a]	Added N lost as NH_3[b]	Yield
		—%—	—bu/a—
Corn	None	—	83
	Urea	16	122
	UAN[c] solution	12	125
	Ammonium nitrate	2	132
			—ton/a—
Grass pasture	None	—	0.74
	Urea	19	1.09
	Ammonium nitrate	1	1.30

[a] *Nitrogen sources surface-applied at 50 and 100 lb/a of N for corn and 60 lb/a of N for grass pasture. Corn yields are averages of the two rates.*
[b] *Ammonia loss determined by field measurement*
[c] *UAN = a mixture of urea and ammonium nitrate*
Source: Oberle, S.L., and L.G. Bundy. Proc. 1984 Fert., Aglime & Pest Mgmt. Conf. 23:45–57.

Table 9-3. Nitrogen fertilizers.

Fertilizer	Chemical formulation	Analysis ($N–P_2O_5–K_2O$)	Physical form	Method of application
Ammonium nitrate	NH_4NO_3	33-0-0	dry prills	Broadcast or sidedress. Can be left on the soil surface.
Ammonium sulfate	$(NH_4)_2SO_4$	21-0-0	dry granules	Broadcast or sidedress. Can be left on the soil surface.[a]
Anhydrous ammonia	NH_3	82-0-0	high-pressure liquid	Must be injected 6–8 inches deep on friable[b] moist soil. Excessive loss will occur from wet soils.
Aqua ammonia	NH_4OH	20-0-0 to 24-0-0	low-pressure liquid	Must be injected 2–3 inches deep on friable[b] moist soils. Excessive loss will occur from wet soils.
Calcium nitrate	$Ca(NO_3)_2$	15.5-0-0	dry granules	Broadcast or apply in the row. Can be left on the soil surface.
Diammonium phosphate	$(NH_4)_2HPO_4$	18-46-0	dry granules	Broadcast or apply in the row. Can be left on the soil surface.[a]
Low-pressure nitrogen solutions	NH_4NO_3 + NH_3 + H_2O	37-0-0 41-0-0	low-pressure liquid	Must be injected 2–3 inches deep on friable[b] moist soils. Excessive loss will occur from wet soils.
Potassium nitrate	KNO_3	13-0-44	dry granules	Broadcast or apply in the row. Can be left on the soil surface.
UAN or pressureless nitrogen solutions	NH_4NO_3 + urea + H_2O	28-0-0 32-0-0	pressureless liquid	Spray on surface or sidedress. Incorporate surface applications to prevent volatilization loss of NH_3 from urea.
Urea	$CO(NH_2)_2$	45-0-0	dry prills or granules	Broadcast or sidedress. Incorporate surface applications to prevent volatilization loss of NH_3 from urea.

[a] *Incorporate on high pH soils.*
[b] *Friable soils are those which are easily crumbled or pulverized.*

Ammonium nitrate contains 33% nitrogen—half ammonium nitrogen, half nitrate-nitrogen. It attracts moisture from the air and cakes up during periods of high humidity. It is made into spherical pellets (prills) and coated with a conditioning agent to prevent caking. Never combine ammonium nitrate and urea because the mixture has a much greater affinity for water than either material alone.

Ammonium sulfate contains only 21% nitrogen. Consequently, shipping and handling cost per pound of nitrogen are high. It is a strongly acidifying fertilizer and may be preferred where a low pH is needed. It is sometimes used as a source of sulfur (24% S). Also, it does not pick up moisture from the air as readily as ammonium nitrate or urea.

Manure. Manure contains substantial amounts of nitrogen, but much of the nitrogen is in the organic form and is not all available in the first year following application. The amount of nitrogen available to a crop depends on the type of manure, the application rate, the method of application, and the consecutive years of application. Fertilizer nitrogen applications should be reduced or eliminated following manure applications. Table 9-4 lists first-year nitrogen credits for solid and liquid manure. Additional information on using manure as a nutrient resource can be found in chapter 10.

Legumes. Nitrogen contributions from legume plants were previously discussed in the "Reactions in Soils: Symbiotic Fixation" section of this chapter and are shown in table 9-1.

Precipitation. In rural areas of Wisconsin, precipitation accounts for about 10 pounds of available nitrogen (ammonium + nitrate-nitrogen) per acre annually. This is a small addition on a per-acre basis, but it is a significant contribution to the total nitrogen budget for the state. In fact, the amount of nitrogen contributed from the atmosphere over the entire state (36 million acres) is roughly equal to that applied as fertilizer on 10 million cropland acres. Lightning in an electrical storm can create enough energy to cause some oxygen (O_2) and nitrogen (N_2) to form various nitrogen oxides. These combine with water to form nitric acid (HNO_3). Various nitrogen oxides (primarily N_2O and NO) are emitted into the atmosphere by denitrification and by internal combustion engines. A small portion of these oxides reacts with oxygen to form nitrates, which return to the soil in precipitation.

Table 9-4. Nitrogen content and first-year credits for solid and liquid manure.

Type of manure	Total nitrogen available in first year	Application method	Nitrogen content of manure: Solid Total	Solid Credit	Liquid Total	Liquid Credit
	— % —		— lb/ton —		— lb/1,000 gal —	
Beef	25	Surface	14	4	20	5
	35	Incorporated[a]	14	5	20	7
Dairy	30	Surface	10	3	24	7
	40	Incorporated[a]	10	4	24	10
Poultry	50	Surface	40	20	16	8
	60	Incorporated[a]	40	24	16	10
Swine	50	Surface	14	7	50[b]	25[c]
	65	Incorporated[a]	14	9	50[b]	33[c]

[a] *Injected or incorporated within 72 hours of application.*
[b] *Value for liquid indoor-pit swine manure. Use 34 and 25 for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
[c] *Value for liquid indoor-pit swine manure. Use 17 (22 if incorporated) and 13 (16 if incorporated) for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590.

Timing of nitrogen fertilizer applications

The timing of nitrogen fertilizer applications can markedly affect their efficiency and the potential for nitrogen losses. Supplying the needed nitrogen just prior to the crop's greatest demand maximizes the efficiency of nitrogen applications. For spring-planted crops, sidedress and spring preplant applications provide greater nitrogen efficiency than fall applications, which are usually 10 to 15% less effective in increasing crop yields.

Sidedress applications of nitrogen during the growing season are effective on all soils. Proper timing is essential to provide available nitrogen when the crop uses the nitrogen rapidly. For corn, this is usually 6 to 12 weeks after planting. To provide adequate nitrogen during this period of rapid nitrogen use, sidedress applications should be made no later than 6 weeks after planting. Benefits from using sidedress nitrogen instead of preplant applications are greatest on sandy soils or on fine-textured, poorly drained soils, and in years when rainfall is above normal. Research on sandy irrigated soils has shown consistently higher corn yields with sidedress applications than with preplant treatments. Further discussion of this topic can be found in the "Methods of Fertilizer Application" section of this chapter.

Spring preplant applications are usually as effective as sidedress treatments on medium-textured, well-drained soils. The risk of leaching or denitrification in these soils is low.

Multiple or split applications of nitrogen through irrigation systems are also effective. For corn, these applications should be timed so that some nitrogen is applied by the sixth week after planting and most of the recommended nitrogen is applied by the tenth week after planting

Fall applications are most effective on medium-textured, well-drained soils, where nitrogen loss through leaching or denitrification is usually low. They are *not* effective on sandy soils, shallow soils over fractured bedrock or fine-textured poorly drained soils. If fall treatments are to be made on medium-textured, well-drained soils, they should be limited to application of ammonium forms of nitrogen only (anhydrous ammonia, urea, ammonium sulfate), and they should be delayed until soil temperatures are below 50°F to slow the conversion of ammonium to nitrate by soil organisms. This conversion can be delayed also by use of nitrification inhibitors (see below). Price and convenience advantages associated with fall-applied nitrogen must be weighed against the possibility of nitrate-nitrogen losses and lower effectiveness.

Nitrification inhibitors such as nitrapyrin (N-Serve) or dicyandiamide (DCD) used with ammonium forms of nitrogen fertilizer can reduce nitrogen losses on soils where leaching or denitrification is likely. Nitrification inhibitors slow the conversion of ammonium to nitrate by soil organisms (Reaction 3 in figure 9-2). Because leaching and denitrification occur through the nitrate form of nitrogen, maintaining fertilizer nitrogen in the ammonium form should reduce nitrogen losses through these processes.

Nitrification inhibitors are likely to increase crop yields when used with spring preplant nitrogen applications on sandy soils or fine-textured, poorly drained soils. Yield increases are also likely from inhibitor use with fall-applied nitrogen on medium-textured, well-drained soils. However, spring-applied nitrogen fertilizer is usually more effective than fall-applied nitrogen even with use of a nitrification inhibitor. Using nitrification inhibitors with spring preplant nitrogen on medium-textured, well-drained soils or with sidedress applications on any soil type is not likely to improve yields.

Urease inhibitors such as NBPT (Agrotain) used with surface-applied urea-containing fertilizers can reduce ammonia losses and improve nitrogen efficiency. However, they do not consistently increase yields. The decision to use a urease inhibitor should be based on the risk of nitrogen loss that could be controlled, the cost of using the inhibitor, and the cost and convenience of other nitrogen sources or placement methods that are not subject to ammonia loss. Alternatives include injecting or incorporating the urea-containing fertilizers or using non-urea nitrogen sources.

Nitrogen fertilizer timing summary

To minimize leaching or denitrification losses, follow these general recommendations.

Sandy soils. Nitrogen should be applied as a sidedress treatment. For irrigated crops, part of the nitrogen may be applied through the irrigation water. Fall or spring preplant treatments will result in excessive losses on these soils. If spring preplant applications must be made, apply ammonium forms of nitrogen treated with a nitrification inhibitor. For irrigated crops, apply part of the nitrogen through the irrigation water.

Well-drained silty or clayey soils. Spring preplant or sidedress applications can contain any form of nitrogen. If fall applications must be made, use ammonium forms of nitrogen with a nitrification inhibitor.

Poorly drained soils. Sidedress applications of nitrogen should be made on these soils. Use of a nitrification inhibitor is recommended for spring preplant treatments.

Additional information on nitrogen management practices is contained in chapter 11.

Phosphorus

Soils generally contain 500 to 1,000 ppm of total (inorganic and organic) phosphorus, but most of this phosphorus is in a "fixed" form that is unavailable for plant use. Soluble phosphorus in fertilizer or other nutrient sources is quickly converted to less-available forms when added to the soil. In spite of this, soil test summary reports show that available phosphorus has been increasing steadily over the years. Although some Wisconsin soils may require phosphorus additions for optimum yields, the past use of phosphorus fertilizer and applications of manure have led to unnecessarily high phosphorus levels on the majority of fields. Wisconsin soil test results for field crops had an average soil test phosphorus level of 52 ppm extractable phosphorus for over 650,000 samples analyzed between 1995 and 1999. This value is excessively high for most crops.

Function in plants

Phosphorus (P) is a major constituent of the nucleus of plant cells. Because of this, plants need it in continuous supply for all cell division including flowering, fruiting, and seed formation. Phosphorus is also an important component of the compounds that transfer energy within the plant. Such energy transfers are necessary to build plant tissue and to absorb plant nutrients and water.

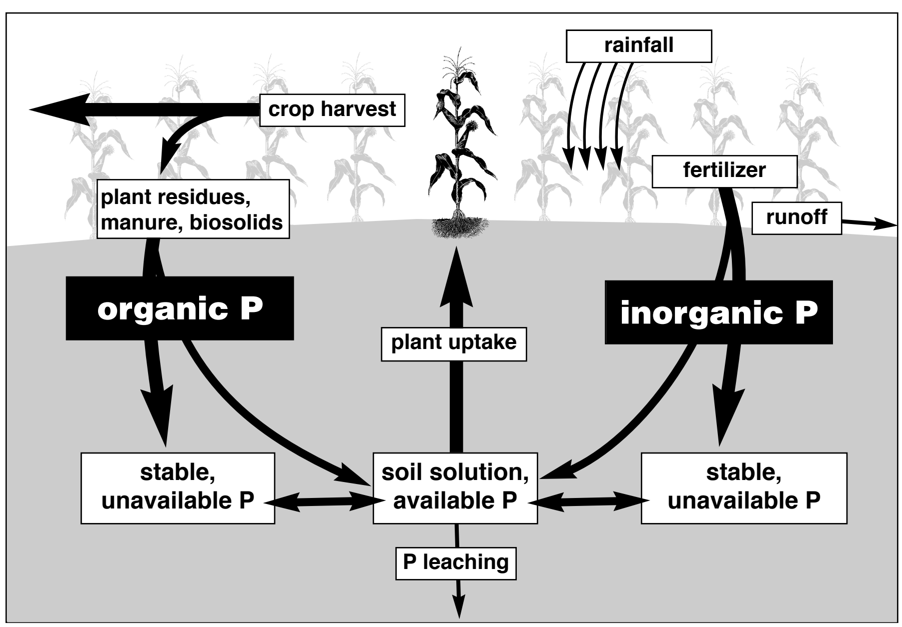
The leaves of phosphorus-deficient plants most often appear dark bluish green, frequently with tints of purple or bronze. On corn, purpling occurs around the margins of the lower leaves, and the plant is short and dark green. Some corn hybrids exhibit a purple tinge on the lower stalk of young plants, a condition that can be confused with phosphorus deficiency. Reddening of corn leaves and stalks in the fall is not an indication of phosphorus deficiency, but of a process that occurs naturally as corn matures. Phosphorus-deficient alfalfa is stunted and dark bluish green, but purpling does not occur.

Reactions in soils

The two main types of phosphorus in soils are organic and inorganic (figure 9-4). The organic form is found in humus and other organic materials. The inorganic portion occurs in various combinations with iron, aluminum, calcium, and other elements, most of which are not soluble in water. Both organic and inorganic forms of phosphorus are important sources for plant growth, but their availabilities are controlled by soil characteristics and environmental conditions.

Phosphorus fixation. One of the unique characteristics of phosphorus is its immobility in soil. Practically all soluble phosphorus from fertilizer or manure is converted in the soil to water-insoluble phosphorus within a few hours after application (figure 9-4). Phosphorus occurs in the soil solution as the negatively charged phosphate ion $H_2PO_4^-$ in acid soils or $HPO_4^=$ in alkaline soils. These ions react readily with iron, aluminum, and manganese compounds in acid soils and with calcium compounds in neutral and alkaline soils. They become strongly attached to the surfaces of these compounds or form insoluble phosphate precipitates. These reactions remove immediately available phosphate

Figure 9-4. The phosphorus cycle.



Source: S.J. Sturgul and L.G. Bundy. 2004. Understanding Soil Phosphorus. *University of Wisconsin-Extension publication A3771.*

ions from the soil solution. Unlike nitrate ions, phosphate ions rarely leach, even in sandy soils. Studies of highly fertilized, intensively farmed land indicate that the annual loss of phosphorus in drainage water seldom exceeds 0.1 pounds per acre. The plow layer of the soil usually retains almost all (98 to 99%) of the applied phosphorus. This means that very little phosphorus moves into or through the subsoil. Acid soils fix more phosphorus than neutral soils; liming acid soils to a pH of 6.0 to 6.8 increases the availability of both soil and fertilizer phosphorus.

The concentration of phosphorus in the soil solution is about 0.02 to 0.1 ppm. If this were the only source of phosphorus available to plants, the supply would be exhausted in a few hours when crops are growing rapidly. But this does not happen because the phosphorus removed from solution by plants is quickly replenished from many slowly available sources including that "fixed" by iron, aluminum, and calcium compounds (figure 9-4). A fertile soil is able to maintain the phosphorus concentration in the soil solution at a level high enough to meet the needs of crops during periods of peak demand.

Phosphorus in organic matter. The relative amounts of organic and inorganic phosphorus vary considerably. In Wisconsin, organic phosphorus accounts for 30 to 50% of the total phosphorus in most mineral soils. Decomposition (mineralization) of organic matter converts organic forms of phosphorus to inorganic available forms. As with the mineralization of organic nitrogen, organic phosphorus is released more rapidly in warm, well-aerated soils. This explains why crops grown in cold, wet Wisconsin soils often show growth response to row-applied (starter) phosphorus even though the soil may be well supplied with phosphorus or broadcast phosphorus fertilizer has been added.

Sources of phosphorus

In addition to organic matter and soil mineral contributions, phosphorus is also supplied to soil and plants by commercial fertilizers, manure, and other organic byproducts.

Phosphorus fertilizers

Rock phosphate. Rock phosphate is the original source of nearly all phosphorus fertilizer sold in the United States. Mined rock phosphate is too insoluble (less than 1% water soluble) to be a useful source of phosphorus for crops, except when very finely ground and applied to soils with a pH below 6.0. During the manufacture of fertilizer, insoluble rock phosphate is treated with an acid to convert it to more-available superphosphate or ammonium phosphate. This process neutralizes much of the acid; application of phosphate fertilizer results in very little residual acidity when it is applied to the soil. The common phosphate fertilizers, listed in table 9-5, are seldom applied alone in Wisconsin. Usually they are

Table 9-5. Sources of phosphorus fertilizer.

Name of fertilizer	Chemical formula	Fertilizer analysis $N\text{-}P_2O_5\text{-}K_2O$	Water solubility
		%	%
Ammoniated superphosphate	variable	variable	60
Ammonium polyphosphate	$NH_4H_2PO_4 + (NH_4)_3HP_2O_7$		
Liquid		10-34-0	100
Dry		15-62-0	100
Diammonium phosphate	$(NH_4)_2HPO_4$	18-46-0	>95
Monoammonium phosphate	$NH_4H_2PO_4$	11-48-0	92
Ordinary superphosphate	$Ca(H_2PO_4)_2 + CaSO_4$	0-20-0	85
Rock phosphate	$3Ca_3(PO_4)_2CaF_2$	0-32-0	<1
Triple superphosphate	$Ca(H_2PO4)_2$	0-46-0	87

manufactured or blended with nitrogen, potassium, or both to form a mixed fertilizer such as 6-24-24 or 9-23-30. As shown in table 9-6, the various sources of phosphorus are equally effective in improving crop yields.

Orthophosphate versus polyphosphate. Sources of phosphorus containing the $H_2PO_4^-$ or $HPO_4^=$ ions are called orthophosphates. Polyphosphates contain a mixture of orthophosphate and some long-chain phosphate ions such as pyrophosphate, $(HP_2O_7)_3^-$. Commercially produced polyphosphate contains approximately 50% orthophosphate and 50% long-chain phosphate compounds.

Claims that polyphosphates are superior to orthophosphates exaggerate their ability to partially chelate or combine with certain micronutrients and hold them in an available form. Research has not demonstrated that this difference improves yields or increases nutrient uptake in most soils. Polyphosphate ions react with soil moisture to form orthophosphates relatively rapidly (1 to 2 weeks). On almost all soils, orthophosphate and polyphosphate fertilizers are equally effective.

The main advantage of polyphosphate is in the production of higher analysis grades of both liquid and dry fertilizers. Also, in liquid fertilizers polyphosphates can bind micronutrients such as zinc and manganese and hold them in solution; whereas with orthophosphates, these trace elements would precipitate.

Water solubility. The amount of water-soluble phosphorus in the different sources of available phosphorus varies considerably (table 9-5). However, when phosphorus is broadcast and incorporated or when it is topdressed on forages, water solubility makes little or no difference. University of Wisconsin research shown in table 9-6 illustrates that the differences in water solubility among ammoniated superphosphate (60% soluble), concentrated superphosphate (85% soluble), and monoammonium phosphate (92% soluble) did not influence yields. Increasing the amount of water-soluble phosphorus above 60% did not increase yields. All commonly used phosphorus fertilizers presently sold in Wisconsin (except rock phosphate) contain at least 85% water-soluble phosphorus.

Table 9-6. Effect of various sources of row-applied phosphorus on corn yield (Arlington, WI).

Fertilizer grade	Sources of phosphorus in commercial 6-24-24	Corn yield (% of control)
——	Control—no phosphorus added	—
6-24-24	Ammoniated superphosphate	+13.5
6-24-24	Concentrated superphosphate	+16.7
6-24-24	Monoammonium phosphate	+16.7

Source: Schulte, E.E. and K.A. Kelling. 1996. Soil and Applied Phosphorus. *University of Wisconsin-Extension publication A2520.*

Liquid versus dry phosphate. Compared to conventional dry fertilizers, liquid fertilizers are easier to handle, mix, and apply. Despite claims to the contrary, research has shown that liquid phosphate does not improve fertilizer phosphorus availability or recovery. Soil interactions control phosphorus uptake, not the physical form of the fertilizer applied.

Rock phosphate versus superphosphate. Rock phosphate is sometimes recommended instead of superphosphate for building up the "reserve" level of phosphate in soil. The phosphorus in rock phosphate becomes available only when the soil is acid (below pH 5.5), and therefore its use by Wisconsin dairy farms is not recommended. The pH should be about 6.8 for high-quality alfalfa and at least 6.0 to 6.2 for most other agronomic crops. Research in the 1950s clearly demonstrated that rock phosphate is not an effective phosphorus source in most soils.

Manure

Manure contains substantial amounts of phosphorus but, similar to nitrogen, much of the phosphorus is in the organic form and is not all available in the first year following application. The amount of manure-phosphorus available to a crop depends on the type of manure, the application rate, and the consecutive years of application. Fertilizer phosphorus applications should be reduced or eliminated following manure applications. Table 9-7 lists first-year nitrogen credits for solid and liquid manure. Additional information on using manure as a nutrient resource can be found in chapter 10.

Methods of phosphorus fertilizer application

Plants need relatively large amounts of phosphorus early in the life cycle. Root development is limited in cool, wet soils, and very little phosphorus is released from soil organic matter. Some studies have found band-applied phosphorus to be nearly twice as efficient as broadcast phosphorus in cold soils. In well-drained, fertile soils that warm up early in the spring, however, row and broadcast applications are often equally effective. Since phosphorus moves very little from the point of application, row fertilizer should be placed 1–2 inches to the side and below the seed. Seed-placed or pop-up starter fertilizers can also be used, but the application rates must be reduced to avoid damage to the seed and young plants. Optimum starter fertilizer rates depend on soil test levels, the distance between fertilizer and seed, soil texture, and the salt index of the fertilizer applied. See "Methods of Fertilizer Applications" in this chapter for more detailed information on starter fertilizer.

Potassium

Soils commonly contain over 20,000 ppm of total potassium (K). Nearly all of this potassium is a structural component of several soil minerals, such as mica and feldspar, and is unavailable to plants. Plants can use only the exchangeable potassium on the surface of soil particles and potassium dissolved in the soil water. This often amounts to less than 100 ppm.

Large quantities of potassium are removed when whole plants are harvested, such as alfalfa, corn silage, and other forages. Grain and seed harvests remove much less potassium. Most Wisconsin soils need relatively large quantities of applied potassium because of removal by crops and because Wisconsin soils have little native exchangeable potassium.

Function in plants

Plants need large quantities of potassium. Unlike nitrogen and phosphorus, potassium does not become part of organic compounds formed by the plant. It is involved in the opening and closing of stomata (leaf pores). Potassium also balances the negative charges of organic and inorganic anions within the plant. It appears to be involved in starch formation, translocation of sugars, nitrogen assimilation, and several other metabolic processes. Potassium uptake is also linked to increased resistance to disease and lodging, increased carbohydrate production, and improved winter hardiness of alfalfa.

On corn, soybean, and other field crops, potassium deficiency appears as a yellowing or scorching of the margins of older leaves. In alfalfa, the deficiency appears as whitish-gray spots along the outer margin of the recently matured and older leaflets. As the deficiency becomes more severe, the affected area increases, and the leaves or leaflets may become completely yellow and/or drop off. Because potassium is a very mobile element within the plant, deficiency appears on the older leaves first.

Table 9-7. Phosphorus content and first-year credits for solid and liquid manure.

Type of manure	Total P_2O_5 available in first year	P_2O_5 content of manure — Solid		P_2O_5 content of manure — Liquid	
		Total	Credit	Total	Credit
	— % —	— lb/ton —		— lb/1,000 gal —	
Beef	60	9	5	9	5
Dairy	60	5	3	9	5
Poultry	60	50[a]	30[b]	16	6
Swine	60	10	6	42[c]	25[d]

[a] *Value for chicken manure. Use 40 and 21 for turkey and duck, respectively.*
[b] *Value for chicken manure. Use 24 and 13 for turkey and duck, respectively.*
[c] *Value for liquid indoor-pit swine manure. Use 16 and 23 for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
[d] *Value for liquid indoor-pit swine manure. Use 10 and 14 for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590.

Reactions in soils

The three forms of soil potassium are unavailable, slowly available or fixed, and readily available or exchangeable potassium.

Unavailable soil potassium is contained within the crystalline structure of micas, feldspars, and clay minerals. Plants cannot use the potassium in these very insoluble forms. Over long periods, these minerals weather or break down, releasing their potassium as the available potassium ion (K^+). This process is far too slow to supply the full potassium needs of field crops. However, trees and long-lived perennials obtain a significant portion of their potassium requirement from the weathering of minerals containing potassium.

Slowly available potassium is associated with clay minerals. As mentioned in chapter 2, individual clay particles are composed of many layers of mineral matter, each separated by water. The layers within certain clay particles are "collapsed" and have trapped or "fixed" the potassium ion. In this trapped or fixed position potassium is considered to be slowly available. Plants cannot use much of the slowly available potassium during a single growing season. However, the supply of fixed potassium largely determines the soil's ability to supply potassium over extended periods of time. For instance, the sandy and silty soils of central and north-central Wisconsin inherently have lower soil tests for available potassium because these soils have a very low supply of fixed potassium. In contrast, the red clay soils of eastern Wisconsin are examples of soils that contain significant amounts of slowly available potassium.

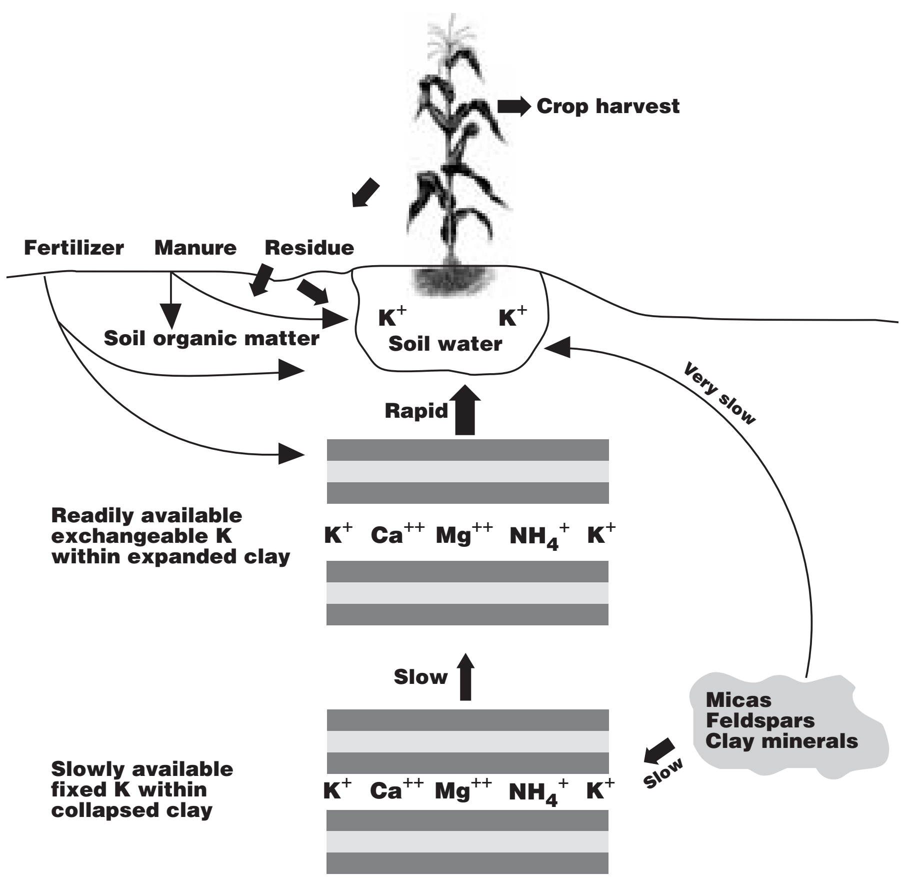
Readily available potassium is dissolved in soil water or held on the surface of clay particles, within "expanded" clay layers, or other soil colloids. Dissolved potassium levels in soil water are usually 5 to 10 ppm. Plants absorb dissolved potassium readily, and as soon as the concentration of potassium in the soil solution drops, more is released into the solution from the exchangeable forms. Most soil tests for available potassium measure the readily available forms but not the unavailable and slowly available forms.

Since clay and organic matter particles hold potassium ions in an exchangeable or available form, potassium does not leach from silty or clayey soils. Some leaching may take place in very sandy soils because sandy soils do not contain enough clay to hold the potassium.

Organic matter particles hold most positively charged nutrients tightly. Potassium is an exception because the attraction between potassium ions and organic matter particles is relatively weak. Consequently, some potassium leaches from organic soils (peats and mucks). Loss of potassium by leaching is one reason sandy and organic soils often test relatively low in available potassium, especially when tested in the spring. These soils require precise annual potassium applications, since it is not possible to build up high potassium reserves.

Figure 9-5 illustrates the forms and reactions of potassium in soil. Plants take up potassium from the soil solution, but this is rapidly replenished

Figure 9-5. Forms and availability of soil potassium.



from the exchangeable potassium reserves on organic and mineral colloids. Potassium added as fertilizer, manure, or crop residue is readily soluble and goes into solution. It then becomes attracted to the negative cation exchange sites. Some of the exchangeable potassium may become "fixed" by entrapment in certain clay minerals. Fixed potassium is released slowly when solution potassium drops to low levels. Most soil potassium (95 to 98%) is present in insoluble minerals that release potassium very slowly upon chemical weathering.

Sources of potassium

In addition to organic matter and soil mineral contributions, potassium is also supplied to soil and plants by commercial fertilizers, manure, and other organic byproducts.

Potassium fertilizers

The most common source of potassium for use on field crops is potassium chloride, or muriate of potash (0-0-60). Most of the U.S. supply of potassium chloride is mined from vast underground deposits in Saskatchewan, although some is also mined in the western U.S. It is the least expensive source of potassium and is as effective as other materials (table 9-8) for most cropping situations. Other sources of potassium fertilizer are used for crops needing sulfur or magnesium applications as well. Also, some crops such as smoking tobacco require the sulfate form of potassium to maintain crop quality. The tobacco does not burn properly when chloride has been added to the soil. Potassium nitrate is often used in greenhouses to reduce the incidence of salt injury, but it is generally too expensive to use in the field. When high rates of potassium are needed or when soil salinity is a problem, potassium fertilizer applications should be split or materials with a lower salt index, such as potassium sulfate or potassium magnesium sulphate, should be used.

Chloride versus sulfate. The fertilizer source of potassium is sometimes debated, especially for row fertilizers. Some advisors maintain that the chloride in potassium chloride reduces the uptake of phosphorus, while the sulfate in potassium sulfate does not. However, research does not show that the sulfate form of potassium is any better than the chloride form.

The names chlorine and chloride are frequently confused. The element chlorine exists in nature as chloride salts of calcium, magnesium, potassium, and sodium. Chlorine gas (Cl_2), which is used for water purification, is manufactured from chloride salts and is extremely reactive and unstable. The non-reactive chloride is the form present in soils and the form found in fertilizer. In fact, the potassium chloride in fertilizer (KCl) is simply a salt, similar to table salt (NaCl), and will not affect soil organisms when applied at recommended rates.

Red versus white potash. Muriate of potash is mined as a mixture of potassium chloride and small quantities of sodium chloride, clay, and several impurities, including iron. The iron impurities give muriate of potash its reddish color. Removing the impurities gives a white product containing 62% potash, slightly higher than the 60% potash in red potash. White potash has no agronomic advantage over red potash and is more expensive. Since white potash contains fewer impurities, it does have an advantage when used in a mixed liquid fertilizer because it does not precipitate as easily as red potash.

Manure

Manure contains substantial amounts of potassium, but, similar to nitrogen and phosphorus, some of the potassium is in the organic form and is not all available in the first year

Table 9-8. Potassium fertilizers.

Name of fertilizer	Chemical formula	Fertilizer analysis (%) $N-P_2O_5-K_2O$	Salt index
Potassium chloride (muriate of potash)	KCl	0-0-60 to 0-0-62	116
Potassium-magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	0-0-22	43
Potassium nitrate	KNO_3	13-0-44	74
Potassium sulfate	K_2SO_4	0-0-50	46

following application. The amount of manure potassium available to a crop depends on the type of manure, the application rate, and the consecutive years of application. Fertilizer potassium applications should be reduced or eliminated following manure applications. Table 9-9 lists first-year potassium credits for solid and liquid manure. Additional information on using manure as a nutrient resource can be found in chapter 10.

Secondary nutrients

Calcium, magnesium, and sulfur are known as secondary nutrients, but this does not mean that they play a secondary role in plant nutrition. They simply do not limit plant growth as frequently as nitrogen, phosphorus, or potassium, the primary nutrients.

Calcium

Calcium (Ca) is relatively abundant in soils and rarely limits crop production. It makes up about 3.6% of the earth's crust. It is present in soil minerals such as amphibole, apatite, calcite, dolomite, feldspar, gypsum, and pyroxene. Calcium is a component of cell walls and is also important for cell division and elongation, permeability of cell membranes, and nitrogen metabolism. It is different from most plant nutrients in that it is only moved within the plant by the water moving from the roots through the leaves.

Calcium deficiency is rare for Wisconsin field crops. The few known instances were usually associated with acid soils (pH 5.0 or less) low in organic matter. When calcium is deficient, a plant's terminal buds and roots fail to develop. Deficiency symptoms show up first at the growing points because calcium is immobile in plants. In calcium-deficient corn, the new leaf tips stick together and prevent the normal emergence and unfolding of new leaves, a condition known as buggy whipping. However, other stresses such as herbicide injury more commonly cause buggy whipping.

Reaction in soils. Calcium is the predominant positively charged ion (Ca^{++}) held on soil clay and organic matter particles because it is held more tightly than magnesium (Mg^{++}), potassium (K^{+}), and most other exchangeable cations. Parent materials from which soils are formed also usually contain more calcium than magnesium or potassium. Therefore, soils normally have large amounts of exchangeable calcium (300 to 5000 ppm). Leaching of calcium through soils does not normally occur to any appreciable extent because of its relatively strong attraction to the surface of clay particles.

Calcium/magnesium ratios. Claims regarding the "balance" of calcium and magnesium and the need to adjust the ratio of calcium to

Table 9-9. Potassium content and first-year credits for solid and liquid manure.

Type of manure	Total K_2O available in first year	K_2O content of manure — Solid — Total	Credit	— Liquid — Total	Credit
	— % —	— lb/ton —		— lb/1,000 gal —	
Beef	80	11	9	20	16
Dairy	80	9	7	20	16
Poultry	80	30	24	12	10
Swine	80	9	7	30[a]	24[b]

[a] *Value for liquid indoor-pit swine manure. Use 20 and 22 for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
[b] *Value for liquid indoor-pit swine manure. Use 16 and 18 for liquid outdoor-pit and liquid, farrow-nursery, indoor-pit swine manure, respectively.*
Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590.

magnesium in Wisconsin soils are unsubstantiated. Those who favor this idea suggest that Wisconsin soils contain low or deficient levels of calcium and/or toxic levels of magnesium, and that calcitic limestone ($CaCO_3$) or gypsum ($CaSO_4$) is needed to correct this condition. Research conducted in Wisconsin does not support these claims. Soils with a pH above 6.0 usually contain adequate amounts of exchangeable calcium for agronomic crops, and magnesium levels in Wisconsin are not toxic. Calcium/magnesium ratios typically range from 1:1 to 8:1, which research has proven to support normal plant growth. Dolomitic lime ($CaCO_3$ + $MgCO_3$) has a calcium/magnesium ratio (about 2:1) that is within the range for normal crop growth. Dolomitic limestone is considerably less expensive than calcitic limestone and gypsum. Research does not support using more expensive products to add calcium or change the calcium/magnesium ratio. Consult Extension publication *Soil Calcium to Magnesium Ratios—Should You Be Concerned?* (A2986) for more information.

Sources of calcium. Limestone applied to correct soil acidity is the predominant source of applied calcium. The limestone quarried in Wisconsin contains 300 to 400 pounds of calcium per ton. The amount of calcium normally added in limestone applications, combined with the relatively large amounts of exchangeable calcium in Wisconsin soils, far exceeds the 25 to 100 pounds per acre annually removed by crops. Dolomitic lime is recommended for correcting soil acidity in Wisconsin, although some calcium is supplied from other sources. Table 9-10 lists the amount of calcium in several liming and fertilizing materials. Gypsum contains 20 to 22% calcium. It is not recommended as a source of calcium except for soils with a low cation-exchange capacity supporting crops that require an acidic soil.

Table 9-10. Sources of calcium.

Material	Approximate chemical formulation	Percent calcium
Calcitic lime	$CaCO_3$	40
Dolomitic lime	$CaCO_3 + MgCO_3$	22
Gypsum	$CaSO_4 \cdot 2H_2O$	22
Ordinary superphosphate, 0-20-0	$Ca(H_2PO_4)_2 + CaSO_4$	20
Paper mill lime sludge	————	38
Slaked lime	$Ca(OH)_2$	54
Triple superphosphate, 0-46-0	$Ca(H_2PO_4)_2$	14

Magnesium

Magnesium (Mg) is abundant in Wisconsin soils. It makes up about 2.7% of the earth's crust. Many common soil minerals contain magnesium, including amphibole, biotite, chlorite, dolomite, montmorillonite, olivine, pyroxene, serpentine, and vermiculite. Soils developed from coarse-grained rocks low in these minerals tend to be low in magnesium. Most fine-textures soils and soils developed from rocks high in magnesium minerals contain adequate amounts. Magnesium is a component of chlorophyll in plants and is also an activator of several enzyme systems within the plant.

A deficiency of magnesium results in an interveinal yellowing (chlorosis) of the plant leaves. Because magnesium moves readily from lower to upper parts of the plant, the deficiency appears first on the lower leaves. As the deficiency becomes more severe, the leaves may turn reddish purple. Deficiency symptoms are not definitive, and it is sometimes difficult to distinguish between magnesium deficiency or toxicity of manganese, although the latter cases are usually confined to newer plant growth.

Animals grazed on grass pastures low in magnesium sometimes develop hypomagnesemia, or grass tetany. This problem occurs primarily where calcitic limestone ($CaCO_3$) is used as a liming material. Grass tetany is rare in Wisconsin because dolomitic limestone ($CaCO_3$ + $MgCO_3$) has been used on most of our soils and because forage legumes, which contain higher levels of magnesium than do grasses, make up a substantial part of livestock rations.

Reaction in soils. Magnesium ions are held on the surface of clay and organic matter particles. While this exchangeable form of magnesium is available to plants, it will not leach easily from the soil.

Acid soils, especially sands, often contain relatively low levels of magnesium. Neutral soils or those with a high pH usually contain more than 500 parts per million (ppm) of exchangeable magnesium. Use of dolomitic lime has prevented magnesium deficiency in most of Wisconsin. However, a few of the soils that may be deficient are listed below:

- soils limed with materials low in magnesium, such as paper mill waste, marl, or calcitic limestone;
- acid sandy soils (usually in central and north-central Wisconsin);
- organic soils containing free calcium carbonate or marl.

In sandy soils, application of high rates of potassium or ammonium fertilizer often heightens magnesium deficiency. High concentrations of these cations in the soil solution interfere with magnesium uptake by plants. This interference, called antagonism, usually does not occur when the soil contains more exchangeable magnesium than exchangeable potassium.

Sources of magnesium. The most economical way of correcting magnesium deficiency in an acid soil is to apply dolomitic limestone. If soil pH is already high, however, or if the crop requires an acid soil (such as potato and some fruits), then other carriers of magnesium such as Epsom salts ($MgSO_4 \cdot 7H_2O$) or potassium-magnesium sulfate ($K_2SO_4 \cdot 2MgSO_4$) must be used. If excessive potassium fertilization has induced magnesium deficiency, Epsom salts are the best source. Correction of magnesium deficiency with Epsom salts or potassium-magnesium sulfate requires 50 to 100 pounds of magnesium per acre when broadcast or 10 to 20 pounds per acre when applied in a band alongside the row. Table 9-11 provides the magnesium content of common magnesium sources.

Sulfur

Sulfur (S) is present in plants at concentrations similar to those of phosphorus, calcium, and magnesium. Legume forages and cole crops (broccoli, cabbage, etc.) have relatively high sulfur requirements. Like nitrogen, sulfur is taken up as an anion ($SO_4^{=}$).

Function in plants. Sulfur is a component of the amino acids cysteine, cystine, and methionine. These amino acids are among the building blocks of protein, and shortage of sulfur retards synthesis of proteins.

Sulfur, as a constituent of nitrate reductase, is involved in the conversion of nitrate into organic nitrogen. Sulfur deficiency consequently interferes with nitrogen metabolism, which explains why nitrate accumulates when sulfur is deficient and why sulfur deficiency resembles nitrogen deficiency in many crops. However, the symptoms usually are not as dramatic and are not localized on the older leaves. Lack of sulfur appears as a light green coloring of the whole plant. Legumes, especially alfalfa, have a high sulfur requirement, so deficiencies usually appear on these crops first. Corn, small grains, and other grasses show sulfur deficiencies less frequently. Sulfur deficiency in corn sometimes mimics other deficiencies such as manganese or magnesium in that it causes interveinal chlorosis: the upper leaves tend to be striped, with the veins remaining a darker green than the area between the veins.

Table 9-11. Sources of magnesium.

Material	Chemical formula	Percent magnesium
Dolomitic lime	$CaCO_3 + MgCO_3$	8–20
Epsom salts	$MgSO_4 \cdot 7H_2O$	10
Kieserite	$MgSO_4 \cdot H_2O$	18
Potassium magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	11

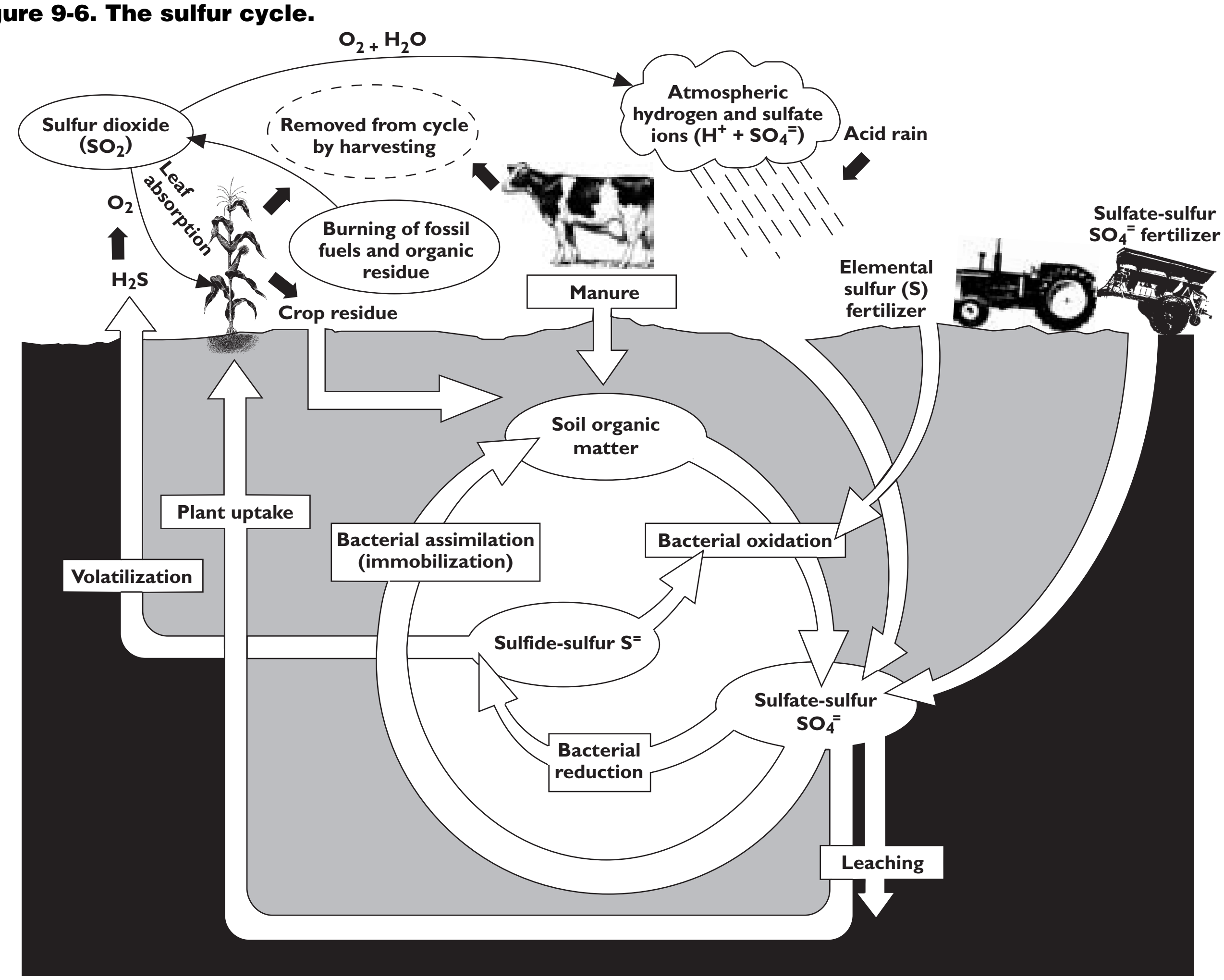
Reactions in soils. Sulfur transformations are very similar in some respects to those of nitrogen. Most sulfur in the soil is unavailable as a part of the soil organic matter. As shown in figure 9-6, organic sulfur and reduced sulfide sulfur ($S^=$) combine with oxygen to form available sulfate-sulfur ($SO_4^=$) in warm, well-aerated soils. This process is very similar to the conversion of organic nitrogen into available ammonium (NH_4^+) and nitrate-nitrogen (NO_3^-).

Available sulfate-sulfur is tied up by bacteria during the decomposition of crop residues rich in carbon. Available sulfur can also be changed into unavailable sulfide sulfur in waterlogged soils. Fortunately, this immobilized or reduced sulfur is usually only temporarily unavailable. As the soil warms or as aeration improves, this unavailable sulfide sulfur combines with oxygen to again form available sulfate-sulfur. But under prolonged waterlogged conditions, as in a marsh, sulfur can be lost as hydrogen sulfide gas (H_2S).

Harvesting and leaching remove sulfur from soil. Sulfate-sulfur is not readily held by soil particles, except for acid clays, so in most soils it can be leached below the root zone. However, sulfate-sulfur does not leach as readily as nitrate-nitrogen, and some acid, clayey subsoils contain sizeable reserves of available sulfate.

Sources of sulfur. Soils commonly contain 200 to 600 pounds of total sulfur per acre. Nearly all is in the unavailable, organic form. As organic matter decomposes, a small portion of this sulfur is converted into available (inorganic) sulfate-sulfur. Approximately 2.8 pounds of sulfur per acre are released annually from each 1% organic matter in Wisconsin soils. Another source of sulfur is atmospheric deposition, which results from the burning of coal and, to a lesser extent, oil and gas. This atmospheric sulfur is

Figure 9-6. The sulfur cycle.



washed from the air and deposited on the land in rainwater and snow. Each year, precipitation typically deposits 5 to 15 pounds of sulfate-sulfur per acre in Wisconsin. Western and northern Wisconsin receive about 5 pounds of sulfate-sulfur per acre annually; the remainder of the state gets about twice as much.

All sulfate forms of sulfur fertilizer are equally effective when surface-applied or incorporated (table 9-12). Elemental sulfur, however, is insoluble and must be transformed into sulfate-sulfur by soil bacteria before plants can use it. The rate of this transformation depends on particle size and degree of mixing with the soil. To be effective, elemental sulfur should be worked into the soil well in advance of the time the crop needs it. Without mechanical incorporation, elemental sulfur is incorporated to some extent by falling into cracks when the soil dries or by the activity of earthworms and burrowing insects. If the soil is known to be deficient in sulfur, include some sulfate-sulfur in topdress applications for immediate sulfur availability.

Sandy soils may require annual applications of sulfate forms of sulfur because the sulfate leaches through these soils relatively rapidly. Irrigation water, however, may contain sufficient sulfate-sulfur for the crop. In these cases, response to fertilizer sulfur is likely only in years with above-average rainfall, when little irrigation water is applied.

Manure is another source of sulfur. The sulfur contribution from manure varies with animal species and rate of application (table 9-13). About 60% of total manure sulfur becomes available to crops in the year of application. An additional source of sulfur is the subsoil. Clayey, acidic subsoils may contain substantial amounts of plant-available sulfate-sulfur. Annual sulfur-supplying capacities of subsoils are considered low at 10 pounds per acre, medium at 20 pounds per acre, or high at 40 pounds per acre.

Row crops and small grains require about 10 pounds of sulfur per acre in sulfur-deficient areas. Alfalfa requires 25 to 50 pounds per acre if applied during the seeding year or 15 to 25 pounds per acre when topdressed on established alfalfa. These treatments generally will supply enough sulfur to last 2 to 3 years. Sulfur may be applied as row fertilizer, but thiosulfate should not be seed-placed.

Table 9-12. Sulfur fertilizers.

Material	Chemical formula	Fertilizer analysis $N–P_2O_5–K_2O$	Sulfur content
		— % —	— % —
Very soluble			
Ammonium sulfate	$(NH_4)_2SO_4$	21-0-0	24
Potassium sulfate	K_2SO_4	0-0-50	18
Potassium-magnesium sulfate	$K_2SO_4 \bullet 2MgSO_4$	0-0-22	23
Ammonium thiosulfate[a]	$(NH_4)_2S_2O_3 + H_2O$	12-0-0	26
Magnesium sulfate (Epsom salts)	$MgSO_4 \bullet 7H_2O$	0-0-0	14
Ordinary superphosphate	$Ca(H_2PO_4)_2 + CaSO_4$	0-20-0	14
Slightly soluble			
Calcium sulfate (gypsum)	$CaSO_4 \bullet 2H_2O$	0-0-0	17
Insoluble			
Elemental sulfur	S	0-0-0	88–98

[a]*Ammonium thiosulfate is a 60% aqueous solution.*

Micronutrients

Plants need only very small amounts of micronutrients (trace elements) for optimum growth. While a deficiency of any essential element greatly reduces plant growth, the overuse of some micronutrients can be detrimental. The danger of building up toxic levels is greater on coarse-textured soils such as sands and sandy loams than on finer-textured soils.

Micronutrients should be applied only in the following situations:

- when the soil test is low,
- when definite micronutrient deficiency symptoms appear on the plant,
- when plant analyses indicate low levels in the plant, and
- on specific crops that have a very high micronutrient requirement.

Boron

Boron (B) is needed by plants for cell division, cell wall synthesis, and pollen germination. Boron deficiencies in Wisconsin are more widespread than deficiencies of any other micronutrient. Only 0.5 to 2.5% of boron in the soil is available to plants. Soils may contain 0.5 to 2.0 parts per million (ppm) of available boron, but more than 5.0 ppm of available boron can be toxic to many agronomic crops. Lack of boron often limits production of forage legumes (alfalfa, clover, trefoil) and of some vegetable crops in the state. Plants take up less than 0.5 pounds of boron per acre, yet lack of this nutrient can reduce yields severely. When deficient, the plants' growing points stop developing and will eventually die if the deficiency persists.

Crops vary in their need for boron. Crops with a high requirement include alfalfa, beet, canola, cauliflower, celery, sunflower, tomato, birdsfoot trefoil, and forage brassicas. Those with a medium requirement are apple, asparagus, broccoli, brussels sprouts, cabbage, carrot, lettuce, melons, radish, red clover, spinach, tobacco, and vetch.

The storehouse for most of the boron in soils is the soil organic matter. As a result, most of the available boron is in the plow layer, where organic matter is highest. Soils low in organic matter are deficient in boron more often than other soils.

When the surface soil dries out, plants are unable to feed in the zone where most of the available boron is present. This can lead to boron deficiency. When rain or irrigation moistens the soil, the plants can again feed from the surface soil and the boron deficiency often disappears.

Like nitrates, boron is not readily held by the soil particles and moves down through coarse-textured soils, often leaching below the root zone of many plants. Because less leaching occurs on fine-textured silts and clays, these soils are not boron deficient as often as sands.

On alfalfa, the easiest way to apply boron is in combination with topdressed fertilizers. If a soil tests low in available boron or if a deficiency appears, apply 0.5 to 1.0 pounds of boron per acre each year or 2 pounds per acre once in the rotation as a topdressing for forage legumes. For forage legumes grown on sandy soils, an annual application of 0.5 to 1.0 pounds of boron per acre minimizes the leaching effect. Never use a borated

Table 9-13. Sulfur content and first-year credits for solid and liquid manure.

Type of manure	Total sulfur available in first year	Sulfur content of manure — Solid — Total	Solid — Credit	Liquid — Total	Liquid — Credit
	— % —	— lb/ton —		— lb/1,000 gal —	
Beef	60	1.5	0.9	2.3	1.4
Dairy	60	1.3	0.8	2.3	1.4
Poultry	60	4.0	2.4	5.0	3.0
Swine	60	2.5	1.5	4.2	2.5

Source: University of Wisconsin Soil & Forage Analysis Laboratory, Marshfield, WI.

fertilizer in the row for corn or soybean, or in the drill for oats. The boron concentrated in a band is toxic to germination of these crops and may cause severe injury.

Manganese

Manganese (Mn) functions as an enzyme activator for steps in photosynthesis. It is an element found in plant tissue at concentrations ranging from 10 to 500 ppm or more. In most plants, it is deficient at less than 10 ppm and toxic when the concentration exceeds about 300 ppm. Deficiency symptoms are most common in oats, snapbeans, and soybeans grown in high pH (6.5 or greater) mineral soils and neutral to alkaline organic soils. Symptoms appear as interveinal chlorosis of the younger leaves because manganese is an immobile element. In oats, the symptoms show up as specks of dead tissue, giving the deficiency the name "gray speck disease."

Crops with high manganese requirements include beans (lima, snap), lettuce, oat, onion, radish, raspberry, soybean, spinach, sorghum-sudan, and wheat. Those with medium manganese needs are barley, beet, broccoli, brussel sprout, cabbage, carrot, cauliflower, celery, corn, cucumber, pea, potato, tobacco, and tomato.

Manganese availability increases as soil pH decreases. Manganese toxicity is common in acid soils below pH 5.5, especially when these soils are low in organic matter and temporarily waterlogged. Acid, sandy soils are likely to contain high manganese levels. Crops susceptible to manganese toxicity include asparagus, forage legumes, mint, and pea. Manganese toxicity of potato has also been identified on extremely acid soils (pH less than 5.0).

One of the main reasons for liming acid soils, especially for legumes, is to prevent manganese toxicity. The amount of manganese in solution decreases 100-fold for each unit rise in soil pH (as from 5.0 to 6.0). Where manganese deficiency exists as a result of high pH, it is easier to correct the deficiency by adding a manganese fertilizer than by attempting to acidify the soil.

Broadcast applications of manganese fertilizer or attempts to build soil test manganese levels are not recommended, particularly on high pH, high organic matter soils because of their capacity to rapidly fix manganese. Band application reduces chemical fixation by reducing contact with soil particles. Mixing manganese with ammonium nitrogen in a fertilizer band further improves its availability as a result of the acidity produced as ammonium converts to nitrate.

Although chelated manganese is effective as a foliar application, its use as a soil application can actually aggravate the deficiency. Apparently, the manganese chelate converts to the more stable iron chelate causing the plant to take in more iron, which suppresses the uptake of manganese.

Zinc

Zinc (Zn) is required for the synthesis of a growth hormone (indoleacetic acid) by plants. Also, it functions as an enzyme activator in carbohydrate metabolism and protein formation. Deficiency symptoms usually appear first on relatively young leaves early in the growing season. On corn, a broad band of bleached tissue appears on either side of the midrib. The deficiency begins at the base of the leaf and usually stays in the lower half of the leaf.

In broadleaf plants, zinc deficiency results in a shortening of internodes (rosetting) and a decrease in leaf size (little leaf). Snapbean develops a yellowing between the leaf veins (interveinal chlorosis). However, it is very difficult to distinguish between zinc and manganese deficiencies in this crop.

Crops generally take up less than 0.5 pounds of zinc per acre, yet when zinc is deficient, crop yields are reduced markedly. Plants vary considerably in their requirements for zinc. Crops with high zinc requirements include corn, onion, and spinach. Those with medium requirements are barley, beans, beets, canola, cucumber, lettuce, lupine, potato, radish, sorghum-sudan, soybean, tobacco, and tomato. Other crops have low zinc requirements and seldom exhibit zinc deficiency. In Wisconsin, zinc deficiencies have been observed on corn, snapbean, and a few other vegetable crops.

Scalped or severely eroded soils are more apt to be zinc deficient than well-managed soils. Also, sands, sandy loams, and organic soils are more likely to be zinc deficient than silty or clayey soils. This is due to the fact that sandy and organic soils originally contain low total zinc levels. Severe soil compaction can also reduce zinc availability.

Soil acidity (pH) influences the availability of zinc more than any other factor, with lower zinc solubility as the pH increases. Therefore, zinc deficiency usually is limited to soils with a pH above 6.5. Overliming of soils, especially sands, may induce zinc deficiency.

Copper

Copper (Cu) serves as an activator of several enzyme systems in plants. It is present in soils at concentrations of 2 to 100 ppm with an average value of about 30 ppm. Beets, lettuce, onion, spinach, sunflower, and tomato have relatively high copper requirements. Copper deficiency is rare in Wisconsin. Occurrences have been confined to acid organic soils. Organic matter binds copper more tightly than any other micronutrient. Copper toxicity in some sandy soils has resulted from repeated use of copper-containing fungicides over many years.

Iron

Iron (Fe) is required for synthesis of chlorophyll by plants, but it is not part of the chlorophyll molecule. Iron is very immobile in plants, so deficiency symptoms appear on new growth. The veins of young leaves remain green, but the area between the veins becomes yellow (chlorotic). Each new leaf emerges paler than the one before. Eventually, new leaves, including the veins, are creamy white, devoid of chlorophyll.

Iron deficiency has rarely been observed on field or vegetable crops in Wisconsin, except that iron chlorosis has occasionally been observed on soybeans grown on alkaline soils (pH above 7.0). However, turfgrass, pin oak trees, and some ornamentals such as yews occasionally develop iron deficiency when grown on alkaline soils. The deficiency can be corrected by spraying the foliage several times with ferrous sulfate or an iron chelate. Soil applications are not very effective because of the rapid transformation of iron contained in fertilizer to unavailable forms in the soil. An exception is soil application of the stable chelate, FeDDHA, that has had some success in correcting iron deficiency.

Molybdenum

Plants need extremely small amounts of molybdenum (Mo). Normal tissue concentrations are 0.03 to 1 ppm. Molybdenum is required for symbiotic nitrogen fixation and for converting nitrate ions into organic nitrogen in the plant. Hence, the first symptom of molybdenum deficiency is nitrogen deficiency. If the deficiency is severe, the leaf edges of some vegetable crops may become brown and curl upward (cupping). Cupped leaves may look rolled and show interveinal chlorosis. Molybdenum deficiency in cauliflower leads to a classic condition known as whiptail, in which leaves sometimes appear crinkled or withered. Broccoli, cauliflower, lettuce, onion, spinach, and table beets are responsive to this element; corn, small grains, and potato are not.

Soil acidity has a marked influence on the availability of molybdenum. As soil pH decreases, the availability of molybdenum decreases. Liming alone is usually enough to correct a deficiency. Legume crops grown on very acid soils should be seed-treated with molybdenum. Soil applications of molybdenum are not recommended because only 1 ounce per acre is required, and this amount would be difficult to spread evenly even if mixed with another fertilizer. Seed treatment or foliar sprays are the recommended application techniques. Follow molybdenum recommendations closely because excess molybdenum in feed or forage can cause animal health problems (molybdenosis).

Chlorine

The earth's crust contains about 500 parts per million of chlorine (Cl), with average soil concentration estimated at 100 ppm. Chlorine is a "universal contaminant." It is present as chloride in ocean water and gets into the atmosphere as ocean spray. Plants require chlorine for certain photochemical reactions in photosynthesis. Chlorine uptake affects the degree of hydration of plant cells and balances the charge of positive ions in cation transport. Chlorine deficiency has been induced in the laboratory, but it has never been observed under field conditions in Wisconsin. Response to chlorine, expressed as reduced incidence of disease and higher yield in small grains, has been observed in a few studies in Oregon and the Dakotas. The soils in these states have high levels of potassium so potassium chloride fertilizer (0-0-60) is seldom applied. However, because Wisconsin soils tend to be inherently low in potassium, application of potassium chloride fertilizer and manure has precluded chlorine deficiency.

Nickel

Nickel has recently been identified as an essential plant nutrient. It is needed by plants to form the enzyme urease which breaks down urea-nitrogen for plant use. Nickel is also involved in plant uptake of iron from soil. Deficiencies of nickel are not known to exist in Wisconsin. Generally, there is greater concern about nickel toxicity, particularly on soils where sewage sludge has been applied. (See chapter 11 for further information.)

Summary of the fate of applied nutrients

The chemical form of the plant nutrients in fertilizers and the reactions which take place after they are added to soil have been discussed. All nutrients applied as fertilizer must first dissolve in soil moisture. Some remain in solution until they are absorbed by plant roots or leach with percolating water. Most nutrients, however, move out of soil solution and form insoluble compounds and organic complexes, except for cations which are held on the soil cation exchange sites.

Nutrients with similar chemical properties undergo similar chemical reactions when applied to the soil. The fate of applied nutrients is summarized in table 9-14. Nitrate, sulfate, borate and chloride ions tend to remain in solution. Phosphorus, iron, manganese, and molybdenum form insoluble compounds. Elemental sulfur is insoluble, but it is slowly oxidized to soluble sulfate by sulfur-oxidizing bacteria in soil.

Copper, boron and zinc form stable organic complexes. Iron and manganese do so to a lesser extent.

Calcium, magnesium, potassium and ammonium-nitrogen are the predominant exchangeable cations. Much lesser amounts of copper, iron, manganese, and zinc are also found in the soil as exchangeable cations. Exchangeable ammonium is relatively high immediately after application but is quickly converted to nitrate under favorable temperature, moisture, and pH conditions.

Table 9-14. Fate of applied nutrients under normal soil conditions.

Nutrient added	Chemical form(s) of the added nutrient	Where found in the soil	Leaching susceptibility
Nitrogen Sulfur Boron Chlorine	NO_3^- $SO_4^=$ H_3BO_3, $H_2BO_3^-$ Cl^-	soil solution	high
Phosphorus Sulfur Manganese Iron Molybdenum	$H_2PO_4^-$, $HPO_4^=$ S[a] Mn^{++} Fe^{++}, Fe^{+++} $MoO_4^=$	insoluble compounds	very low
Boron Copper Zinc	$H_2BO_3^-$ Cu^{++} Zn^{++}	organic complexes	very low
Nitrogen Potassium Calcium Magnesium	NH_4^+[b] K^+ Ca^{++} Mg^{++}	soil exchange sites	low to moderate

[a] *Elemental sulfur (S) is slowly converted to sulfate ($SO_4^=$).*
[b] *Ammonia (NH_3) is immediately changed to ammonium (NH_4^+) when injected into the soil. Ammonium (NH_4^+) is rapidly converted to nitrate (NO_3^-) by soil bacteria during the growing season.*

Fertilizer analysis

The analysis of fertilizer is given in terms of the percent total nitrogen, available phosphate (P_2O_5), and water-soluble potash (K_2O), as determined in a laboratory. Fertilizer grade is the guaranteed minimum analysis in percent of the major plant nutrient elements in the fertilizer. If an analysis of 6-24-24 is given for a fertilizer material, it contains 6% total nitrogen, 24% available phosphate, and 24% water soluble potash. An application of 200 pounds per acre of 6-24-24 would mean that 12 pounds of nitrogen (200 lb x 6% N), 48 pounds of phosphate (200 lb x 24% P_2O_5) and 48 pounds of potash (200 lb x 24% K_2O) were applied.

Expression of the phosphorus and potassium in the oxide form, even though there is no phosphate nor potash in fertilizer, is a carryover from the early days of agricultural chemistry. It would be simpler and less confusing to express the content of phosphorus and potassium on the elemental basis (P and K), but the oxide analysis (P_2O_5 and K_2O) has become so entrenched that it would be difficult to change. Table 9-15 summarizes phosphorus and potassium terminology.

To convert from one means of expression to another, use the following conversion factors:

Phosphorus (P) = phosphate (P_2O_5) x 0.44
Phosphate (P_2O_5) = phosphorus (P) x 2.29
Potassium (K) = potash (K_2O) x 0.83
Potash (K_2O) = potassium (K) x 1.20

At the present time, fertilizer phosphorus and potassium are still guaranteed on the oxide basis, and likely will remain so, because the fertilizer industry has no interest in changing to the elemental basis. A few common fertilizers expressed both ways are given below:

Oxide basis	Approximate elemental basis
—— % ——	—— % ——
10-20-20	10-9-17
6-24-24	6-10-20
9-23-30	9-10-25
0-15-30	0-7-25

When a fertilizer such as 6-24-24 (6-10-20 on the elemental basis) is used, farmers sometimes question why they have to buy 46% filler with their 54% (6% + 24% + 24% = 54%) fertilizer. There is little, if any, filler in the fertilizer sold today; in this example the remaining 46% is carrier. The elemental forms of phosphorus and potassium are very unstable. In their pure form, these materials are so reactive that they immediately burst into flames if exposed to air. To apply plant nutrients like phosphorus and potassium they have to be combined with another element—a carrier—to form a fertilizer salt. In nature they are combined with other elements—carriers—to form salts. Fertilizer salts are stable and can be handled easily. For example, the most concentrated commercial source of potassium is potassium chloride. It is a 50:50 mixture of potassium (K) and chloride (Cl) so it contains no filler; it consists entirely of potassium and the chloride carrier.

Forms of commercial fertilizer

Fertilizers are sold in different forms: as dry granules; as a pressureless liquid; and, in the case of nitrogen, as a high-pressure liquid. No difference in crop response has been noted between the different forms of fertilizer when equivalent amounts of plant nutrients are applied. Two pounds of liquid 8-8-8 is just as effective as 1 pound of dry 16-16-16. The choice of which form of fertilizer to apply should be made on the basis of cost per pound of plant nutrient, convenience, and availability of materials.

Occasionally, extravagant claims are made for certain liquid or dry fertilizers made from "special" sources of plant nutrients. These claims are not

Table 9-15. Phosphorus and potassium terminology.

Element name and symbol	Oxide name and symbol	Plant uptake form
Phosphorus (P)	Phosphate (P_2O_5)	$H_2PO_4^-$
Potassium (K)	Potash (K_2O)	K^+

substantiated by research results. Furthermore, since plants take up the ionic form of the nutrient, differences between the various carriers or sources of plant nutrient would not be expected.

Fertilizer grades

Fertilizer materials are sold according to different percentages of plant nutrients, commonly called fertilizer grades. A fertilizer ratio is the relative proportion of the percentages of nitrogen, phosphate, and potash in the mixture. A 6-24-24 fertilizer, for example, has a ratio of 1:4:4. When comparing the cost of different fertilizers, valid comparisons can be made only between fertilizer grades having the same ratio of $N:P_2O_5:K_2O$. A 5-20-20 and a 6-24-24 have the same ratio (1:4:4). The 5-20-20 should cost ⅚ as much as the 6-24-24. Similarly, 5-10-10 should cost half as much as 10-20-20. A method of comparing the costs of fertilizers with different grades is discussed in chapter 13.

Premium grades of fertilizer are available for some crops. These contain slightly higher levels of micronutrients than that removed by the crop and, therefore, may be regarded as a maintenance application. This, however, is not always a profitable practice because there may be sufficient levels of some micronutrients in the soil to last for hundreds of years.

Another important point is that if a severe deficiency of a micronutrient exists, most "premium" grades will not contain enough of the deficient nutrient to correct the problem. Whenever soils are deficient in boron, copper, manganese, or zinc, use a special mix fertilizer that contains the required amount of the deficient micronutrient.

Manufactured and blended fertilizers differ in the composition of individual fertilizer granules. A manufactured, or homogeneous, fertilizer is chemically combined so that each granule theoretically has the same composition. A blended fertilizer is a mixture of particles of different materials to give the desired composition. Which is better? Field studies have shown that blended fertilizers made up of particles of the same size and density are just as effective as manufactured fertilizers. However, manufactured fertilizers have some advantage when including ingredients such as micronutrients or pesticides because the additives can be more evenly combined with the fertilizer particles.

Liquid versus dry fertilizer is a choice that should be based on convenience in handling, cost of nutrients, and availability of equipment

Table 9-16. Comparison of liquid and dry starter fertilizers for corn.

Material	Form	Rate of application	Nutrients applied N	P_2O_5	K_2O	Corn yield[a]
		lb/a				bu/a
Control	—	0	0	0	0	125
Seed-placed						
9-18-9	liquid	36	3.2	6.5	3.2	133
7-14-7	liquid	46	3.2	6.5	3.2	128
Side (row) placed						
6-24-24	liquid	100	6	24	24	139
6-24-24	dry	100	6	24	24	137
6-24-24	liquid	200	12	48	48	141
6-24-24	dry	200	12	48	48	138

[a] *Three-year average except for control (two-year average).*
Source: Wolkowski, R.P., and K.A. Kelling. 1985. J. Fert. Issues 2:1–4.

for handling, storage, and application. The fact that nutrients in liquid fertilizer are already dissolved does not make them more available to plants. Availability is controlled by the reactions these nutrients undergo with soil particles when added to the soil, the same as with dry materials. When applied at the same rate, there is no difference in performance between liquid and dry fertilizer (table 9-16). However, as would be expected, lower rates of seed-placed fertilizer are not as effective as much higher rates of side-placed fertilizer.

Liquid fertilizer is often more costly than dry fertilizer because (1) there is a cost involved in adding water to make a liquid and in transporting the liquid, and (2) more expensive, purified materials must be used to prevent impurities and precipitates from plugging applicator hoses, valves, and nozzles. However, the extra cost of liquid fertilizer may be offset by the convenience, ease of handling, improved mixing of additives, or other factors.

Methods of fertilizer application

There are many methods of fertilizer application. The principal methods are discussed below.

Starter or row application

Starter or row application of fertilizer is often needed to get a row crop off to a fast start in the spring. This treatment is particularly valuable during a cool, wet spring when nitrogen and phosphorus are not released fast enough from organic matter to satisfy the early needs of the crop. Starter fertilizers promote vigorous seedling growth by providing a high concentration of readily available nutrients near the germinating seed.

A minimal amount of starter fertilizer is recommended for corn planted in Wisconsin soils that are slow to warm in the spring. For corn grown on medium and fine-textured soils, a minimum application of 10 pounds nitrogen, 20 pounds P_2O_5, and 20 pounds K_2O per acre is recommended as a starter at planting. In most cornfields, all the recommended P_2O_5 and K_2O can be applied as starter fertilizers. On soils with test levels in the excessively high range, starter fertilizer applications in excess of 10 pounds N, 20 pounds P_2O_5, and 20 pounds K_2O per acre should be avoided.

Corn yield responses to starter fertilizer additions do occur on soils that are excessively high in phosphorus and potassium. The probability of a yield response can be estimated using site-specific information about individual fields. Crop yield increases with starter additions are much more likely if soil test potassium levels are less than 140 ppm and/or the corn is planted too late to achieve its full yield potential. Responses are more likely with late planting dates and long-season relative maturity hybrids. The probability of response to starter fertilizer on excessively high testing soils at a range of hybrid relative maturity and planting dates is shown in table 9-17.

Table 9-17. Probability of obtaining a positive economic return from starter fertilizer for corn grown on soils with excessively high phosphorus and potassium levels.[a]

Corn relative maturity ratings	Planting date: 4/25	5/1	5/5	5/10	5/15	5/20	5/25	5/30
	% probability							
90	10	15	20	25	30	35	40	45
95	15	20	25	30	35	40	45	50
100	20	25	30	35	40	45	50	55
105	25	30	35	40	45	50	55	60
110	30	35	40	45	50	55	60	65

[a] *This table does not alter current recommendations for early planting and selection of corn hybrids with appropriate relative maturities for the production zone.*

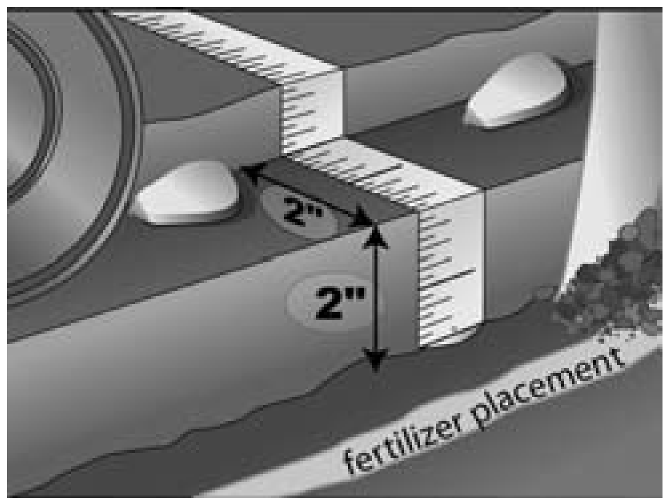
Source: Bundy, L.G. and T.W. Andraski. 1999. Site-specific factors affecting corn response to starter fertilizer. J. Prod. Argic. 12:664-670.

Salt injury to germinating seeds can occur when nitrogen or potassium fertilizers are placed too close to the seed or at too high a rate. The seed or seedling dehydrates because water moves out of tissue membranes to dilute the salt. This is the same process that causes your skin to wrinkle when you swim for a long time in the ocean. There should always be some soil between fertilizer and seed. Exceptions are that very small amounts of fertilizer can be applied directly with the seed. Salt injury can also result from excessive rates of other soluble fertilizers, as well as organic amendments. Starter fertilizers are typically applied in a band about 2 inches below and 2 inches to the side of the seed (figure 9-7).

As noted previously, the phosphate ion is rapidly fixed when it comes in contact with the soil. Concentrating the phosphorus in a band delays fixation as compared to a broadcast application. For this reason row-applied phosphorus tends to be more effective than broadcast phosphorus. Table 9-18 shows that 40 pounds per acre of row-applied phosphate was more effective than 80 pounds per acre of broadcast phosphate on a phosphorus-deficient soil.

By itself, row nitrogen has no advantage over broadcast nitrogen. Experiments using ammonium nitrate alone in the row or in combination with broadcast nitrogen show that the row nitrogen was merely additive to the broadcast nitrogen. Nevertheless,

Figure 9-7. Starter fertilizer in a 2x2 placement.



Source: S.J. Sturgul and L.G. Bundy. 2004. Understanding Soil Phosphorus. *University of Wisconsin-Extension publication A3771.*

Table 9-18. Effect of row-applied and broadcast phosphate when applied to a phosphorus-deficient soil[a] (Arlington, WI).

Annual phosphate (P_2O_5) application: Broadcast	Row	Corn yield[b]
lb/a[c]		% of control
0	0	—
0	40	+ 10.1
80	0	+ 4.0
80	40	+ 11.1

[a] *The initial soil test for available phosphorus was 12 ppm.*
[b] *Four-year average.*
[c] *Each treatment was applied each year for 4 years.*
Source: Powell, R.D. 1974. Proc. 1974 Fert., Aglime & Pest Mgmt. Conf. 13:23-31.

nitrogen should be included in row fertilizer because it improves the availability of phosphorus, possibly by keeping phosphorus more soluble.

Some potassium should always be included in the row fertilizer, regardless of the soil test level. This is particularly important in no-till and ridge-till systems where the soil tends to be more compacted than moldboard- or chisel-plowed fields. Corn grown on a Plano silt loam responded to row fertilizer (100 lb/a of 8-48-12) at all soil test potassium levels, but the response decreased as soil test potassium increased (table 9-19). Response was greatest in the ridge-plant system at low soil potassium.

A side-placement applicator is now used for application of most row fertilizer. The fertilizer is placed far enough from the seed to prevent salt damage, but the plant roots grow into the fertilizer band within a few days.

Table 9-19. Effect of tillage and row fertilizer on corn yield (Arlington, WI).

Tillage system and rate of 8-48-12	Soil test K, ppm Very low	High	Excessive
	— yield, bu/a —		
Ridge till			
100 lb/a	127	163	165
0 lb/a	82	151	162
Response	45	12	3
Chisel plow			
100 lb/a	156	167	171
0 lb/a	143	160	163
Response	13	7	8
Moldboard plow			
100 lb/a	163	176	169
0 lb/a	143	171	162
Response	20	5	7

Source: Schulte, E.E. 1980. Proc. 1980 Fert., Aglime & Pest Mgmt. Conf. 19:113–121.

Table 9-20. Maximum recommended starter fertilizer rates for corn.

Placement method	Soil type: Sands	Soil type: Silts and clays
	— lb/acre fertilizer —	
With seed (pop-up)	50[a]	50[a]
Side (2" x 2") placement	300	500

[a] *Limit combined nitrogen and potash (K_2O) to 10 lb/acre.*

In summary, crop response to row fertilizer is greatest under the following circumstances:

- soil phosphorus or potassium is low
- cold, wet conditions that retard early plant growth
- reduced tillage
- compacted soils
- for corn, longer season hybrids that are planted late.

Row fertilization can also be accomplished by using a seed-placed or "pop-up" application. With this treatment, a small amount of fertilizer is placed directly with the seed. The main advantage of this treatment over the conventional row treatment is that the starter response is obtained with much less fertilizer to handle at planting time. Also, this system does not use an additional fertilizer disk opener, an advantage in reduced tillage systems. Conventional row fertilizer is unnecessary as long as the seed-placed treatment is augmented with broadcast fertilization of any needed phosphorus and potassium. Application rates for seed-placed fertilizers must be reduced to avoid damage to the seed and young plants (table 9-20).

Seed-placed fertilizer treatments are not without drawbacks. Seed-placed fertilizer should not be used on soybeans, snapbeans, and other large-seeded legumes because these crops are extremely sensitive to salt injury. Also, they may delay emergence of corn a day or two, and high application rates can reduce germination. This is especially true on sandy soils. To minimize problems, limit the rate of

N + K_2O to 10 pounds per acre. This means that a mixed fertilizer such as 6-24-24 would have to be limited to 33.3 pounds per acre (33.3 lb/a x .06 = 2 lb of N; 33.3 lb/a x .24 = 8 lb of K_2O). Never use urea in seed-placed fertilizer. A band of concentrated urea produces gaseous ammonia that inhibits germination and damages seedlings.

Broadcast and topdress applications

Broadcast fertilizer is spread uniformly over the surface of the field and incorporated before planting by tillage or cultivation. Topdressed fertilizer is applied uniformly over the surface after emergence of the crop, usually a small grain or legume forage. In dry seasons, phosphorus and potassium applied before plowing may give better yield results than applications after plowing. This is because plowing incorporates the nutrients more deeply than disking, making them more available during dry weather.

Fertilizer can be broadcast as a topdressing on established alfalfa and grass pastures. Even though this topdressed fertilizer remains near the surface of the soil, these crops make very good use of it.

Broadcast and topdress applications can be made with farm spreaders or commercial trucks or trailers. Bulk-spread materials can be either manufactured fertilizer, such as 6-24-24, or blended fertilizer made by mixing materials such as 18-46-0 and 0-0-60.

Most fields are not uniform with respect to fertility. A fertilizer recommendation based on average soil test levels for a field may be too low for parts of the field and too high for others. Variable rate spreading technology permits the adjustment of the rate of a given nutrient "on-the-go." This technology requires an accurate fertility map based on intensive sampling. The fertility map with known geographic coordinates is computerized and used to adjust fertilizer rates in a variable rate spreader fitted with global positioning equipment.

Yield variability across a field is more often a result of variability in soil properties such as texture, compaction, or water-holding capacity than soil fertility. Technology is now available to measure yields electronically while harvesting. A map prepared from this data can be used for field inspection of low-producing areas and soil sampling based on yield level. If yield variability is due to soil physical characteristics or low fertility, fertilizer rates can be adjusted accordingly for such areas. Such precision farming has the potential for reducing fertilizer costs and environmental problems arising from over-fertilization.

Sidedress applications

Sidedress applications place fertilizer, typically nitrogen, next to or between the rows during the growing season. These treatments are effective on all soils, but offer the greatest advantage on sandy soils and poorly drained soils. Sidedress applications place nitrogen in the soil just before the plant needs it most, reducing the amount of time nitrogen is exposed to loss by leaching or denitrification.

Potential loss of nitrogen from urea that cannot be incorporated in no-till or other conservation tillage programs limits the choices of nitrogen fertilizer. Also, sidedressed nitrogen remains exposed on the soil surface where it is more vulnerable to loss by volatilization when herbicides rather than cultivation are used to control weeds.

Split-sidedressed nitrogen applied to corn on Plainfield sandy loam increased yield by 5 to 21% compared to preplant nitrogen, depending on the rate applied (table 9-21). Equally important from an environmental standpoint, recovery of applied nitrogen increased from 37 to 47% with preplant nitrogen to 57 to 84% with split-sidedressed nitrogen.

To coincide with plant uptake, sidedress applications to corn should be made no later than 6 weeks after planting. Do not sidedress with anhydrous ammonia when the soil is too wet. Wet soil does not seal well behind the injector knives. Some nitrogen will be lost, and the crop may be injured by the escaping ammonia gas.

Injection

Fertilizer can be injected using knives. This technique deposits the fertilizer in rows or bands, so the knives should be spaced close enough to allow for uniform distribution. Another injection technique is the spoke wheel injector. Liquid fertilizer is forced under high pressure through spokes of a wheel that penetrate the soil to the desired depth. Fertilizer is injected when the spoke enters the soil.

Foliar application

Plants can absorb small amounts of nutrients through their leaves. The usefulness of foliar applications depends on the total quantity of a nutrient needed by the crop. For instance, zinc and manganese can be applied successfully as foliar sprays because corn requires less than 0.3 pounds per acre of these nutrients. On the other hand, plants require so much nitrogen, phosphorus, and potassium that foliar applications would be impractical. Fifteen to 20 separate foliar applications would need to be made to provide enough of these nutrients on a deficient soil and to avoid leaf burn. Furthermore, foliar applications of the primary nutrients do not significantly increase yields when the recommended amount of fertilizer is applied to the soil.

Dribble application

Nitrogen solution is sometimes dribbled onto the soil surface with drop nozzles from a sprayer. The object is to minimize the amount of surface to which the urea is exposed. When a row crop is cultivated, nitrogen can be dribbled onto the soil surface and then incorporated with the cultivator.

Fertigation

Fertigation is the application of fertilizer in irrigation water. Nitrogen is the principal nutrient applied by fertigation, although potassium, sulfur, and micronutrients can also be applied this way. Phosphorus is seldom applied by fertigation because it forms precipitates of calcium, magnesium, or iron phosphates that could plug up nozzles. Nitrogen is applied mainly as 28% nitrogen solution. Do not use anhydrous ammonia because it can cause precipitation of iron and calcium and because ammonia will be lost to the atmosphere.

There are several advantages to fertigation:

- It allows the grower to apply nutrients, especially nitrogen, close to the time of rapid plant uptake, lessening the chances of loss by leaching.
- It eliminates one or more field operations.
- It provides an opportunity to correct nutrient deficiencies that show up or are diagnosed when the crop is too tall for conventional application equipment.

Apply soluble nutrients near the middle of the irrigation period. This prevents them from being leached below the root zone and gives sufficient water to carry them into the soil. Check valves must be used to ensure that fertilizer does not back-siphon into the well and groundwater.

Table 9-21. Effect of rate and time of nitrogen application on corn yield and recovery of applied nitrogen on an irrigated, sandy soil (Hancock, WI, 2003–04).

N rate	Yield		Nitrogen recovery	
	Preplant	Split-sidedress	Preplant	Split-sidedress
lb/acre	bu/acre		%	
0	96	96	—	—
50	122	142	47	84
100	145	175	45	79
150	164	194	42	73
200	180	202	40	66
250	193	202	37	57
Average	161	183	42	72

[a] *Split-sidedress treatments applied 4 and 7 weeks after planting.*
Source: Bundy. L.G., and T.W. Andraski. 2004. Unpublished data.

Questions

1. A farmer in southern Wisconsin grows continuous corn on a low-lying field that is somewhat poorly drained. The corn often shows signs of nitrogen deficiency despite the fact that 400 pounds per acre of ammonium nitrate (33-0-0) is broadcast on this deep silt loam soil each fall. What is the most likely reason for the appearance of the nitrogen deficiency?
2. Crops on irrigated sandy soils show very little difference between non-leachable ammonium sources of nitrogen and leachable nitrate sources. Why?
3. How can nitrogen losses from fall-applications be minimized?
4. A farmer harvests one-half of a well-fertilized corn field for silage corn and the other half for ear corn. The following year the field is planted to oats. Which half of the oats field will be more apt to lodge? Why?
5. If nitrogen fertilizer is surface applied and not incorporated, ammonium sulfate or ammonium nitrate is recommended instead of urea. Why?
6. Identify the source of nitrogen which is
   a. difficult to apply to wet, stony, high-residue soils.
   b. also a carrier of sulfur.
   c. apt to cause plant damage when improperly sidedressed.
   d. used more rapidly by plants, especially when applied to cool soils.
7. The phosphate in one 5-20-20 fertilizer is 100% water soluble, while the phosphate in another 5-20-20 fertilizer is only 60% water soluble. In comparing these two fertilizers on corn, no difference in response is noted. Why?
8. Under what soil and cropping conditions would rock phosphate be a satisfactory source of phosphorus?
9. Why doesn't phosphate ($H_2PO_4^-$), a negatively charged ion, leach out of the soil?
10. Explain why a band application of phosphate is often more effective than an equivalent amount of broadcast phosphate.
11. What is the most commonly used source of potassium? Why?
12. Potassium does not leach generally. However, some leaching will take place on very sandy soils and organic soils. Explain why.
13. Most Wisconsin soils contain lower levels of available potassium than soils in neighboring states, even though our use of potash per cropland acre is as high or higher than most of these states. Explain why.
14. Explain why calcium deficiency is not a problem on soils with a pH of 6.0 or above.
15. What soil conditions can cause magnesium deficiencies?
16. What soil and cropping conditions would have the most response to sulfur fertilizer?
17. Is elemental sulfur or potassium sulfate more effective when topdressed on established alfalfa? Give reasons.
18. Discuss the soil conditions favoring deficiency and the crops most likely to show the deficiency for each of the following micronutrients:
    a. Boron
    b. Manganese
    c. Zinc
    d. Copper
    e. Iron
    f. Molybdenum
19. Some micronutrients can be applied successfully as a foliar spray, but foliar application of nitrogen, phosphate, and potash is not recommended. Explain.
20. Could 40 pounds per acre of 10-10-10 be applied safely as a seed-placed or pop-up treatment on corn? On soybeans? Give reasons.
21. Outline a nitrogen fertilization program for corn grown on irrigated sands in central Wisconsin that will minimize leaching losses.

CHAPTER

10

Soil amendments

"And by plentiful dunging, which is owing to flocks and herds of cattle, the earth produces her fruit in great abundance."

Columella, L.J.M. Circa 40 A.D.

A soil amendment is any material applied to the soil to improve crop yield or quality. Technically, commercial fertilizers are amendments, but the term is generally used to describe materials other than fertilizers.

Organic amendments

The principal organic soil amendments used in Wisconsin are manure, municipal biosolids (sewage sludge), and whey. Crop residue is not considered an amendment unless it is harvested and transported to another field. Other organic amendments include compost, sawdust, wood chips, fibrous paper mill sludge, leaves, grass clippings, and peat moss.

Manure

Manure is a byproduct of Wisconsin's vibrant animal agriculture industry. The manure produced by the state's dairy cows alone is estimated to be 33.6 million tons annually. Manure generated in such quantities is a significant source of nutrients for crops and soils. It is also a resource that must be managed appropriately to fully utilize its nutrients in a manner that minimizes environmental risk. Unfortunately, because of its low value per unit volume and handling problems, manure is too often treated as a waste.

When manure is applied to cropland, its nutrients are recycled as soil microorganisms process it for food and energy. When applied at recommended rates, manure provides the following benefits:

- It adds essential plant nutrients.
- It acts as a mulch.
- It adds organic matter to soil.
- It improves soil structure.
- It improves tilth.
- It increases cation exchange capacity.
- It improves infiltration of water.
- It reduces runoff.

Composition. Manure is a good source of nitrogen, phosphorus, potassium, and other nutrients but it varies greatly in composition. Table 10-1 provides an estimate of the *total nutrient content* of manure. Numerous factors affect the nutrient content of manure, including: animal species and age, bedding type and amount, feed composition and digestibility, and manure handling and storage procedures. The composition of liquid manure depends on how much water is used to dilute the fresh manure so that it can be handled as a liquid.

In addition to nitrogen, phosphate, and potash, manure contains all of the other essential nutrients. Subsequently, soils to which manure is applied regularly are rarely deficient in sulfur or micronutrients.

There are other benefits of applying manure to soil. On the soil surface, manure acts as a mulch and reduces erosion. Incorporating it into the soil improves water infiltration and soil structure, which in turn reduces erosion and provides a better environment for root development.

Only a portion of the total nutrients in manure is available to plants after application to soils. Some nutrients are "tied up" in the organic matter of the manure and are released over a number of years. To accurately assess manure nutrient credits, it's essential to account for the *available nutrient content* of manure (table 10-2). For example, even though a ton of dairy manure may contain 10 pounds of nitrogen, 5 pounds of phosphate, and 9 pounds of potash, the available nutrient credits (reductions in commercial fertilizer to apply) are only 3 pounds of nitrogen, 3 pounds of phosphate and 7 pounds of potash for each ton. Incorporating the dairy manure reduces volatilization losses of nitrogen so the manure-nitrogen credit can be increased an additional 1 pound of nitrogen per ton of manure. The available nutrient content of manure increases when manure is applied to the same field for 2 or more consecutive years. See the references cited in table 10-2 for additional information.

Laboratory analysis provides the best estimate of the nutrient content of manure—provided a representative sample(s) is submitted to the lab. Detailed instructions on collecting and handling a representative manure sample and copies of the information sheet that needs to accompany a manure sample can be found online at the University of Wisconsin Soil and Forage Analysis Lab's web site (uwlab.dyndns.org/marshfield). The nutrient content of manure can vary significantly from the values in table10-2. In addition to livestock species, animal bedding, livestock feed, manure dilution, storage, and mixing are all variables that influence nutrient content. The nutrient content averages in table 10-2 should only be used when lab analysis has not been done. An example of manure analysis reports from the

Table 10-1. Estimated total nutrient content of solid and liquid livestock manure.

Species	Dry matter	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
Solid manure	**— % —**		**lb/ton**	
Dairy	24	10	5	9
Beef	35	14	9	11
Swine	20	14	10	9
Chicken	60	40	50	30
Turkey	60	40	40	30
Liquid manure			**lb/1,000 gal**	
Dairy	6	24	9	20
Beef	5	20	9	20
Swine—indoor pit	7	50	42	30
Swine—outdoor pit	4	34	16	20
Swine—farrow-nursery indoor pit	3	25	23	22
Poultry	3	16	10	12

Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590. Wis. Conservation Planning Technical Note WI-1.

Table 10-2. Average first-year available nutrient content of solid and liquid livestock manure.[a]

Species	Dry matter	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
Solid manure	— % —		lb/ton	
Dairy	3	4	3	7
Beef	4	5	5	9
Swine	7	9	6	7
Chicken	20	24	30	24
Turkey	20	24	24	24
Liquid manure			lb/1,000 gal	
Dairy	7	10	5	16
Beef	5	7	5	16
Swine—indoor pit	25	33	25	24
Swine—outdoor pit	17	22	10	16
Swine—farrow-nursery indoor pit	13	16	14	18
Poultry	8	10	6	10

[a] *Averages are based on information collected from Wisconsin soil testing laboratories. Values are subject to revision. Consult www.datcp.state.wi.us/arm/agriculture/land-water/conservation/nutrient-mngmt/planning.jsp for the latest information.*

Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590. Wis. Conservation Planning Technical Note WI-1.

University of Wisconsin soil testing lab can also be found on the previously mentioned web site.

When reading manure nutrient analysis results, be certain to use the *available* nutrient content—not total nutrient content—when calculating manure nutrient credits. Some labs may report only the total nutrient content values. Table 10-3 lists the estimated first-year nutrient availability from various manures.

Nutrient crediting. Nutrient credits are the reductions in fertilizer application that can be made when manure (or other non-commercial

Table 10-3. Estimated nutrient availability from livestock manure.

Species	Nitrogen (N) surface	Nitrogen (N) incorporated	Phosphate (P_2O_5)	Potash (K_2O)
		%[a]		
Dairy	30	40	60	80
Beef	25	35	60	80
Swine	50	65	60	80
Poultry	50	60	60	80

[a] *Values are the percentage of available nutrients relative to the total nutrient content of manure. If manure has been applied to the same field at similar rates for 2 consecutive years, increase the nutrient values in the table by 10 percentage points. If manure has been applied to the same field at similar rates for 3 consecutive years, increase the nutrient values in the table by 15 percentage points.*

Adapted from: USDA-NRCS. 2005. Wisconsin Field Office Technical Guide. Sec. IV. Spec. 590. Wis. Conservation Planning Technical Note WI-1.

fertilizer sources of plant nutrients) is applied to soil. In order to use manure as a nutrient resource, both the available nutrient content and the manure application rate must be known. For example, if dairy manure containing 3 pounds of plant-available nitrogen per ton is applied at 20 tons per acre, a nitrogen credit of 60 pounds per acre can be subtracted from the soil test recommendation for nitrogen.

Estimating application rates. Manure must be applied uniformly across fields and the application rate must be known if manure is to be used as a fertilizer resource. Manure application rates cannot be estimated visually! To get a reasonably accurate estimate of application rates, the manure spreader must be calibrated. For solid manure, this is done by determining the weight of the spreader and the area covered. The insert *Know How Much You Haul!* provides details on how to do this.

Incorporation. Incorporating or injecting manure by tillage soon after application—generally, within 3 days—can conserve nitrogen by limiting ammonia losses. It can also control odors. However, tillage to incorporate manure, especially in spring, can increase sediment and phosphorus losses by increasing soil erosion. Unincorporated, spring-applied manure can lower runoff volume and erosion by increasing residue cover and water infiltration into the soil.

Incorporated manure can also lower phosphorus losses in runoff in some cases. Incorporating manure in the fall often lowers runoff volume and total phosphorus losses. Unincorporated manure applied in the fall to relatively smooth (sealed) soil surfaces such as those found following no-till corn or soybean or established alfalfa often increases phosphorus losses. Winter applications of unincorporated manure are particularly susceptible to phosphorus losses.

Manure management guidelines. Additional guidelines and recommendations for manure management include the following:

- Do not exceed tolerable soil loss (T) on fields receiving manure.
- Limit manure application to the annual crop removal rate for phosphorus unless it is incorporated. If incorporated, higher rates can be applied to meet the nitrogen needs of the crop to be grown.
- Realize that when applying manure to meet the nitrogen needs of a subsequent crop, an over-application of phosphorus and potassium is likely to result.
- Monitor soil test phosphorus levels on fields receiving manure. If levels reach 100 ppm or more, reduce manure application rates and plant a crop that removes substantial amounts of phosphorus, such as alfalfa or silage corn.
- Do not apply manure to frozen soils within 1,000 feet of lakes and 300 feet of rivers and streams.
- Never apply manure in grass waterways, terrace channels, near open surface drains, or other areas where water flow may concentrate.
- If manure is to be applied to unfrozen soils within 1,000 feet of lakes and 300 feet of rivers and streams, use one or more of the following precautions: (1) install or maintain buffers along the water body, (2) maintain at least 30% crop residue cover, (3) incorporate manure within 72 hours leaving adequate crop residue cover.
- If manure is applied to frozen soils on slopes of 9% or less and protect these areas from upslope runoff.
- Do not apply manure to frozen soils on slopes between 9 and 12% unless contour strips, terraces or other conservation measures are in place.
- Do not apply manure to frozen or snow-covered soils on slopes greater than 12%.
- Do not apply manure where there is less than 20 inches of soil over bedrock unless it can be applied in the fall when soil temperatures are below 50°F and limited to 120 pounds of available nitrogen per acre.
- On sandy soils where crops are not growing, delay fall application until soil temperatures are below 50°F. If a perennial or cover crop is growing, fall application can be made at any time.

Other considerations. For greatest efficiency of manure nutrient utilization, have the manure analyzed and the soil tested. Apply more manure to fields testing low in phosphorus and potassium and less manure to fields with a high soil test.

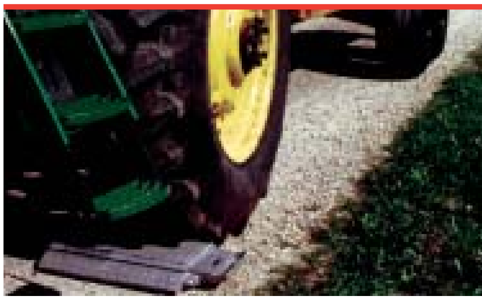
As long as the manure is handled properly, daily spreading or seasonal spreading from a manure storage system is equally effective at improving crop yield.

A number of university publications, available from county Extension offices or the web sites cited in this chapter, discuss manure management in greater detail. Be aware that various federal, state, and local regulations may impact manure management strategies. The USDA-Natural Resources Conservation Service's nutrient management standard (Wisconsin Field Office Technical

Know How Much You Haul !

To use manure as a quality, dependable fertilizer, you must accurately figure your spreading rate and calculate your manure nutrient credits. This whole process can take less than a hour! All you need to get started is this sheet, a calculator and portable axle scales. Contact your land conservation department, county extension agent or the Nutrient and Pest Management Program (877) 426-0176 for assistance with scales.

STEP 1. DETERMINE LOAD WEIGHT



TOOLS NEEDED: CALCULATOR, PORTABLE AXLE SCALES

Using a typical load size, the tractor with spreader is weighed empty and full, axle by axle.

What is typical? If you normally haul one load every day at about the same time, weigh a load with 24 hours worth of manure. Or if you normally wait until the spreader is filled to capacity, weigh the spreader filled.

STEP 2. DETERMINE SPREADING RATE

TOOLS NEEDED: CALCULATOR AND FIELD RECORDS OR MEASURING WHEEL*

You can now calculate your tons per acre spreading rate using field records on how many loads you put on a particular field of known acreage (see equations on other side). This rate can be considered the "standard" for the farm. Make sure you use typical ground speed, PTO speed and spreader settings.

To develop variable rates (such as high, medium and low) experiment with different speeds and spreader settings. These rates could be useful when dealing with fields that have special fertilizer, tillage or environmental considerations.

You can get an **estimate of a per acre rate right away by using a measuring wheel on the area just spread. Use caution with this method since it does not take into account overlap or load tapering.*

STEP 3. DETERMINE MANURE NUTRIENT CREDITS

TOOLS NEEDED: CALCULATOR

Using University of WI guidelines (table on other side) you can estimate the available nutrient content per ton of the manure you are spreading. You can also have your manure analyzed for its specific nutrient content. From either of those numbers, you can figure your manure nutrient credits per acre. (If you develop variable rates, use additional sheets to determine their manure nutrient credits.) Now you have the information you need to accurately use manure as a fertilizer!

It's a good idea to repeat this process for any different types of spreaders or manure you routinely apply on your farm. For more copies of this publication or information on developing a nutrient management plan for your farm, contact your land conservation department, county extension agent or the NPM program.

Spreader Information | Manufacturer / Manure Type / Ground Speed / PTO Speed / Spreader Settings

STEP 1. DETERMINE LOAD WEIGHT

FULL

	Left wheel		Right wheel		Full total lb
Rear tractor axle					
Front spreader axle					
Rear spreader axle					
		+		=	

EMPTY

	Left wheel		Right wheel		Empty total lb
Rear tractor axle					
Front spreader axle					
Rear spreader axle					
		+		=	

Full total - Empty total ______ ÷ **2000** = ______ **Tons Manure/Load**

STEP 2. DETERMINE SPREADING RATE

Method 1: Using field records, enter the number loads applied on a known acreage.

# of loads		# of acres		loads /acre		Tons Manure/Load		**Tons / Acre**
	÷		=		x		=	

Method 2: Estimation only. Using a measuring wheel, measure the area just spread with a single load.

[Tons Manure/Load ______ x 43,560 ft^2/Acre] ÷ [ft wide ______ x ft length ______] = **Tons / Acre Estimate** ______

STEP 3. DETERMINE MANURE NUTRIENT CREDITS

Enter the available nutrient content of manure

	lb/Ton		Tons / Acre		**lb/Acre**
N		x		=	
P_2O_5		x		=	
K_20		x		=	

Multiply the nutrient content by the spreading rate to get the pounds per acre of each nutrient.

Nutrients available for crop use in the first year after spreading solid manure.

Animal	Inc.* N	Not Inc. N	P_2O_5	K_2O
	lb/ton			
Dairy	4	3	3	7
Beef	5	4	5	9
Swine	9	7	6	7
Chicken	24	20	30	24

* Incorporated into the soil within 72 hours after spreading.

Source: Department of Soil Science, College of Agricultural and Life Sciences, University of Wisconsin-Madison, University of Wisconsin-Extension.

For more copies of this publication, please contact the Nutrient and Pest Management Program's Regional offices: Southwest (800) 745-9712, Southcentral (800) 994-5853, Southeast(800) 994-5852, Northwest (800) 228-8672, Northeast (920) 391-4652 or our UW-Madison office at (608) 265-2660. Visit our website (ipcm.wisc.edu).

Guide – Standard 590) contains numerous manure application restrictions. A current version of the nutrient management standard can be found on the Wisconsin Department of Agriculture, Trade and Consumer Protection site at www.datcp.state.wi.us/arm/agriculture/land-water/conservation/nutrient-mngmt/planning.jsp.

Biosolids

Biosolids (sewage sludge) are a product of the biological treatment of wastewaters. These materials are created from a variety of industries, including the processing of sewage by municipalities, food processing, and paper making. They are the result of the current best technology for purifying industrial and municipal wastewater, with the goal of returning the greatest percentage of the water as clean effluent to surface or ground water. Biosolids contain the undecomposable solids from the wastewater and the cells of bacteria that processed the waste material. There are three options for the management of biosolids: (1) land application to utilize nutrients and organic matter, (2) landfilling, and (3) incineration. Landfilling and incineration are often more expensive options and have significant environmental drawbacks.

The creation and use of municipal biosolids are regulated by the Wisconsin Department of Natural Resources. State code contains standards supplied by the U.S. Environmental Protection Agency that were created following a national review process. The standards specify criteria for pathogens, heavy metals, and vector (flies, rodents, etc.) attraction. Wisconsin recognizes two types of municipal biosolids based on these three factors. Class A biosolids have exceptional quality and are safe enough to be used in horticultural applications. A well-known example is Milorganite produced by the Milwaukee Metropolitan Sewerage District. Most other materials are classified as Class B materials and are generally applied in bulk to agricultural land following the strict criteria described in the following paragraphs.

Composition. The nutrients and other components of a biosolid reflect the origin of the wastewater. There is a risk of pathogens in municipal biosolids, which is addressed through treatment using biological digestion, heat, or lime. It is further addressed through restrictions that prevent spreading within critical distances from wells, schools, dwellings, etc. and through the type of crop that can be grown on the amended soil. There is a valid concern regarding the heavy metal content of biosolids. Heavy metals are elements such as lead, mercury, and cadmium that can be toxic to animals if ingested in certain concentrations. The risk of contacting heavy metals in biosolids is managed by applying them to soils that have a pH of 5.5 or higher. At such pH levels, the heavy metals become tied up in the soil, significantly reducing their availability to plants. They are further restricted through the establishment of maximum, or ceiling, concentrations in soils. Risk of accumulating toxic levels of heavy metals is considered to be low when the concentration of metals in biosolid falls below these levels. A list of these elements, the ceiling concentrations, and the concentrations for three Wisconsin communities is shown in table 10-4.

Table 10-4. Biosolid heavy metal ceiling concentrations and the heavy metal content of three Wisconsin biosolid materials.

Element	Ceiling concentration	— Average concentrations, 2002 — Appleton	Waupaca	Weyauwega
	ppm			
Arsenic	75	3.7	4.6	3.1
Cadmium	85	0.6	1.4	0.8
Copper	4,300	167	208	128
Lead	840	12.9	15.5	28.6
Mercury	57	0.3	1.2	0.5
Molybdenum	75	11.9	12.5	30.5
Nickel	420	10.7	7.6	6.5
Selenium	100	0.1	2.6	1.0
Zinc	7,500	224	281	274

Source: P. Grienier. 2002. City of Appleton.

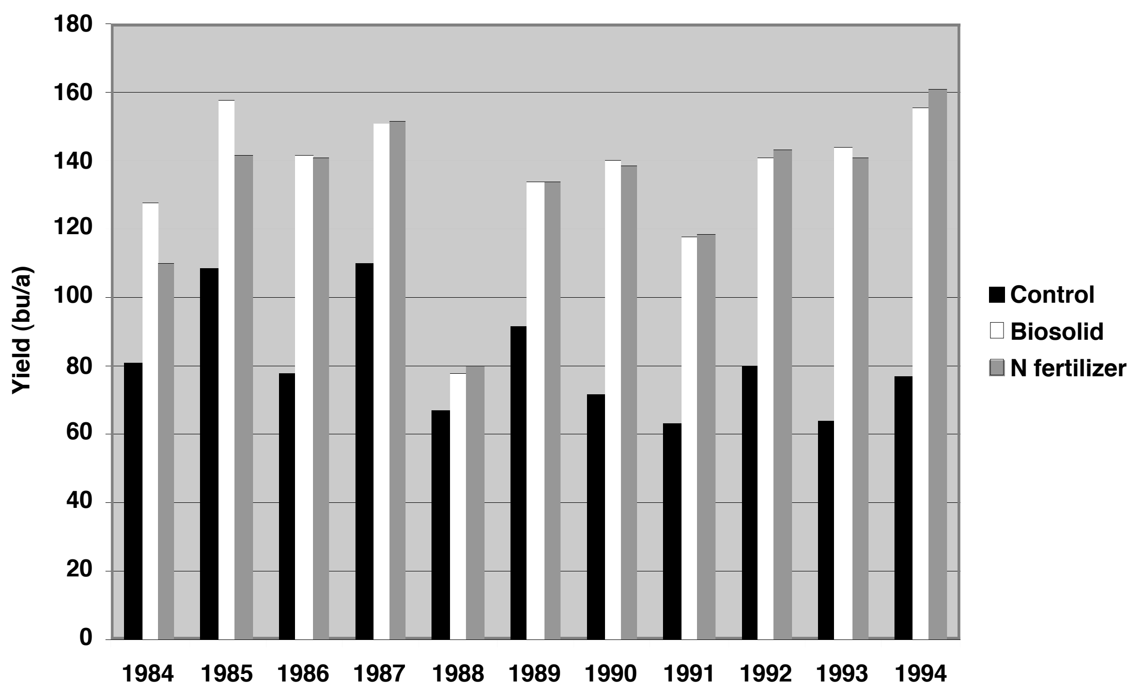
Application of biosolids. Fields for the land spreading of biosolids must be individually approved based on specific site criteria. University of Wisconsin soil test recommendations are used to determine the rate of biosolid application. Crop selection is determined by the potential contact with the soil. For example, crops grown in the soil (e.g., carrot, potato) cannot be harvested from a treated soil within 38 months of application. For crops that may touch the soil (e.g., green beans, peas), the period is 14 months. The period for common field crops like corn and soybean is 1 month. Most biosolid application rates are based on the nitrogen need of the crop. Current rules provide a biosolid nitrogen credit of 25% of the organic nitrogen content plus 100% of the mineral nitrogen. Before selecting a biosolid application rate, credits for legumes and manure, or previous biosolid applications must first be subtracted from the recommended nitrogen rate. Several municipalities have opted to use lime stabilization in their biosolid management process. Lime-stabilized biosolids are an excellent liming material and should be used as a substitute for aglime rather than a nitrogen fertilizer.

Biosolids are an excellent source of nitrogen and when applied properly replace the need for nitrogen fertilizer. Figure 10-1 shows a comparison between fertilizer and biosolids applied for 11 consecutive years at Elkhorn, Wisconsin. Similar to manure, application of biosolids to meet crop nitrogen needs will result in the over-application of phosphorus. This relationship is even more significant in the case of biosolids because treatment processes sequester phosphorus in the solids so that the effluent phosphorus concentration is low. Table 10-5 shows the soil test phosphorus values P at Elkhorn following the long-term application of biosolids.

Whey

Whey is a byproduct of cheese making. It is the liquid remainder of milk after the solids (curds) are removed. About one-third of the whey produced by cheese plants in the United States is applied to the land. The remainder is fed directly to animals or is processed into foods, pharmaceuticals, or industrial products.

Figure 10-1. Corn response to 11 years of biosolid and nitrogen fertilizer application (Elkhorn, WI, 1984–94).



Source: Peterson, A.E. 2002. Dept. of Soil Sci. Univ. Wis.-Madison.

Composition. Whey is an excellent source of plant nutrients. Based on the analysis in table 10-6 half an acre-inch would provide adequate nitrogen for corn. Whey contains 5 to 6% solids, most of which is lactose, with the remainder being protein and nutrients.

Handling of whey. Whey is typically spread through irrigation systems or by truck spreading; that is, by opening a valve at the rear of a tank truck and directing the whey onto a spreader baffle.

The soluble carbohydrates in whey are a readily available source of energy for soil microorganisms. Whey stimulates the growth of these organisms and they multiply rapidly. This improves the soil structure and the rate of water infiltration.

Whey should not be applied to alfalfa for several reasons. First, alfalfa does not need the added nitrogen. Second, the rapid stimulation of microbial activity coupled with the water added with the whey depletes soil oxygen temporarily, inducing manganese toxicity in alfalfa. And third, the high sodium chloride content of some wheys can cause salt damage.

Miscellaneous organic amendments

A number of other organic amendments are available in some localities. These include peat moss, wood chips, sawdust, fibrous paper mill waste, leaves, and lawn clippings. Aside from sawdust and wood shavings used for bedding, most of these materials are not widely available and have no advantage over manure. They are better suited to lawns, gardens, and small specialty farms. Near urban areas, the availability of leaves, leaf compost, and yard waste is likely to increase. Municipalities must restrict leaves, yard waste, and lawn clippings from their landfills and many have set up yard waste composting sites. When available, these materials can be applied advantageously to agricultural land. For fields where organic amendments are unavailable, the best way to maintain soil organic matter is to fertilize adequately with commercial fertilizer and then return to the soil the large yield of residue that will be left after the crop is harvested.

Any material that adds organic matter to the soil economically should be encouraged. Carbonaceous material low in nitrogen, such as sawdust and wood shavings, will induce nitrogen deficiency if applied at high rates without including a supplementary source of nitrogen. Leaves are borderline. If incorporated in the fall, they should break down by spring. There is no advantage to composting the leaves before incorporation. The same processes take place in the soil as

Table 10-6. Nutrient analysis for whole whey.[a]

Nutrient	Amount per acre-inch[b]
	— lb —
Nitrogen (N)	330
Phosphate (P_2O_5)	250
Potash (K_2O)	480
Calcium	80
Magnesium	15
Chlorine	265
Sodium	115

[a] *Not representative of whey permeate or deproteinized whey.*
[b] *One acre-inch is 27,300 gals/acre. Solid content is 14,890 lb/acre-inch.*
Source: Kelling,K.A., and A.E. Peterson. 1981. Using Whey on Agricultural Land—A Disposal Alternative. *University of Wisconsin-Extension publication A3098.*

Table 10-5. Soil test phosphorus content following 16 consecutive years of biosolid application (Elkhorn, WI 1979–94).[a]

Treatment	Sampling depth (in) 0–6	6–12	12–18	18–24	24–30	30–36
	ppm					
Control	75	20	18	25	27	26
3 ton/a	210	160	23	27	38	32
6 ton/a	270	230	38	22	38	27

[a] *Soil samples collected in 2002.*
Source: Peterson, A.E. 2002. Dept. of Soil Sci. Univ. Wis.-Madison.

Table 10-7. Carbon to nitrogen ratios (C:N) of selected organic amendments.

Amendment	Carbon to nitrogen ratio
Alfalfa hay	12:1
Rotted manure	15:1
Grass clippings	19:1
Tree leaves	60:1
Cornstalks	60:1
Straw	80:1
Sawdust	500:1
Wood shavings	500:1

Source: Schulte, E.E., and K.A. Kelling. 1989. Organic Soil Conditioners. *University of Wisconsin-Extension publication A2305.*

in a compost heap. The ratio of carbon to nitrogen (C:N) in several materials is shown in table 10-7. If the carbon to nitrogen ratio is greater than 30, microorganisms will use available soil nitrogen for their needs. If the carbon to nitrogen ratio is less than 20, microorganisms will mineralize the organic nitrogen and increase the supply of available nitrogen (NH_4^+-N + NO_3^--N) in the soil. If the carbon to nitrogen ratio is between 20 and 30 the level of available nitrogen remains unchanged.

Inorganic amendments

Ground limestone, paper mill lime sludge, and gypsum are the inorganic amendments most commonly applied to soil. The benefits of liming materials were discussed in chapter 6, "Soil Acidity and Liming."

Gypsum

In some Great Plains and Western states, high levels of sodium in soils cause the clay to disperse rather than form aggregates. Water does not move through these soils easily, and they are difficult to work. Because of the sodium, the pH is over 8.3. These soils can be reclaimed by replacing the sodium with calcium, and gypsum ($CaSO_4 \cdot 2H_2O$) is often used for that purpose. Wisconsin has very few, if any, naturally occurring high-sodium soils although the use of road salt can cause sodium problems in ditches along some sections of major highways and streets. Gypsum applied to soils unaffected by sodium provides no benefit to soil structure. If the soil is low in sulfur or calcium, gypsum is a good source. Otherwise, it has no value as an additive.

Scraps of gypsum wallboard, a material commonly used to cover interior walls, are usually landfilled

Table 10-8. Yield response of alfalfa to the application of crushed wallboard at four Wisconsin locations.

Treatment	Arlington	Ashland	Lancaster	Spooner
	tons/a			
Control	4.0	2.6	4.2	3.4
Sulfur[a]—50 lb/a	4.0	2.7	4.0	3.6
Crushed wallboard				
1 ton/a	4.1	2.7	4.2	3.7
4 tons/a	3.9	2.8	4.1	3.8
16 tons/a	4.1	2.8	4.1	3.9

[a] *Applied as gypsum fertilizer.*
Source: Wolkowski, R.P. 2003. Using Recycled Wallboard for Crop Production. *University of Wisconsin-Extension publication A3782.*

along with other construction debris. It is estimated that approximately 1 pound of wallboard waste is created for every square foot of construction area; resulting in about 1 ton of scrap per home. Rather than being disposed, wallboard can be pulverized and applied to soil to supply calcium and/or sulfur.

A study that evaluated the response of alfalfa to the application of wallboard was conducted over a 3-year period at four Wisconsin locations. The study compared the agronomic rate of sulfur applied with gypsum fertilizer to rates of crushed wallboard ranging between 1 and 16 tons per acre. Yield data from the second hay year are shown in table 10-8. These data show a small but significant positive response to the wallboard application at Ashland and Spooner. Both of these locations are in northwestern Wisconsin, a region where the contribution of sulfur in rainfall is low.

Large applications of available calcium will displace other positively charged ions from soil-clay surfaces, subjecting them to loss from the soil by leaching. To prevent this, University of Wisconsin research results suggest that crushed wallboard applications be limited to 2 tons per acre on sandy soils and 5 tons per acre on medium-textured soils.

Non-traditional soil amendments

Increasing fertilizer prices and the search for ways to produce crops more efficiently have spurred the introduction of many non-traditional soil amendments. These amendments are classified into six categories: (1) soil conditioners, (2) mineral nutrient sources used in a nonconventional manner, (3) wetting agents and surfactants, (4) biological inoculants and activators, (5) plant stimulants and growth regulators, and (6) nonconventional soil management programs.

Non-traditional soil amendments should be used with caution and not as a substitute for tried and proven practices. A few products show beneficial results, but the yield increases have been small. There is a significant amount of information available about many of these products. All of the land-grant universities in the North-Central region share in developing a database on nonconventional products. Information from this database is published as a compendium of research reports entitled *Nonconventional Soil Additives: Products, Companies, Ingredients, and Claims*. This publication is frequently updated and can be found on the University of Wisconsin Soil Science Extension web site at www.soils.wisc.edu/extension/publications/NCR.htm. Before trying any of these products, seek out available information and then use it only on a small scale initially. Understand the conditions and crop for which the product is recommended, have clear instructions concerning application, and know what the product is expected to accomplish. Compare the performance of these products against customary practices.

Soil conditioners

Soil conditioners are materials that claim to improve the physical condition of the soil. In general, this implies improved soil structure through better aggregation. Materials promoted as soil conditioners include unprocessed rock phosphate or ground limestone that may be combined with composted organic materials. Mineral deposits that are unprocessed except for grinding, such as granite, glauconite, clay, and natural deposits consisting mostly of gypsum or sand, are sometimes sold as soil conditioners. Humates or humic acids discarded during the mining of coal are pulverized and also sold as soil conditioners. Salts from evaporated sea water or sulfates in combination with organic extracts or materials such as kelp or whey may be similarly marketed as conditioners.

Advertising materials suggest that the products will loosen compacted soil, improve water infiltration, make tillage easier, eliminate wet spots, improve the moisture-holding capacity, stimulate soil microorganisms, reduce drought damage, or create a better root environment. Four commercially available soil conditioners tested in Illinois, South Dakota, and Wisconsin as additives for corn showed no benefit.

Mineral nutrient sources

Some amendments in this category have a guaranteed nutrient content on the label and are promoted as being needed in very small quantities. Other products contain small quantities of secondary or micronutrients. Some contain small quantities of non-essential elements. Many of the materials are extracted, composted, or fermented from various organic sources such as fish, seaweed, whey, or manure. Increased yields, reduced fertilizer need, balanced nutrition, a natural form of plant food, low salt content, and increased nutrient availability are some of the claims offered.

However, not all products fulfill the manufacturer’s claims. For example, one product purportedly would reduce the amount of fertilizer needed in the regular fertilizer program. A Wisconsin study testing that claim found no yield increase. In this study, the fertilizer was placed with the seed at rates of 1 and 2 quarts per acre and applied as a foliar application at 1 quart per acre at the 8-leaf stage, as recommended by the manufacturer. As seen in table 10-9, the low rate of additional fertilizer applied to the seed or on the plant leaves gave no increase in yield over fertilizer alone.

Wetting agents and surfactants

Wetting agents and surfactants have been used with herbicides and insecticides for many years. Some research has shown that nonionic wetting agents can increase water infiltration on water-repelling soils (such as peats or turf with a heavy thatch cover). These materials have no effect on wettable soils. The claims made for wetting agents and surfactants include loosening of tight soils, increased water infiltration, increased moisture-holding capacity, improved tile drainage, and elimination of wet spots. Some also claim increased nutrient availability, increased protein content of crops and increased yield. None of five wetting agents tested in a Kansas State study had any influence on crop yield or infiltration of water. Application of a wetting agent at the recommended rate of 2 quarts per acre to Plano silt loam, with or without nitrogen, had no effect on corn yield (table 10-10).

Biological inoculants and activators

Inoculation of leguminous crop seed with *Rhizobium* bacteria to ensure good nodulation and nitrogen fixation is a well-accepted practice. Soil inoculation with free-living nitrogen fixers has not been very successful. Other inoculants containing organisms claimed to enhance organic matter decomposition have given negative results in trials conducted in Illinois, Minnesota, and Wisconsin. Some inoculants are claimed to produce growth-stimulating substances by organisms on the seed, in the soil, or near plant roots. Claims for these inoculants have not been substantiated by research. A mixture of several

Table 10-9. Influence of seed-placed and foliar applications of a12-6-6 liquid fertilizer on corn yield[a] (Arlington, WI).

Seed-placed	Foliar	Corn yield
—— qt/a[b] ——		bu/a
0	0	139
1	1	140
2	1	136

[a] *All plots received 100 lb/a of 9-23-30 fertilizer as a row treatment plus 150 lb/a of supplemental nitrogen.*
[b] *One quart of 12-6-6 weighed about 2.5 lb and contained 0.3 lb nitrogen, 0.15 lb phosphate (P_2O_5) and 0.15 lb potash (K_2O).*
Source: Kelling, et al. 1980, 81. Unpublished research report. Dept. of Soil Sci., UW-Madison.

Table 10-10. Influence of a wetting agent on corn yield[a] (Arlington, WI).

Nitrogen applied	Wetting agent	Corn yield
lb/a	qt/a	bu/a
0	0	62
0	2	59
93	0	132
93	2	131
168	0	144
168	2	144

[a] *Three-year average.*
Source: Wolkowski, et al. 1985. Agron. J. 77: 695–698. Reproduced with permission of the American Society of Agronomy, Inc., Madison, WI.

microorganisms applied as a seed coating and as a soil inoculum did not affect the yield of corn at either of two sites in 3 years (table 10-11).

Plant stimulants and growth regulators

Plant growth regulators are compounds other than nutrients that affect plant processes in some beneficial way to increase yield, improve quality, or facilitate harvesting. Growth regulators have been used successfully on horticultural crops to control rooting, fruit set, ripening, shape, and fruit drop. A number of naturally occurring products have been marketed for field crops with claims for growth regulation. Some are produced by fermentation of agricultural waste products. They are promoted for use by soil, seed, or foliar application. The claimed benefits often include nutrient release, better rooting, drought resistance, improved quality, and higher yields.

An activator consisting of a culture of *Lactobacillus* bacteria on a whey base with an extract of Norwegian kelp was tested on alfalfa in Illinois and on potatoes in Wisconsin (table 10-12). Small but statistically significant yield increases were obtained in both cases when examined over 3 years but not when only 1 year was considered. Use of this product on corn and soybeans in Wisconsin gave no beneficial effect.

Table 10-11. Influence of a soil inoculant[a] on corn yield.

Nitrogen applied[b]	Soil inoculum	Seed coat	Corn yield
lb/a	lb/a	g/25 lb seed	bu/a
0	0	0	79
0	6	10	84
75	0	0	131
75	6	10	132
150	0	0	139
150	6	10	137

[a] *The soil inoculant was labeled as containing* Actinomyces thermophilus, Azotobacter chroococum, Mixobacter *spp.,* Streptomyces fulvourides, *and* Bacillus subillus *in a whey base. The seed coating was purported to contain growth regulators and micronutrients. Results are the average of 3 years at two locations.*
[b] *All plots received 200 lb/a of 9-23-30 as a starter.*
Source: Wolkowski, R.P., and K.A. Kelling. 1984. Agron. J. 76: 189–192. Reproduced with permission of the American Society of Agronomy, Inc., Madison, WI.

Table 10-12. Influence of a growth stimulant on alfalfa and potato yields.[a]

Activator added (oz/a)	Crop yield
Alfalfa	ton/a
0	6.00
4	6.15
8	6.26
16	6.27
32	6.64
Potato	cwt/a
0	107
4[b]	113

[a] *Standard fertilizer recommendations were applied to all treatments.*
[b] *Three applications.*
Source: Kelling et al. 1983. Solutions, May/June: 18–26.

Questions

1. A farmer spreads dairy manure at a rate of 25 tons per acre on an 80-acre field.

a. How many pounds per acre of total nitrogen, phosphate, and potash will the field receive?

b. How many pounds of these nutrients will be available to crops in the growing season following manure application? (Assume that the manure is incorporated the same day that it is applied.)

2. What benefit do manure, sewage sludge, and whey offer besides supplying nutrients?

3. How do sewage sludge and whey compare with manure as plant nutrient sources?

4. It is recommended that land to which sewage sludge will be applied should be limed to a pH of 6.5 or higher. Why?

5. Explain how applying sawdust to soil could induce nitrogen deficiency in crops.

6. Of what value is gypsum as a soil amendment? Under what conditions would you recommend that it be used?

7. Under what conditions are wetting agents useful in crop production?

CHAPTER 11

Environmental concerns and preventive soil management practices

"The earth has always nurtured us, despite our scornful abuse, and we can no longer continue to behave as its ungrateful offspring. It is time for us to nurture the earth in return."

D.J. Hillel. Out of the Earth, *1991*

Nutrients, pesticides, and other substances need to be managed properly to meet crop requirements without harming human or animal health or the quality of our water resources. Nutrients of concern with respect to water quality are nitrogen and phosphorus. Generally, nitrate-nitrogen is a groundwater concern and phosphorus is a surface water issue; however, nitrogen can also be factor in some surface water quality problems. Excess nitrates in drinking water can cause human and animal health problems, while excess phosphorus in lakes and streams can lead to algal blooms and excessive growth of aquatic plants. Pesticides used to control weeds, insects, and diseases can cause health problems if they get into drinking water or food. (Discussion of pesticide management is beyond the scope of this soil management publication.) Lastly, heavy metals, occurring naturally or added incidentally, are also of some concern because at high concentrations they interfere with various plant and animal metabolic processes.

Nitrates in groundwater

Groundwater supplies approximately 70% of the drinking water in Wisconsin. Nitrate is the most common contaminant of groundwater. Federal and state drinking water standards specify that water used for human consumption should not contain more than 10 ppm of nitrate-nitrogen (NO_3^--N). This value is equivalent to 44 ppm nitrate (NO_3^-). Laboratories report water nitrate content as either nitrate-nitrogen or nitrate. Many private wells in Wisconsin exceed this level.

The health concern with nitrate contamination of drinking water is largely focused on infants under 6 months of age. Infants, as well as young livestock, are susceptible to a condition called methemoglobinemia, or "blue baby syndrome" if they consume water or formula that contains elevated levels of nitrate-nitrogen. Bacteria in a baby's mouth and stomach convert ingested nitrate to nitrite (NO_2^-). The nitrite reacts with iron in the blood's hemoglobin, reducing the capacity of blood to carry oxygen. The result, in rare circumstances, can be fatal to infants. Although water containing more than 10 ppm of nitrate-nitrogen is not recommended for human consumption, adults and livestock may be able to tolerate considerably higher levels. However, pregnant women and nursing mothers should also avoid drinking water high in nitrate. Chronic health effects due to long-term ingestion of water containing high levels of nitrate are being investigated.

Sources of nitrate include nitrogen released from organic matter through microbial decomposition, nitrogen fixed from air by nitrogen-fixing organisms, and nitrogen added in manure, fertilizer, sludge, rain, or other inputs. Nitrate is a soluble, negatively charged ion. It is not held on cation exchange sites in the soil, nor is it adsorbed onto colloid surfaces. Hence, it moves with percolating water. Nitrate movement is greatest when the inputs exceed plant requirements and in soils where percolation to groundwater is high.

The map, *Groundwater Contamination Susceptibility in Wisconsin*, shows where groundwater is most easily contaminated with nitrates and pesticides. This map considers only the likelihood of water moving from the soil surface to the water table. It does not consider the type of contaminant or the amount in the soil. The main factors involved in determining susceptibility of groundwater to contamination are the type of bedrock, depth to bedrock, depth to the water table, soil texture, and other characteristics of surface deposits occurring between the topsoil and bedrock. The text accompanying the map explains the importance of most of these factors.

Farmers have no control over the amount of nitrate contributed by rainfall or soil organic matter. They can, however, manage the inputs from fertilizer, legumes, and manure to prevent groundwater contamination.

Table 11-1. Recovery of applied nitrogen by corn in relation to the amount applied.

Rate of nitrogen	Corn yield	Nitrogen recovery in grain Incremental	Total
— lb/a —	— bu/a —	%	
0	93	—	—
40	115	45	45
80	131	45	40
120	138	20	37
160	144	17	32
200	145	0	25

Source: Bundy et al., 1992. Nutrient Management—Practices for Wisconsin Corn Production and Water Quality Protection. *University of Wisconsin-Extension publication A3557.*

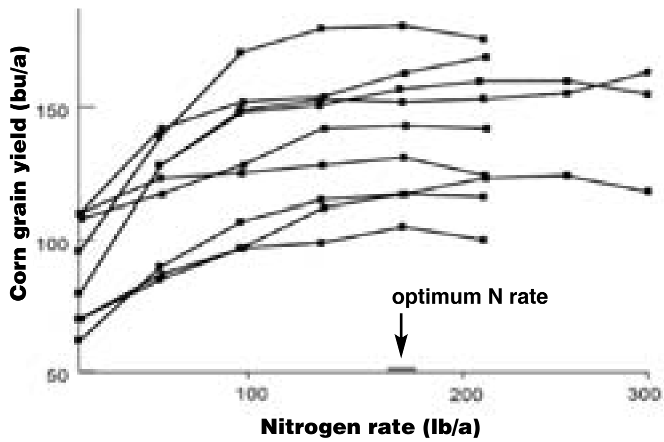
Rate of application

Nitrogen applied but not recovered by crops can contribute nitrate to groundwater through leaching. Recovery of applied fertilizer nitrogen decreases as the amount added increases. The results of a research trial on corn, presented in table 11-1, demonstrate this principle. The crop recovered less nitrogen with each successive increment of fertilizer. The optimum economic yield was obtained with 160 pounds of nitrogen per acre. This would usually be the best rate to apply. However, if nitrate contamination of groundwater is a major problem in the area, using lower rates of nitrogen could help reduce nitrate losses because more of the applied nitrogen is recovered by the crop at lower nitrogen rates.

Only a portion of the nitrogen not recovered by the crop may find its way to the groundwater. Some will be immobilized by soil microorganisms and become part of the pool of organic nitrogen, some may undergo denitrification and be returned to the atmosphere, and some will simply remain in the root zone and be available to plants the next season. Nevertheless, the potential exists for some of the unused nitrogen to enter the groundwater.

In the past, some farmers added extra nitrogen as “insurance” to make sure plants had enough nitrogen to take advantage of favorable weather conditions. Decades of Wisconsin research has shown that the optimum economic rate of nitrogen for corn is independent of weather variables that influence yields. In other words, it takes about the same amount of

Figure 11-1. Corn yield response to nitrogen application over several years on a Plano silt loam soil.



Source: Adapted from Bundy et al., 1992. Nutrient Management—Practices for Wisconsin Corn Production and Water Quality Protection. *University of Wisconsin-Extension publication A3557.*

nitrogen to reach the economic optimum in a poor year as it does in a good year (figure 11-1). The reason for this is that recovery of available nitrogen is higher under favorable growing conditions so that a higher yield is possible. Plant roots proliferate more under good growing conditions, enabling the plant to extract more soil nitrogen than it could under poorer conditions.

The best way to determine the optimum economic rate of nitrogen to apply is to have the soil tested in a laboratory using procedures developed by the University of Wisconsin. Current recommendations for corn are based on soil organic matter, soil texture, growing degree days, and yield potential of the soil. Recommendations for other crops are based on soil organic matter and yield goal.

Methods to improve nitrogen rate recommendations

Nitrogen recommendations for corn can be fine-tuned by testing the soil for the amount of nitrate in the soil profile. Two tests are available, a preplant soil profile nitrate test and a pre-sidedress soil nitrate test. Soil testing for nitrogen allows corn nitrogen recommendations to be adjusted for the numerous year- and site-specific conditions that can influence nitrogen availability.

The preplant soil profile nitrate test, taken in the spring prior to corn planting, measures the carryover nitrate-nitrogen in the top 2 feet of soil and estimates the amount present in the third foot. Most soils contain about 50 pounds per acre of nitrate-nitrogen in the top 3 feet of soil in the spring, even when no nitrogen was applied the previous year. This “background” level represents nitrogen present at a level too low for plants to extract. The total nitrate in the top 3 feet of soil minus 50 pounds per acre for background nitrogen is subtracted from the nitrogen recommendation. Suppose a preplant soil profile nitrate test shows nitrogen is already present at 140 pounds per acre and the nitrogen recommendation calls for 160 pounds per acre. The recommendation adjusted for soil profile nitrate would be calculated using the following equation:

Soil test N recommendation	–	Soil profile NO_3^--N credit (profile N – background N)	=	Adjusted N recommendation
160 lb/a	**–**	**90 lb/a** (140 lb/a – 50 lb/a)	**=**	**70 lb/a**

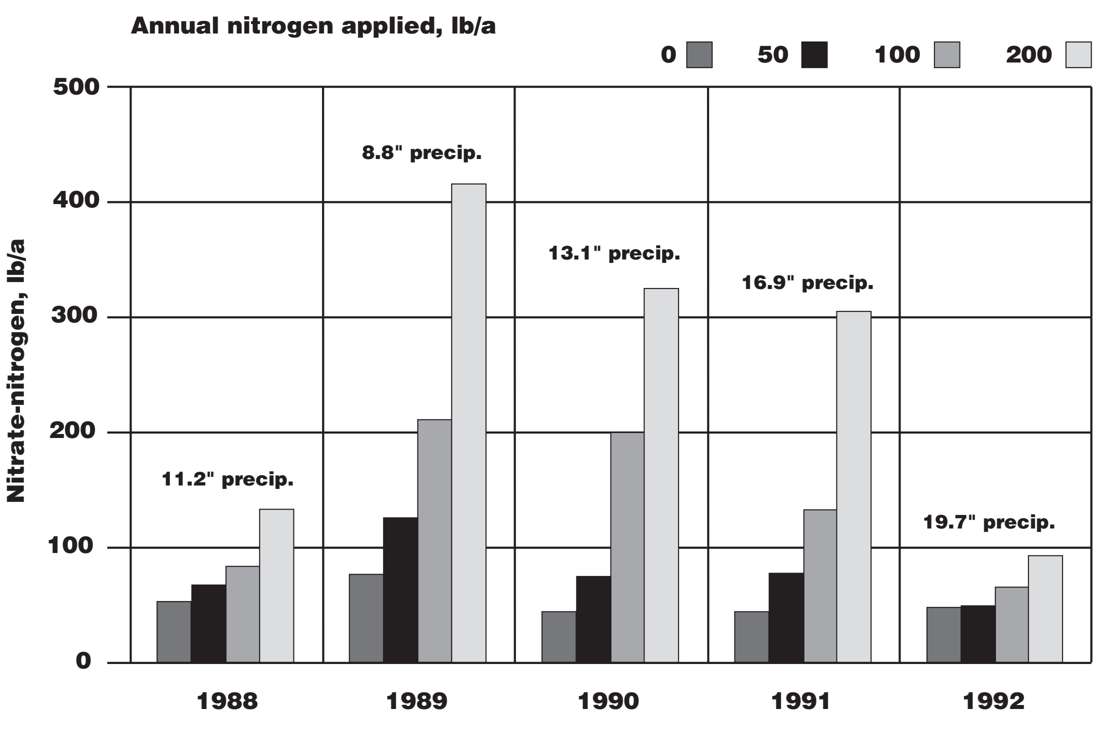
In years with below-normal precipitation in the fall, winter, and spring, substantial amounts of residual nitrate-nitrogen can carry-over from one growing season to the next. Measuring and accounting for residual nitrogen can reduce nitrogen recommendations for corn significantly. For example, in April of 1989, 1990, and 1991 the average nitrate-nitrogen in the top 3 feet of soil was 202, 193 and 124 pounds per acre, respectively, for samples received by the UW-Soil and Plant Analysis Lab. Precipitation during the 1988 and 1989 growing seasons was very limited as reflected in the higher levels of residual soil nitrate for 1989 and 1990. Adjusting nitrogen rates for residual nitrate not only lowers a grower's fertilizer bill, it also reduces the amount of nitrate available for leaching to groundwater.

The residual nitrate level in the soil profile depends on three main factors: soil type, prior precipitation, and previous nitrogen application rates. Carry-over of nitrate-nitrogen is always expected to be low on sandy soils. In other soils, carry-over of nitrogen can be expected if precipitation during the previous growing season and over-winter period is low (table 11-2). Figure 11-2 illustrates a study on a Dubuque silt loam that showed higher nitrogen applications resulted in higher residual nitrate levels following the dry years of 1988 and 1989. Carry-over nitrogen was lowest in 1992, a year with the highest over-winter precipitation.

Because soil sampling for the preplant soil profile nitrate test occurs early in the spring, it will not measure any nitrogen released from fall or spring manure applications or previous legume crops.

The pre-sidedress nitrate test is the other soil test for nitrogen available to corn growers. Samples for this test are collected from the top foot of soil when corn is 6 to 12 inches tall. With its later sampling period, the pre-sidedress nitrate test can measure the amount of nitrogen released from previous legumes and manure applications. This test can be a valuable tool for confirming the amount of nitrogen credited from manure or previous legume crops. If the soil contains 21 ppm or more, no additional nitrogen is needed. If there is less than 21 ppm nitrate-nitrogen, a sidedress application is warranted at the rates shown in table 11-3.

Figure 11-2. Nitrate-nitrogen to a depth of three feet as influenced by the rate of nitrogen applied the preceding year on a Dubuque silt loam. The numbers above the bars for each year are the amounts of overwinter precipitation (October–April) in inches.



Source: Bundy et al., 1993. Proc. 1993 Fert., Aglime & Pest Mgmt. Conf. 32:213–222.

Table 11-2. Potential for nitrogen carryover based on soil type and overwinter precipitation.

Soil type	—— Overwinter precipitation —— Below normal	Normal	Above normal
	Potential for nitrogen carryover		
Sandy soils	low	low	low
Loams	high	medium	low
Silt loams, silty clay loams	high	high	low

Nitrogen credits

When a soil test recommendation calls for a given amount of nutrients, the recommendation is often interpreted as meaning commercial fertilizer. However, nutrients added in manure or other organic byproducts and nitrogen from previous leguminous crops are a source of fertilizer nutrients that should be accounted for and "credited" against the base nutrient recommendations given from the soil test report.

Legume crops, when grown in rotation, supply substantial amounts of nitrogen to crops that follow. A good stand of alfalfa will provide all the nitrogen needed by a following crop of corn. If information on previous legume crops is provided when submitting soil samples to the laboratory, Wisconsin soil test recommendations will automatically credit the nitrogen contribution and subtract it from the amount recommended. Sometimes cropping plans change and it becomes necessary for farmers or their advisors to make these adjustments. Table 9-1 tells how much nitrogen to subtract from the amount recommended.

Manure can supply high levels of nitrogen, as well as other nutrients. The nitrogen credits for various kinds of manure are presented in table 10-2. These values are based on averages of many manure analyses. Analyzing the manure for nutrient content will yield more precise credits. County Extension offices have information on how to collect manure samples and where to have them analyzed.

Timing of nitrogen applications

The more time that elapses between nitrogen application and uptake by the crop, the more opportunity there is for leaching of nitrate to groundwater or loss by denitrification. Loss by leaching is of greater concern on sandy soils than on silt loams or silty clay loams. The problem is greatest on irrigated sands. Corn uses nitrogen slowly for the first month after planting. Rapid uptake begins about 6 weeks after planting and continues until tasseling. Uptake continues until maturity but at a slower pace.

To minimize the risk of nitrate leaching, do not apply nitrogen in the fall, especially on coarse-textured soils. Fall to spring precipitation, soil texture,

Table 11-3. Corn nitrogen recommendations based on the pre-sidedress soil nitrate test (PSNT).

PSNT result	——Soil yield potential[a]—— Very high/high	Medium/low
—N (ppm)—	——N application rate (lb/a)——	
21	0	0
20–18	60	40
17–15	100	40
14–13	125	80
12–11	150	80
< 10	160[b]	120[b]

[a] *To determine a soil's yield potential, consult University of Wisconsin-Extension publication Soil Test Recommendations for Field, Vegetable and Fruit Crops (A2809).*

[b] *No adjustment made to corn recommendations.*

and soil moisture all influence the potential for loss of fall-applied nitrogen. If fall applications must be made, limit them to ammonium forms of nitrogen (anhydrous ammonia, urea, ammonium sulfate) on medium-textured, well-drained soils. Fall applications should be delayed until soil temperatures are below 50°F. If applications of nitrogen must be made with soil temperatures greater than 50°F, include a nitrification inhibitor with the fertilizer to further reduce the risk of leaching.

Spring preplant applications of nitrogen are environmentally sound on well-drained, medium-textured soils. When making spring preplant applications on sandy or poorly-drained soils, use ammonium forms of nitrogen treated with a nitrification inhibitor. Sidedress applications are more effective on sandy soils than preplant applications with nitrification inhibitors. On corn, make sidedress applications 4 to 6 weeks after planting.

Multiple (or split) applications of nitrogen during the growing season are another option for reducing losses on sandy soils. Additional information on the timing of nitrogen applications and how it affects crop yield and the potential for loss of nitrate is discussed in chapter 9.

Nitrification inhibitors slow the bacterial conversion of ammonium (NH_4^+) to nitrate (NO_3^-). They can be used with ammonium or ammonium-forming fertilizers. The effectiveness of the inhibitor depends on when it is applied and on soil conditions. The probability of increasing corn yields in Wisconsin by using nitrification inhibitors is summarized in table 11-4.

Manure management

Manure applications can become an environmental concern if manure nutrients are not credited against fertilizer recommendations or if applications result in manure runoff to lakes or streams. The latter is especially a concern during the winter when the ground is frozen. During this period, soluble ammonium and nitrate-nitrogen may be lost in substantial quantities in runoff water. Winter or spring runoff can also carry organic nitrogen from manure solids. The best way to prevent winter nitrogen loss is by avoiding winter application of manure on frozen sloping land.

The use of manure storage facilities is recommended for periods when land application is inadvisable. These facilities should be constructed and located to minimize runoff losses and direct seepage to groundwater. Chapter 10 gives more detailed recommendations for handling manure.

Irrigation scheduling

Over-irrigation and excess rainfall can cause substantial leaching of nitrate to groundwater. Furthermore, over-irrigation is uneconomical. See chapter 4 for a discussion of irrigation scheduling as a means of reducing leaching.

Table 11-4. Relative probability of increasing corn yield by using nitrification inhibitors.

	Time of nitrogen application		
Soil	**Fall**	**Spring preplant**	**Spring sidedress**
Sands and loamy sands	not recommended	good	poor
Sandy loams and loams	fair	good	poor
Silt loams and clay loams			
well-drained	fair	poor	poor
somewhat poorly drained	good	fair	poor
poorly drained	good	good	poor

Urease inhibitors

Urease inhibitors are chemical compounds that can be added to urea or urea-containing fertilizers to slow the action of the soil enzyme "urease" in converting urea to ammonium compounds in soil. The advantage of slowing urease activity is to reduce ammonia volatilization losses from surface-applied urea-containing fertilizers. The challenge in deciding if and when to use a commercially available urease inhibitor is the identification of those situations where its use will conserve fertilizer nitrogen and result in a yield benefit. Typically, urease inhibitors have their greatest potential for benefit in cropping situations that are high risk for losing significant amounts of nitrogen through ammonia volatilization and no other practical management alternatives are available.

Best management practices for nitrogen

The following management practices will help to minimize nitrogen losses and protect water quality.

- Apply nitrogen at recommended rates.
- Use soil nitrate tests when appropriate.
- Credit nitrogen contributions from legumes, manure, and other organic byproducts.
- Do not apply nitrogen fertilizer in the fall.
- Use nitrification inhibitors when soil conditions and nitrogen application timing may promote leaching.
- Incorporate or inject manure.
- Manage fall manure applications carefully on excessively well-drained soils (i.e., sands).
- Store manure in properly located and constructed facilities during periods when land application is not advisable.
- Manage barnyards and feedlots to minimize leaching and runoff losses.
- Schedule irrigation to minimize leaching.
- Manage fertigation systems carefully.
- Diversify crop rotations to include crops that can use residual nitrogen.
- When possible, plant a fall cover crop.

Phosphorus in surface water

Phosphorus is usually not a problem in groundwater because: (1) elevated concentrations in drinking water do not pose a health threat, and (2) the concentration of phosphorus in the water that percolates through soil solution is low, even on heavily fertilized soils. However, phosphorus is a problem in runoff because it encourages the growth of algae and nuisance weeds in surface waters, especially in lakes or reservoirs where water movement is very slow.

Nutrient enrichment of surface water (eutrophication) occurs in nature, and it is a natural process of the aging of lakes that takes place regardless of farming practices. However, nutrient runoff accelerates the process. Excess nutrients in surface water cause algae blooms and abnormally high production of algae and aquatic plants. As the aquatic plant material decomposes, it depletes the oxygen supply in the water, killing fish and other aquatic organisms. In addition, nuisance growth of aquatic vegetation reduces the recreational and aesthetic value of lakes. For those communities drawing their drinking water from surface water, certain algae can cause taste and odor problems, and may pose health hazards.

The growth of algae and other aquatic plants can be limited by restricting the supply of any of the essential elements. Because phosphorus is the element most often limiting growth in fresh water environments, and possibly the most easy to control, it is seen as the "villain" in eutrophication.

Rate of application

Applying more phosphorus than crops need is unwise economically as well as environmentally. Soil testing should be used to determine the amount of phosphorus to apply. Soil test laboratories base phosphorus recommendations on realistic yield goals to ensure optimum yields.

Phosphorus credits

Phosphorus applied as manure should be credited against fertilizer recommendations. Table 10-2 identifies how much phosphorus credit to take for various kinds of manure. Land application of manure to cropland recycles nutrients, but can also lead to the build-up of phosphorus in soils, which in turn, increases the potential for losses via runoff and soil erosion. Manure is often applied to cropland at rates to meet the nitrogen need of the crop. The available nitrogen and phosphorus contents of dairy and other animal manures are about equal (table 10-2). However, the nitrogen need of corn, for example, is generally two to three times greater than the phosphorus need (table 11-5). The consequence of applying manure at rates to meet the nitrogen need of corn is that phosphorus applications will exceed crop removal (figure 11-3). The result is the build-up of phosphorus in cropland soils. Long-term manure applications have elevated the soil phosphorus level of many soils above the range necessary for optimum crop growth. This trend is especially prevalent in areas of concentrated livestock operations. Once soil test phosphorus exceeds optimum levels, future manure applications should be limited to rates that only replace the phosphorus removed by the crop.

Credits for phosphate in sewage sludge, whey, and other waste materials have not been established. These materials are typically applied on the basis of their available nitrogen content and the nitrogen needs of the crop to be grown. Subsequently, more phosphorus will be applied than the crop requires. To minimize potential environmental problems, sludge or whey should not be applied to sloping land where erosion is not controlled.

One option for drawing down high soil test phosphorus levels is to plant crops that remove large quantities of phosphorus. Such crops include legume forages and corn silage.

Manure management

As with nitrogen, a general management practice for phosphorus is to avoid manure applications to sloping frozen lands. Losses of phosphorus in runoff vary greatly from year to year and depend on conditions such as the amount and timing of winter and spring precipitation, depth of snow cover, and spring freeze-thaw patterns.

As stated in the manure management for nitrogen section of this chapter, the use of manure storage facilities is recommended for periods when land application is unsuitable. These facilities should be constructed and located to minimize runoff and seepage losses.

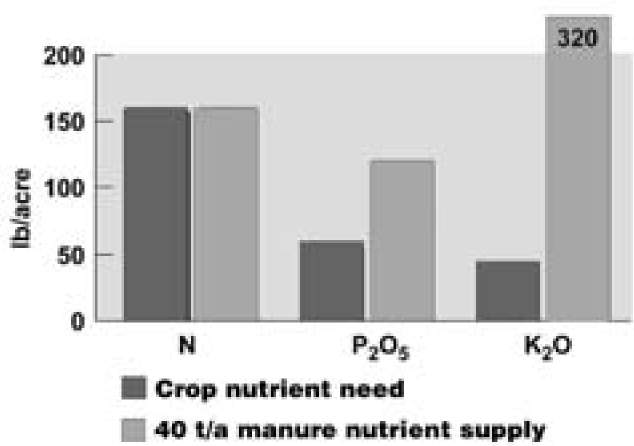
Until recently, the recommendation for land-applied manure was to incorporate it within 3 days of application whenever possible. Similar to fertilizer-phosphorus, manure-phosphorus will bind with soil particles when they are in close contact. Incorporating manure reduces the amount of dissolved (or soluble) phosphorus in runoff because phosphorus can bind to soil particles. However, incorporating manure

Table 11-5. Recommended nutrient application rates for corn grain at optimum soil test levels.

Corn target yield	— Application rates — N	P_2O_5	K_2O
bu/a	annual lb/a		
200	160	75	55
160	160	60	45
120	160	45	35

Source: Kelling et al., 1998. Soil Test Recommendations for Field, Vegetable, and Fruit Crops. *University of Wisconsin-Extension publication A2809.*

Figure 11-3. Nitrogen-based manure application strategy for corn.



Source: Sturgul, S.J. and L.G. Bundy, 2004. Understanding Soil Phosphorus. *University of Wisconsin-Extension publication A3771.*

involves tillage, which can increase soil erosion. Loss of sediment by soil erosion increases total phosphorus loss (total phosphorus is the sum of sediment- and dissolved-phosphorus). Manure broadcast on the surface (without incorporation) acts as mulch, lowering soil erosion. Unincorporated manure applications tend to reduce total phosphorus losses by lowering soil erosion but increase dissolved phosphorus losses. Incorporating manure with tillage may lower dissolved phosphorus losses but tends to increase total phosphorus losses. Recent Wisconsin findings suggest that the traditional management recommendation for incorporating manure may not minimize cropland phosphorus losses if total phosphorus reductions are the objective. This is particularly true for spring manure applications. With regulatory agencies currently using total phosphorus as the parameter on which to base regulations, a general recommendation to surface apply manure without incorporation to fields with soil conservation practices in place is appropriate. As a general practice, using conservation tillage, whether no-till or reduced tillage, will help keep soil particles on the field by increasing surface residue, which will in turn lower the loss of phosphorus in runoff to lakes and streams.

Chapter 10 gives more detailed recommendations for managing manure.

Erosion control

Most of the phosphorus found in surface water is associated with the organic matter and soil particles that erode from the land. The key to minimizing nutrient contributions to surface waters is to reduce the amount of runoff and eroded sediment that reaches surface waters. Numerous management practices for runoff and soil erosion control have been researched, developed, and implemented. Runoff and erosion control practices range from changes in agricultural land management (cover crops, diverse rotations, conservation tillage, contour farming, and contour strip cropping) to the installation of structural devices (buffer strips, diversions, grade stabilization structures, grassed waterways, and terraces). The most commonly used, widely adopted, and easily accomplished conservation practice is maintaining surface residue through various types of conservation tillage. See chapter 5 for a discussion of soil conservation practices.

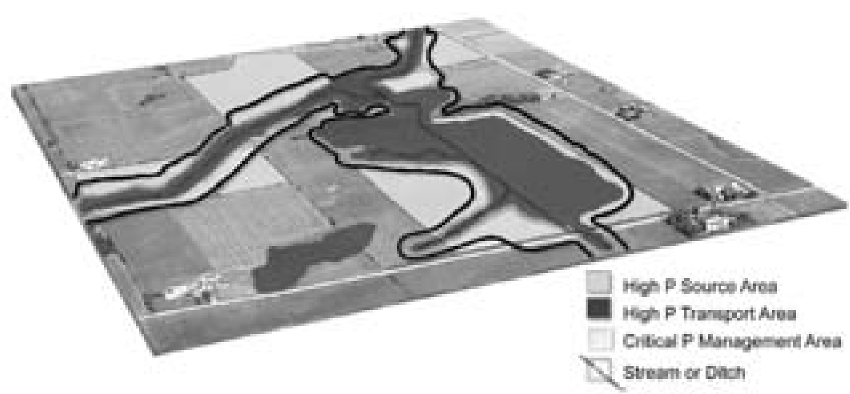
Identification of landscape areas prone to phosphorus loss

Phosphorus that reaches a lake or stream often originates from small areas within a watershed. One study found that less than 10% of the area within the investigated agricultural watersheds was responsible for 90% of the phosphorus contained in runoff.

Source areas vary in location and magnitude of phosphorus contribution due to weather conditions such as the intensity and length of rainfall, as well as land characteristics such as soil moisture, soil erodability, soil water storage capacity, topography, etc. Not all areas that would be obvious phosphorus sources have a pathway to surface water. On the other hand, not all areas with high potential for transport have a significant source of phosphorus. The many factors influencing phosphorus movement from the landscape make it challenging to identify areas prone to losing phosphorus. Various landscape assessment tools have been developed over the years to identify sites requiring improved management to minimize environmental risk.

The phosphorus index is one tool that calculates the risk of phosphorus loss from individual fields and provides management recommendations to reduce those losses. The phosphorus index evaluates both source and transport factors in its determination of phosphorus loss potential (figure 11-4). With the

Figure 11-4. Critical phosphorus source and transport area identification.



Source: Sturgul, S.J. and L.G. Bundy, 2004. Understanding Soil Phosphorus. *University of Wisconsin-Extension publication A3771.*

identification of critical areas where both source and transport factors coincide, appropriate management practices can be applied to reduce phosphorus losses. A phosphorus index has been developed for Wisconsin and can be found at wpindex.soils.wisc.edu.

Best management practices for phosphorus

A summary of the best management practices to minimize phosphorus losses are as follows:

- Use soil-erosion control practices to minimize soil loss and runoff.
- Apply phosphorus at recommended rates for the crop to be grown.
- Base phosphorus application rates on realistic yield goals.
- Credit phosphorus contributions from manure and other organic byproducts.
- Incorporate broadcast applications of phosphorus fertilizer.
- Incorporate or inject manure in a manner that does not increase soil erosion.
- Avoid applying manure to sloping frozen or saturated soils.
- Store manure in properly located and constructed facilities during periods when land application is not advisable.
- Target fields with low soil test phosphorus levels for manure applications.
- Control runoff from barnyards and feedlots.
- Do not surface-apply manure on sloping, no-till cropland.
- Install buffer strips adjacent to surface waters receiving runoff from cropped fields.
- Use the phosphorus index to identify fields prone to excessive phosphorus loss.

More extensive information on the management of phosphorus can be found in University of Wisconsin-Extension publication *Understanding Soil Phosphorus: An Overview of Phosphorus, Water Quality, and Agricultural Management Practices* (A3771).

Nutrient management planning

Formal plans detailing a farm's nutrient application strategy have been developed for many farms in Wisconsin. A nutrient management plan is required for participation in various federal and state farm programs involving cost-sharing. A farm nutrient management plan can also be a requirement of county ordinances dealing with the construction of manure storage facilities or livestock expansion.

Ideally, a farm nutrient management plan is a strategy for obtaining the maximum return from on- and off-farm fertilizer resources in a manner that protects the quality of nearby water resources. Each of the basic components to all farm nutrient management plans are described below.

Soil testing

Complete and accurate soil tests are the starting point of any farm nutrient management plan. All cropland fields must be tested or have been tested recently, generally within the last 4 years. From the soil test results, base fertilizer recommendations for each field are given.

Assessment of on-farm nutrient resources

The amount of crop nutrients supplied to fields from on-farm nutrient resources such as manure, legumes, and organic wastes needs to be determined and deducted from the soil test report's base fertilizer recommendations. Manure applications to fields supply crops with nitrogen, phosphorus, and potassium—as well as sulfur and organic matter. Legume crops such as alfalfa, clover, and soybean supply nitrogen to the crops that follow them.

Nutrient crediting

Once the on-farm nutrient resources are determined, commercial fertilizer applications need to be adjusted to reflect these nutrient credits. This action not only reduces commercial fertilizer bills, but it also protects water quality by eliminating nutrient applications in excess of crop need. Excessive nutrient additions to cropland can result in contamination of groundwater as well as lakes and streams.

Management skills come into play when determining nutrient credits. For example, to properly credit the nutrients supplied from manure, a grower must know both the manure application rate and the crop-available nutrient content of the manure. To credit the nitrogen available to crops following alfalfa, the condition of the alfalfa stand as well as last cutting date and soil texture need to be known.

Consistency with the farm's conservation plan

A nutrient management plan needs to be consistent with a farm's soil conservation plan. The conservation plan is an important component of any nutrient management plan for it contains needed information on planned crop rotations, field slopes (which is important when planning manure applications), and conservation measures needed to maintain soil erosion rates at "T" or tolerable rates. In the event that a soil conservation plan does not exist, or the existing plan does not meet "T", the information contained in a conservation plan will have to be obtained before the nutrient management plan can be developed.

Manure inventory

Probably the most challenging aspect of developing and implementing a farm nutrient management plan is the advance planning of manure applications to cropland fields.

This involves estimating the amount of manure produced on the farm and then planning specific manure application rates for individual cropland fields. Sounds challenging—and it is, but there are some tricks to the trade. One of them is calibrating your manure spreader. This can be done using scales—either platform scales or portable axle scales available from the county Extension or Land Conservation office. Once calibrated, the number of tons (or gallons) of manure the spreader typically holds is known. With this information, specific manure application rates for fields can be planned.

Manure spreading plan

The majority of any nutrient management plan for livestock farms will deal with the manure spreading plan. The amount of manure a farm produces has to be applied to fields in a manner that makes sense both environmentally and agronomically. Planned manure applications should be made at rates that do not exceed crop nutrient need as identified in the soil test report. The nutrient management plan should also prioritize those fields that would benefit the most from the manure-supplied nutrients while posing minimal threats to water quality. Also, the nutrient management plan will identify those fields with manure spreading restrictions. Examples of such restrictions would be fields adjacent to lakes and streams, sloping fields where the threat of spring runoff prohibits manure applications in the winter, and fields in the vicinity of wells, sinkholes, or fractured bedrock.

The seasonal timing of manure applications to cropland will also be identified in a nutrient management plan. The timing of planned manure applications will depend upon each farm's manure handling system. Manure application periods for a farmer with manure storage will be significantly different from that of a farmer who has to haul manure on a daily basis.

The 590 nutrient management standard

The 590 standard is a United States Department of Agriculture—Natural Resources Conservation Service document that defines the minimum requirements and components of an acceptable nutrient management plan. The 590 nutrient management standard periodically changes with revisions, but basically requires producers to follow University of Wisconsin recommendations for nutrient inputs to cropland. The standard also contains additional restrictions on the timing and location of nutrient applications to agricultural fields. A current version of the nutrient management standard can be found at www.datcp.state.wi.us/arm/agriculture/land-water/conservation/nutrient-mngmt/planning.jsp.

Non-essential elements

Plants take up some elements from the soil solution simply because they are present even though they are not needed by the plant. Some of these are essential to animals, such as cobalt, iodine, and selenium. At high concentrations these non-essential elements may pose a potential health threat if they get into the food chain. Selenium, for example, is found at toxic concentrations for grazing animals in some plant species that accumulate this element in the Great Plains, but it is sometimes deficient in forage grown in Wisconsin soils. Low selenium in the diet of animals causes "white muscle" disease.

All elements occur naturally in soils and in the earth's crust. They become of concern only when the level is high enough to threaten human and animal health. Table 11-6 identifies the potential toxicity level of several elements and table 11-7 lists their sources.

One source of heavy metals is municipal biosolids (sewage sludge). Table 10-4 lists the concentrations of

Table 11-6. Potential toxicity of several elements taken up by plants.

Element	Symbol	Essentiality		Toxicity	
		Plants	Animals	Plants	Animals
Arsenic	As	No	No	Moderate	High
Cadmium	Cd	No	No	Moderate	High[a]
Cobalt	Co	No	Yes	Low	Moderate
Chromium	Cr	No	No	Low	Low
Copper	Cu	Yes	Yes	Moderate	Moderate
Iron	Fe	Yes	Yes	Low	Low
Lead	Pb	No	No	Low	High[a]
Manganese	Mn	Yes	Yes	Moderate	Moderate
Mercury	Hg	No	No	Low	High[a]
Molybdenum	Mo	Yes	Yes	Moderate	High
Nickel	Ni	No	Yes	High	Moderate
Selenium	Se	No	Yes	Moderate	High
Zinc	Zn	Yes	Yes	Moderate	Low

[a] *Cumulative effects.*
Source: Keeney, D.R., et al. 1975. Guidelines for the Application of Wastewater Sludge to Agricultural Land in Wisconsin. *DNR Tech. Bull 88. Madison, WI.*

each of the heavy metals found in sewage sludge. Interestingly, those concentrations are much lower than those collected two decades earlier. Recycling of metals and tighter U.S. Environmental Protection Agency (EPA) and Wisconsin Department of Natural Resources (DNR) restrictions are probably responsible for this decrease. Also, many municipalities work with industry to pre-treat wastewaters to lower the input of heavy metals.

Research shows that heavy metals do not accumulate uniformly within a plant—seeds and fruits usually contain much lower levels of heavy metals than do the vegetative plant parts. In a 6-year study, the concentrations of heavy metals in corn were measured when Milwaukee sewage sludge was applied annually at a rate of 6 ton/a (dry weight basis). Researchers found elevated concentrations of cadmium, copper, and zinc in corn earleaf and stover tissue but not in the grain (table 11-8). In fact, none of the six metals tested accumulated in the grain.

Heavy metal loading from biosolid application is regulated by monitoring the elemental content of waste materials and maintaining levels below EPA-specified ceiling concentrations. A risk assessment that evaluated 14 potential pathways of exposure to humans established these concentrations such that 100 years of consecutive applications would not present an unnecessary risk.

Table 11-7. Sources of metals in the environment.

Element	Source — General	Source — Specific
Arsenic	Agricultural	Arsenical pesticides used in the past.
Cadmium	Agricultural Industrial	Impure phosphate fertilizers. Electroplating, pigments, chemicals, alloys, automobile radiators and batteries.
Chromium	Industrial	Refractory bricks, plating of metals, dying and tanning, corrosion inhibitors.
Copper	Electrical Plumbing Industrial Agricultural	Wire, apparatus. Copper tubing, sewage pipes. Boilers, steampipes, automobile radiators, brass. Fungicides, fertilizers.
Lead	Plumbing Industrial	Caulking compounds, solders. Pigments, production of storage batteries, gasoline additives, anti-corrosive agents in exterior paints, ammunition.
Mercury	Electrical Industrial Household Agricultural	Apparatus. Electrolytic production of chlorine and caustic soda, measuring and control instruments, pharmaceuticals, catalysts, lamps (neon, fluorescent and mercury-arc), switches, batteries, rectifiers, oscillators, paper and pulp industries. Paints, floor waxes, furniture polishes, fabric softeners, antiseptics. Fungicides.
Nickel	Industrial	Electroplating, stainless and heat-resisting steels, nickel alloys, pigments in paints and lacquers.
Selenium	Industrial	Photocopiers, rectifiers in electrical equipment.
Zinc	Agricultural Household Industrial Plumbing	Pesticides, superphosphates. Pipes, utensils, glues, cosmetic and pharmaceutical powders and ointments, fabrics, porcelain products, oil colors, antiseptics. Corrosion-preventive coating, alloys of brass and bronze, building, transportation and appliance industries. Galvanized sewage pipes.

Source: Keeney, D.R. et al. 1975. Guidelines for the Application of Wastewater Sludge to Agricultural Land in Wisconsin. *DNR Tech. Bull 88. Madison, WI.*

Table 11-8. Effect of sewage sludge and fertilizer on the concentration of heavy metals in corn.

Amendment	Cd	Cr	Cu	Ni	Pb	Zn
	ppm					
Ear leaf						
Control	0.29	1.16	6.8	1.22	1.61	19
Sludge[a]	0.35	1.08	10.2	1.15	1.35	80
Fertilizer[b]	0.20	0.96	7.8	1.06	1.12	24
Stover						
Control	0.21	0.21	1.6	0.63	<1.0	18
Sludge[a]	0.22	0.20	1.52	0.74	<1.0	22
Fertilizer[b]	0.14	0.23	1.38	0.42	<1.0	15
Grain						
Control	<0.08	0.33	1.69	0.68	<0.86	16.4
Sludge[a]	<0.08	0.52	1.57	1.05	<0.86	19.8
Fertilizer[b]	<0.08	0.66	1.57	0.90	<0.86	16.0

Abbreviations: *Cd = cadmium; Cr = chromium, Cu = copper, Ni = nickel, Pb = lead, Zn = zinc.*

[a] *Sludge applied at 6 ton/a per year.*

[b] *Fertilizer (N, P_2O_5, K_2O) equivalent to that in 3 ton/a of sludge.*

Source: Peterson, A.E. 1990. Unpublished report. Dept. of Soil Sci., UW-Madison.

Questions

1. Why are nitrogen and phosphorus potential "environmental pollutants"?

2. Under what conditions might you expect to find high levels of nitrate in groundwater? What can be done to reduce leaching of nitrate?

3. Why is applying more than the recommended amount of nitrogen as "insurance" not a sound practice?

4. List at least two reasons why irrigation scheduling is recommended.

5. How does phosphate find its way into surface water? How can this be reduced?

6. Discuss the pros and cons of applying sewage sludge to agricultural land.

7. What can be done to ensure that heavy metals in sewage sludge applied to agricultural land do not build up to unacceptable levels?

CHAPTER 12

Soil testing, soil test recommendations, and plant analysis

"This we know: The earth does not belong to man; man belongs to the earth. Man did not weave the web of life; he is merely a strand in it. To harm the earth is to heap contempt upon its creator."

Chief Seattle, 1852
(Reply to United States Government wanting to purchase Indian tribal lands in the Northwest)

There are a number of ways of evaluating the nutrient status of soils and the crops grown on them. The most commonly used methods include the following:

- fertilizer trials in the field,
- greenhouse experiments,
- observation of crop symptoms,
- plant analysis,
- tissue testing in the field, and
- soil testing.

Each method has limitations. Fertilizer trials are expensive and time-consuming so they cannot be run on very many fields, and the results from one field cannot be transferred easily to another. Greenhouse experiments require specialized facilities and are costly, and the yield response is often quite different from that which occurs in the field. Visual symptoms indicate only severe deficiencies, and they often appear so late that any remedial action may be only partially successful. Plant analysis and tissue tests are conducted during the growing season to help identify problems, but they generally cannot be used to predict the amount of fertilizer or lime needed. Of the methods mentioned above, soil testing is the only rapid and inexpensive method which can be used to reliably estimate lime and fertilizer needs in advance of when the crop is grown. Soil tests are the only truly predictive tests available.

Soil testing

Wisconsin laboratories analyze about 250,000 soil samples each year. The results of these tests guide Wisconsin farmers in an annual expenditure of about 165 million dollars for lime and fertilizer. It is estimated that Wisconsin farmers have increased their collective crop income by over 400 million dollars as a result of using lime and fertilizer.

Even though these statistics point out the importance of soil testing, some confusion exists as to the meaning and usefulness of soil test results. Some people view the soil test as only a "gimmick" to sell more lime and fertilizer. Others regard it as an infallible and almost magical method of predicting exactly how much of each plant nutrient needs to be supplied to the crop. In fact, the soil test is neither a gimmick nor an exact science but an estimate. The accuracy of the estimate depends on how well the soil sample represents the field, the quality of the lab analysis, and the accuracy of the calibrations used to interpret the data.

A sound soil testing program requires a tremendous amount of field, greenhouse, and laboratory research. Scientists must identify the various forms of the available nutrients in the soil, find chemical extractants that will remove an amount of the nutrient proportional to that extracted by crops, and determine the response to different rates of lime and fertilizer at various soil test levels. Furthermore, this research has to be conducted over a wide range of soil, crop, and climatic conditions. The value of a soil testing program is directly proportional to the quality and quantity of its research backing.

A soil testing program is usually divided into four phases:

1. Collecting the sample.
2. Analyzing the soil.
3. Interpreting the results.
4. Making the recommendations.

With representative sampling of the field, accurate analysis of the soil, and correct interpretation of the test results, the lime, phosphorus and potassium requirements can be predicted with a relatively high degree of accuracy. Also, while not as precise, soil tests can serve as a guide for nitrogen and some of the secondary and micronutrients. Soil testing does have some limitations, but it is the only practical way of predicting crop response to lime and fertilizer.

Soil sampling

Soil samples are taken to provide an estimate of the fertility status of a field and to show the size and location of any variability that may exist. A fertilizer or lime recommendation based on soil analysis is good only if the soil sample analyzed is representative of the field from which it was taken. If a sample does not represent the general soil conditions of the field, the recommendations based on this sample will be useless, or worse, misleading. An acre of soil to a 6-inch depth weighs about 1,000 tons, yet less than 1 ounce of soil is used for each test in the laboratory. Therefore, it is very important that the soil sample is characteristic of the entire field. For these reasons, multiple composite samples composed of several soil cores need to be taken from a given field.

Goals of a soil sampling program

When sampling soils for testing and obtaining fertilizer and lime recommendations, the most common objectives are to:

1. Obtain samples that accurately represent the field from which they were taken;
2. Estimate the amount of nutrients that should be applied to provide the greatest economic return to the grower;
3. Provide some estimate of the variation that exists within the field and how the nutrients are distributed spatially; and
4. Monitor the changes in nutrient status of the field over time.

The ultimate goal of a soil fertility program needs to be considered before taking any samples, as that will determine how many are needed and where to sample. For example, if the intent is to fertilize the entire field using a single application rate, fewer samples will need to be collected than if a variable rate of fertilizer application was planned within the field. The second application strategy, known as site-specific management, requires special equipment to change rates of manure, lime, or fertilizer on the go. To select between the sampling strategies, consider analytical costs, field fertilization history, and the likelihood of response to variable fertilization. Each approach is outlined in the following text.

Sampling fields for a single recommendation

With conventional sampling, a single set of soil test results and associated fertilizer and lime recommendations will be based on sample averages. The sampling guidelines in table 12-1 are based on when the field was last tested (more or less than 4 years) and whether the field was responsive or non-responsive the

Table 12-1. Recommended sample intensity for uniform fields.

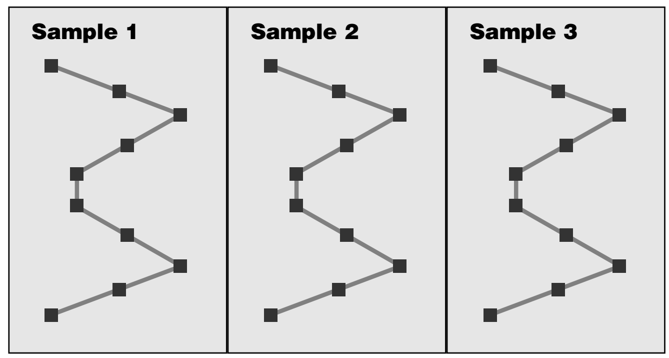
Field characteristics	Field size (acres)	Suggested sample number[a]
Fields tested more than 4 years ago and fields testing in the responsive range	all fields	1 sample/ 5 acres
Non-responsive fields tested within past 4 years	5–10	2
	11–25	3
	26–40	4
	41–60	5
	61–80	6
	81–100	7

[a] *Take a minimum of 10 cores per sample.*

last time it was tested (if within 4 years). The *responsive* range is considered to be where either soil test phosphorus or potassium levels are in the high category or lower. A *nonresponsive* field is one where both soil test phosphorus and potassium levels are in the very high or excessively high categories.

To assure accurate representation of the nutrient needs of the field, each sample should be made up of a minimum of 10 cores. Research has shown that taking 10 to 20 cores provides a more representative sample of the area than when samples are made up of fewer cores. Use a W-shaped sampling pattern (figure 12-1) when gathering composite samples. Be sure to thoroughly mix the cores before placing approximately 2 cups in the soil sample bag.

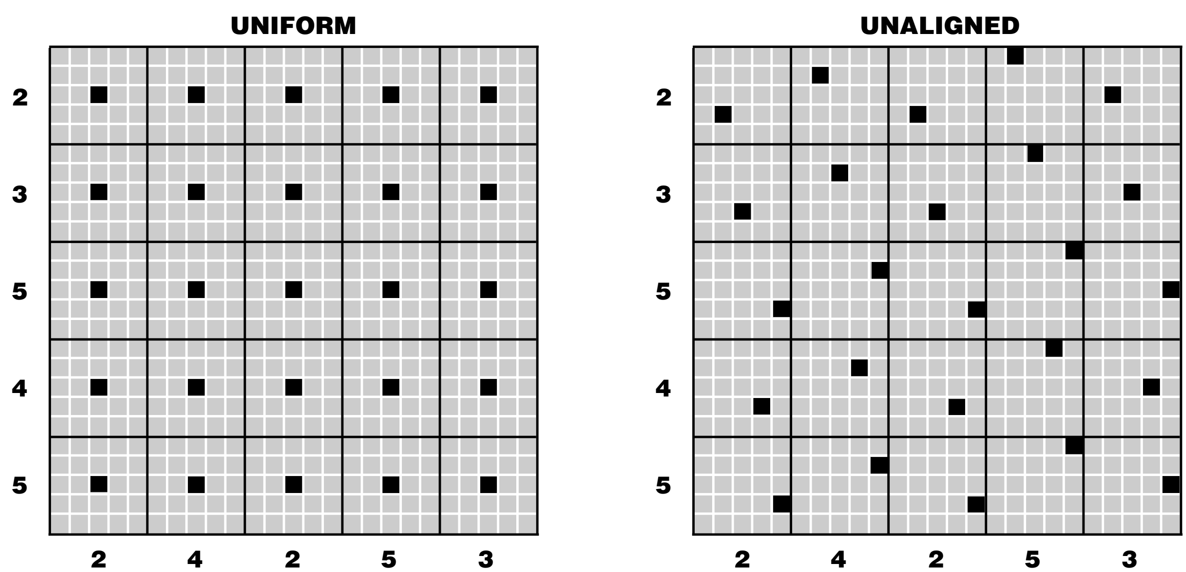
Figure 12-1. Recommended W-shaped sampling pattern for a 15-acre field. Each sample should be composed of at least 10 cores.



Sampling fields for site-specific (grid sampling) management

Site-specific management, or grid sampling, requires a more intensive soil sampling scheme that differs from sampling for single rate applications. Samples should be taken within a relatively small radius (10 feet) of a known point within a field rather than as a composite of cores taken over a broader area. This method is known as grid-point soil sampling. The points are most conveniently and accurately located with differentially corrected global positioning systems (GPS) that use satellite radio signals to find positions with a repeatable accuracy of 3 to 10 feet. The area or grid size selected is a compromise between cost and desired accuracy. Most commercial samples are collected on a 1 to 2.5 acre grid (200 to 330 foot spacing). The most simple grid pattern is the uniform pattern; however, unaligned grid patterns (figure 12-2) ensure that the soil sampling points are staggered or randomized within the grid to prevent biasing the results by previous nutrient applications (fertilizer bands, manure strips, etc.).

Figure 12-2. Examples of grid sampling patterns for site-specific fields.



Soil test data are mathematically manipulated to create management maps showing areas having different fertilizer needs. These methods interpolate expected values between the known sample points and create contoured boundaries that are used to variably apply fertilizer materials. Variable-rate fertilizer equipment directly reads the information from the management map and changes the rate of application as the spreader drives across the field.

Grid soil sampling is best suited to fields that are expected to have significant areas in the responsive soil test range. An example would be a relatively large field near the barn that has received differential applications of manure.

Regardless of the sampling strategy used, soil must be collected from several locations within the defined sampling area. Fertilizer recommendations become increasingly accurate as the number of cores per sample and the number of samples increases. However, the value of that accuracy must be weighed against both the expense and the practicality of taking more samples.

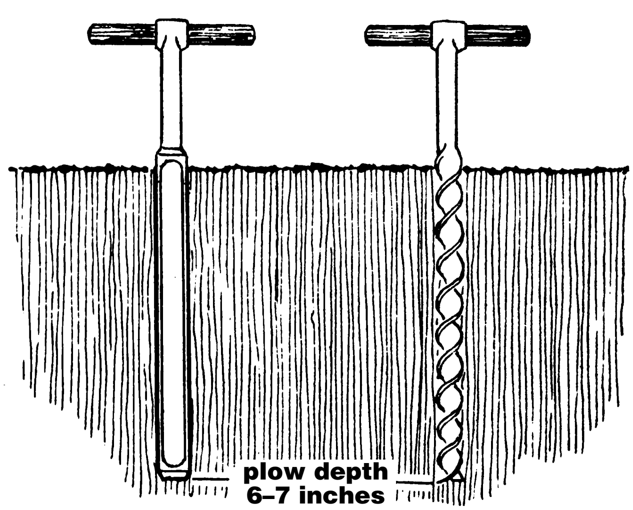
How to collect soil samples

Guidelines for sampling soil in Wisconsin are given below:

1. Use a soil sample probe or soil auger to take samples (figure 12-3).
2. If manure or crop residues are on the soil surface, push these aside and do not include in the sample.
3. Insert the probe or auger into the soil to plow depth or at least 6 inches.
4. For non-responsive fields larger than 5 acres, obtain, at a minimum, the number of samples specified in table 12-1. For responsive fields that have not been sampled in the past 4 years, take one composite sample for every 5 acres. Collect at least two composite samples for every field. Cores from two or three small contour strips may be combined if they are cropped and fertilized the same.
5. Take at least 10 soil cores or borings for each composite sample.
6. Avoid sampling nonrepresentative areas of a field such as dead and back furrows, fence lines, lime, sludge or manure piles, rows where fertilizer was band-applied, eroded knolls, low spots, etc.
7. Avoid sampling any area that varies widely from the rest of the field in color, fertility, slope, texture, drainage, or productivity. If the distinctive area is large enough to receive lime or fertilizer treatments different from the rest of the field, sample it separately.
8. Place the sample (about 2 cups) in a soil sample bag. Sample bags are available from all soil testing labs.
9. Identify the bag with name, field identification, and sample number.
10. Record the field and sample location on an aerial photo or sketch of the farm and retain for future reference.
11. Fill out the soil information sheet and submit it along with the soil samples to a soil testing laboratory. The more completely and carefully this sheet is filled out, the better the recommendations will be. A sample of the soil information sheet is attached.

For samples to be useful in tracking changes in a field from one sampling period to the next, it is essential that all

Figure 12-3. Soil sampling tools. The soil sample probe (left) povides a uniform sample to the depth of tillage. The soil auger (right) works best when collecting samples in stony soil.



Soil & Plant Analysis Lab
8452 Mineral Pt Rd
Verona, WI 53593
(608) 262-4364

Department of Soil Science
College of Agricultural and Life Sciences
University of Wisconsin - Madison/Extension

Soil & Forage Analysis Lab
8396 Yellowstone Drive
Marshfield, WI 54449
(715) 387-2523

Date Rec'd

Soil Information Sheet for Field, Vegetable and Fruit Crops

Lab No (Lab Use Only)	**County** FSA No.	**Method of Payment**
	Name	Account ID
	Address	Amount paid
	City State Zip	Cash
County Code	Email Address	Check No.
TOTAL NUMBER OF SAMPLES	**PLOW DEPTH**	Credit Card No________-________-________-________
		Exp Date ______/______ VISA ____ MC ____

						4-YEAR CROP ROTATION			FERTILIZER CREDIT INFORMATION						
									Previous Legume Crop			Manure Applied to Field Since Last Crop			
FIELD ID	SAMPLE NO(S)	Check if Irrigated	SOIL NAME (if known)	Acres in Field	Slope %	Sequence to be Grown (crop code)	Ck if Conserv Tillage	Yield Goal	Legume Crop (crop code)	Legume Forage % stand (circle)	Check if more than 8" regrowth in fall	Manure Code (See below)	Application Rate T/a gal/a	Application Method (Circle one)	Consecutive Years of Application (circle)
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
										< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+

Special Soil Tests (additional fee)

(List field or sample identification)

Calcium/Magnesium	Zinc
Boron	Sulfate
Manganese	Other

Soil tests recommended if:

growing corn (field or sweet) **Zn and SO_4-S**
growing legume forage **B and SO_4-S**
growing small grain or soybean (with soil pH >7.0) **Mn**
growing potato or apple (with pH < 5.5) **Ca/Mg**
growing specialty or vegetable crops **B, Zn, and Mn**
acid or sandy soil with high amounts of applied K **Ca/Mg**

Manure Code List

Solid	**Liquid**
1 Dairy	11 Dairy
2 Beef	12 Veal calf
3 Swine	13 Beef
4 Duck	14 Swine, indoor pit
5 Chicken	15 Swine, outdoor pit
6 Turkey	16 Swine, farrow-nursery indoor pit
7 Sheep	17 Duck
8 Horse	18 Poultry

INSTRUCTIONS

NAME AND ADDRESS - Print clearly

Fill in the FSA Farm No (optional) and County from which the sample(s) were taken.
Fill in the e-mail address if you would like results emailed.

METHOD OF PAYMENT

Fill in your Account ID (if applicable), cash, credit card, or check payable to: **UW Soil Testing Lab**

FIELD ID and **SAMPLE NO(S)**

Record the field and sample identification for each field on the same line. **Please number samples consecutively.**
.

EXAMPLE

Field ID	Sample No(s)
1	1-4
2	5
3	6-8

SOIL NAME

Write the soil name (not the abbreviation) from an FSA farm plan or county soil survey map.
Example: Fayette silt loam, write "Fayette". If the field has more than one soil type, use the most predominant soil found in the field. A more precise soil test recommendation can be given if the soil name is included.

4-YEAR CROP ROTATION

Indicate the intended crops to be grown for the next four years. **Use the crop codes(s) listed in the table below**.
Enter a yield goal no more than 10-15% higher than the prior 5-year average for each crop. Base the yield goal for corn on yield of No. 2 corn at 15.5% moisture. Yield goal for alfalfa should be based on dry matter in T/a. Base yield of other crops on the yield unit shown in parenthesis ( ). Give yield goals to the nearest ½ T for crop units expressed in T/a.
Check if conservation tillage leaves more than 50% residue cover when corn follows corn.

Crop Code	Crop Name	Yield Unit
1	Alfalfa	(tons)
2	Alfalfa, seeding year	(tons)
3	Asparagus	(lbs)
4	Barley	(bu)
5	Beans, dry (kidney, navy)	(bu)
6	Beans, lima	(lbs)
7	Beets, table	(tons)
8	Brassicas, forage	(tons)
9	Broccoli	(tons)
10	Brussel sprouts	(tons)
11	Buckwheat	(lbs)
12	Cabbage	(tons)
13	Canola	(bu)
14	Carrots	(tons)
15	Cauliflower	(tons)
16	Celery	(tons)
17	Corn, grain	(bu)
18	Corn, silage	(tons)
19	Corn, sweet	(tons)
20	Cucumber	(bu)
21	Flax	(bu)
22	Ginseng	(lbs)
23	Lettuce	(tons)
24	Lupin	(bu)

Crop Code	Crop Name	Yield Unit
25	Melon	(tons)
26	Millet	(bu)
27	Mint, oil	(lbs)
28	Oats	(bu)
29	Oatlage	(tons)
30	Oat-pea, forage	(tons)
31	Onion	(cwt)
32	Pasture, unimproved	(tons)
33	Pasture, managed	(tons)
34	Pasture, legume grass	(tons)
35	Peas, canning	(lbs)
36	Peas, chick, field, cow	(tons)
37	Peppers	(tons)
38	Popcorn	(bu)
39	Potato	(cwt)
40	Pumpkin	(tons)
41	Reed canarygrass	(tons)
42	Red clover	(tons)
43	Rye	(bu)
44	Snapbean	(lbs)
45	Sod	(-)
46	Sorghum, grain	(bu)
47	Sorghum, forage	(tons)

Crop Code	Crop Name	Yield Unit
48	Soybeans	(bu)
49	Spinach	(tons)
50	Squash	(tons)
51	Sunflower	(lbs)
52	Tobacco	(lbs)
53	Tomato	(tons)
54	Trefoil, birdsfoot	(tons)
55	Triticale	(lbs)
56	Truck crops	(-)
57	Vetch, hairy, crown	(tons)
58	Wheat	(bu)
59	Miscellaneous	--
60	Apple	--
61	Blueberry	--
62	Cherry	--
63	Cranberry	--
64	Raspberry	--
65	Strawberry	--
66	CRP, alfalfa	--
67	CRP, red clover	--
68	CRP, grass	--

FERTILIZER CREDIT INFORMATION: Legume-sod plowdown or manure application may reduce nutrient need.
Previous Legume Crop: Enter the crop code for the previous legume crop grown on the field. For all forage crops that were plowed down, indicate the % legume remaining in stand and check if there was more than 8 inches of regrowth in the fall before the stand is killed.
Manure Applied to Field Since Last Crop: If manure was applied to the field since harvesting the last crop, choose manure code from **Manure Code List** on front of Information Sheet. Specify the approximate rate of application in T/a for solid or 1000 gal/a for liquid manure, the application method (surface applied, incorporated within 72 hrs or injected) and the number of consecutive years manure has been applied to this field.

SPECIAL SOIL TESTS: Special tests may be run on individual samples, or all the samples from the same field may be combined at the lab for a single field analysis. If the special test(s) is requested on a field basis only, enter the field ID.
If the special test(s) is requested for each sample, enter the field ID and sample no.

cores be taken to exactly the same depth. Small differences in sampling depth, especially from conservation or reduced tillage fields, can dramatically affect soil test results.

Tillage considerations

When sampling fields that have not been tilled since the last application of row fertilizer, take the soil cores midway between crop rows. This will help avoid sampling the old fertilizer band, which would give falsely high soil test results for phosphorus and potassium. Sample freshly plowed fields by inserting the soil probe or auger into a footprint. This slight compaction ensures extraction of a solid uniform core of soil from the plow layer.

- With moldboard plowing, sample soils to 6 inches or the depth of the plow layer. Although subsoils do contribute nutrients to a crop, the phosphorus and potassium recommendations are not accurate enough to justify the extra cost of taking and analyzing subsoil samples. Subsoil fertility is factored into the nutrient recommendations based on the soil type or area of the state.
- With chisel plowing and offset disking, take soil samples to ¾ of the tillage depth. When possible, take soil samples before fall or spring tillage to avoid residual fertilizer bands and to more accurately determine sampling depth.
- With no-till, take soil samples to a depth of 6 to 7 inches. Sample between rows to avoid old fertilizer bands. When nitrogen is surface-applied, an acid layer may develop near the soil surface. Such an acid layer could reduce the effectiveness of some herbicides. If you suspect an acid layer, take a separate sample to a depth of only 2 inches. When such a sample is submitted for soil testing, indicate that it is from the surface layer (0 to 2 inches) of a no-till field.
- With till-plant and ridge tillage, sample ridges to the 6-inch depth and between rows (furrows) to a depth of 4 inches. Combine soil cores from ridges and furrows in equal numbers to make up the composite sample.

Timing and frequency

Soil samples can be taken at any time; however, early fall is preferred because farmers will then have adequate time to plan, purchase, and apply needed lime and fertilizer. When samples are submitted in the spring, farmers may not receive the soil test report back in time for planting.

Sampling frozen soil should be avoided unless uniform soil borings or cores can be obtained to the appropriate depth. Normally, this requires the use of a portable power boring tool. Do not use a pick or spade to remove a few chunks of frozen soil from the surface.

For field crops, sampling the soil once every 4 years or once in crop rotation is sufficient. For crops grown on sands or for high-value crops such as potatoes, samples should be gathered every year. More detailed information on soil sampling is given in Extension publication *Sampling Soils for Testing* (A2100). It is available from any county Extension office.

Field history is needed to make accurate recommendations. This information should be reported on the soil information sheet (sample attached) when soil samples are taken. The more completely and carefully this sheet is filled out, the better the recommendations will be. Read the instructions on the back side of the sheet. Be sure to include the soil series name for each field. The soil series can be obtained from a farm's conservation plan.

The soil samples and a completed soil information sheet can be left at any county Extension office for forwarding to an approved soil testing laboratory. If this is not convenient, soil samples can be sent directly to the soil testing laboratory or delivered in person.

The Department of Soil Science, UW-Madison and UW-Extension, operates soil testing laboratories at Madison, 8452 Mineral Point Road, Verona, WI 53593 and Marshfield, 8396 Yellowstone Drive, Marshfield, WI 54449. Private soil testing laboratories, which are certified by the Wisconsin Department of Agriculture, Trade and Consumer Protection (WDATCP) are also available. The locations of WDATCP-approved laboratories can be obtained from county Extension offices or online at uwlab.soils.wisc.edu. Fees for the various soil tests offered by the UW labs are also available on this web site.

Analyzing the soil

A routine soil test in Wisconsin includes analysis of the soil for water pH, buffer pH, organic matter, phosphorus, and potassium. Upon request, special tests are available for nitrate-nitrogen, calcium, magnesium, sulfur, boron, manganese, and zinc. Soil tests are not routinely done for copper, iron, or molybdenum because application of these nutrients very seldom results in crop response in the field. A reliable soil test cannot be developed unless the results of that test are calibrated with field responses to application of that nutrient.

Secondary or micronutrient soil tests are available on request. Table 12-2 describes situations where such tests may be of use.

The analytical procedures used in Wisconsin are outlined in detail in a publication entitled *Wisconsin Procedures for Soil Testing, Plant Analysis and Feed and Forage Analysis*, which is available from either UW Soil Testing Laboratory.

Interpreting the analytical results

Soil tests for the available nutrients are categorized as being very low, low, optimum, high, very high, or excessively high. Such interpretations indicate the probability of response to nutrient application. Table 12-3 shows the ranges of these probabilities.

When a soil test for phosphorus or potassium falls into the very low or low category, nutrient applications are warranted. If a soil test falls in the optimum range, no adjustment is needed in the current fertilizer program, and future applications about equal to the amount of nutrients removed in crop harvest are recommended. When the soil tests high or very high, apply some nutrients, but reduce the rates. If the soil tests excessively high, omit nutrient applications for 2 to 3 years or until the tests drop to the optimum or high range.

The interpretations of soil tests for phosphorus and potassium depend on the crop to be grown and the contribution of the subsoil. Some subsoils supply appreciable amounts of phosphorus and/or potassium during the growing season; others do not. The Wisconsin soil testing program recognizes six subsoil fertility groups and six crop demand levels for

Table 12-2. Soil conditions that favor secondary and micronutrient deficiencies.

Element	Where most likely needed
Calcium	Acid sands and soils where high calcium-demanding crops are grown.
Magnesium	Acid sands and sandy soils that have been limed with marl or paper mill sludge.
Sulfur	Light-colored soils, especially sands and sandy loams in west central and northwestern Wisconsin.
Boron	Sandy and low organic matter soils, all soils that will be cropped to alfalfa for a long period of time, and soils that are planted to vegetable crops.
Manganese	Soils with a high pH (above 7.0) and high organic matter content, especially in eastern, southeastern and south central Wisconsin.
Zinc	Soils with a low organic matter content, high pH, and high level of available phosphorus, especially the sandy soils in central Wisconsin and high pH mucks and peats.

Table 12-3. Interpretations of the soil test levels.

Soil test level	Percent of fields expected to give a profitable yield increase	Description
	%	
Very low	>90	Buildup to optimum level should occur over a 5- to 8-year period.
Low	60–90	Somewhat more nutrients are required than what crop removes.
Optimum	30–60	Yields are optimized at nutrient additions approximately equal to crop removal. This is the economical and environmental optimum level.
High	5–30	Some nutrients are required, about half of that removed by the crop.
Very high	~5	Used only for potassium; gradual drawdown recommended.
Excessively high	<2	No fertilizer needed or recommended except a small amount of row-placed starter.

phosphorus and potassium. For interpretations of soil tests for these and other nutrients, see Extension publication *Optimum Soil Test Levels for Wisconsin* (A3030).

The optimum soil pH for Wisconsin crops is given in table 6-4. The soil organic matter test primarily measures the humus in soil and is not changed appreciably by adding manure or crop residue. When these fresh organic materials decompose, most of the organic carbon contained therein returns to the atmosphere as carbon dioxide (CO_2). Only a very small portion remains as a residue to become part of the soil humus. The amount of organic matter a soil contains depends mainly on the original vegetation, soil texture, soil drainage, degree of erosion, and tillage. Since the organic matter content is an inherent characteristic of the soil and cannot be changed easily, it is not possible to establish optimum soil test levels for organic matter. However, the amount of organic matter in a soil affects its ability to supply nitrogen during the growing season and is used in the nitrogen recommendation program.

In the past, soil testing was used primarily to correct plant nutritional problems. Phosphorus and potassium levels have been increasing gradually over the years so that now the average soil tests for phosphorus and potassium are well above the optimum. Although there are still soils testing very low and low in these elements, many fields now test excessively high. Soil testing currently identifies more fields where fertilizer applications should be reduced or eliminated than fields where increases in current application rates are required.

Soil test recommendations

All soil test recommendations are based on field research work that measures yield increase with several rates of fertilizer at various soil test levels. As shown in figure 12-4, large quantities of fertilizer have to be applied to a low testing soil to achieve optimum yields; moderate amounts of fertilizer are needed on a medium testing soil; and only a very small quantity of fertilizer is required on a high testing soil.

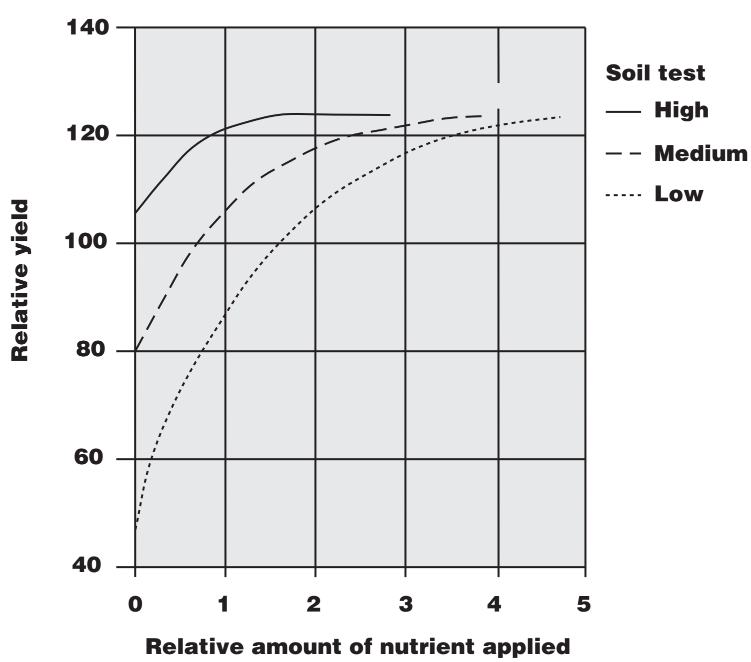
Nitrogen recommendations

Nitrogen recommendations indicate the amount of fertilizer needed if no nitrogen is supplied from other sources, such as manure, legume crops, or carryover from previous applications of nitrogen fertilizer. Growers should make allowances for these inputs, if they are present, and reduce fertilizer nitrogen accordingly. See chapters 9 and 10 for information on crediting nitrogen from non-commercial fertilizer sources.

It is important to remember that crop recovery of nitrogen decreases as the rate applied increases. Also, excess nitrogen increases the risk of leaching.

Research trials conducted throughout the state over many years have shown that the optimum nitrogen rate for corn is similar in high- and low-yielding years. However, plants use nitrogen much more efficiently in good-yielding years, resulting in higher recovery of available nitrogen by the crop. Corn recovers more available

Figure 12-4. Theoretical yield response to increasing rates of fertilizer when applied to soils containing low, medium or high available nutrient levels.



Source: Barber, S.A. 1973. Reprinted from Soil Testing and Plant Analysis, rev. ed., page 202, with permission from the Soil Science Society of America, Inc., Madison, WI.

nitrogen under favorable growing conditions and less under poor conditions such as those caused by drought stress or cold weather.

Nitrogen recommendations for corn on medium- and fine-textured soils are based on soil yield potential, organic matter content, and soil texture (table 12-4). Every named soil in Wisconsin is assigned a yield potential ranking of very high, high, medium, or low. This ranking is based on individual soil characteristics, such as drainage, rooting depth, and water holding capacity, as well as the length of the growing season. Sandy soils (sands and loamy sands) are given separate nitrogen recommendations which are dependant upon organic matter content and irrigation. Non-irrigated sandy soils have a lower yield potential because moisture is inadequate in most years. Nitrogen recommendations for additional crops are given in Extension publication *Soil Test Recommendations for Field, Vegetable, and Fruit Crops* (A2809).

Phosphate and potash recommendations

Phosphate and potash recommendations are based on crop demand level, subsoil fertility, crop yield goal or soil yield potential.

Wisconsin crops are placed in one of six crop demand categories, depending on their phosphate and potash requirements. An optimum soil test in one category may be a low test level in another category. Thus, a soil phosphorus test of 10 ppm might be considered optimum for soybeans but low for alfalfa, and more phosphate would be recommended for alfalfa. Crops growing on soils testing in the optimum range will give optimum yield and profit when the quantity of nutrients applied approximately equals the amount in the harvested part of the crop (table 12-5).

The subsoil group accounts for the phosphorus and potassium supplying power of the subsoil and, thereby, the optimum soil test level of the plow layer in relation to crop needs. It is also used to determine the amount of phosphate or potash needed to change a given soil test level a desired amount. The amount of phosphate or potash (in pounds per acre) required to change soil test phosphorus or potassium by 1 ppm is defined as the *soil buffering capacity*. The buffering capacity is always greater than 1 because

- the mathematical units for added fertilizer are in lb/a while the soil test value is in ppm, and
- fertilizer is sold on the oxide basis while soil test values are reported on the elemental basis (1 ppm P = 2.29 ppm P_2O_5, 1 ppm K = 1.2 ppm K_2O).

For example, since a 7-inch layer of a typical silt loam soil weighs 2,000,000 pounds, an application of 2 pounds per acre (2 pounds fertilizer to 2,000,000 pounds soil) would equal 1 ppm. Therefore, 2 pounds per acre of phosphorus (4.58 pounds of P_2O_5) or 2 pounds per acre of potassium (2.4 pounds of K_2O) would be required to increase the soil test by 1 ppm if all of the added phosphorus and potassium remained available. But

Table 12-4. Nitrogen recommendations for corn.

Soil organic matter	Medium & fine-textured soils — Yield potential[a]		Sandy soils	
	Low/medium[b]	High/very high	Non-irrigated	Irrigated
— % —	nitrogen, lb/a[c]			
<2.0	150	180	120	200
2.0–9.9	120	160	110	160
10.0–20.0	90	120	100	120
>20.0	80	80	80	80

[a] *To determine a soil's yield potential, see UWEX publication* Soil Test Recommendations for Field, Vegetable, and Fruit Crops *(A2809) or contact your agronomist or county agent.*
[b] *Irrigated non-sandy soils with a medium/low yield potential should use the high/very high recommendation.*
[c] *If more than 50% residue cover from a previous corn crop remains on the surface, increase nitrogen by 30 lb/acre.*

Table 12-5. Estimates of the nitrogen, phosphate, and potash removed in the harvested portion of several Wisconsin crops.

Crop	Yield	Nutrients removed		
		Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
	per acre	lb/a		
Alfalfa	4 ton	240[a]	52	240
Beets, table	17 ton	210	20	120
Broccoli	5 ton	120	10	20
Cabbage	25 ton	200	40	180
Carrots	25 ton	140	45	240
Corn, field	150 bu			
grain		120	55	40
stover		51	14	150
Corn, sweet	7 ton	45	25	40
Cucumber	350 bu	120	10	30
Lettuce	18 ton	140	40	160
Oats	90 bu	60	30	90
Peas	5000 lb	50[a]	20	40
Potato	400 cwt	80	60	200
Red clover	3.5 ton	140[a]	35	150
Snapbean	7000 lb	205[a]	17	35
Soybean	50 bu	190[a]	45	50
Trefoil, birdsfoot	3.5 ton	150[a]	45	175
Wheat	65 bu	85	45	25

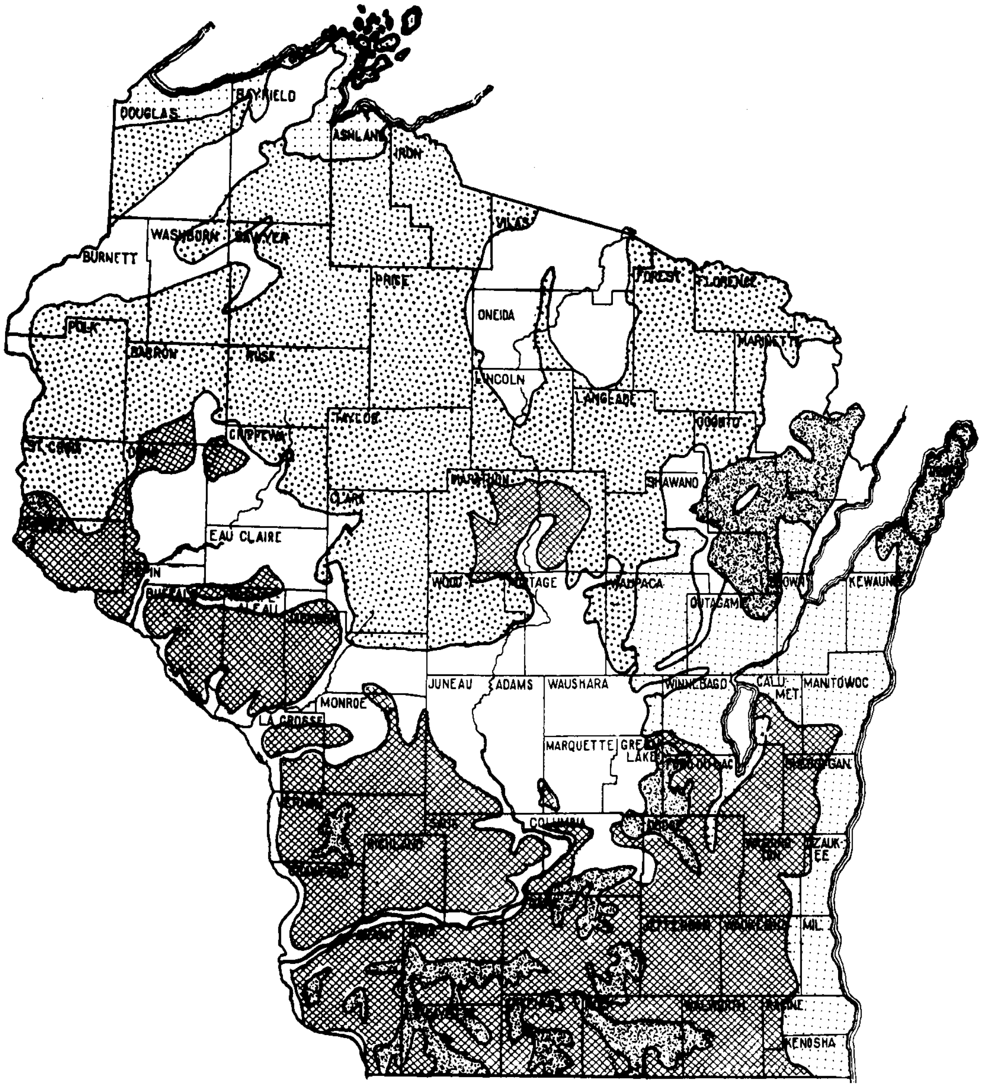
[a] *Leguminous crops get most of their nitrogen from the air.*

some of each of these nutrients reacts with the soil to become “fixed” or not extractable by crops nor by the tests used to measure their availability. Considering both soil fixation and the conversion factors noted above, the amount of phosphate and potash needed to change soil test values is considerably greater than 1. The table at the bottom of figure 12-5 gives the phosphorus and potassium buffering capacities of the six subsoil groups used in the Wisconsin soil test recommendation program.

The data presented in figure 12-5 are from laboratory studies. In the field, the amount of change in soil test phosphorus or potassium will also depend on the degree of mixing of phosphate and potash with the soil and the amount of phosphorus and potassium extracted by roots from the subsoil and deposited on the soil surface in crop residue.

The Wisconsin soil testing program divides all of the soils in the state into six subsoil fertility groups according to the relative levels of available phosphorus and potassium in the subsoil. The approximate location of these groups in the state and their relative levels of subsoil fertility are shown in figure 12-5. A special group, X, not shown in figure 12-5 is used for phosphorus recommendations only. Group X soils have a pH of 7.5 or higher. If the soil name is not given on the soil information sheet accompanying samples to the lab, the soil sample is placed in a subsoil group based on its organic matter content, pH, texture, color and county of origin. The subsoil fertility groups for all 700+ Wisconsin soils are given in Extension publication *Soil Test Recommendations for Field, Vegetable, and Fruit Crops* (A2809).

Figure 12-5. General subsoil fertility groups, based on available phosphorus and potassium in subsoils.



Subsoil group	Description	Legend	Nutrient supply power [a]	Nutrient buffering capacity[b] P_2O_5	K_2O
A	Southern, forested; medium and fine texture		P high, K medium	18	7
B	Southern, prairie; medium and fine texture		P medium, K medium	18	7
C	Red; medium and fine texture		P low, K high	18	7
D	Northern; medium and fine texture		P medium, K low	18	6
E	Sandy, coarse texture		P variable, K low	12	6
O	Organic soil[c]		P variable, K low	18	5

[a] *All data refer to subsoils (8 to 30 inch) only. Low, medium, and high ratings are relative and are not defined in absolute units.*

[b] *The soil nutrient buffering capacity is the approximate amount of fertilizer in lb/a (oxide basis) required to change the soil test level (elemental basis) by 1 ppm.*

[c] *Subsoil group O is for organic soils (> 10% organic matter) and is not based on subsoil fertility.*

Table 12-6. Yield goals for corn and alfalfa as influenced by soil yield potential.

Relative yield potential	— Typical yields — Corn	Alfalfa	Acceptable yield goals Corn	Alfalfa
	bu/a	tons/a DM[a]	bu/a	tons/a DM[a]
Very high	140–180	5–7	130–220	3.5–8.0
High	120–140	4–5	100–180	3.0–7.0
Medium	90–120	3–4	80–160	2.5–5.5
Low	70–90	2–3	60–140	1.0–4.0

[a] *DM = dry matter.*

The amount of fertilizer recommended also depends on the yield goal for the crop to be grown. Yield goals should be realistic—not more than 10 to 15% above the previous 3- to 5-year average. When the yield goal for corn or alfalfa is not given on the soil information sheet, the computer assigns a yield goal based on the soil yield potential. If the soil name is not given, the yield potential is estimated based on location within the state (county) and soil texture. For other crops, a middle yield goal range is used. The relative yield potentials and acceptable yield goals used are shown in table 12-6.

When soil phosphorus or potassium is in the optimum range, economic return from fertilizer additions is maximized by applying nutrients at rates about equal to the amounts removed in the harvested part of the crop. Soils testing very low or low will require nutrients beyond the amount removed by the crop. This will improve crop yields and slowly build these nutrient levels to the optimum range. Soils testing high or very high will receive recommendations less than crop removal. No fertilizer is recommended for soils testing in the excessively high range, except for a small amount of starter fertilizer. Research has shown that 40 to 50% of soils testing in the excessively high range will still respond to starter. This nutrient recommendation system was established to provide the maximum profit to the farmer on a year-to-year basis with soil tests maintained in the responsive range and adequate amounts of nutrients applied each year.

Phosphate and potash recommendations for corn and alfalfa are given as examples in tables 12-7 and 12-8. Recommendations for other crops may be found in Extension publication *Soil Test Recommendations for Field, Vegetable, and Fruit Crops* (A2809).

The soil test report averages the soil test values for all samples from the same field and compares the individual values against the average. For phosphorus, if an individual value exceeds the mean by more than 5 ppm, that value is rejected and a new mean is calculated. For potassium, the rejection limit is 20 ppm. No more than two samples may be rejected from fields with five or more samples and only one value from fields with three or four samples. If there are only two samples from a field, neither will be eliminated. The adjusted average field values are used to make nutrient application recommendations.

Aglime recommendations

Because farmers can select any crop as part of their rotation, the target pH for aglime recommendations is based on the most acid-sensitive crop (table 6-4) from those selected, except when potatoes are chosen. The amount of lime recommended is the amount needed to reach the field target pH for that rotation. When potatoes are to be grown, the pH should not exceed the optimum pH for potatoes.

Because of minor fluctuations inherent in soil sampling and pH measurement, the lime requirement is calculated only when the soil pH is more than 0.2 pH unit below the target pH.

Table 12-7. Corn fertilizer recommendations for phosphate and potash.

Yield goal	Soil test interpretation category[a] VL[b]	L[b]	Opt	H	EH[c]
bu/a	P_2O_5 to apply, lb/a				
71–90	0–90	50–70	30	15	0
91–110	70–100	60–80	40	20	0
111–130	75–105	65–85	45	25	0
131–150	85–115	75–95	55	25	0
151–170	90–120	80–100	60	30	0
171–190	100–130	90–110	70	35	0
191–220	105–135	95–115	75	40	0
	K_2O to apply, lb/a				
71–90	50–80	40–65	25	15	0
91–110	55–85	45–70	30	15	0
111–130	60–90	50–75	35	15	0
131–150	65–95	55–80	40	20	0
151–170	70–100	60–85	45	20	0
171–190	75–105	65–90	50	20	0
191–220	80–110	70–95	55	25	0

[a] *VL = very low, L = low, Opt = optimum, H= high, EH = excessively high.*
[b] *The precise amount recommended varies with the subsoil fertility level. See Extension publ.* Soil Test Recommendations for Field, Vegetable, and Fruit Crops *(A2809) for more information.*
[c] *A small amount of starter fertilizer (10-20-20) is recommended for most row crops.*

The amount of aglime needed to achieve the desired pH is calculated from the pH of the soil, the organic matter content of the soil as measured by loss of weight upon ignition (i.e. burning) and the pH buffering capacity of the soil as measured by a buffer pH test. In reality, both organic matter content and the buffer test are indicators of the soil pH buffering capacity or reserve acidity.

The formulas used for calculating the amount of aglime needed to reach different pH levels are given in Extension publication *Soil Test Recommendations for Field, Vegetable, and Fruit Crops* (A2809). An example of the formula used for calculating the lime requirement to pH 6.3 is given in chapter 6.

Aglime recommendations are made on the basis of liming materials with neutralizing indices (NI) of 60-69 and 80-89. (See chapter 6 for a discussion of lime quality and neutralization index). The lime requirement can be adjusted for other lime grades using table 6-8 or the following formula:

$$\text{Lime requirement of lime to be used (ton/a)} = \text{ton/a of 60–69 lime recommended} \times \frac{65}{\text{NI of lime to be used}}$$

Table 12-8. Alfalfa fertilizer recommendations for phosphate and potash.

Yield goal	Soil test interpretation category[a] VL[b]	L[b]	Opt	H	VH	EH
ton/a	P_2O_5 to apply, lb/a					
1.5–2.5	55–75	45–65	25	10	0	0
2.6–3.5	65–85	55–75	35	15	0	0
3.6–4.5	80–100	70–90	50	25	0	0
4.6–5.5	95–115	85–105	65	30	0	0
5.6–6.5	105–125	95–115	75	35	0	0
6.6–7.5	120–140	110–130	90	45	0	0
	K_2O to apply, lb/a[c]					
1.5–2.5	135–150	125–135	100	50	25	0
2.6–3.5	185–200	175–185	150	75	40	0
3.6–4.5	235–250	225–235	200	100	50	0
4.6–5.5	285–300	275–285	250	125	60	0
5.6–6.5	335–350	325–335	300	150	75	0
6.6–7.5	385–400	375–385	350	175	90	0

[a] *VL = very low, L = low, Opt = optimum, H= high, VH = very high, EH = excessively high.*
[b] *The precise amount recommended varies with the subsoil fertility level. See Extension publ.* Soil Test Recommendations for Field, Vegetable, and Fruit Crops *(A2809) for more information.*
[c] *If the alfalfa stand will be maintained for more than 3 years, increase topdressed potash by 20%.*

Aglime recommendations are limited to a maximum of 8 tons per acre for potatoes and 12 tons per acre for other crops even though more lime may be required to reach the targeted pH. This is done to avoid the possibility of localized overliming because it is difficult to do a good job of mixing more than 12 tons per acre of lime throughout the tilled (plow) layer uniformly.

Aglime recommendations are calculated for a tillage depth of 7 inches. If deeper tillage is indicated on the soil information sheet, the lime recommendation is adjusted by 1-inch depth increments to a maximum of 9 inches (table 6-9). Lime cannot be mixed effectively deeper than 9 inches, and no research in Wisconsin has shown any benefit from liming soil deeper than that.

Secondary nutrient recommendations

Soils are not tested routinely for secondary and micronutrients. These tests must be requested specifically. All secondary nutrients and micronutrients for which soil tests are available are interpreted in terms of their relative availability (table 12-9). When the soil test falls into the very low or low range for a given nutrient, recommendations are made if the crop demand for that nutrient is medium or high.

Calcium deficiency is rare for most crops and highly unlikely if aglime recommendations are followed. Crops such as apples and potatoes in which the storage organs are not part of the plant transpiration stream sometimes benefit from supplemental calcium in terms of improved disease resistance or crop quality. Also, extra calcium is often beneficial for celery.

The use of dolomitic limestone has prevented magnesium deficiency in most Wisconsin soils. Some soils low in this element include: (1) soils where liming materials low in magnesium such as paper mill lime sludge, marl, or calcitic lime have been repeatedly applied at high rates, (2) very acid and sandy soils where high rates of potassium and/or ammonium nitrogen have been applied, and (3) calcareous organic soils. The most economical way to avoid magnesium deficiency is to follow a good liming program using dolomitic limestone. Other suitable magnesium carriers are Epsom salts ($MgSO_4 \bullet 7H_2O$) and potassium-magnesium sulfate ($K_2SO_4 \bullet 2MgSO_4$). A row application of 10 to 20 pounds of magnesium per acre is recommended annually on magnesium-deficient soils where liming is undesirable.

Sulfur deficiency is most likely to occur with high sulfur-demanding crops such as alfalfa, canola or forage brassicas, and cole crops grown on sandy soils or other soils low in organic matter and located away from urbanized areas. Available sulfur includes sulfur in precipitation, sulfur released from soil organic matter, sulfur from applied manure and subsoil sulfur, in addition to the sulfate sulfur ($SO_4^{=}$) measured by soil analysis. Recent surveys have shown that precipitation contains about 5 pounds of sulfur per acre in western and northern Wisconsin counties, as shown in figure 12-6, and 10 to 15 pounds of sulfur per acre in the remainder of the state.

Table 12-9. Interpretation of soil test values for secondary nutrients and micronutrients.

Element	Soil texture code[a]	Soil test interpretation category[b] VL	L	Opt	H	EH
		ppm				
Calcium	1, 4	0–200	201–400	401–600	>600	—
	2, 3, 4	0–300	301–600	601–1000	>1000	—
Magnesium	1, 4	0–25	26–50	51–250	>250	—
	2, 3, 4	0–50	51–100	101–500	>500	—
Boron	1, 4	0–0.2	0.3–0.4	0.5–1.0	1.1–2.5	>2.5
	2, 4	0–0.3	0.4–0.8	0.9–1.5	1.6–3.0	>3.0
	3, 4	0–0.5	0.6–1.0	1.1–2.0	2.1–4.0	>4.0
Zinc	1, 2, 3, 4	0–1.5	1.6–3.0	3.1–20	21–40	>40
Manganese OM <6.1%	1, 2, 3, 4	—	0–10	11–20	>20	—
			Soil pH[c]			
OM >6.0%	1, 2, 3, 4	—	>6.9	6.0–6.9	<6.0	—
Sulfur availability index[d]			**Low**	**Medium**	**High**	
	1, 2, 3, 4	—	<30	30–40	>40	—

[a] *Soil texture codes: 1 = sands, 2 = silts and clays, 3 = organic soils, 4 = red soils.*

[b] *Soil test interpretation categories: VL = very low, L = low, Opt = optimum, H= high, EH = excessively high.*

[c] *When soil organic matter exceeds 6.0%, manganese availability is based on soil pH; the manganese soil test is not used.*

[d] *Sulfur availability index includes estimates of sulfur released from organic matter, sulfur in precipitation, subsoil sulfur and sulfur in manure if applied, as well as $S0_4$-S determined by soil test.*

Sulfur contributed by organic matter is estimated by multiplying the percent organic matter content by 2.8. Sulfur in manure, if applied, depends on the kind of animal and application rates. Subsoil sulfur is estimated from data collected from surveys of subsoil sulfur and ranges from 5 pounds per acre on sandy soils to 20 pounds per acre on organic soils.

A sulfur availability index (SAI) is calculated by summing the available sulfur inputs as shown below. This SAI has been calibrated against 600 alfalfa plant tissue samples.

If the SAI is less than 30, sulfur should be added; if it is greater than 40, no sulfur is needed; and if it is between 30 and 40, the need for sulfur is borderline and should be confirmed with plant analysis. If needed, apply the amount of sulfur shown in table 12-10.

Calculating the sulfur availability index (SAI)

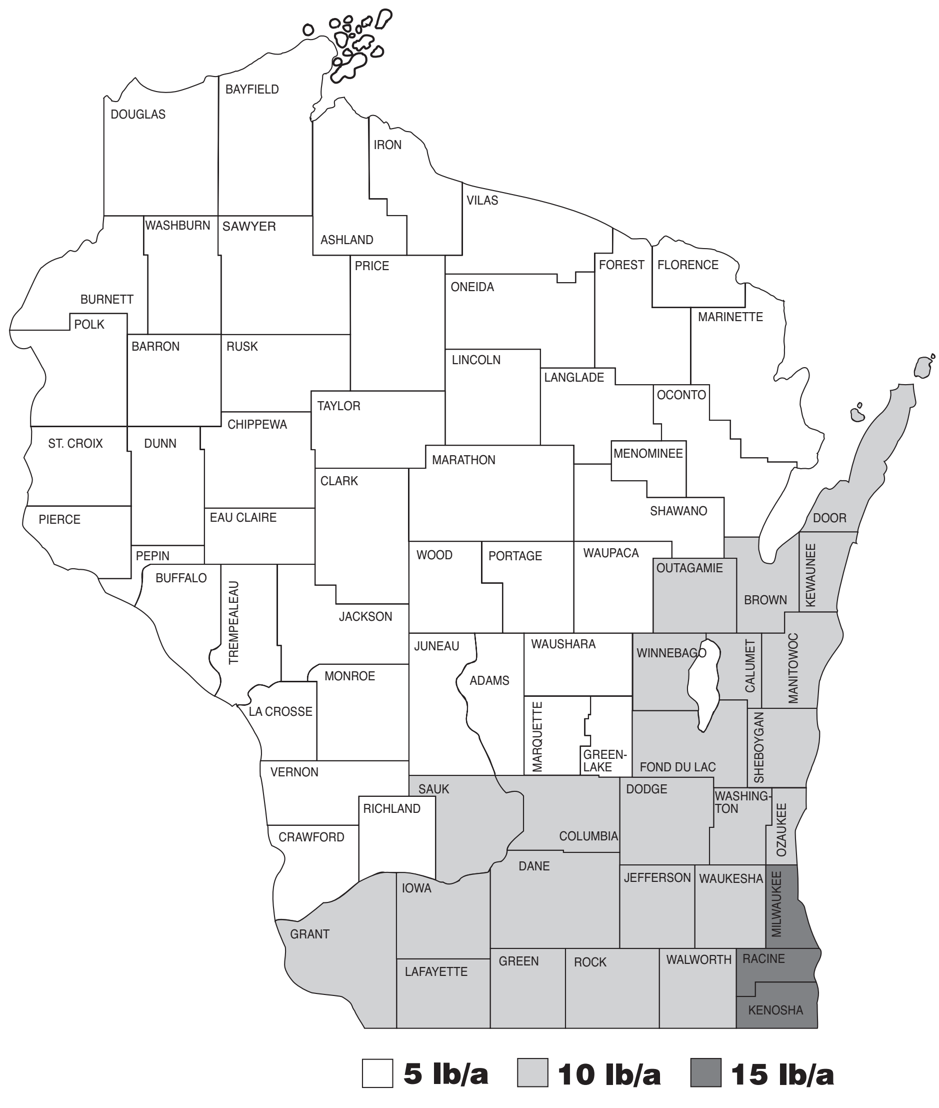
SAI = (OM-S) + (manure-S) + (pptn-S) + (subsoil-S) + (soil test SO_4-S) where:

- **OM-S (sulfur in organic matter) = % organic matter x 2.8 lb/a**
- **manure-S = ton/a of manure x lb available S per ton**
- **pptn-S (sulfur in precipitation) = 5, 10, or 15 lb/a depending on county**
- **subsoil-S = 5, 10, or 20 lb/a depending on soil**
- **soil test SO_4-S = ppm S (from lab test) x 4**

Table 12-10. Sulfur fertilizer recommendations.

Crop	Sulfur to apply (lb/a)
Forage legumes	
Incorporated at seeding	25–50
Topdressed on established stand	15–25
Corn, small grains, vegetable and fruit crops	10–25

Figure 12-6. Sulfate sulfur in precipitation.
Source: National Atmospheric Deposition Program. 1999.



Micronutrient recommendations

Plants need only very small amounts of micronutrients for good growth. While a deficiency of any nutrient will reduce crop yields, the overuse of micronutrients can produce a harmful level in the soil which may be more difficult to correct than a deficiency.

Soil tests are available from Wisconsin labs for boron, manganese, and zinc. Copper, iron, and molybdenum are rarely ever deficient in Wisconsin so soil tests have not been adequately calibrated for these elements. Plant analysis can be used to evaluate the status of copper and iron, and is often used to confirm soil tests for boron, manganese, and zinc as well.

Use of micronutrients is recommended when the soil test is low or very low, when verified deficiency symptoms appear in the plant, or when certain crops have very high requirements such as boron for beets. Crops vary in their micronutrient requirements (table 12-11). If the soil tests low or very low in a micronutrient, response to application of that nutrient (1) *likely will* occur if the crop has a high requirement for that nutrient, (2) *probably will* occur if the crop has a medium requirement, or (3) *most likely will not* occur if the crop has a low requirement for the nutrient.

Table 12-11. Relative micronutrient requirements of Wisconsin crops.

Crop code	Crop	Micronutrient[a] Boron	Copper	Manganese	Molybdenum	Zinc
1	Alfalfa	High	Medium	Low	Medium	Low
2	Alfalfa seeding	High	Medium	Low	Medium	Low
3	Asparagus	Medium	Low	Low	Low	Low
4	Barley	Low	Medium	Medium	Low	Medium
5	Bean, dry (kidney, navy)	Low	Low	High	Medium	Medium
6	Bean, lima	Low	Low	High	Medium	Medium
7	Beet	High	High	Medium	High	Medium
8	Brassica, forage	High	—	—	High	—
9	Broccoli	Medium	Medium	Medium	High	—
10	Brussels sprout	Medium	Medium	Medium	High	—
11	Buckwheat	Low	—	—	—	—
12	Cabbage	Medium	Medium	Medium	Medium	Low
13	Canola	High	Medium	Medium	Medium	Medium
14	Carrot	Medium	Medium	Medium	Low	Low
15	Cauliflower	High	Medium	Medium	High	—
16	Celery	High	Medium	Medium	Low	—
17	Corn, grain	Low	Medium	Medium	Low	High
18	Corn, silage	Low	Medium	Medium	Low	High
19	Corn, sweet	Low	Medium	Medium	Low	High
20	Cucumber	Low	Medium	Medium	Low	Medium
21	Flax	—	—	—	—	—
22	Ginseng	—	—	—	—	—
23	Lettuce	Medium	High	High	High	Medium
24	Lupin	Low	Low	Low	Medium	Medium

(continued)

Table 12-11. Relative micronutrient requirements of Wisconsin crops *(continued).*

Crop code	Crop	Micronutrient[a] Boron	Copper	Manganese	Molybdenum	Zinc
25	Melon	Medium	—	—	—	—
26	Millet	Low	—	—	—	—
27	Mint, oil	Low	Low	Medium	Low	Low
28	Oat	Low	Medium	High	Low	Low
29	Oatlage	Low	Medium	High	Low	Low
30	Oat-pea forage	Low	Medium	High	Low	Low
31	Onion	Low	High	High	High	High
32	Pasture, unimproved	Low	Low	Medium	Low	Low
33	Pasture, managed	Low	Low	Medium	Low	Low
34	Pasture, legume-grass	High	Medium	Low	High	Low
35	Pea, canning	Low	Low	Medium	Medium	Low
36	Pea (chick, field, cow)	Low	Low	Medium	Medium	Low
37	Pepper	—	—	—	—	—
38	Popcorn	—	—	—	—	—
39	Potato	Low	Low	Medium	Low	Medium
40	Pumpkin	—	—	—	—	—
41	Reed canarygrass	Low	Low	Medium	Low	Low
42	Red clover	Medium	Medium	Low	Medium	Low
43	Rye	Low	Low	Low	Low	Low
44	Snapbean	Low	Low	—	—	—
45	Sod	Low	Low	Medium	Low	Low
46	Sorghum, grain	Low	Medium	High	Low	High
47	Sorghum-sudan forage	Low	Medium	High	Low	Medium
48	Soybean	Low	Low	High	Medium	Medium
49	Spinach	Medium	High	High	High	High
50	Squash	—	—	—	—	—
51	Sunflower	High	High	—	—	—
52	Tobacco	Medium	Low	Medium	—	Medium
53	Tomato	High	High	Medium	Medium	Medium
54	Trefoil, birdsfoot	High	—	—	—	—
55	Triticale	Low	Low	Medium	—	—
56	Truck crops	Medium	Medium	—	—	—
57	Vetch (crown, hairy)	Medium	—	—	—	—
58	Wheat	Low	Medium	High	Low	Low
66	CRP, alfalfa	High	Medium	Low	Medium	Low
67	CRP, red clover	Medium	Medium	Low	Medium	Low
68	CRP, grass	Low	Low	Medium	Low	Low

— = no data

[a] *Iron (Fe) and chloride (Cl) deficiencies have not been noted on field crops in Wisconsin.*

Table 12-12 gives fertilizer recommendations for boron, manganese, and zinc based on relative crop requirements and soil test results. Copper recommendations (table 12-13) are based on plant analysis or the appearance of visible deficiency symptoms. Deficiencies of iron can be corrected by foliar applications of ferrous sulfate (1% solution) or iron chelates (0.2% solution). Soil applications with the chelate FeDDHA have also been successful. Follow the manufacturer's recommendations.

Deficiencies of molybdenum can often be corrected simply by liming. If liming does not correct the deficiency or if the pH must be kept low, apply 1.0 ounce per acre of ammonium or sodium molybdate as a seed treatment. No recommendations have been formulated for chlorine because this element has never been reported to be deficient in Wisconsin.

Soil test report

An example of a soil test report is shown on the following page.

Field information is reported in the upper left section of the soil test

Table 12-12. Soil test recommendations for boron, manganese, and zinc.

Crop requirement	Soil test	Boron[a]	Manganese: Row $MnSO_4$	Manganese: Row MnEDTA	Manganese: Foliar $MnSO_4$	Manganese: Foliar MnEDTA	Zinc: Row[b]	Zinc: Broadcast[b]	Zinc: Foliar
		lb/a							
High	Low	2	5	0.8	1	0.15	2	6	1.0/0.15[c]
	Very low	3	—[d]	—[d]	—[d]	—[d]	2	8	1.0/0.15[c]
Medium	Low	1	3	0.5	1	0.15	1.5	4	1.0/0.15[c]
	Very low	2	—[d]	—[d]	—[d]	—[d]	2	5	1.0/0.15[c]
Low	Low	0	*	*	*	*	*	*	*
	Very low	*	—[d]	—[d]	—[d]	—[d]	*	*	*

[a] *Apply broadcast or topdress.*
[b] *Recommendations are for $ZnSO_4$; use one-fourth these rates if applied as zinc chelate.*
[c] *Apply 1.0 lb/a zinc sulfate or 0.15 lb/a ZnEDTA.*
[d] *There is no very low category for manganese.*
* *Confirm the need for micronutrient with plant analysis before applying fertilizer.*

Table 12-13. Copper fertilizer recommendations.[a]

Crop requirement	Sands: Broadcast	Sands: Band	Silts and clays: Broadcast	Silts and clays: Band	Organic soils: Broadcast	Organic soils: Band
	lb/a					
High	10	2	12	3	13	4
Medium	4	1	8	2	12	3
Low	*	*	*	*	*	*

[a] *Recommendations are for inorganic sources of copper. Apply copper chelates at one-sixth the above rates.*
* *Confirm the need for micronutrient with plant analysis before applying fertilizer.*

Samples Analyzed By:
UW Soil & Plant Analysis Lab

SOIL TEST REPORT

COOPERATIVE EXTENSION
University of Wisconsin-Extension
University of Wisconsin-Madison
Department of Soil Science

LAB #: 12345

County: Dane
Account No.: 556996
Date Received: 11/10/2005
Date Processed: 11/11/2005
Slope: 2%
Acres: 5
Plow Depth: 8"
Soil Name: Antigo
Field Name: 1

This Report is for:
Bucky Badger

NUTRIENT RECOMMENDATIONS

Cropping Sequence	Yield Goal	Crop Nutrient Need			Fertilizer Credit				Nutrients to Apply		
		N	P2O5	K2O	Legume N	Manure N	P2O5	K2O	N	P2O5	K2O
	per acre	lbs/a			lbs/a	lbs/a			lbs/a		
Corn, grain	111-130 bu	120	45	65	0	0	0	0	120	45	70
Soybean	46-55 bu	0	20	80	0	0	0	0	0	20	80
Alfalfa seeding	1-3 tons	0	45	130	0	0	0	0	0	45	130
Alfalfa	4.6-5.5 tons	0	85	280	0	0	0	0	0	85	280

The lime required for this rotation to reach pH 6.8 is 2 T/a of 60-69 lime or 1.5 T/a of 80-89 lime.

ADDITIONAL INFORMATION

If lime has been applied in the last two years, more lime may not be needed due to incomplete reaction.

Year 1: If corn harvested for silage instead of grain add extra 30 lbs P2O5 per acre and 90 lbs K2O per acre to next crop.

Nitrogen credit for alfalfa seeding assumes significant alfalfa growth occurred in the seeding year.

Starter fertilizer (e.g. 10+20+20 lbs N+P2O5+K2O/a) is advisable for row crops on soils slow to warm in the spring.

A soil nitrate test may better estimate actual corn needs.

If conservation tillage leaves more than 50% residue cover when corn follows after corn, add an additional 30 N lbs/a.

If alfalfa will be maintained for more than three years, increase recommended K2O by 20% each year.

TEST INTERPRETATION

Cropping Sequence	Very Low / Low / Optimum / High / Very High / Excessive
Corn, grain	PPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPP KKKKKKKKKKKKKKKKKKKKKKKKKKK
Soybean	PPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPP KKKKKKKKKKKKKKKKKKKKKKKKKKK
Alfalfa seeding	PPPPPPPPPPPPPPPPPPPPPPPPPPPPPP KKKKKKKKKKKKKKKKKK
Alfalfa	PPPPPPPPPPPPPPPPPPPPPPPPPPPPPP KKKKKKKKKKKKKKKKKK
Rotation pH	XXXXXXXXXXXXXXXXXXXXXXX

LABORATORY ANALYSIS

Sample Identification	Soil pH	O.M %	Phosphorus ppm	Potassium ppm	Calcium ppm	Magnesium ppm	Estimated CEC	Boron ppm	Manganese ppm	Zinc ppm	Sulfate-Sulfur ppm	Sulfur Avail. Index	Texture Code	Sample Density	Buffer Code
1	6.5	2.6	15	95									2	1.01	6.8
Adjusted Averages	6.5	2.6	15	95											

Soil & Plant Analysis Lab
Madison - (608) 262-4364

Explanation of Soil Test Report
Department of Soil Science
University of Wisconsin - Madison

Soil & Forage Analysis Lab
Marshfield - (715) 387-2523

GENERAL INFORMATION

Soil test results from samples with the same field identification are averaged for making a field recommendation. If individual sample results within a field are greatly higher than the average soil test values, results of the high testing sample(s) is not used in determining the field recommendation.

LABORATORY ANALYSIS PROGRAM

The laboratory analysis methods used are: pH — water and SMP buffer; OM — loss-of-weight on ignition; available P — Bray P_1; available K– Bray P1 ; exchangeable Ca & Mg — 1.0 N ammonium acetate; B — hot water; Zn — 0.1 N hydrochloric acid; Mn — 0.1 N phosphoric acid; SO4-S — 2N acetic acid containing 500 ppm P.

Soil test nutrients reported as parts per million (ppm) represent a weight per unit volume based on the assumption that an acre plow layer of medium textured soil weighs 2 million pounds. Soil test results in ppm can be converted to lbs/a by multiplying by 2. Laboratory texture code refers to soil texture/type. The sulfur availability index (SAI) includes SO_4-S in the soil sample plus estimates of S from soil OM, precipitation, manure and the subsoil. Estimated cation exchange capacity (CEC) is determined by summing values for exchangeable K, Ca, and Mg, and adjusting for OM content. Sample density is reported as grams of oven-dried (105°C), ground soil per cubic cm (g/cm^3) and is not the same as field bulk density.

SOIL TEST INTERPRETATION AND CROP NUTRIENT NEEDS

Crop nutrient needs are determined by several factors. Crop yield potential, soil texture and organic matter content determine crop N requirements. Yield goal, soil test level, soil name, and nutrient buffering capacity are used to estimate the need for P_2O_5 and K_2O. If soil test P and K levels are in the optimum (Opt) category, recommended applications will approximately replace the nutrients removed by the harvested crop for the specified yield goal. Soils testing in the H, VH, or E categories will require 50, 25 or 0%, respectively, of the recommendation for the Opt category. Soils testing in the VL or L categories reflect the need for additional nutrients such that the soil test level will be brought up to the Opt category over a 5-8 year period. These needs differ between crops and soils and are based, in part, on the soils' P and K buffering capacities.

FERTILIZER REPLACEMENT CREDITS

The nutrient needs section of the soil test report lists the nutrient quantities that are needed to optimize profitability. These nutrient additions can be from sources other than commercial fertilizer. The application of manure or the incorporation of legume-sod, soybean or legume cover crop residue will usually result in considerable amounts of nutrients being returned to the soil. See UWEX publication(s) - A3580 (Credit What You Spread) and A 3591(Credit Legume Nitrogen) for further information.

Manure

Nutrient credits are specific for each type of animal (dairy, beef, poultry, swine or veal), herd management (solid/liquid, finish/farrow), application method (injected, surface, or incorporated within 72 hours) and years of consecutive application. For example, each ton of solid dairy manure receives a credit of 4 lbs available N if injected or incorporated (3 lbs if surface applied), 3 lbs of available P_2O_5 and 8 lbs of available K_2O . Nutrient credits are slightly higher if manure has been applied for 2 or more consecutive years on the same field. The credit for each 1000 gallons of liquid dairy manure is 10 lbs of available N (8 lbs if surface applied), 8 lbs of available P_2O_5 and 21 lbs of available K_2O . Credits for other types of manure will differ.

Legume Sod

Where a legume sod is plowed down, the amount of nitrogen credit subtracted from the N recommendation depends on the type of legume, stand density, soil texture and the amount of regrowth before a killing frost. When alfalfa is plowed down on sandy soils, the N credit is 140 lbs N/a for a good stand (>4 plants/ft^2), 110 lbs N/a for a fair stand (1.5-4 plants/ft^2) and 80 lbs N/a for a poor stand (<1.5 plants/ft^2). For other soils, the N credit is 190 lbs N/a for a good stand, 160 lbs N/a for a fair stand and 130 lbs N/a for a poor stand. The N credit is reduced by 40 lbs N/a if the legume sod is harvested/killed with less than 8" regrowth in the fall. If the legume grown is red clover or birdsfoot trefoil instead of alfalfa, the credit is calculated as 80% of the alfalfa credit. Second year credit of 50 lbs N/a will be given for fair or good stands. No second year credit is given on sandy soils.

Soybeans

Where the previous crop was soybeans, a credit of 40 lbs N/a is given. No credit is given on sandy soils.

Legume Vegetables

A credit of 20 lbs N/a is given when the previous crop was a leguminous vegetable, such as snapbeans or peas. No credit is given on sandy soils.

NUTRIENTS TO APPLY

The amount of nutrients to apply reflects the amount of fertilizer credit supplied by manure or legume plowdown. Circumstances which have not been considered in the printed recommendations include: conservation tillage, cold soils, use of an N availability test and keeping alfalfa for more than 3 years. If those conditions apply, client adjustment of the values on the soil test report or use of new recommendations based on N availability test results is required.

WORKSPACE FOR CALCULATING YOUR TOTAL ANNUAL FERTILIZER REQUIREMENTS

Crop: Year:				Crop: Year:				Crop: Year:			
	N	P_2O_5	K_2O		N	P_2O_5	K_2O		N	P_2O_5	K_2O
	lbs/a				lbs/a				lbs/a		
Nutrients to Apply				Nutrients to Apply				Nutrients to Apply			
- Additional credits				- Additional credits				- Additional credits			
+ Additional needs				+ Additional needs				+ Additional needs			
Adjusted Need				Adjusted Need				Adjusted Need			
Fertilizer Applied				Fertilizer Applied				Fertilizer Applied			
Rate	Grade N - P_2O_5 - K_2O			Rate	Grade N - P_2O_5 - K_2O			Rate	Grade N - P_2O_5 - K_2O		

LIME PROGRAM

Lime recommendations are given for the two most common lime grades used in Wisconsin (60-69 and 80-89). Recommendations are made to bring the soil pH to the optimum level for the most acid sensitive crop in the rotation specified. No lime is recommended unless the measured soil pH is more than 0.2 units below the optimum pH for the listed three-year rotation. Where lime with a neutralizing index (NI) other than 60-69 or 80-89 is used, adjust the lime requirements as indicated in the following formula:

$$\text{Lime Requirement} = (\text{T/a 60-69 required}) \times \frac{65}{\text{Midpoint of NI grade lime to be used}}$$

report. The field history given on the information sheet when the soils are submitted for analysis is the same information reported in this section of the report.

Field nutrient recommendations for fertilizer and lime are presented in the upper portion of the report. These recommendations are based on the average results of all samples from one field and are presented for the 4-year crop rotation selected. If no specific crop rotation is selected, recommendations for a corn-soybean-alfalfa seeding-alfalfa rotation are given. Aglime recommendations for the specific crop sequences are presented directly beneath the fertilizer recommendation for each option. The amount of aglime needed to raise the soil pH for the most acid-sensitive crop in the sequence is shown for lime grades with neutralizing indexes of 60-69 and 80-89.

The fertilizer recommendations on the soil test report form are adjusted for previous legume crops or applied manure if this information is given on the information sheet. These adjustments are also shown in the upper portion of the report. Below the fertilizer recommendations is additional information for modifying the recommendations based on crop management practices. The total nutrient requirement can be applied as a combination of manure, legume, commercial fertilizer, or other nutrient source. Applications can be made as a row treatment, a broadcast treatment, or as a combination of the two. The decision on how to apply the required nutrients depends largely on the total amount needed, soil type, crop to be grown, and personal preference.

A graphic presentation of the interpretations of the adjusted average soil test for phosphorus and potassium are shown in the center section of the report. Lines of repeated "P"s and "K"s extend into the appropriate interpretation level for each crop.

The laboratory analysis results for each sample are located in the lower portion of the report. Routine soil tests include soil pH, buffer pH (reported in the buffer code column), organic matter, phosphorus, and potassium. Organic matter results are reported in percent and nutrient tests in ppm.

Plant analysis

Uses of plant analysis

Plant analysis is used to measure the concentration of essential elements in plant tissue. It is a more precise diagnostic tool for identifying nutritional disorders than soil tests or observations of visual deficiency symptoms. Plant analysis can accurately identify deficiencies of macronutrients and most micronutrients. In fact, for some nutrients, such as copper and iron, plant analysis is the only practical diagnostic tool available. In addition, plant analysis can be used to evaluate fertilizer efficiency, to study nutrient interactions, and to identify or confirm nutrient toxicities. It is also used to make fertilizer recommendations for perennial shrubs and trees.

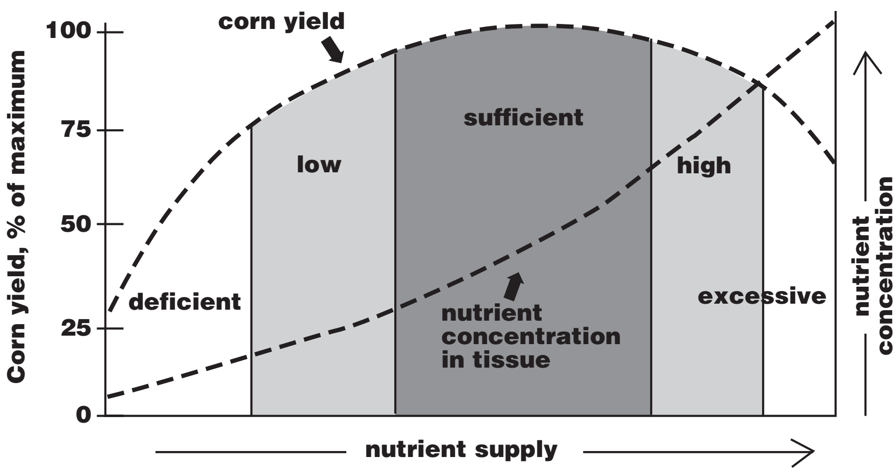
Plant analysis and a good soil test can furnish a guide to more efficient crop production. Soil tests provide a good estimate or prediction of lime and fertilizer needs. Plant analysis records the actual uptake of plant nutrients and allows an evaluation of fertilizer and management practices by providing a nutritional "photograph" of the crop.

Soil tests and plant analyses often need to be used in combination with on-site inspection to help pinpoint a problem. For example, plant analysis might show a corn plant being low in phosphorus even though the soil test shows there is sufficient soil phosphorus. Only on-site inspection will reveal that the deficiency is due to cold weather, rootworm damage, or some other factor.

Identification of nutritional disorders. The main use of plant analysis is the identification of nutritional disorders. For that reason, carbon, hydrogen, and oxygen are not analyzed because they come from the air or water and virtually never limit plant growth. Molybdenum is analyzed only on request because it is difficult to analyze, is seldom deficient, and is used as an internal standard on some analytical equipment. Chlorine is not analyzed because it is always sufficient under Wisconsin field conditions. Plant analysis is also used to test for aluminum and sodium, even though they are not essential elements, because aluminum can be toxic in acid soils, and sodium improves the quality of some crops, such as beets and celery.

Plant analysis is unique from other crop diagnostic tests in that it gives an overall picture of the nutrient levels within the plant at the time the sample was taken. This picture shows the concentration levels for each of the analyzed nutrients. Figure 12-7 shows the relationship between nutrient concentration levels and crop growth. Increasing the concentration of a deficient nutrient will increase crop growth until it reaches a maximum yield. Further additions of the element will cause the concentration of that element in the plant to rise more rapidly because it is not being diluted by added dry matter accumulation. Eventually, toxicity of that element may occur.

Figure 12-7. Relationship between nutrient supply, corn yield and nutrient concentration in ear leaf tissue.



Source: Adapted from Brown, 1970.

Evaluation of fertilizer efficiency. Another use of plant analysis is to evaluate fertilizer efficiency. Soil scientists use plant analysis to study nutrient uptake from fertilizer and organic amendments and to evaluate different methods of application and other nutrient management practices. Adding nutrients to the soil is no guarantee that they will be assimilated by the plant. Added nutrients might be unavailable to plants, or they might react with a particular soil to form unavailable compounds. Plant analysis can also be used to show the effect of lime on the availability of native and applied elements.

Interactions among plant nutrients. Nutrient interactions can also be studied using plant analysis, sometimes revealing unknown relationships among essential elements. While plant physiologists sometimes make these interactions a deliberate study, more often they discover these relationships when they summarize results of many plant analyses.

Limitations of plant analysis

Interpreting plant analysis results is difficult because of the many variables that influence nutrient concentrations. In general, good relationships can be developed between soil nutrient supply, nutrient levels in the plant, and crop yield for a given location in any one year. However, differences in location, plant variety, time, and management often cause variations in these relationships and make them more difficult to interpret. Nutrient levels in plants differ depending on the plant part sampled, stage of maturity, hybrid, and climatic conditions. So, interpretation of the results of plant analysis must take these factors into consideration.

Another limitation of plant analysis is knowing how the factor that is limiting plant growth affects other nutrients. For example, nitrogen deficiency can limit the uptake of phosphorus and some of the micronutrients to the extent that they appear to be "low." At the same time it can cause potassium to accumulate. In addition, plant analysis usually detects only the one element that inhibits plant growth the most. Rarely are two or more elements acutely deficient at the same time. A corn plant, for example, may be deficient in potassium; but, because potassium is limiting growth, there may be sufficient phosphorus for the reduced amount of dry-matter production even if soil phosphorus is low. When potassium is added as a remedial treatment, dry-matter production increases sharply; then phosphorus becomes deficient.

Decomposition of plant tissue, due to aging or damage such as that caused by wind, hail, or frost, will result in a loss of carbon (as CO_2 through respiration and microbial activity). This dry matter loss will tend to concentrate most nutrient elements, thereby giving erroneously high readings.

Collecting plant samples

A critical aspect of plant analysis is sample collection. Plant composition varies with age, the portion of the plant sampled and many other factors. Therefore, it is important to follow a standard sampling procedure.

Plants need to be sampled at specific times during the growing season to interpret the analytical results accurately. These results are compared against a set of calibrated standards that are linked to a given stage of crop growth. The back of the plant analysis information sheet (attached) outlines the proper stage of growth, plant part, and number of plants to sample for major agronomic and horticultural crops. If a crop is sampled at any other point in the growing season, an accurate interpretation of the analysis will be more limited. Do not take samples after flowering, silking, and/or pollination.

3/04

PLANT ANALYSIS INFORMATION SHEET

Department of Soil Science
College of Agricultural and Life Sciences
University of Wisconsin-Madison/Extension

UW Soil & Plant Analysis Laboratory
8452 Mineral Point Road
Verona, WI 53593 (608) 262-4364

Date Rec'd (Lab Use Only)	NAME AND ADDRESS		METHOD OF PAYMENT	
Lab No.	Name		Amount paid	or Acct. ID
	Address		Cash or Check No.	PO#
	City State	Zip	Credit Card	
County Code ________	County sample(s) came from:		Credit Card No________-________-________-________	Exp_____/_____

Sample No.	Field ID	Stage of growth Interpretations only for those listed. (Choose number on back)	Plant part sampled (Choose letter on back)	Crop	Plant appearance (Circle one)	Soil submitted for routine test (pH, OM, P and K) (Circle one)
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No
					Normal Abnormal	Yes No

In addition to routine test (pH, organic matter, phosphorus, and potassium), check soil special test(s) if requested: There is an added charge per test. Report will list fields individually unless designated otherwise:

Check special test(s) desired:		List fields
Calcium/Magnesium (Ca/Mg)	___	____________________
Boron (B)	___	____________________
Manganese (Mn)	___	____________________
Sulfur (SO_4-S)	___	____________________
Zinc (Zn)	___	____________________

DRIS indices available for: alfalfa, apple, corn, celery, lettuce, millet, oat, potato, grain sorghum, tomato and wheat

- PASS indices available for: alfalfa, corn and soybean
- Best information for non-diagnostic stage of growth/plant part can be obtained by comparing good and bad appearing plants from the same field.

If you would like to have results emailed please provide email address below:
Email to: ____________________

Comments, special instructions, billing information (if different from above):

Field Crops	**Stage of Growth**	**Plant Part Sampled**	**Number of Plants**
Alfalfa, red clover, birdsfoot trefoil, crown vetch	**1** Bud to first flower	**A** Top 6"	30-40
Alfalfa hay, red clover hay	**2** Harvest	**B** Whole plant	15-20
Corn, field	**3** 12" tall	**C** Whole plant	10-15
	4 Pre-tassel	**D** Leaf below whorl	15-20
	5 Tassel to silk	**E** Ear leaf	15-20
	6 Ensiled/chopped	**F** Whole plant	10-15
Corn, sweet	**7** Tassel to silk	**G** Ear leaf	15-20
Beans, soybeans, dry lima, snapbeans, peas (canning, chick peas)	**8** Prior to or at initial flowering	**H** 4th petiole and leaflet or 4th petiole only	20-25
Potato	**9** Prior to or at initial flowering	**I** 4th petiole and leaflet or 4th petiole only	40-50
	10 Tuber bulking	**J** 4th petiole and leaflet or 4th petiole only	40-50
Wheat	**11** Tillering	**K** Newest fully developed leaf	30-40
Wheat, barley, rye, canary grass, triticale, brome grass, oat, orchard grass	**12** Prior to heading	**L** Newest fully developed leaf	30-40
Sorghum, grain	**13** Prior to heading	**M** 2nd fully developed leaf	15-20
Sorghum-sudan	**14** Prior to heading	**N** Newest fully developed leaf	15-20

Fruits	**Stage of growth**	**Plant part sampled**	**Number of Plants**
Apple, cherry (sour)	**15** Current season's shoots	**O** Fully developed leaf at midpoint of new shoots	10-20
Strawberry	**16** At renovation before mowing	**P** Fully developed leaflets and petioles	10-20
Raspberry	**17** August 10 to September 4	**Q** 6th and 12th leaf blade and petiole from trifoliate	10-20
Cranberry	**18** August 15 to September 15	**R** Current season's growth above berries	35-50

Vegetables	**Stage of growth**	**Plant part sampled**	**Number of Plants**
Onion	**19** Midseason	**S** Tops, no white	10-20
Carrots, celery, ginseng, cauliflower	**20** Midseason	**T** Youngest mature leaves	10-20
Tomato	**21** Midseason	**U** Newest fully developed leaf	10-20
Cabbage, lettuce	**22** Midseason	**V** Wrapper leaf	10-20
Pepper	**23** Prior to or at early fruit development	**W** Petiole and leaflet	10-20

To minimize economic losses, sample plants as soon as they show any abnormality, even if it is earlier than the stage of growth shown on the plant analysis information sheet. In such a case, collect and submit the entire above-ground portion of the plant for analysis. Avoid any diseased or insect-damaged plants. When taking samples for trouble-shooting in a field, be sure to include a healthy specimen from the same area. If normal and abnormal plants are tested, comparison of the results between the two can often diagnose the problem. A comparison sample is particularly helpful in the analysis of some plants such as flowers and shrubs where a large database is not available for interpreting the results.

Prepare a plant sample for shipment by removing any roots and foreign material from the sample. Plant samples contaminated with soil particles will have erroneously high results for iron, aluminum, and manganese. To remove soil particles, shake or dust off the plant tissue—DO NOT WASH tissue since soluble nutrients will be leached out of the sample.

Complete a plant analysis information sheet (sample attached) available from University laboratories, county Extension offices or uwlab.soils.wisc.edu/madison. The Extension office will also have names and addresses of private laboratories that offer plant analysis services.

If the tissue sample is to be mailed, air-dry the sample for at least 1 day to avoid mold growth during shipment. Never mail samples on Thursday, Friday, or Saturday since the tissue may deteriorate in the post office over the weekend. Place the plant sample in a large paper envelope for shipment. Do not use plastic or polyethylene bags since plant tissue molds more readily in such bags. It is not necessary to air dry samples that will be delivered to the lab within a day after collection of the sample. Refrigerate these samples if possible.

A soil sample should be submitted along with all plant analysis samples. The soil sample should be taken from the same area as the plant sample. For some problems, the soil sample results will substantially improve interpretations of the plant analysis. For example, plants suffering from manganese toxicity are often associated with low pH soils.

Interpretation of plant analyses

Critical value and sufficiency range approaches

For most diagnostic purposes, plant analyses are interpreted on the basis of "critical" or "sufficiency" levels for each nutrient. The critical level has been defined as that concentration below which yields decrease or deficiency symptoms appear. For many nutrients, yield decreases even before visible deficiency symptoms are observed. Because the exact concentration of a nutrient below which yields decline is difficult to determine precisely, some define the critical level as the nutrient concentration at 90 or 95% of maximum yield.

As previously mentioned, the nutrient composition of a plant changes as the plant matures and with the portion of the plant sampled; therefore, critical levels are defined for a specific plant part at a specified stage of maturity. For most crops, there is a fairly broad optimum range of concentration over which yield will be maximized rather than a single point.

Nutrient ranges representing deficient, low, sufficient, high, and excessive concentrations for corn and alfalfa used by the University of Wisconsin Soil and Plant Analysis Laboratory are shown in table 12-14. For some nutrients, excessive levels have not been well-defined because growth is not depressed by excessive uptake. These ranges are useful guidelines for interpreting plant analyses, but they must not be used dogmatically. Knowledge of hybrid requirements, unusual soil or climatic conditions, or other extenuating information should be considered.

DRIS or nutrient ratio approach

The Diagnosis and Recommendation Integrated System (DRIS) simultaneously considers nutrients on a ratio basis in relation to crop growth. The DRIS approach to interpreting the results of plant analysis involves creating a database from the analysis of thousands of samples of a specific crop. The nutrient ratios corresponding to the highest yielding portion of the population are established as the standard (norms) and used as the basis for comparison. A ratio of plant nutrient concentrations by itself cannot be used to diagnose plant problems, but combinations of different nutrient ratios can be combined mathematically to determine what nutrients are most likely to limit yield. The results of such calculations are the "DRIS indices."

An index of 0 is considered optimum; however, although finer-tuning may be possible, DRIS indices are normally calibrated so that those within the range of about –15 to +25 are considered normal and "in balance." A DRIS index less than –25 indicates a likely deficiency, whereas those between –15 and –25 represent a

Table 12-14. Interpretive plant nutrient ranges for corn and alfalfa in Wisconsin.

	Tissue nutrient interpretive level				
Nutrient	**Deficient**	**Low**	**Sufficient**	**High**	**Excessive**
CORN—ear leaf at tasseling to silking					
Nitrogen, %	<1.75	1.75–2.75	2.76–3.75	>3.75	—
Phosphorus, %	<0.16	0.16–0.24	0.25–0.50	>0.50	—
Potassium, %	<1.25	1.25–1.74	1.75–2.75	>2.75	—
Calcium, %	<0.10	0.10–0.29	0.30–0.60	0.61–0.90	>0.90
Magnesium, %	<0.10	0.10–0.15	0.16–0.40	>0.40	—
Sulfur, %	<0.10	0.10–0.15	0.16–0.50	>0.50	—
Zinc, ppm	<12	12–18	19–75	76–150	>150
Boron, ppm	<2.0	2.0–5.0	5.1–40.0	40.1–55.0	>55.0
Manganese, ppm	<12	12–18	19–75	>75	—
Iron, ppm	<10	10–49	50–250	251–350	>350
Copper, ppm	—	<3	3–15	16–30	>30
ALFALFA—top 6 inches of plant at first flower					
Nitrogen, %	<1.25	1.25–2.50	2.51–4.00	>4.00	—
Phosphorus, %	<0.20	0.20–0.25	0.26–0.45	>0.45	—
Potassium, %	<1.75	1.75–2.25	0.26–3.40	3.41–4.25	>4.25
Calcium, %	—	<0.70	0.70–2.50	>2.50	—
Magnesium, %	<0.20	0.20–0.25	0.26–0.70	>0.70	—
Sulfur, %	<0.20	0.20–0.25	0.26–0.50	>0.50	—
Zinc, ppm	—	<20	20–60	61–300	>300
Boron, ppm	<20	20–25	26–60	>60	—
Manganese, ppm	<15	15–20	21–100	101–700	>700
Iron, ppm	—	<30	30–250	>250	—
Copper, ppm	—	<3.0	3.0–30.0	>30.0	—

possible deficiency. Values greater than +100 may be an indication of possible nutrient excess. The greater the magnitude of the nutrient index, either positive or negative, the more likely that element is out of balance in the plant.

The principal advantages of the DRIS system are that stage of maturity, plant part, and cultivar are less important than they are for the critical level or sufficiency range approaches to interpreting plant analyses. Thus, by using DRIS as an interpretive approach, it is possible to sample alfalfa at the pre-bud stage and obtain meaningful results, rather than waiting until first flower.

DRIS norms are not available for all crops and some users of the DRIS system tend to interpret the results too dogmatically. Some regard every negative index as representing a deficiency and pay no attention to positive indices. Since not all of the nutrient norms used to develop DRIS indices have been evaluated under field conditions, experience has shown that the evaluations should not be made disregarding nutrient concentrations altogether. The University of Wisconsin recommends that the two interpretive approaches—DRIS and critical value/sufficiency range—be used together.

Plant Analysis with Standardized Scores (PASS)

The Plant Analysis with Standardized Scores (PASS) system was developed at the University of Wisconsin to combine the strengths of the sufficiency range (SR) and DRIS methods. The SR provides easily interpreted, categorical, independent nutrient indices. The DRIS gives difficult to calculate, easily interpreted, numerical, dependent nutrient indices, and a ranking of the relative deficiencies. The strengths of the SR are the weaknesses of the DRIS and vice-versa. The PASS system combines an independent nutrient section and a dependent nutrient section. Both types of indices are expressed as a standardized score and can be combined to make more effective interpretations. Research has demonstrated that PASS results in more correct diagnoses than either of the other two systems. To date, however, the PASS system has been developed only for alfalfa, corn, and soybean.

Tissue testing

Tissue testing offers a quick field test of plant sap. Unlike plant analysis, which is a quantitative laboratory analysis of plant tissue, a tissue test is semi-quantitative. Results are interpreted as high, medium, low, or deficient rather than in exact percentages or parts per million. Most test kits analyze only nitrogen, phosphorus, and potassium. A soil pH kit is a useful supplement to the tissue-testing kit in areas with low or high pH soils.

Tissue testing can help interpret plant growth problems in the field. Even if it does not identify nitrogen, phosphorus, or potassium as deficient, these nutrients can be ruled out, and attention can be focused elsewhere. For questionable test results and for results needing to be verified, submit samples to a laboratory for complete plant analysis.

Tissue test kits can give false results if the reagents deteriorate or become contaminated.

Questions

1. What is the minimum number of composite soil samples that should be taken from a 35-acre field that has not been tested in the past 10 years? How many cores or borings should be in each composite sample?

2. To what depth should the soil be sampled in the following tillage systems: 1) moldboard plow, 2) chisel plow, 3) ridge tillage, 4) no-till?

3. If a farmer has soil that consistently tests in the excessively high range for phosphorus and potassium, what fertilizer recommendations should be made for corn? for established alfalfa?

4. Assume a farmer has a field of continuous corn in Dubuque silt loam that tests 10 ppm in available phosphorus (P). Also, assume that enough row fertilizer is applied each year to replace what is being removed when the ear corn is harvested. About how much broadcast phosphate (P_2O_5) would have to be applied to increase the available phosphorus (P) in the soil to 20 ppm?

5. Assume a soil test for available potassium (K) is 60 ppm in a Miami silt loam and that a farmer broadcasts and thoroughly incorporates the 300 pounds per acre of 0-0-60 (180 pounds of K_2O) recommended for this field in the fall. If this field was resampled and tested again in the spring, what would be the expected level of available potassium (K) on the new soil test?

6. If a toxicity is suspected, such as boron toxicity, which of the following diagnostic aids will more accurately define the problem: soil test, plant analysis, or a tissue test? Why?

7. A soil sample from an alfalfa field tests "low" in available zinc, but no recommendations for zinc are given on the soil test report. Why?

8. Why is sulfur rarely recommended for a Tama silt loam soil in Grant County?

9. What is the difference between plant analysis and tissue testing? When would each be used?

CHAPTER 13

Economics of lime and fertilizer use

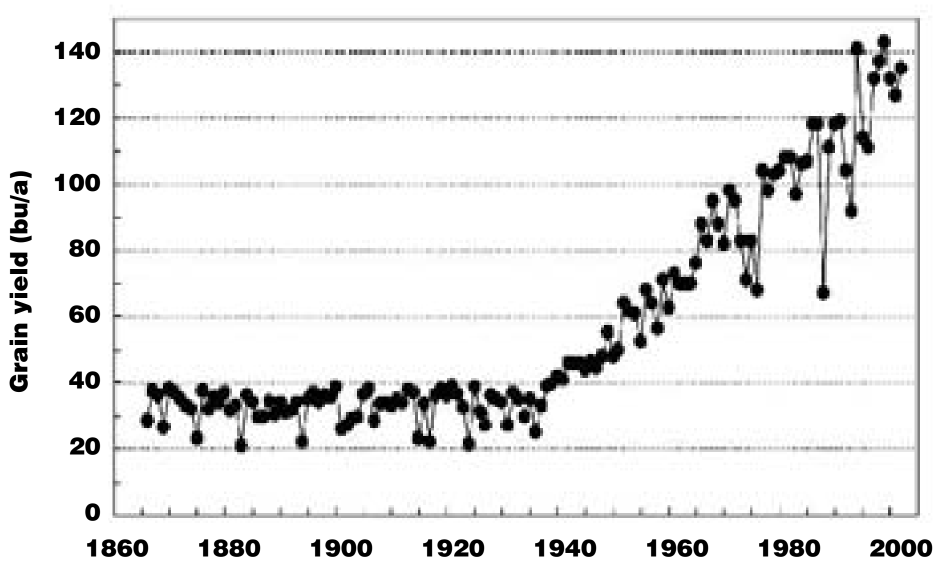
"Farm people are not… indifferent to economic opportunities to improve their lot. They are calculating economic agents who reckon marginal costs and returns to a fine degree."

Theodore W. Schultz,
"Knowledge is Power in Agriculture" *in*
Challenge, *September–October 1981*

Corn yields in Wisconsin, like other states, were almost constant for 800 years prior to 1940 (figure 13-1). Much of the increase between 1940 and 1955 can be attributed to the introduction of hybrids. Most of the sustained increase from 1955 on is attributed to the use of fertilizers and pesticides and improved agronomic practices. Future yield increases will rely not only on science and technology but also on better management practices to identify and then eliminate production constraints while maintaining or improving environmental quality.

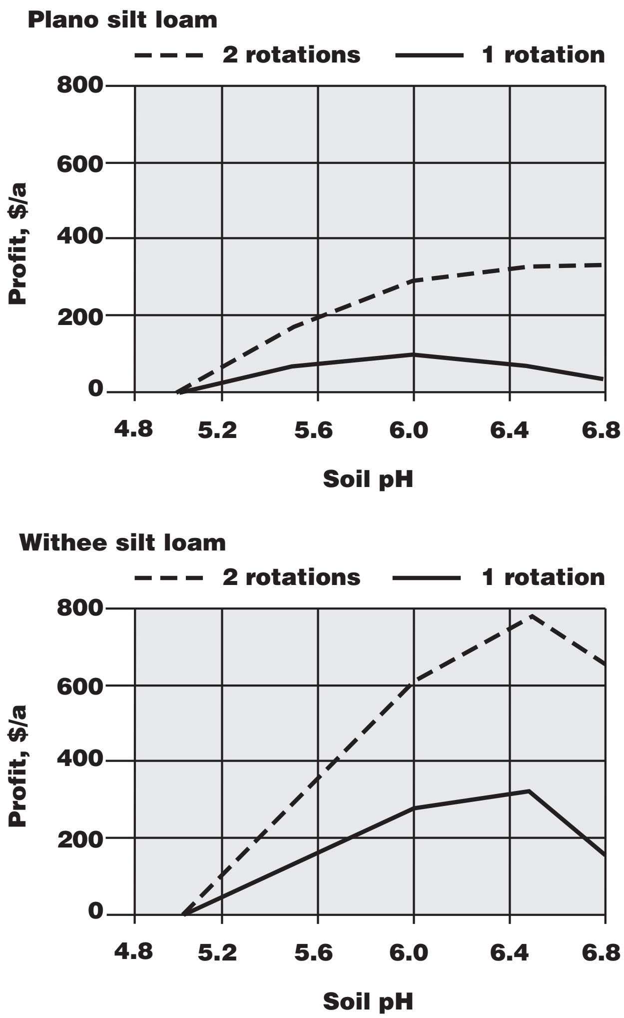
In Wisconsin, fertilizer use on corn increased steadily until the early 1980s. Since then, rates have remained constant or declined somewhat. However, this does not mean that high rates of fertilizer are always profitable. A summary of over 650,000 soil samples analyzed by Wisconsin soil testing labs during 1995 through 1999 found that soil test phosphorus and potassium averaged excessively high or high, respectively, for most field crops. This means that most growers would be unlikely to see profitable response to more than recommended amounts of

Figure 13-1. Wisconsin corn yields from 1866 to 2000.



Source: United States Department of Agriculture (USDA).

Figure 13-2. Net profit for one and two rotations (alfalfa-alfalfa-corn-soybean-corn) in Plano and Withee silt loams limed from pH 5.0 to 6.8.



phosphate and potash. Nevertheless, there are still some soils testing less than optimum in pH, phosphorus or potassium, and it is on these soils where the greatest response to lime and fertilizer can be expected.

One of the keys to profitable crop response is to base lime and fertilizer applications on soil test recommendations. A few farmers forego potential profitability by not applying recommended rates of fertilizer and lime, while others cut their profits by using more than the recommended rates. Some waste money by failing to credit the nutrients contributed by previous leguminous crops or manure. Before applying more than the recommended amount of lime or fertilizer, make sure that such practices are profitable by considering the following:

- Check soil test levels and keep them within the optimum range. See Extension publication *Optimum Soil Tests for Wisconsin* (A3030).
- Give credits to manure and previous leguminous crops.
- Study and observe research and demonstration trials conducted on nearby experimental farms.
- Set up trials to determine whether treatment response pays for the cost of the treatment.

The best way to evaluate expenditures on various inputs is to estimate the relative return from incremental investments. Usually the return per dollar invested in lime and fertilizer is higher than for most other inputs, such as additional breeding stock, new buildings, or new machinery. Also, the money invested in lime and fertilizer is turned over much faster than with investments such as machinery. As a result, the purchase of lime and fertilizer should have a high priority, especially on farms with low or optimum fertility soils.

Another reason why the return on lime and fertilizer is quite favorable is that prices for these items have not risen as much as most other farm inputs. For example, while the price of fertilizer increased by about 250% from 1950 to 1985, the costs of wages, machinery, and land have increased by 700, 725, and 1,000%, respectively.

Returns from aglime

Liming is considered a capital investment because it improves the inherent productivity of the soil and, therefore, has value for more than 1 year. Once the optimum soil pH is achieved, it will be several years before lime is needed again. Therefore, when considering the return from liming, an estimate of the value of crop yield increases over a 5- to 10-year period will be needed. As shown in figure 13-2, raising the soil pH above 5.0 resulted in substantial profits when the values of the yield increases were calculated for two 5-year rotations (alfalfa-alfalfa-corn-soybean-corn). Only modest profits were realized in one rotation.

Research plots on Plano silt loam had a maximum profit at about pH 6.0 for one rotation and at pH 6.8 for two rotations. Results were different on Withee silt loam because of the difference in the amount and cost of aglime, and the difference in the magnitude of the crop response. (Prices were $12 per ton for aglime on Plano and $20 per ton for aglime on Withee, $75 per ton for alfalfa plus $1 per ton for each 0.1 pH above 5.0, $2 per bushel for corn, and $7 per bushel for soybean.) Although crop yields on Withee silt loam are generally lower than on Plano silt loam, response to aglime is higher because manganese toxicity at low pH is more of a problem in the Withee soil. The maximum profit for both one and two rotations on the Withee soil occurred at about pH 6.5. If alfalfa were kept for 3 or 4 years, as it often is on Withee soil, the maximum profit for a long rotation would shift toward pH 6.8.

Returns from the use of fertilizer

Farmers often want to know the most profitable rate of fertilizer to apply. This is not an easy question to answer because of the various factors which must be considered including:

- expected yield increase from each increment of fertilizer,
- level of management,
- price of fertilizer,
- price of commodity,
- added cost of handling the extra crop yield, and
- value of residual carryover of fertilizer.

Because of the uncertainty of weather, prices, etc., many of these factors have to be estimated at the beginning of the growing season or when the fertilizer is being applied. In spite of the difficulties involved, estimating these variables and conducting field trials can help determine the most profitable fertilizer rate.

One way of finding the most profitable rate of fertilization is to determine the added (marginal) return from incremental additions. Compare added fertilizer costs with the added crop value for each increment of fertilizer. Table 13-1 illustrates how to determine marginal returns. In this study, increasing nitrogen applications from 0 to 200 pounds per acre resulted in a yield increase from 93 to 145 bushels of corn per acre. The first two 40-pound increments gave the highest return per dollar invested. However, the greatest profit was obtained when 160 pounds of nitrogen

Table 13-1. Yield of corn and return from added nitrogen (Janesville, WI).

Nitrogen added	Cost of 40 lb N[a]	Yield	Yield increase	Value of yield increase[b]	Profit per acre: From each N increment	Profit per acre: From all N added	Return per dollar spent[c]	Cost of producing extra corn
lb/a	$	bu/a	bu/a	$	$/a	$/a	$/a	$/bu
0	—	93	—	—	—	—	—	
40	13.20	115	22	44	30.80	30.80	2.33	0.60
80	9.20	131	16	32	22.80	53.60	2.39	0.58
120	7.87	138	7	14	6.13	59.73	1.78	1.12
160	7.20	144	6	12	4.80	64.53*	1.67	1.20
200	6.80	145	1	2	–4.80	59.73	0.29	6.80

** Maximum profit*
[a] *Nitrogen applied as anhydrous ammonia at $0.15/lb + prorated share of an $8/a application fee.*
[b] *Corn valued at $2/bu.*
[c] *Calculated by dividing the value of the additional yield by the cost of each additional 40 lb of nitrogen.*
Source: Adapted from Bundy et al., 1992. Nutrient Management: Practices for Wisconsin Corn Production and Water Quality Protection. *University of Wisconsin-Extension publication A3557.*

was applied per acre. (This is the amount that would be recommended on the basis of a soil test.) Application of either 120 or 200 pounds of nitrogen per acre would have resulted in a loss of $4.80 per acre in profit when compared to the 160 pound per acre rate.

Note that the yield response of fertilizer follows the "law of diminishing returns." Based on the value of corn at $2.00 per bushel, the first 40 pounds of nitrogen gave a return of $30.80 per acre; the second 40-pound increment returned $22.80 per acre; the third increment returned $6.13 per acre; the fourth increment returned $4.80 per acre; but the yield increase for the fifth increment did not pay for the nitrogen application. The highest profit, in this example, was at the 160 pounds per acre application rate.

Availability of capital

Whenever financially possible, a grower should try for the highest net return per acre for fertilizer, where the last dollar invested in fertilizer is just returned in the value of the additional production. If a grower is unable to invest enough money in fertilizer to obtain optimum yields, try for a yield where the last dollar invested in fertilizer gives a return equal to what it would give if invested elsewhere in the business.

For example, suppose that the purchase of additional protein supplement will return $2.00 per dollar invested. Based on the data from table 13-1, it would be more profitable to use limited money for the protein supplement rather than applying the third 40-pound increment of nitrogen because it returned only $1.78 per dollar invested. In this situation, however, at least 80 pounds of nitrogen per acre should always be applied because the second 40-pound increment of nitrogen returns $2.39 per dollar invested. Farmers with limited capital should concentrate on starter applications of phosphorus and potassium and moderate levels of nitrogen on second-year corn, especially where manure is not applied. When topdressing hay, priority should be given to the lowest testing fields in the first or second production years.

Price changes

Changes in the price of fertilizer or in the value of the crop can change profit returns. However, if the response to fertilizer levels off abruptly at higher rates of fertilization as it does in the nitrogen data presented in figure 13-4 and table 13-1, then *minor* price fluctuations will have little effect on the optimum fertilization rate.

Crops such as corn respond well to fertilizer up to a certain point and then response abruptly levels off. These crops seem to hit a "yield barrier" because of weather, variety, and other limiting factors. For these crops, the optimum rate of fertilization usually is not affected by *modest* year-to-year price changes. For other crops and nutrients, such as alfalfa response to potash, the response curve is more gradual and continuous. In this case, the value of the feed largely determines the optimum rate of fertilization.

Due to recent *substantial* increases in the cost of nitrogen, economic optimum rates for corn are now being affected by major increases in nitrogen prices. As stated repeatedly in this book, the goal of the University of Wisconsin fertilizer recommendation program is to provide nutrients at rates that produce the greatest economic return. Using typical corn and nitrogen fertilizer prices during the 1980s and 1990s, Wisconsin researchers found that moderate changes in corn prices or nitrogen fertilizer costs do not cause major changes in optimum nitrogen recommendations. Corn:nitrogen price ratios in the range of 10:1 or greater have little impact on economic optimum rates (table 13-2). At these price ratios, the greatest return from nitrogen applied to the two soils shown in table 13-2 was at university recommended rates. The reason for little if any change in optimum nitrogen fertilizer rates for corn with historically typical variations in prices is due to the broad plateau of the corn:nitrogen response curve. Because of the relative flatness in this region of the curve, shifts in corn or nitrogen prices at corn:nitrogen price ratios higher than 10:1 do not have major effects on optimum nitrogen rates.

Increases in the cost of nitrogen fertilizers, have reduced corn:nitrogen price ratios to the point that economic optimum nitrogen rates for corn are now being affected. This is also illustrated in table 13-2. At corn:nitrogen price ratios of 8:1 or less (i.e. when nitrogen costs $0.25 per pound or greater and corn sells for $2.00 per bushel), the economic optimum rate drops from traditional values to levels below current university recommendations.

The impact of corn:nitrogen price ratios on the optimum rates for corn on southern Wisconsin silt loam soils is shown in figure 13- 3. Similar to nitrogen fertilizer response curves, the curve in figure 13-3 has a broad plateau. Thus, economic optimum rates for corn are relatively stable at corn:nitrogen ratios higher than 10:1. At corn:nitrogen ratios below 10:1, economic optimum rates drop significantly.

Residual carryover

Substantial amounts of phosphorus and potassium are carried over from one year to the next. Also, some carryover of nitrogen can occur, especially in a dry year. The residual effect of any carryover fertilizer should be considered when calculating the profitability of a fertilizer treatment. For example, the cost of a corrective application of phosphorus and potassium may not be returned the first year following application, but this treatment may also increase the yield of subsequent crops. Corrective applications are profitable as long as the added yield from all the crops in the rotation, discounted for time, will return more than the cost of the fertilizer. The Wisconsin soil test recommendation program suggests building very low and low soil tests over an 8- to 10-year period. However, do not make corrective applications if residual fertilizer will cause environmental problems.

Figure 13-3. Relationship between corn:nitrogen price ratios and economic optimum nitrogen rate for corn on southern Wisconsin silt loam soils (1991–2003).

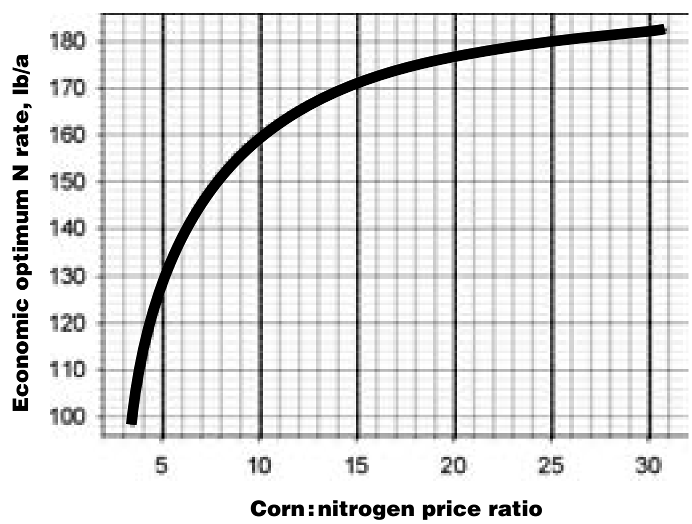
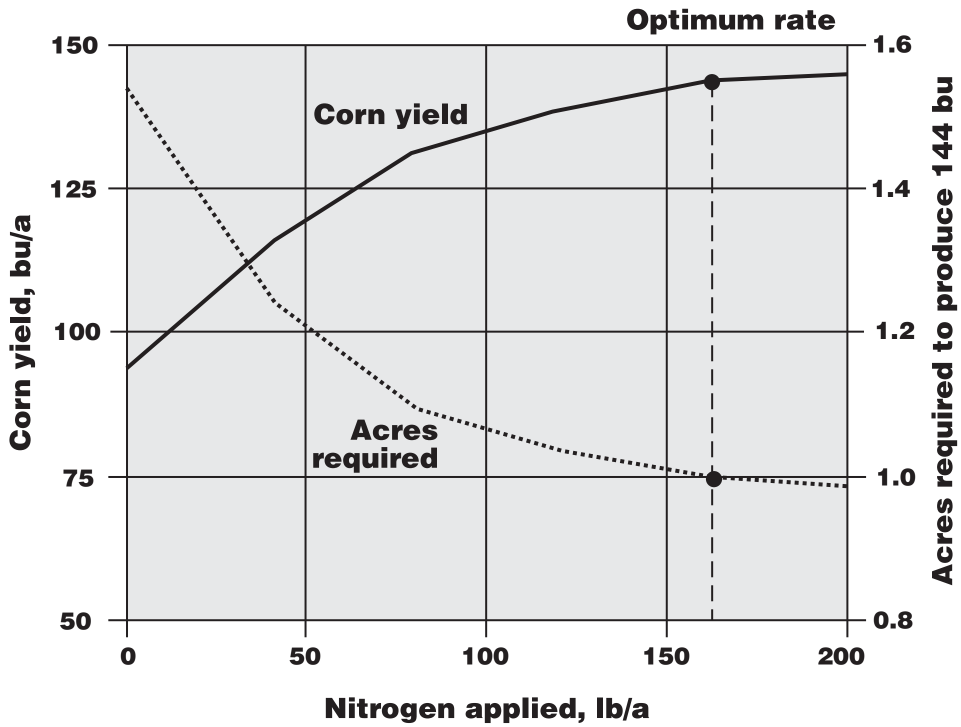


Table 13-2. Net return from fertilizer nitrogen at recommended, higher, and lower rates for corn production at various corn:nitrogen price ratios on two Wisconsin soils. *(Shaded values indicate maximum profit and economic optimum nitrogen rate.)*

Soil	N rate	Yield increase from fertilizer N	Net economic return from fertilizer[a] — Corn:nitrogen price ratio ($/bu and $/lb) 13.3:1 ($2.00/15¢)	10.0:1 ($2.00/20¢)	8.0:1 ($2.00/25¢)	6.7:1 ($2.00/30¢)	5.7:1 ($2.00/35¢)
	lb/a	bu/a	$/a				
Plano	130	50.1	75.60	69.10	62.60	56.10	49.60
	160[b]	54.4	79.80	71.80	63.80	55.80	47.80
	190	56.1	78.60	69.10	59.60	50.10	40.60
Withee	90	24.3	30.10	25.60	21.10	16.60	12.10
	120[b]	27.5	32.00	26.00	20.00	14.00	8.00
	150	28.2	28.90	21.40	13.90	6.40	–1.10

[a] *Calculated as: (value of yield increase from N) – (cost of N) – (cost of N application (assumed $5/acre)).*
[b] *Recommended (base) N rate prior to taking legume/manure N credits.*

Figure 13-4. Acreage required to produce 144 bushels of corn at different rates of applied nitrogen.



Source: Bundy et al., 1992. Nutrient Management Practices for Wisconsin Corn Production and Water Quality Protection. *University of Wisconsin-Extension publication A3537.*

Substituting fertilizer for land

An important economic principle is that fertilizer and land can be substituted for one another to produce a given quantity of feeds or forages. Figure 13-4 charts the data from table 13-1 to illustrate the relationship between fertilizer rates and acreage.

In this example, the optimum rate of nitrogen of 160 pounds per acre produced a yield of 144 bushels per acre. To produce the same amount of corn while decreasing the fertilizer requires more acreage. For example, if only 50 pounds of nitrogen had been applied per acre, then 1.2 acres would have been needed to produce 144 bushels. Since land costs are high, it is more economical to increase crop production by applying more fertilizer on existing acreage than by buying or renting more land. Also, there are fixed costs that have to be met regardless of yield, such as costs of tillage, planting, taxes, and herbicides. It is usually better to concentrate these fixed costs on fewer acres and use part of the savings for inputs such as fertilizer that increase per-acre yields.

Table 13-1 also provides information on the question of whether to invest in more fertilizer or more land. At the optimum fertilization rate, 160 pounds per acre of nitrogen, the last 40-pound increment of nitrogen produced corn at a cost of $1.20 per bushel. In this example, extra land would be more profitable than extra fertilizer only where corn could be grown for less than $1.20 per bushel on the additional land.

Calculating the cost of plant nutrients

No appreciable difference exists in crop response among different forms or analysis of fertilizer when the same amounts of plant nutrients are applied. Therefore, money can be saved by determining the cost per pound of plant nutrient in various fertilizers and purchasing one that supplies the needed plant nutrients at lowest cost.

Single nutrient fertilizer

Calculating the cost per pound of a nutrient in a single element fertilizer is relatively easy. Examples are illustrated below for anhydrous ammonia (82-0-0) and triple superphosphate (0-46-0).

Example 1:

a. Calculate the pounds of nitrogen (N) per ton of anhydrous ammonia (82-0-0):

2,000 lb/ton x 0.82 = 1,640 lb N

b. Calculate the cost per pound of nitrogen, assuming anhydrous ammonia costs $330 per ton:

$330 ÷ 1,640 lb N = $0.20/lb N

Example 2:

a. Calculate the pounds of phosphate (P_2O_5) per ton of triple superphosphate (0-46-0).

2,000 lb/ton x 0.46 = 920 lb P_2O_5

b. Calculate the cost per pound of P_2O_5, assuming triple superphosphate costs $280 per ton.

$280 ÷ 920 lb P_2O_5 = $0.30/lb P_2O_5

Mixed fertilizer

Mixed fertilizers contain more than one nutrient. An example is diammonium phosphate (18-46-0). When determining the cost per pound of the two or three nutrients (N, P_2O_5, and K_2O) in a mixed fertilizer, first determine what proportion of the total price is for each nutrient. Using a price of $0.20 per pound for nitrogen sold as urea or 28% N solution, $0.20 per pound for P_2O_5 as triple superphosphate, and $0.12 per pound for K_2O as muriate of potash, the ratio of these costs is 2:2:1.2. A procedure for calculating the cost per pound of each nutrient in a mixed fertilizer is outlined below using 5-14-42 at $162 per ton or $8.10 per 100 pounds as an example.

High analysis fertilizers are usually less expensive per pound of plant nutrient. The higher concentration translates to savings in transportation, handling, and storage because less weight is handled per pound of plant

a. Determine the nutrient units: Multiply the N by 2, P_2O_5 by 2, and K_2O by 1.2; then add up the products obtained.

Nutrient	Analysis		Price factor		Nutrient units
N	5	x	2	=	10
P_2O_5	14	x	2	=	28
K_2O	42	x	1.2	=	50
				Total	88

b. Take the total nutrient units for each nutrient, divide by the total for all nutrients, and multiply by the price per 100 lb of the mixed fertilizer. This gives the division of the cost of the mixed fertilizer among the N, P_2O_5 and K_2O.

Nutrient	Nutrient units		Total nutrient units		Price of 100 lb of 5-14-42		Cost of nutrient per 100 lb
N	(10	÷	88)	x	$8.10	=	$0.92
P_2O_5	(28	÷	88)	x	$8.10	=	$2.58
K_2O	(50	÷	88)	x	$8.10	=	$4.60
						Total	$8.10

c. Divide the cost of each nutrient by its analysis to get the cost per pound of each plant nutrient.

Nutrient	Cost of nutrient per 100 lb		Analysis		Cost per lb of nutrient
N	$0.92	÷	5	=	$0.18
P_2O_5	$2.58	÷	14	=	$0.18
K_2O	$4.60	÷	42	=	$0.11

Table 13-3. Effect of rotation on corn yields.

Previous Crops	Nitrogen applied to corn, lb/a 0	75	150	300
	corn yield, % of control			
Corn-corn	control	+46	+60	+49
Corn-soybeans	+60	+69	+72	+63
Alfalfa-alfalfa	+70	+76	+77	+69

nutrient. The cost of application must also be considered because some materials such as anhydrous ammonia can be relatively costly to apply.

Other ways to cut fertilizer costs include buying fertilizer in bulk and buying during the off-season. Bulk fertilizer is less expensive than bagged fertilizer. However, the convenience and superior storing quality of bagged fertilizer for a starter application sometimes makes it the most practical choice. Bulk spreading is virtually always used for broadcast and topdress applications; bagged fertilizer is used mainly for starter fertilizer. Buying fertilizer in the fall or winter usually offers an advantage in terms of off-season discounts.

Calculating profits from improved soil management

Farmers cannot afford to adopt improved soil management practices unless those practices increase farm income. Each group of related practices can best be evaluated by means of a partial farm budget. A partial farm budget compares the added costs and reduced returns of a proposed management practice against the reduced costs and added returns resulting from such a practice. This allows farmers to calculate the impact of a management practice change on net farm income. Added costs and returns are most easily figured on an annual basis.

Annual costs for long-term capital investments

Some soil management practices require a capital investment which benefits crops for more than 1 year. Examples include terraces, tile and surface drainage, lime, and corrective applications of fertilizer. The annual cost of capital improvements consists of annual depreciation, interest on investment, repair and up-keep costs (if any), insurance, and possible increased taxes because of the improvement.

Annual depreciation can be computed by dividing the total costs of the improvement by the number of years it is estimated to last. An interest charge should be included since the capital invested could earn interest in some other use.

When evaluating profitability any cost sharing available through various county, state, or federally funded programs should be deducted from the cost of the practice.

Sources of increased returns

Increased returns resulting from improved soil management may be due to any of the following items:

- the market value of increased crop yields,
- a larger proportion of high-return crops grown in the rotation,
- a permanent increase in the value of the farm (as with increased tillable acres due to drainage).

Comparison of net returns

Some management practices cost little to implement but can improve crop yields substantially. These include

- timeliness of tillage, planting, and harvesting,
- variety selection,
- plant population,
- crop rotation,
- equipment adjustment (seed depth, fertilizer calibration, spray calibration),
- uniform spreading of manure, and
- taking appropriate credits for manure and previous leguminous crops.

Corn yields, for example, decrease by roughly 1 buhels per acre for every day planting is delayed beyond May 5 in southern Wisconsin. If tillage is not completed and the planter ready to go on time, weather can delay planting further. If weeds are not sprayed or cultivated on time, they can get out of control and cause serious yield losses.

A study of various crop rotations on the Lancaster, WI Research Station showed that corn invariably yielded better following a rotation crop than in continuous corn regardless of the amount of nitrogen applied (table 13-3). This is probably due to the influence of the rotation crop in breaking the life cycles of some insect and disease pests. Corn following alfalfa rarely responds to more than a small application of nitrogen. Corn following soybeans without added nitrogen produced as much as continuous corn receiving 150 pounds of nitrogen per acre. Corn following alfalfa yielded even more. Most states give a soybean nitrogen credit of about 40 pounds nitrogen per acre, which is worth about $10 per acre at a nitrogen cost of $0.25 per pound. Alfalfa nitrogen credits are typically two to three times this amount.

Increasing plant population can often increase yields with only a slight increase in the cost of seed. Adjusting the planter for the proper depth of planting takes a few minutes of time but can make a big difference in germination and, ultimately, in the yield.

The returns from farming soils to their productive capacity is illustrated in table 13-4. These data show an increase in net return of 35 to 80% when crops are grown under a high level of management compared to average management.

Feeding higher crop yields through livestock

Improved soil management practices are usually the least expensive way to get the feed needed for livestock expansion. Many Wisconsin farmers limit their livestock production to the reliable amount of feed that can be produced on their farms. On these farms, increased livestock expansion is closely tied to the additional feed that can be produced through improved crop and soil management.

An increase in livestock can also be accomplished by purchasing feeds or by purchasing or renting additional land. However, these alternatives are often less economical than improving crop production on present land.

In summary, there are many ways to increase profits through crop or livestock production. The key to making the most of each dollar spent lies in careful analysis of the value of each farm input. Select the most profitable inputs first, followed by those inputs that are likely to give less return per dollar invested but which should still be profitable.

Table 13-4. A comparison of net returns per acre for corn, oats, and alfalfa under average and high-level management on a Fayette silt loam.

	Corn		Oats		Alfalfa	
	Average	High	Average	High	Average	High
Return						
Yield per acre	100 bu	140 bu	75 bu	100 bu	3.0 ton	4.0 ton
Price per unit, $	2.00	2.00	1.25	1.25	75.00	85.00*
Gross value per acre, $	200.00	280.00	93.75	125.00	225.00	340.00
Costs						
Power & machinery	31.44	35.44	15.72	17.72	69.00	74.10
Seed	17.00	20.00	3.00	4.00	9.45	13.40
Fertilizer	39.40	43.90	25.70	31.60	26.50	36.00
Spraying	19.81	19.81	—	5.00	—	5.00
Hauling & storage	20.00	28.00	15.00	20.00	15.00	20.00
Total cost	127.65	147.15	59.42	78.32	119.95	148.50
Net value per acre (Return costs)	$72.35	132.85	34.33	46.68	105.05	191.50

**With improved management, the alfalfa is assumed to be of higher quality.*

Questions

1. Why should aglime be considered as a capital investment?

2. Would you lime alfalfa to a pH of 6.5 or 6.8 on rented land? Why?

3. Explain why the returns from liming are much greater over two 5-year rotations of corn-oats-alfalfa-alfalfa-alfalfa, as compared to only one 5- year rotation.

4. What is the cost per pound of N, P_2O_5 and K_2O in a 15-40-5 priced at $220.00 per ton if the nutrient:price ratio is 1.6:1.9:1.0?

5.. Use of incremental rates of K_2O gave the following alfalfa yields:

K_2O application	Yield
lb/a	ton/a
0	2.5
50	3.2
100	3.7
150	4.0
200	4.1
250	4.2

What is the return per dollar spent for fertilizer and the profit per acre for each 50-pound increment of K_2O, assuming that K_2O costs $0.11 per pound and that alfalfa is worth $80.00 per ton? In this example what is the optimum rate of application?

6. Which of the following fertilizers is the least expensive in terms of cost per unit of plant nutrient:
3-13-33 at $140.00 per ton;
7-17-27 at $142.00 per ton; or
5-10-30 at $128.00 per ton?
Assume that N and P_2O_5 are selling for $0.21 per pound and K_2O for $0.13 per pound.

7.. Would it be more profitable to apply 160 pounds per acre of nitrogen on 50 acres of corn or 80 pounds per acre on 100 acres? Why?

8. Using figure 13-4, estimate how much acreage will be required to produce 144 bushels per acre of corn if only 75 pounds per acre of nitrogen are applied?

9. The use of a certain herbicide is expected to increase the yield of corn by 12 bushels per acre. If the herbicide costs $10.00 per acre, when is it more profitable to apply the herbicide than another 40 pounds per acre of nitrogen? Use the data in table 13-1 for the cost of nitrogen and the value of corn.

10. Why, in general, is it more profitable to increase production on a farm by increasing yields per acre rather than by increasing acreage under production? What can be done to increase yields per acre when there is no more land available to put into production.

Index

O

P

Q

R

S

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Produced by Cooperative Extension Publications, University of Wisconsin-Extension. L.G. Deith, editor; S.A. Anderson, designer. Cover photo by B.W. Hoffmann, Life Sciences Communication.

This material is based upon work supported in part by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture under Agreement No. 2002-51130-01950. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture.

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A3588 Management of Wisconsin Soils R-10-2005-1.5M