Chesapeake Bay Region
Nutrient Management
Training Manual

Authors: *Steve Nagle, Greg Evanylo, W. Lee Daniels, Douglas Beegle and Velva Groover*

Editor: *Frank Coale*

Chesapeake Bay Program

This manual was prepared by the Virginia Tech Department of Crop and Soil Environmental Sciences in Blacksburg. Faculty from the University of Maryland (Dr. Frank Coale) and the Pennsylvania State University (Dr. Douglas Beegle) Departments of Agronomy also participated in its development. Final review of the manuscript was performed by Dr. George Hawkins. Cover drawing and back cover map by Katie Haering.

This project was conceived, funded and coordinated by:

The Nutrient Subcommittee and the Nutrient Management Workgroup of the Chesapeake Bay Program

The USEPA Chesapeake Bay Program

The Maryland Dept. of Agriculture, Office of Resource Conservation

The Pennsylvania Dept. of Agriculture, Bureau of Plant Industry

The Pennsylvania Dept. of Environmental Protection, Bureau of Land and Water Conservation

The Virginia Dept. of Conservation and Recreation, Division of Soil and Water Conservation

TABLE OF CONTENTS

JANUARY 1997

ACKNOWLEDGMENTS

This manual contains sections that were adapted in whole or in part with permission from the following sources:

Nutrient Management Handbook. Second Edition. 1993. Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation. Richmond, VA.

Soil Fertility Manual. 1993. Potash and Phosphate Institute, Norcross, GA. Item # 50-5100. pp. 116.

Efficient Fertilizer Use. Fertilizing for Maximum Profit. Third Edition. 1992. IMC Fertilizer, Inc. Mundelein, IL. DBFT2-001C. pp. 243.

In addition, a number of other papers, reports, and bulletins were used in the preparation of this manual and are cited in the references section.

We appreciate the efforts of Mr. Russ Perkinson in coordinating this contract effort over time.

Chapter 1. Introduction and General Nutrient Management Concepts

PURPOSE OF NUTRIENT MANAGEMENT PLANNING

The efficient use of nutrients in agricultural production systems has important environmental implications. The potential exists, for accelerated nutrient loss, when the amount of essential nutrients exceeds the uptake needs of a crop over time. Nutrient reactions and pathways in the soil-water system are complex and nutrients vary in their potential for transport to surface water and groundwater. Similarly, certain nutrients pose serious water quality threats while others are of little concern. The purpose of this manual is to familiarize the reader with the soil reactions and potential loss pathways of the essential plant nutrients and provide a framework for effective nutrient management planning.

Nutrient management involves the implementation of practices that permit efficient crop production and protect water quality from nutrient pollution. A *nutrient management plan* is a written, site-specific plan that addresses these issues. The goal of farm nutrient management planning is to minimize adverse environmental effects, primarily upon water quality, while optimizing farm profits. It should be recognized that some level of nutrient loss to the environment will occur even when the best nutrient management practices are employed; however, these losses should be lower than would occur without nutrient management. In this manual, we will give the reader the information required to generate nutrient management plans for the Chesapeake Bay region; however, specific nutrient management plans must be tailored on a farm or field basis.

Components of a Nutrient Management Plan

Nutrient management plans must be developed on a site-specific basis and must be carefully tailored to specific soils and crop production systems. While each state in our region may have differing approaches to this process, the following steps will generally be essential:

1. Obtain accurate soil information for each field or management unit and analyze representative soil samples from each management unit. This may require a new farm soil map or a revision of existing United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) mapping coverage.

2. Determine the crop yield potential for each field, based on the known productivity of the soils present coupled with the intended management practices.

3. Identify the total plant nutrient needs to achieve this expected yield potential.

4. Determine the plant-available nutrients in manures or biosolids to be used, considering the type of organic material to be used and its method of application.

5. Estimate the nutrient contribution that can be expected from residual effects or carryover from previous fertilizer, manure or biosolid applications.

6. Include credit for N supplied to a row crop following a previous legume.

7. Recommend application rates for manure, other organic nutrients, and/or commercial fertilizers to supply the needed nutrients at the appropriate time for optimal crop production.

This process must be followed for all fields and production systems within a given planning area. The nutrient planning process is totally dependent upon the synthesis of information and data on the soils, cropping systems, manures, and management practices being employed over time. Therefore, care should be taken to ensure that the information used to specify the nutrient management plan is current and accurate.

RELATIONSHIPS AMONG ENVIRONMENT, NUTRIENTS AND WATER QUALITY

The long term impact of agricultural production systems on water quality is an issue important to the general public, land use regulators, and property owners alike. Potential surface water impacts include sedimentation, eutrophication, and overall water quality degradation due to presence of nutrients or toxins in the water and sediments. The loss and degradation of aquatic ecosystems are the major perceived threat from these impacts, along with public health and drinking water considerations. Groundwater concerns center around the potential migration of pesticides and nitrates in recharge waters, and the resultant degradation of drinking water quality. Contaminated groundwater can also serve as a source of local or regional surface water recharge, so impacts of a given production practice usually affect both water resources to some extent.

Water Balance, Crop Production, and Pollutant Migration

In order to fully understand the adverse effects of excessive nutrient losses on water quality, we first need to understand the basic role of water in the supply and loss of nutrients from a cropped field. Also important are the factors that influence the pathway and movement of water in that system. Crop production is driven by plant transpiration of soil water that is controlled by several soil/site factors. Rain falling on the landscape is either intercepted by the plant canopy or falls directly to the soil surface. Much of the intercepted rainfall is evaporated back to the atmosphere, but a majority still reaches the soil via canopy drip or stemflow. Rainwater, hitting the soil surface, either infiltrates into the soil or runs off as surface flow, depending on the infiltrative capacity of the soil and the intensity of the rainfall. Well aggregated, gently sloping soils tend to have high infiltrative capacities while poorly aggregated, steeply sloping soils are more prone to lose water to runoff. Runoff waters can carry suspended sediments, organic matter, nutrients (N and P), pesticides, and other contaminants to local surface waters.

Once water has infiltrated the soil, a certain amount of it will be held by the soil particles against gravity, and the excess will move downward to recharge groundwater. Water held by the soil within the active rooting depth of the crop is available for transpiration. The effective rooting depth of crops varies from less than 2 ft for many herbaceous perennials to greater than 10 ft for certain woody species. During the summer months, the vast majority of water that infiltrates the soil is taken up by the plant, and the total amount of water transpired varies widely by plant species. During the winter, when transpirational demand is quite low, deep leaching losses of water below the rooting zone are common. Any water soluble materials such as nitrate (NO_3^-) that are present in the rooting zone at the end of the growing season therefore face the risk of being leached to groundwater over the following winter months. In most watersheds, surface water and groundwater flows are interconnected to some extent.

The direct effects of a cropping system on water quality will be governed by local site parameters such as infiltration, runoff, evapotranspiration and leaching. For instance, soil tillage practices directly influence how much rainfall runs off the field or infiltrates into the soil. Crops vary considerably in their soil water extraction patterns, particularly when an annual crop is compared with a herbaceous perennial. Cropping practices also influence water balance through the effects of the plant canopy on rainfall interception and infiltration/runoff parameters. The interaction of soil tillage with crop type and management therefore directly controls the relative amount of runoff and deep leaching water losses that would be expected for a given crop production system.

Perennial or no-till systems may actually increase groundwater contamination by nutrients because they enhance infiltration and soil moisture content. When compared with conventional tillage, minimum tillage systems will leach more water beyond the rooting zone due to their higher infiltration rates. This coupled with deep continuous macropores (such as open root channels or wormholes), leads to a greater potential for leaching losses of soluble contaminants to groundwater. The ability of a crop to intercept and transpire soil water before it is lost to deep leaching is largely dependent upon its total rooting mass and depth. Switchgrass, for example has a very deep and heavy rooting system compared with most other perennials, and can extract large volumes of soil water from deep in the profile. Significant leaching losses during the summer under switchgrass would therefore not be anticipated, but might occur beneath more shallow-rooted crops, particularly after heavy rain events.

Deep leaching losses are common in most soils during the winter months when plant transpirational demands are low or nonexistent. Cool season perennials and winter annual cover crops are capable of periodic transpiration during the colder months, however, and can play a significant role in preventing leaching losses of soluble contaminants such as nitrate. A vigorous winter cover crop such as annual rye may intercept as much as 3 inches of percolating water per acre, greatly reducing total winter leachates (Meisinger et al., 1991). The water balance relationships discussed here are general and assume that we are comparing contrasting production systems in similar soil-climatic zones. Local rainfall, temperature patterns, and resultant soil water balances vary widely over the various production regions of the Chesapeake Bay watershed. The relative influence of these production systems on runoff and leaching will necessarily need to be evaluated on a local basis. Further detail on the soil's role in the hydrologic cycle is presented in Chapter 2.

Fate and Transport of Nitrogen

Nitrogen (N) is an essential element for plant growth and animal nutrition and is the nutrient taken up in the largest amount by crops. Nitrate (NO_3^-) is the major inorganic form of N in most soils. Nitrate, an anion, is not attracted by the predominately negatively charged soil colloids and is, therefore, quite mobile and move freely with soil water. Nitrogen application to soils beyond that required for plant uptake and maintenance of the soil microbial biomass will generally lead to NO_3^- leaching and long term groundwater degradation. Elevated levels of NO_3^- in drinking water may lead to methemoglobinemia in infants, the formation of carcinogenic nitrosamines in the human stomach, and hypertension. A recent national groundwater study by the United States-Environmental Protection Agency (1990) found detectable NO_3^- in 52% of the 94,600 community water systems tested, indicating widespread movement to groundwater on a national scale. Movement of excessive amounts of N to surface waters can result in a number of undesirable effects such as eutrophication and associated algal blooms and oxygen depletion. Most fresh water ecosystems are phosphorus limited, but certain lakes and coastal estuarine systems are limited by N (NRC, 1978).

Most of the cropping systems described in this manual show a direct and marked yield response to fertilizer N applied to non-legume crops, so fertilizer N applications will be routine across most of cropping systems employed. While leaching losses are generally considered the major environmental threat from N, runoff losses are also possible. The potential of each system to contribute N to surface waters will be directly dependent upon its erosion potential coupled with fertilizer application practices. Nitrogen is lost to surface water as NO_3^-, primarily from recently applied inorganic fertilizers, or in particulate organically-bound forms. Conservation tillage practices can reduce NO_3^- losses in runoff by up to 25% (Baker and Laflen, 1983). Use of winter cover crops, such as cereal rye can be effective for control of surface runoff losses. Further detail on soil N and its fertilizer reaction chemistry is found in Chapters 3, 4 and 6.

Phosphorus and Water Quality

Phosphorus (P) is the second major element utilized by actively growing plants but differs considerably from NO_3^- in its water solubility and mobility. Phosphorus is very immobile in soil and seldom migrates downward to any great extent with soil water movement because it is strongly adsorbed by and/or precipitated as highly insoluble soil mineral phases. Soil solution P levels are typically < 0.01 ppm in most soils, and groundwater levels seldom exceed 0.05 ppm (Reneau et al., 1990). Between 20 and 80% of the total-P in soils is held in organically combined forms with a large amount of the organic-P held by the active microbial biomass. Much of the fertilizer P applied to soils is retained in the near-surface layer in various inorganic precipitates and organically combined forms that prevent it from leaching. Sandy soils or peats may not retain or bind P to the same extent discussed above, but P migration downward to groundwater is still generally minimal.

While the risk of groundwater contamination by P from crop production systems can be assumed to be limited, the solid forms of P that accumulates in surface soil are subject to loss via erosion. Runoff losses to surface waters are the major water quality risk from P. Increased public and regulatory concern over the use and application of P to agricultural lands is based mainly upon the fact that increased P loadings to surface waters may lead to eutrophication. Algal and aquatic weed growth in most inland surface water systems is P-limited and elevated P loadings lead to algal blooms and mats, heavy growth of aquatic plants and weeds, deoxygenation, and occasional problems with drinking water taste and odor.

Because P is strongly adsorbed by soil solids, P runoff from permanently vegetated areas such as perennial sods or forests is minimal, and largely occurs as traces of orthophosphate (PO_4^{-3}) ions in solution. Organic P additions from riparian leaf and stem inputs are also possible. Where erosion risk increases, such as for annual crops with conventional tillage, the total-P loss increases greatly as the P is moved in solid particulate form with the eroding soil. Water soluble P is immediately available for biological uptake while the sediment-bound or particulate P forms are released over longer periods and are referred to as "bioavailable particulate P" as determined by an algal incubation assay (Sharpley and Smith, 1991). The overall impact of a given production system on P loadings to local surface waters will therefore be primarily dependent upon relative rates of sediment loss and the system's influence on P levels in eroding soil surfaces. Further detail on soil P, its reactions, and fertilizer chemistry are given in Chapters 3, 4, and 6.

Utilization of Organic Wastes and Water Quality

Many crop production systems in the Chesapeake Bay region receive various organic waste products as fertilizer amendments. Organic amendments such as manure, municipal wastewater sewage sludge (biosolids), municipal solid waste compost, and other miscellaneous waste products all have the potential to improve soil physical and chemical properties significantly while building organic matter content. Organic amendments are particularly effective at improving the productivity of marginal or degraded lands. Use of these materials is often mandatory for intensive animal production operations and can simultaneously solve a disposal problem for many localities and industries. The nutrient and heavy metal content of organic wastes is highly variable, however, and careful analyses of the waste must be performed to certify quality and to ensure appropriate application rates.

The major water quality concerns associated with the land application of organic wastes are the direct runoff of the organic material and any soluble constituents into surface waters and the migration of NO_3^- to groundwater. Secondary concerns include the movement of heavy metals and microbial pathogens, particularly when sewage sludges are employed. All states regulate land application of organic wastes and minimum standards for sewage sludge are set also by USEPA. Application rates are generally limited by the mineralizable N content, the heavy metal content of the material applied, and local site/soil conditions. Phosphorus runoff concerns have recently been raised in many areas where heavy annual applications of animal wastes have been routine. Maintenance of a minimum soil pH is necessary to limit heavy metal solubility, and application to seasonally wet soils, riparian areas, or steep erosive slopes should be avoided.

Overall Effects of Nutrients on Surface Waters

Excessive N and P concentrations in surface waters generally affect water quality by supplying nutrients to phytoplankton, which are small aquatic plants that grow suspended in the water and include various types of algae. The same forms of these nutrients, which are available to crops, are also available to phytoplankton. Taste and odor problems often occur in drinking water because of excessive algae blooms in surface water.

The primary importance of excess growth of the algae is related to the death and decomposition of these organisms. The decomposition process reduces the dissolved oxygen (DO) content in the water. Since fish and other aquatic organisms require DO, they can be stressed by low DO levels. Low DO affects respiration, growth, and reproduction of aquatic organisms. Under very low DO conditions, death of fish and other aquatic organisms can result.

In a complex system such as the Chesapeake Bay, more adverse effects can occur due to excessive nutrient levels. Phytoplankton is suspended throughout the water column. If not excessive, phytoplankton growth is an important source of food for many higher levels of aquatic organisms. If excessive levels exist, DO in the water will be reduced as described previously. Excessive phytoplankton levels greatly reduce water clarity that greatly reduces light transmission available for the growth of submerged grasses, generally called submerged aquatic vegetation (SAV). The SAV serves as important habitat for fish, crabs, and other species of economic and environmental importance. Due in large part to increased nutrient concentrations in the Bay, areas of SAV beds have been greatly reduced in recent years because of the shading effect of the phytoplankton growth. Vast areas of SAV were well documented from colonial times until the 1960s, during which time the Bay was likely the most productive estuary in the world.

Similar to the limiting factor concept for crop yields, the limiting nutrient for phytoplankton growth, either N or P, will effectively limit the production of phytoplankton in water. Therefore, if a particular water body is high in N concentration as compared to P, relative to aquatic plant needs, the most effective control mechanism may be to place emphasis on reduced P inputs to the system.

In the Chesapeake Bay watershed, P is usually the limiting factor in the upper tributaries. In the saltwater portions of the Bay, P is usually the limiting factor in all seasons except summer, when N is the limiting factor. However, most phytoplankton growth in the Bay occurs during the summer months, making N control strategies very important.

Recognizing Environmentally Sensitive Sites

Obviously, the potential for plant nutrients (particularly N and P) to migrate to surface and groundwater is largely depending upon soil and site conditions. Any combination of soil/site conditions that will lead to either rapid runoff of rainfall or rapid movement of dissolved ions through the soil will lead to water quality risks from almost any land use practice. Thus, an important part of nutrient management planning for agriculture is the recognition and delineation of these sites and conditions and the development of specific management practices (Best Management Practices, BMP) to avoid the anticipated effects.

As discussed in the next section, the soils and landscapes of the Chesapeake Bay region vary greatly, but we do know that a number of particular soil/landscape features and properties are particularly conducive to the loss of nutrient from agricultural practices:

1. *Soils with high leaching potentials*: This includes soils with very coarse textures and those where the water table is at or near the surface during the winter. The combination of these factors poses a particularly profound risk. If accurate soil survey information is available, the *leaching index* for a given soil can be obtained by following the procedures outlined in the NRCS Field Office Technical Guide.

2. *Lands with karst (sinkhole) drainage regimes*: Sinkholes are landscape features commonly found in areas underlain by limestone bedrock or other highly soluble carbonate bearing parent materials. These areas mainly occur in the Valley and Ridge physiographic province (see next section) but may also occur in the lower Coastal Plain in certain instances. Sinkholes are formed by the long term dissolution of carbonates underlying the surface that eventually leaves a cavity that collapses over time. Sinkholes form a direct connection between surface water and groundwater and dye tracer tests have shown that water entering a sinkhole can contaminate nearby drinking wells within hours. If muddy or cloudy water appears in a well after a significant rain, surface water is likely entering the water bearing zones in the rock by direct flow down channels and rock fractures.

If a sinkhole is located in an isolated high area of a field, a grassed buffer should be placed around it. If the sinkhole occurs on a sideslope or below a cropped field, significant runoff may drain into the sinkhole. The field area draining into the sinkhole would be best used for hay crops, pasture, or trees to reduce runoff. If the area is cropped, nutrient management practices should be intense.

3. *Shallow soils over fractured bedrock*: Soils that are shallow (< 40 in.) to bedrock that is fractured are also environmentally sensitive and should be managed like soils with a high leaching index. Although many of these soils are not highly leachable, once the soil water percolates to the fractured rock, the water and any dissolved nutrients can move rapidly to ground water. Lists of shallow soils in each state can be obtained from the NRCS and by reviewing county soil survey reports. Nutrient management practices should be intense in field containing significant areas of these soils and should include such practices as split application of N on crops and the use of winter cover crops to scavenge residual soil N.

4. *Tile drained lands*: Fields that have been artificially drained should be treated as environmentally sensitive due to the direct connection of the tile outlets to surface watersheds. These lands are typically drained because they have a high seasonal water table and therefore have the potential to pollute both the surface water with their drainage discharge and the local water table if nutrients are over-applied relative to crop uptake.

5. *Irrigated lands:* Fields receiving irrigation, because of the increased input of water, are prone to runoff and leaching of water and nutrients. The leaching index approach cannot be used on these areas since it would underestimate the actual leaching potential. To maximize water use efficiency and minimize leaching and runoff, irrigation scheduling methods should be used. These include the use of gypsum blocks, tensiometers, or computerized systems. When these indicators show the need for irrigation, rates and amounts of water should be based upon the soil type and water holding capacity to further reduce water and nutrient losses. In addition intense nutrient management practices should be applied.

6. *Excessively sloping lands*: Lands with steep and long slopes pose a high risk for the surface loss of applied nutrients. Slopes greater than 12 to 15% are prone to loss of surface applied N and P. However, if tillage occurs to incorporate nutrients, significant amounts of sediment loss can occur with nutrients attached if a particularly heavy rainfall event occurs. If manure must be used on slopes, applications should be limited by P soil test needs or crop uptake estimates. Injection is the preferred manure application method. Soil conservation measures should be practiced on highly erodible lands.

7. *Floodplains and other lands near surface waters*: Agricultural land close to surface water can have a more direct impact on surface water quality. Surface flow of runoff water has little chance to be filtered before discharge into adjacent waters if channelized flow develops. Subsurface flow in groundwater can also directly seep into the adjacent surface water body. However, if nitrate contaminated water flows into a wetland area, significant N can be denitrified and lost to the atmosphere, with a reduction in N levels reaching the stream. Manure or biosolids use on floodplains is not a recommended practice. If manure or biosolids must be applied to a floodplain, incorporation or injection application methods should be used to minimize losses if flooding occurs.

The list of environmentally sensitive sites given above is not all-inclusive, but does include most of the major types of land with these concerns in our region. Appropriate setback or buffer areas should be established between these areas and any field receiving nutrient applications, and intensive nutrient management practices should be employed on any lands adjacent to sensitive areas. Each state has its own guidelines for these buffer areas besides regional guidelines such as those associated with the various Chesapeake Bay initiatives.

Soils and Landscapes of the Region

The surface soil landscape of our region is dominated by its underlying geology that in turn controls the landform. Our region possesses five unique physiographic provinces (Figure 1-1) related to the underlying geologic formations and associated landforms. Going from east to west, you would encounter the Coastal Plain, the Piedmont, the Blue Ridge, the Valley and Ridge, and finally, the Appalachian Plateau physiographic provinces. The soils vary considerably from province to province as do their nutrient management concerns. The basic soil/parent material relationships and how they relate to watershed and nutrient management issues are discussed below. The reader is referred to Chapter 2 for additional background on soil/parent material relationships in addition to locally available state and county soil survey reports.

The *Atlantic Coastal Plain* Province extends from the Eastern Shore to its western boundary with the Piedmont at the Fall Zone. Baltimore, Richmond and several major cities are in the Fall Zone. The Coastal Plain is composed almost entirely of unconsolidated fluvio-marine sediments that are predominantly sandy in original texture. Significant deposits of finer textured silts and clays are found interbedded in the sediments, however, along with occasional marl and peat deposits. In general, the soils of the Coastal Plain are younger and sandier to the east and older and higher in clay to the west. The lower Coastal Plain landscapes to the east tend to be quite broad and undissected when compared to the higher landscapes associated with the Upper Coastal Plain. Many soils in the Lower Coastal Plain are quite wet and have been drained for agricultural production. These soils and those lying immediately adjacent to the waters of the Chesapeake Bay are environmentally sensitive and demand careful nutrient management. Many of our Coastal Plain soils are also quite sandy in texture and therefore have high leaching potentials. However, many of these sandy surface soils are underlain by a clay enriched subsoil that can scavenge and hold nutrient cations. Moderate to steep slopes are encountered to some extent in the Middle and Upper Coastal Plain, particularly in areas adjacent to active streams. The Coastal Plain supports some of our most intensive combined row crop/animal production agricultural production systems, particularly on the Delmarva Peninsula and in southside Virginia.

The *Piedmont* Province is underlain by igneous and metamorphic rocks weathered for long periods into soft saprolites that comprise the soil's parent material. In general, the soils are deep, have a high clay content and are commonly severely eroded. The Piedmont

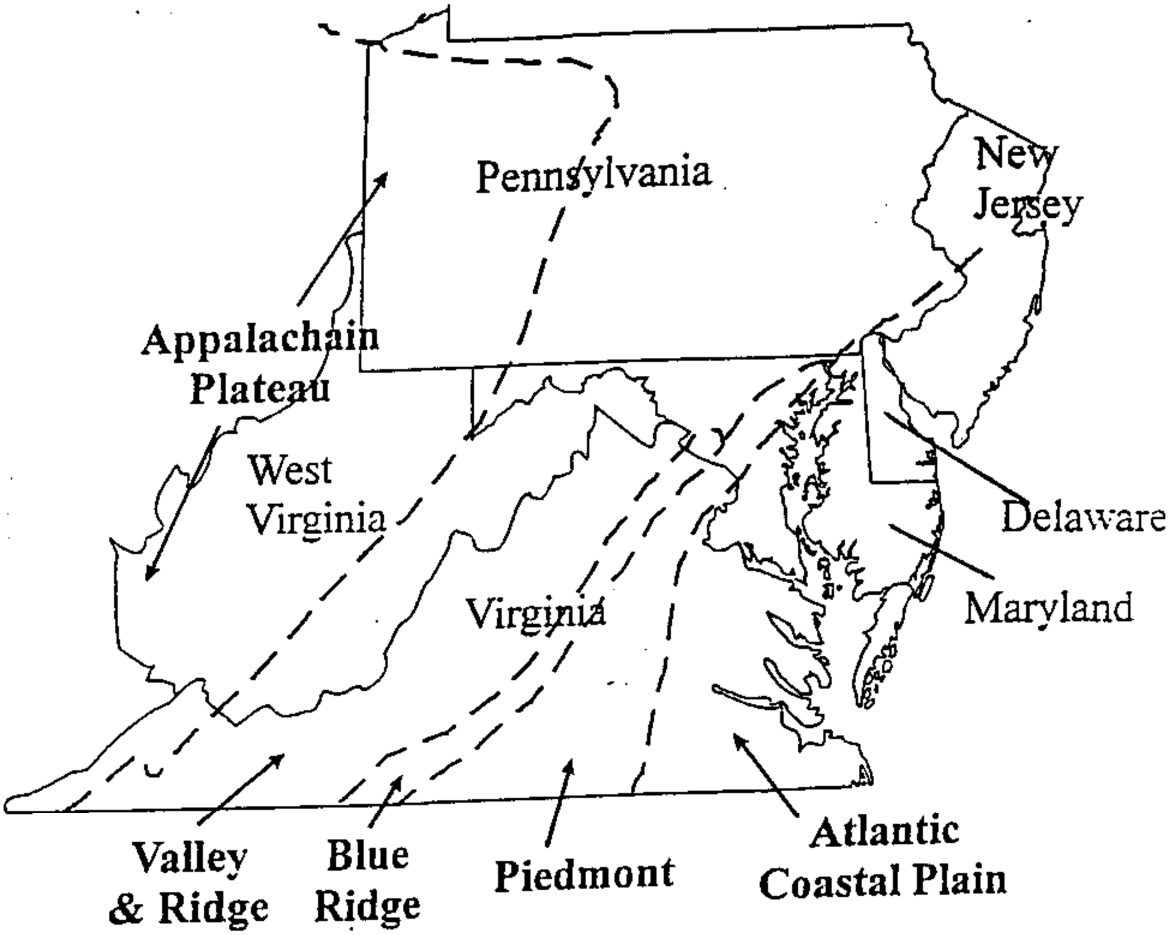


Figure 1-1. Map of the Delaware/Maryland/Pennsylvania/Virginia region showing major soil physiographic provinces.

landscape is a randomly dissected plain with a gentle slope from the base of the Blue Ridge to the Fall zone. Therefore, large flat areas are uncommon in the Piedmont and most agricultural fields are located in the moderately sloping summit and shoulder positions of the local landscape. The local geology of the Piedmont can be quite complex and shallow rocky soils are often intermixed with less management-sensitive soils. Soil wetness is generally a problem only in areas immediately adjacent to streams, although upland "perched" wetlands are common in the Piedmont, particularly in areas of high clay soils. The Piedmont also contains a number of imbedded Triassic Basins that can be quite large and contain soils formed in sediments or from sedimentary rocks which more closely resemble soils of the Coastal Plain or the Appalachian Plateau.

The *Blue Ridge* Province occurs in a narrow strip associated with the Blue Ridge Front of the Appalachian Mountains and is underlain by complex metamorphic and igneous intrusive rocks. Most of the Blue Ridge is quite steep and rocky and not suited to agricultural production. The soils in these areas are typically shallow to bedrock. However, localized areas of the Province are moderately rolling and highly resemble the Piedmont in their basic soil landscape characteristics. In these areas, forage and row crop-based animal production systems are common, and frequently quite intensive.

The *Valley and Ridge* Province is underlain by folded and faulted rocks of sedimentary origin. The valleys are dominantly underlain by limestones and carbonate-rich shales that have weathered into deep productive soils with silty surface layers and clayey subsoils. The ridges are dominantly underlain by harder silica-rich rocks such as sandstones and are covered with shallow, rocky soils on steep slopes and deep loamy soils in coves. Karst terrain and its associated sinkholes commonly occur throughout this Province over the purer limestone parent material. These areas require intensive nutrient management, as discussed earlier. Many soils are also shallow to fractured rock and are therefore sensitive as well. The soil landscape over the limestones is typically moderately rolling, but excessively steep sideslopes are also common. Much of this valley landscape is overlain by river terrace deposits that are typically quite productive, but may contain significant amounts of cobblestones that can limit tillage. Poorly drained soils are typically confined to areas next to streams. Many soils of the region are shallow to fractured rock, particularly those over shales and purer carbonates. The limestone valleys, particularly from the Shenandoah River north, support some of the most intensive row crop and animal production agriculture in our region.

The *Appalachian Plateau* Province is a deeply dissected region underlain by flat-lying sedimentary rocks that are dominantly sandstones, siltstones and shales. Many thin coal seams are also common. The vast majority of this Province is steeply sloping and covered with forest, although rolling uplands on the Plateau are farmed to a significant extent in western Pennsylvania and in some localized areas further south. Thus in some areas, agriculture production activities are intensive, but generally, this Province is dominated by non-agricultural uses throughout most of our region. The soils tend to be coarse textured and frequently shallow to rock. Much of this Province in western Pennsylvania has been extensively reworked by glaciation that has left a mantle of till across it, while the regions to the south are unglaciated.

The preceding section attempts to give a generalized summary of the five basic soil Physiographic Provinces that underlie the region covered by this manual. Of course, soils with contrasting characteristics to those described above may be found in any of the Provinces. For example, major river systems such as the James and Susquehanna cut through the provinces from west to east and have a unique set of floodplain and terrace soils associated with their historic paths. Similarly, much of the northwestern part of our region was subjected to glaciation and therefore its surface soils formed in till and outwash and are considerably different from those soils formed in residual saprolite (weathered rock) further south. In certain areas, particularly the Valley and Ridge Province, the soil's parent material can change drastically over a distance of several feet with concomitant changes in soil properties and land use interpretation. Detailed information on soils, geology, and land use interactions is available from soil survey reports for most counties in our region, and the reader is encouraged to consult this information before any significant project or planning process is undertaken.

ON-FARM NUTRIENT MANAGEMENT PLANNING

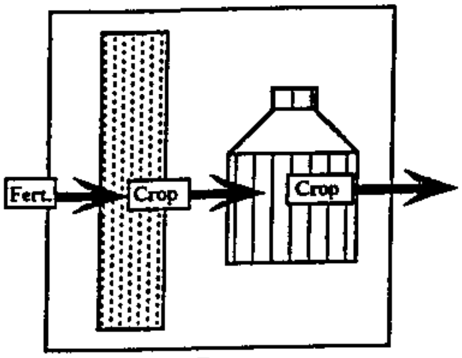
Nutrient Cycles and Management on Different Farm Types

Considering some representative farm types and the management consequences of the nutrient cycles on each is helpful in understanding nutrient management planning. Nutrients come to a modern cash-crop farm in fertilizers and other materials applied directly to the fields (Figure 1-2a). Crops harvested from the fields remove a fraction of the applied nutrients, which leave the farm, when the crops are sold. With this pattern of organization, there is a direct connection between the flow of nutrients and the agronomic or economic performance of the farm. Thus, traditional economic and agronomic incentives can be effective in guiding nutrient use on these farms both for crop production and for environmental protection. Improper management of nutrients can result in significant losses other than removal in cash crop and negative economic consequences for the farmer. Therefore, the cost of practices that reduce nutrient losses on a cash-crop farm can be at least partially offset by decreased costs in purchased fertilizer.

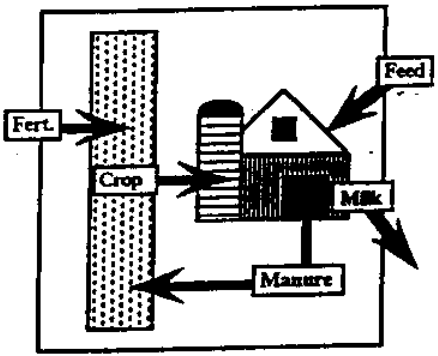
On farms with livestock (e.g., a dairy), a large proportion of the plant nutrients that were in the crops produced as feed for the animals are returned to the farm fields in manure from the animals (Figure 1-2b). With this recycling, the pattern of organization is significantly different from a modern cash-crop farm. Traditionally, crop and livestock farms have been viewed as producing outputs that result from the almost exclusive use of on-farm resources. However, supplementing on-farm crop production with fertilizer, off-farm feeds or other animal inputs is more likely on a modern crop and livestock farm with ruminant animals than on traditional self sufficient crop and livestock farms. Thus, on most modern farms, the manure produced by the animals is no longer spread on the fields where the crops were produced. The plant nutrients in the feed inputs can offset the nutrients removed from the farm as sold animal products.

Feed inputs enable farms to have more animals on fewer acres. Sometimes, these off-farm feed nutrients can exceed what is needed for the crops and result in excess manure nutrients that can be potential sources of water contamination. Thus, accounting for all sources of plant nutrients being applied to fields becomes an important management activity to protect the environment from negative impacts associated with the over-application of nutrients to crop fields.

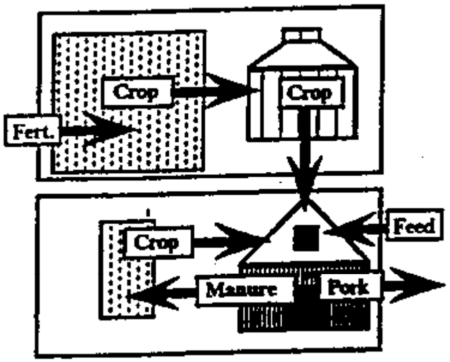
The number of animals in barnyards and holding areas can be greater on intensive livestock farms because ruminant animals often spend part of their time outside of buildings. The result is that the areas around farmyard facilities can be degraded and become sources of nutrient losses from the farm directly to the environment.



a. Cash Crop Farm



b. Dairy Farm



c. Intensive Swine Farm

Figure 1-2. Nutrient cycles on different types of farms.

Finally, neither crop production nor fertilizer use is directly connected to the output of such farms because farms with this pattern of organization sell primarily animal products. Farm performance depends on the animal husbandry skills of the farmer, not just success in crop production. On a farm organized in this manner, the economic viability of the farm is not as sensitive to the decisions about plant nutrient use in the fields as on the cash-crop farm.

Trends in animal housing and the success of crop production on cash-crop farms in specialized geographic regions have made it possible to concentrate large numbers of animals, such as poultry and swine, on small land areas. Most, if not all, of the feed necessary for these animals can be economically transported to the farm where the animals are housed (Figure 1-2c). Although poultry and swine farms may produce crops for off-farm sale, the land areas involved can be quite limited because the focus of the management activity is on animal production. The cash-crop farm and the intensive, modern livestock farm are connected by the flow of feed; however, nutrients in this flow often do not cycle back to their original locations. The application of nutrients to the fields on these farms is not closely related to the major production activity of the farm (i.e., selling animals or animal products). This will usually result in an excess of nutrients on the farm and a high potential for environmental problems. The field-based economic and agronomic incentives that can be effective incentives to manage nutrients on a cash-crop farm (and that will also minimize potential environmental impacts) are not as significant on the intensive livestock production-oriented farm. Further, field-based agronomic practices may be of limited effectiveness in treating the total quantity of nutrients on the farm because of the small land area on the farm. It is unlikely that environmental quality can be protected on poultry and swine farms solely by recycling nutrients for crop production. Successful management of nutrients to protect the environment will depend on support from off-farm people and organizations. Neighbors with land for manure application could cooperate by providing land for manure distribution. Off-farm organizations may deal with manure hauling to locations where the manure can be used directly or transformed into another product, such as compost.

Animal Density and Nutrient Balance

What becomes apparent from this understanding of farm types is that animal density per acre or the proportion of feed coming from off the farm are important features in determining the nutrient status of a farm. On low animal density farms (<1.25 animal equivalent units [AEU's] per acre) or those where little feed (<50%) comes from off the farm, manure nutrients produced on the farm will not meet total crop nutrient needs. In this group an appropriate management objective would be to maximize nutrient use efficiency on the farm. The environmental impact of these operations can be minimal if sound nutrient management principles are applied. Management decisions should be made based on expected crop response to nutrients (i.e., increasing yields or decreasing purchased inputs). Plans should utilize soil tests and manure analysis to assure distribution and timing of manure applications to maximize nutrient availability from the manure and minimize purchase of commercial fertilizer. Examples of practices that would be appropriate on this group of farms include: spring application of manure, immediate incorporation of manure, use of cover crops to scavenge nutrients, no manure spread on legumes, and efficient manure storage.

Farms with medium animal density (1.25 - 2.25 AEU's/acre; 50-80% feed from off farm) supply manure N roughly equivalent to total crop needs, but excessive P supply is likely. An appropriate management objective for these farms would be to maximize environmentally safe nutrient use on the farm. If there is enough or more than enough nutrients on the farm to meet the crop requirements, nutrient use efficiency will likely be a secondary concern. The major concern will be safely using all of the manure produced. There is good potential for environmental benefits from improved management on these farms. Changes in the overall farm management, such as altering the cropping system, may be necessary on this group of farms. A detailed manure management plan will probably be necessary on these farms and will be based on nutrient balance rather than crop response. Most farmers in this group will probably want to take advantage of technical assistance from public agencies and/or private consultants in developing and implementing a manure management plan. The plan will be based on utilizing soil tests and manure analysis in conjunction with appropriate management practices to match as closely as possible nutrients available in manure with crop needs over the entire rotation.

On high intensity farms (>2.25 AEU's/acre; >80% feed from off farm), livestock manure production often significantly exceeds total crop nutrient needs. In this group, the management objective will be to use every available means to remove excess manure not needed for crop production. Alternative off-farm uses for the manure will need to be explored. Often, this will mean locating a market for the manure and arranging the logistics of transportation and appropriate application. The on-farm plans for this group of farms will involve determining the maximum amount of manure that can be safely applied on the farm and the appropriate timing of application to minimize environmental impact. Nutrient management plans will be important for the farms where the manure is ultimately used. High intensity farms have the highest potential to impact the environment negatively. In many cases, unless a favorable marketing arrangement can be developed, implementing improved nutrient management on this group of farms will have a negative economic impact on the farm.

Nutrient Management and the Chesapeake Bay

In 1983, a $27 million, six-year study by the USEPA (1983a) revealed that runoff from farmland is contributing to water quality decline in the Chesapeake Bay. Other studies have shown that many other waters in our region are also damaged by this form of pollution – termed nonpoint source (NPS) pollution -- and that agricultural practices can adversely affect groundwater as well as surface water. Nonpoint source pollution does not come from a single point such as a sewage outfall or an industrial discharge pipe. Nonpoint source pollution includes excess nutrients, pesticides, sediment, heavy metals and toxic substances that, if not controlled, harm our environment and, potentially, human life itself.

Nutrients, particularly P and N, are a major component of the agricultural NPS pollution problem. Bodies of water can tolerate a certain level of nutrients. In fact, life within rivers, streams, lakes and bays could not exist without nutrients. An excess of nutrients may cause ecological problems and can harm aquatic life. It is estimated that 67% of the N and 39% of the P entering the Bay originate from non-point sources (see Fig. 1.3). Cropland agriculture is estimated as producing 60% of the N and 27% of the P entering the Bay. While nutrient loading estimates continue to be the source of debate and further research, NPS pollution loadings from agriculture to the Bay must clearly be reduced and managed in concert with other pollution reduction strategies if the degradation that the Bay has undergone is going to be reversed.

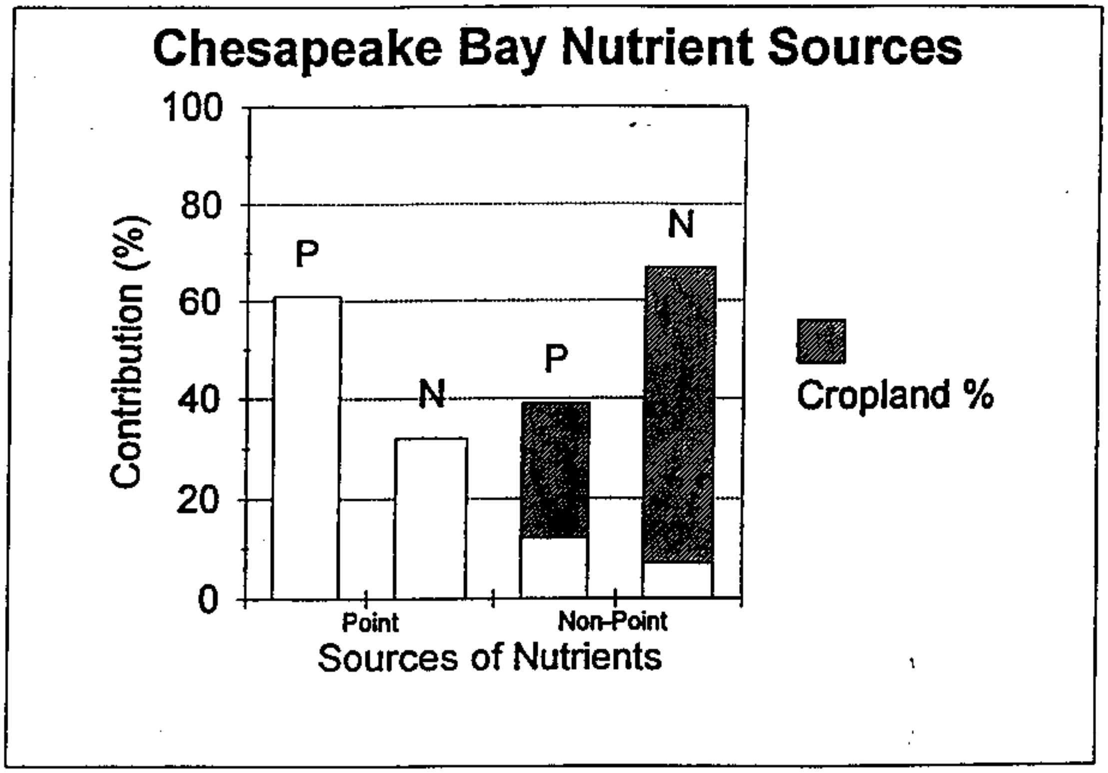


Figure 1-3. Estimated nutrient loadings to the Chesapeake Bay and the contribution of agriculture.

Chapter 2. BASIC SOIL SCIENCE

SOILS AS THREE-PHASE SYSTEMS (SOLID/LIQUID/GAS)

Soil is mainly composed of weathered rock fragments along with decayed remains of plants and animals (called organic matter). It covers the vast majority of the exposed part of the earth in a thin layer. The soil supplies air, water, nutrients, and mechanical support for growing plants. The productivity of a given soil is largely dependent on its ability to supply a balance of these factors to the plant over time.

Volume Composition of a Desirable Surface Soil

A desirable surface soil in good condition for plant growth contains approximately 50% solid material and 50% pore space (Figure 2-1). The mineral material is usually made up of many different kinds and sizes of minerals, ranging in size from particles visible to the unaided eye down to particles so small that they can only be seen with the aid of a very powerful (electron) microscope. This mineral material is about 45 to 48% of the total volume. Organic material makes up about 2 to 5% of the volume and may contain both plant and animal residues in varying stages of decay or decomposition. With ideal moisture conditions for growing plants, the soil pore space would contain about 25% air and 25% water, based on total volume of soil.

Soil characteristics such as texture, structure, chemical composition, drainage, depth, and surface features such as stoniness, slope, and erosion potential largely determine the suitability of a soil for use and its management needs. To a limited extent, the fertility of a soil determines what it may be used for, and to a larger extent the yields that may be expected. However, fertility levels in the soil are not indicative of its productive capacity, which is related to the ability of the soil to provide adequate quantities of the essentials for plant growth over extended periods. Productive capacity is largely determined by soil physical properties.

SOIL FORMATION AND BASIC MORPHOLOGY

Soil Parent Material

Soils have formed from many different kinds of parent material. Some soils form from rock underlying their present location. Others formed from rock that had been moved down slope by gravity or greater distances by flowing water in streams. Still other soils formed in material eroded from soils that had developed from rock. Most of the region's soils developed under forest vegetation; prairie soils further to the west developed under grass vegetation and are quite different. Climatic differences from south to north in the region and from sea level to the highest mountains vary considerably and have had rather marked effect on the soils that have formed. All of these factors, functioning over time,

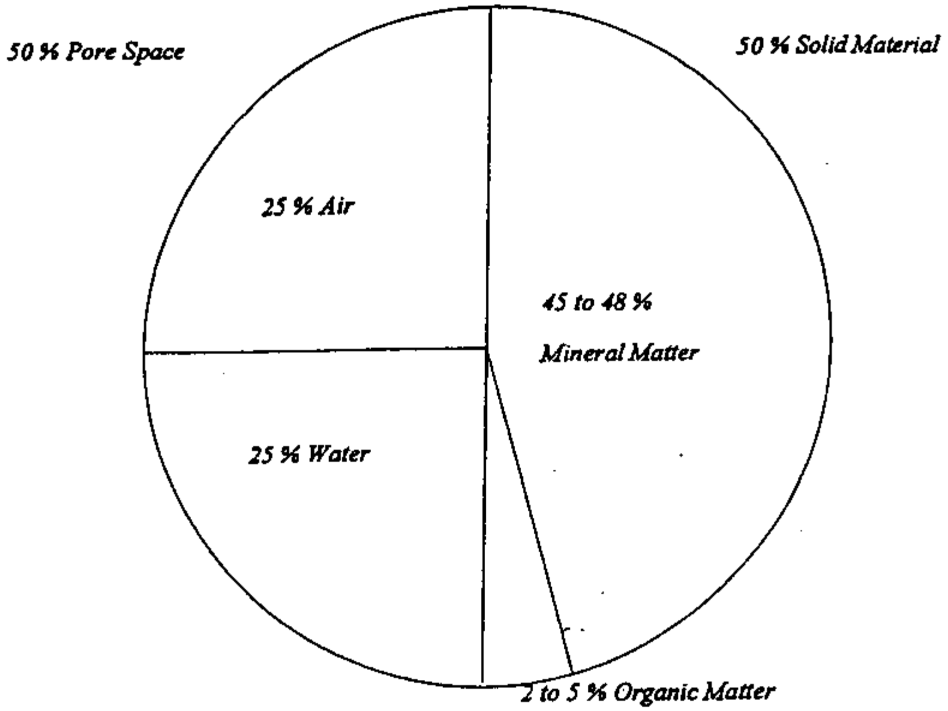


Figure 2-1. Volume composition of a desirable surface soil.

have determined the kind of soil we find in any location. Thus, a soil is the result of parent materials having been acted upon by climate, vegetation, and topography, over a period of time.

Soils, like people, differ because of inherited characteristics (from rocks, etc.) and because of the environmental conditions under which they were formed or developed. The length of time that the environmental factors have acted upon the soil and its parent material also influence its properties. Under the same environmental conditions, the longer a soil and its parent material have been weathered by environmental forces, the more the soil will be shaped by that environment and the less by parent material. Similarly, the shorter the time that environmental factors have been working on a soil, the more the soil properties will resemble the parent material.

Soil Formation

A soil is made up largely of mineral material, ranging in size from ultra-microscopic to a size easily visible to the unaided eye. This material is the product of weathering of rock in situ, or by weathering of transported rock fragments. The weathering of rocks to make a soil is a slow process; it has been going on for millions of years in most of our region. The speed of weathering depends on the hardness of the minerals that make up the rock; the way the minerals are held together (kind, strength, and durability of the cementing material); whether or not the rock has flaws, fractures, or breaks in it; and many other structural factors.

Physical weathering during the early stages of soil formation is largely a mechanical process and probably starts with water freezing in cracks and crevices, wedging and breaking off pieces from the rocks. Rainfall on rocks heated by the sun can also cause breaking and crumbling. Frost forming on the rock surfaces and in cracks break them apart. Trees and other plants send their roots into the cracks and crevices, wedging them apart and also breaking them.

After rocks break down to a size that can retain water and support plant life, the soil-forming processes speed up considerably due to combined mechanical and chemical weathering attack. Plants and animals that grow in the rock fragments die, or parts of them are shed. This organic layer then decays or decomposes, giving off carbon dioxide that is dissolved in water to form carbonic acid, a weak acid solution. The carbonic acid solution reacts chemically and alters many of the minerals in the rocks to make finer soil particles of sand, silt, and clay.

As soil-forming processes continue, some of the very fine soil (<0.05 mm) particles are carried or leached by water from the upper or surface soil into the lower or subsoil layers. As a result of this leaching action, the surface area becomes coarser (because of loss of fine materials) and the subsoil area becomes finer as the soil weathers. This helps explain why most of our soils have more coarse soil particles in the surface soil and more very fine soil particles in the subsoil.

Soil Horizons

Soils are layered and the layers are called horizons. The principal horizons are: A or surface soil, B or subsoil, and C or parent material, and are collectively called the soil profile (Figure 2-2). Unmanaged forest soils also commonly contain an organic O horizon on the surface and an acid-leached E horizon just below the A horizon. Beneath the soil profile, we usually find rock or unconsolidated parent materials, similar to that from which the soil developed. Horizons usually differ in color, texture, consistence, and structure. In addition, there is usually considerable difference in chemical characteristics or composition.

Old/New Nomenclature

Old	New	
O1	Oi	Loose organic debris
O2	Oe	Partially decomposed organic matter
O3	Oa	Decomposed organic matter
A1	A	Formed at surface. Forms as mineral horizon with organic matter mixed in, or through disturbance such as cultivation
A2	E	Light-colored. Maximum eluviation of clay, iron, or aluminum. Prominent in forests, faint in grasslands
A3	EB	Transition from E to B, more like E than B
B1	BE	Transition from E to B, more like B than E
B2	B	Formed as a subsurface horizon. Maximum illuviation. Maximum development of blocky or prismatic structure or both. Common features: • clay coatings on larger particles • residual concentration of sesquioxides • red and yellow colors (from oxides)
B3	BC	Transition from B to C, more like B than C
C	C	Weathered parent material formed residually over bedrock or genetically unrelated material which is neither characteristic of B horizons, nor rock. Includes saprolite, sediment deposits, unconsolidated bedrock, etc..
R	R	Hard bedrock

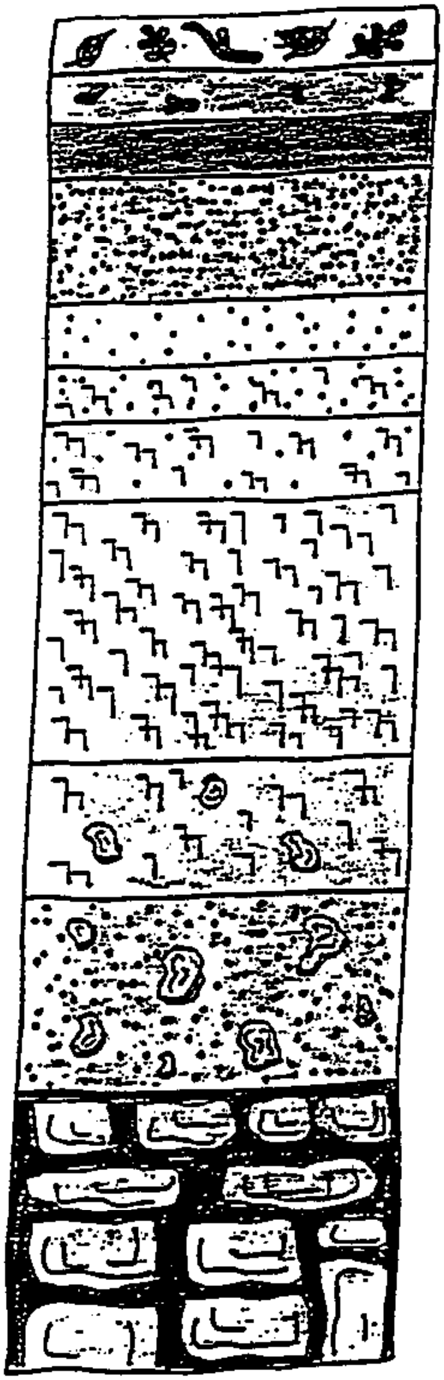


Figure 2-2. Typical soil profile.

The surface soil (A+E) is usually coarser than the subsoil layer and contains more organic matter than the other soil layers. The organic matter imparts a grayish, dark-brownish, or black color to the surface horizon, the color imparted depending largely upon the amount of organic matter present. Soils that are highest in organic matter usually have the darkest surface colors. This surface layer is usually more fertile and has the greatest concentration of plant roots of any horizon of the soil. The surface soil is tilled, fertilized, and limed, and is where our crops are planted and grown. Rain and snow fall on the surface soil and enter the lower horizons by leaching. Plants obtain much of their nutrients and water from the surface soil. The lower portion of the surface soil (E) is often light colored and coarser textured due to leaching losses.

The subsoil layer (B horizon) is usually finer and firmer than the surface soil. Organic matter content of the subsoil is usually much lower than that of the surface layer. Subsoil colors are usually stronger and brighter, with shades of red, brown, and yellow being the colors more frequently observed. The subsoil supports the surface soil and may be considered as a reservoir providing storage space for water and nutrients, and it regulates the temperature and air supply for the deeper roots of plants.

The C horizon is partially decomposed and weathered parent material that has acquired some characteristics of the subsoil and retained some characteristics of the material from which it weathered. It has more of the appearance of the material from which it weathered than the subsoil which has developed above it. For instance, it usually has quite similar structure to the material from which it weathered, but is soft enough to be dug and may crumble to a structureless mass. The parent material influences soil texture and natural fertility, soil acidity, overall depth and, in some cases, the topography on which the soil is formed.

PHYSICAL PROPERTIES

The physical properties of a soil can largely be seen with the naked eye or felt between the thumb and fingers. They are the result of soil parent materials being acted upon by climatic factors (such as rainfall and temperature) and, affected by relief (slope and direction or aspect) and vegetation (kind and amount, such as forest or grass) over a period of time. A change in any one of these influences usually results in a difference in the physical properties of the soil formed. Important physical properties of a soil are texture, organic matter, aggregation, structure, and porosity.

Texture

The relative amounts of the different soil size (<2mm) particles, or the fineness or coarseness of the mineral particles in the soil, is referred to as texture. Soil texture is determined by the relative amounts of sand, silt, and clay. The different size classes of mineral soils are discussed below.

Mineral grains which are >2 mm in diameter are non-reactive in soils and are called coarse fragments. The coarser fine earth particles of the soil are called sand. These particles vary in size from very fine (0.05 mm) to very coarse (2.0 mm) in diameter. Most sand particles can be seen without a magnifying glass. All sands feel rough when rubbed between the thumb and fingers. The relatively fine soil particles that feel smooth and floury are called silt. They vary in size between 0.05 mm and 0.002 mm. When wet, silt feels smooth but is not slick or sticky. When dry, it is smooth and if pressed between the thumb and finger will retain the imprint. Silt particles are so fine that they cannot usually be seen by the unaided eye and are best seen with the aid of a microscope.

Clay is the finest size soil particle with individual particles finer than 0.002 mm .Clay particles can be seen only with the aid of a very powerful (electron) microscope. They feel extremely smooth when dry, and become slick and sticky when wet. Clay will hold the form into which it is molded.

There are 12 primary classes of soil texture. The sand fraction of sands, loamy sands and sandy loams are further subdivided into coarse, fine, and very fine sands for a total of 20 textural classes. Each class name indicates the size of the mineral particles that are dominant in the soil. Texture is determined in the field by rubbing or feeling the soil between the thumb and fingers. This is checked by laboratory or mechanical analysis or separation into clay, silt, and various size sand fractions (called separates). Regardless of textural class, all soils in the Chesapeake Bay region contain sand, silt, and clay, although the amount of a particular particle size may be small. Most Chesapeake Bay region soils have sandy loam, loam, silt loam, or clay loam textures in the surface soil, and sandy clay loam to clay textures in the subsoil. This finer texture in the subsoil results from the soil development processes. The 12 major textural classes are defined by certain limits of the proportion of sand, silt, and clay in a soil (Figure 2-3) as shown in the "textural triangle".

To use the textural triangle you will need to know the percent sand and percent clay of your soil. Silt is determined by difference (100 - [%sand + %clay] = %silt). These are determined by laboratory particle size analysis (PSA). Example: a soil with 40% sand and 30% clay (30% silt) will be a clay loam. With these percentages, first locate the percentage of clay on the left side of the triangle and move inward horizontally, parallel to the base of the triangle. Follow the same procedure for the percent sand moving along the base of the triangle to locate your sand percentage and then moving up and to the left until you intersect the line corresponding to your percent clay value. At this point, read the textural class written within the bold boundary on the triangle.

Effects of Texture

Coarse-textured or sandy soils allow water to infiltrate at a faster rate than fine-textured or clayey soils. After it enters the soil, water moves more freely in coarse-textured than in fine-textured soils, increasing the potential for leaching of mobile nutrients. Since sandy soils are open or porous, they hold less total water and less nutrients for plants than fine-textured soils. In addition, the relatively low water holding capacity and the large amount of air present in sandy soils allows them to warm up faster than fine-textured soils. Sandy soils are also more easily tilled. They are best suited for the production of specialty crops such as vegetables, tobacco, peanuts, and certain fruits.

Fine-textured soils hold more water and plant nutrients and thus require less frequent applications of lime and fertilizer. If irrigated, these soils require less frequent applications of water than extremely sandy ones. Fine-textured soils have a narrower range of moisture conditions under which they can be worked satisfactorily than sandy soils. They also may puddle or form crusts on their surface after rains. This crust is hard for seedlings to break through. If worked too wet they "ribbon" behind the plow and form "clods" that are difficult to break. These soils also break up into large clods if worked when too dry. Fine textured soils are best suited for the production of crops such as corn, small grains, hay, and forages.

Organic Matter

Soil organic matter consists of the decomposed remains of plants and animals. In the soil, organic matter comes from primary plant roots and stubble, plant parts that die and fall off (such as tree limbs and leaves), plant parts that are left when crops areharvested, and animals that die on or in the soil. When temperature and moisture conditions are favorable in the soil, earthworms, insects, bacteria, fungi, and other types of plants and animals use the organic matter as an energy and nutrient source. Through this process, nutrients combined in the residues are made available for use by growing plants.

Soil humus is the most reactive and important component of soil organic matter and is the highly decomposed and resistant material remaining after primary plant and animal residues are decomposed. The digested and decomposing organic material also helps maintain a good balance of mineral, air and water components in the soil. In a sandy soil, the organic material bridges some of the space between the sand grains, thus binding these grains together and increasing water-holding capacity. In a fine textured or clayey soil the organic material helps maintain porosity among the fine soil particles, holding them apart and allowing water to enter and move more rapidly.

Soil organic matter content depends primarily on the kinds of plants that have been growing on a soil, the length of time the plants have been on it, and the soil moisture content or drainage. Soils that have been in grass for long periods usually have a relatively high organic matter content in the surface. Those that have been in trees usually have a relatively low organic matter content in the mineral soil, but do contain a surface litter layer (O horizon). In either case, if the plants have grown on a soil that is poorly drained, the organic matter content is usually higher than where the same plant is grown on a well-drained soil because of differences in available oxygen and other factors needed by the organisms that attack and decompose the organic material.

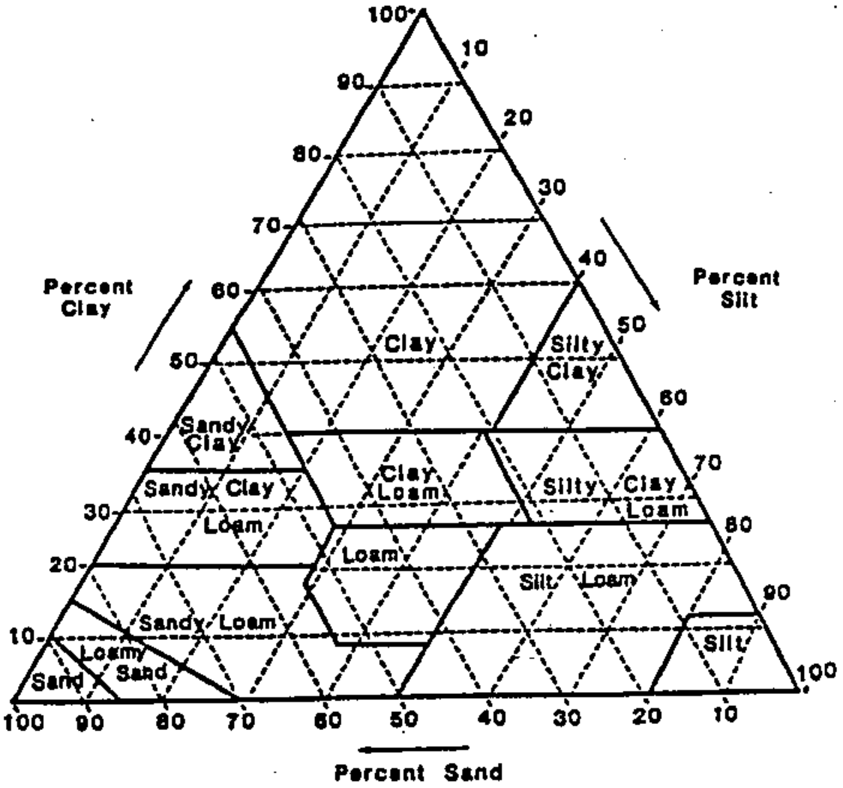


Figure 2-3. Textural triangle.

The percentage of mineral matter and organic matter in a cubic foot of surface soil varies from one soil to another, and within the same soil, depending on the kinds of crops grown, frequency of tillage, and wetness or drainage of the soil. Organic matter will usually be higher in a soil used for hay, pasture, or forest than where used for cultivated crops. Soils that are tilled frequently and have relatively small amounts of plant residues left on and worked into the soil are usually low in organic matter. Plowing and otherwise tilling the soil increases the amount of air in the soil, which increases the rate of organic matter decomposition.

Since air and water fill the pore spaces, the amount of air in a soil at a particular time depends on the amount of water present in the pore spaces. Immediately after a rain, there is more water and less air in the pore spaces than usual. Conversely, in dry periods a soil contains more air and less water. Increasing organic matter content usually has the effect of increasing water holding capacity, but addition of large amounts of undecomposed organic material can reduce water holding capacity until the material has partially decomposed.

In summary, soil organic matter consists of plant and animal residues in various stages of decay. Humus is fully decomposed and stable organic matter. Adequate levels benefit soil in many ways: (1) improved physical condition, (2) increased water infiltration, (3) improved soil tilth, (4) decreased erosion losses, and (5) increased plant nutrition. Most benefits are derived from nutrients and compounds released as organic residues are decomposed in the soil.

Aggregation and Structure

Soil aggregation is the cementing or binding together of several soil particles into a secondary unit, aggregate, or granule. One of the most important functions of the organic fraction of the soil is its promotion of aggregate formation. A granular surface soil structure, encouraged by a good supply of organic matter, greatly enhances the movement of air and water in the root zone.

Soil particles are arranged or grouped together in the soil formation process to form structural pieces (building blocks) called peds or aggregates. These peds vary in size, shape, and distinctness (or grade). Peds in many soils, particularly in the subsoil, have a thin film over their surface which gives them a waxy or oily appearance. These films or surfaces are known as "clay skins." Structure of the soil is closely related to air and water movement within it. Good structure allows favorable movement of air and water, while poor structure slows down movement of air and water. Since plant roots move through the same channels in the soil as the air and water, good structure allows and encourages extensive root development, while poor structure retards or discourages root development.

Structure (formation of peds or aggregates) of the surface soil is promoted by a good supply of organic matter, adequate lime, and working or tilling the soil when its moisture conditions are correct. Conversely, structure is weakened or even destroyed when organic matter is depleted to very low levels, when inadequate lime is used, and when the soil is tilled or worked with either too much or too little moisture in the soil.

Kinds of Structure

The kinds of structure in most Chesapeake Bay region soils are (Figure 2-4):

1. **Granular**-The soil particles are arranged in small, rounded peds. Granular structure is the most common type found in surface soils. It is very common and is usually quite distinct in soils with relatively high organic matter content, particularly where the soil has been in grass and legumes for several years.

2. **Blocky**-The soil particles are arranged to form block-like pieces, which are about as wide as they are high or long. Some blocky peds are rounded on the edges and corners; others are angular. Blocky structure is commonly found in the subsoil, although some fine textured soils have blocky structure in the surface horizons.

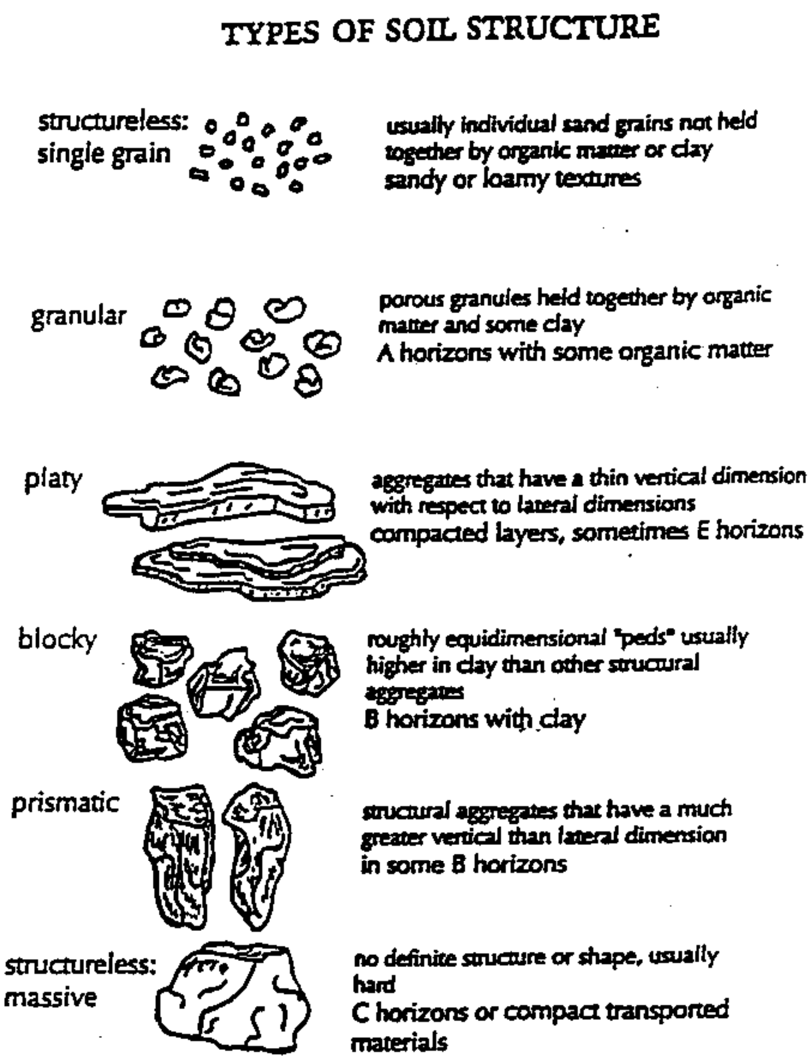


Figure 2-4. Types of soil structure.

3. **Platy**-The soil particles are arranged in plate-like sheets. These plate-like pieces are approximately horizontal in the soil and may occur in either the surface or subsoil. They fit together somewhat like brick or block in a wall and are most common in the subsoil. Platy structure may occur just beneath the plow layer, resulting from compaction by heavy equipment on the soil when it is too wet to work satisfactorily, and are also common in fragipans.

4. **Prismatic**- The individual units are bounded by flat or slightly rounded vertical faces. Units are distinctly longer vertically, and the faces are typically casts or molds of adjoining units. Vertices are angular or subrounded; the tops of the prisms are somewhat indistinct and normally flat. Prismatic structure occurs mainly in subsoils.

Effects of Structure

Structure, or lack of it, is related to air and water movement and root penetration in the soil. The suitability of a soil for the growth of plants and its capacity to produce is related to its structure. Size and shape of the peds is important, particularly the ratio of width to depth. When vertical dimension is approximately equal to horizontal (blocky structure), we expect good air and water movement in the soil. Peds that have greater vertical length than horizontal (prismatic structure) are often associated with subsoils that swell when wet and shrink when dry, resulting in poor air and water movement. Coarse prismatic structure is also commonly associated with massive and dense subsoil layers (e.g. fragipans). When peds have greater horizontal length than vertical (platy structure), downward water and air movement and root development in the soil is slowed down.

Structure of the surface soil will usually be granular. Soil aggregates are rounded and vary in size from very small shot to large pea. With very low organic matter content and continuous cultivated crops being produced, soil structure may be quite indistinct or completely destroyed. High organic matter soils with fine texture may have blocky structure in the surface. Water can enter a surface soil that has granular structure (particularly fine-textured soils) more rapidly than one that has relatively little structure. Water, air, and plant roots move more freely through subsoils that have blocky structure than those with platy structure. Well-aggregated soils may also permit macropore flow of substantial amounts of mobile nutrients, (e.g. NO_3^-). Some soils, particularly along drainage ways, have little or no structure. These soils tend to hold too much water and provide insufficient air for deep-rooted perennial plants, such as alfalfa. Very sandy soils often have little or no structure.

Porosity

Soil porosity is the volume percentage of the total soil bulk not occupied by solid particles. Pore space is commonly expressed as a percentage:

$$\%\ pore\ space = 100 - [\frac{bulk\ density}{particle\ density} x\ 100]$$

Bulk density is the dry mass of soil solids per unit volume of soils, and particle density is simply the density of soil solids which is assumed to be constant at 2.65 g/cm^3. Bulk densities of mineral soils generally are in the range of 1.1 to 1.7 g/cm^3 (Mg/m^3) and vary with a number of factors such as particle density, aggregation, organic matter, particle size, compaction/consolidation, and horizon.

Under field conditions, pore space is filled with water and air. If the particles lie close together, as in graded sands or compact subsoils, the total porosity is low. If they are arranged in porous aggregates, as is often the case in medium-textured soils high in organic matter, the pore space per unit volume will be high.

Two types of individual pore space - macro and micro - occur in soils. Although there is no clear-cut demarcation, pores less than about 0.05 mm in diameter are considered micropores and those larger, macropores. The macropores allow the ready movement of air and percolating water. In contrast, the micropores are mostly filled with water in a moist soil and do not permit much air movement into or out of the soil. The water movement is also slow. Thus, even though a sandy soil may have a relatively low total porosity, the movement of air and water through such a soil is surprisingly rapid because of the dominance of the macropores. Continuous cropping, particularly of soils originally high in organic matter, often results in a reduction of macropore spaces.

Fine-textured soils, especially those without a stable granular structure, allow relatively slow air and water movement despite the unusually large volume of total pore space. Here the dominating micropores often stay full of water. Aeration, especially in the subsoil, is often inadequate for satisfactory root development and desirable microbial activity. Obviously, the size of the individual pore spaces rather than their combined volume is the most important consideration. The loosening and granulating of fine-textured soils promotes aeration not so much by increasing the total pore space as by raising the proportion of macrospaces.

SOIL WATER RELATIONS

Retention/ Water Holding Capacity

Soil water retention and supply characteristics are controlled largely by the interaction of soil texture, bulk density, and aggregation. Sands hold little water because their large pore spaces allow water to drain freely from the soils. Clays adsorb a relatively large amount of water, and their small pore spaces retain it against gravitational forces. Although clay soils have greater total water-holding capacities than sandy soils, not all the moisture is available to growing plants. Clay soils (and those high in organic matter) hold water more tightly than sandy soils. So, while a clay soil holds more water than a sand, more of it is unavailable.

The term "field capacity" defines the amount of water remaining in a soil after downward gravitational flow has stopped. It is expressed as a percent by weight. The amount of water a soil contains after plants are permanently wilted is called the "permanent wilting" percentage. Water is still present at this point, but is held so tightly that plants are unable to use it. Water available to growing plants is that amount contained in the soil between field capacity and the permanent wilting point.

Sandy soils cannot store as much water as clay soils, but a higher percentage of the total water that is present is available in sandy soils. Fine textured soils (clays) are easily compacted, which reduces pore space and limits air and water movement through the soil. Moisture stress can become a problem in fine textured soils, even under high rainfall. Clays are sticky when wet and form hard clods when dry. Hence, proper moisture content is extremely important when tillage is performed. Sandy soils, on the other hand, are inherently droughty because they can hold little total water. They are loose, less likely than clays to be compacted, and are easy to till. However, soils containing high proportions of very fine sand may be easily compacted.

Drainage

Soil drainage is defined as rate and extent of water removal. Included is movement across the surface as well as downward through the soil. Slope or lack of slope (topography) is a very important factor in soil drainage. Other factors include texture of surface and subsoil layers, as well as underlying material, structure, and physical condition due to improper tillage (particularly distortion of structure).

Another definition of drainage relates to an operation for removal of excess water from the soil. This is usually accomplished through a series of ditches of the drains. These ditches may be open or have tile or pipe installed and covered to allow farming or other operations to be performed without interference.

Soil drainage, as defined above, is indicated by soil color, with clear, bright colors indicating well-drained conditions; mixed, drab, and dominantly gray colors indicate impeded drainage. A soil is said to be well-drained when the solum (A+E+B horizon) has clear, bright colors. When the subsoil is mottled (gray predominates) within the solum, the soil has drainage restrictions; the degree ranging from moderately well to somewhat poorly, poorly, and very poorly drained depending upon the depth from the surface to the mottled area. Drainage mottles are also referred to as redoximorphic features. Those soils which are somewhat poorly, poorly, and very poorly drained may need complete drainage systems installed for satisfactory use in production of most crops. Moderately well drained soils need drainage systems installed if a sensitive crop such as alfalfa is to be grown.

Some soils are excessively drained or hold too little water for normal plant growth, particularly during dry, hot periods. Excessively drained or droughty soils are usually quite coarse-textured in the subsoil area, shallow to rock or restrictive layers, or on steep slopes. These soils, unless adequate irrigation water can be applied, are best used for short season crops or those that mature before the hot season begins.

CHEMICAL PROPERTIES

pH and Acidity

The term pH measures and defines the relative acidity or basicity of soil solution. The pH scale covers a range from zero to 14. A pH value of 7.0 is neutral. Values below 7.0 are acid while those above 7.0 are basic. Most productive soils in our region range from 5.5 to 6.5 in pH. An acid is a substance that releases hydrogen ions (H^+).

Soil pH simply measures H^+ activity in a soil:water solution and is expressed in logarithmic terms. The practical significance of the logarithmic relationship is that each unit change in soil pH means a tenfold change in the amount of measured acidity or basicity. That is, a soil with a pH of 6.0 has 10 times as much active H^+, as one with a pH of 7.0. Therefore, lime need increases rapidly as pH drops.

Soils become acid when basic cations (e.g. Ca^{2+})held by soil colloids are replaced by acid forming Al^{3+} ions. Soils formed under conditions of high annual rainfall are more acid than are soils formed under more arid conditions. Most soils of the Chesapeake Bay region were formed under leaching conditions, and they are inherently more acidic than soils of the midwest and western United States.

Cation Retention and Exchange Fundamentals

Soil materials possess a net surface charge (usually negative) that allows them to hold and retain ions against leaching. The net ability of a soil to hold, retain and exchange positively charged ions (cations) like K^+, NH_4^+, Ca^{2+}, Mg^{2+}, and Al^{3+} is referred to as cation exchange capacity (CEC).

Surface charge may arise in clay minerals via two mechanisms:

1) "isomorphous substitution". The substitution of Al^{3+} for Si^{4+} in the clay mineral structure will result in that structure taking on a negative charge at the mineral's surface. Similarly, Fe^{2+} or Mg^{2+} may substitute for Al^{3+}. "Isomorphous" means "same form" (i.e., the minerals surface charge is changed, but the mineral structure remains essentially the same).

2) "pH dependent CEC". Increasing the pH of the soil solution often increases the effective negative charge, or CEC, of the soil via effects on charge of clay minerals and humus. Changes in concentrations of other anions in solution (ex: phosphates, PO_4^{-3} and sulfates, SO_4^{-2}) may have similar effects. The humus fraction is of greater interest because it may exhibit a profound increase in CEC with increasing pH.

CEC and Base Saturation

All soils are composed of inorganic and organic constituents which contribute negative electrical charges. These negative charges are in excess of any positive charges which may exist, giving the soil an overall negative charge. The source of these negative charges comes mainly from the clay and organic fractions of the soil. The mineralogy of the clay fraction greatly influences the quantity of negative charges present. The soil pH has a direct relationship in the quantity of negative charges contributed by both the clay fraction and organic matter. As the soil pH increases, the quantity of negative charges increases and vice versa.

Cations (positively charged ions) that are held against leaching by soils can be replaced by other cations. This means they are exchangeable. Calcium can be exchanged for Al^{3+} and/or K^{+} and vice versa. The higher a soil's CEC, the more cations it can retain. Soils differ in their capacities to hold exchangeable cations. The CEC depends on amounts and kinds of clay and organic matter present. For example, a high-clay soil can hold more exchangeable cations than a low-clay soil. Also, CEC increases as organic matter increases.

The CEC of a soil is expressed in terms of moles of charge per mass of soil and is written as cmol^{+}/kg or meq/100g. Clay minerals usually range from 10 to 150 cmol /kg. Organic matter ranges from 200 to 400 cmol^{+}/kg. So, the kind and amount of clay and organic matter in soils obviously greatly influence the CEC.

Why is it important to understand that soils have negative charges?

There are many practical implications of knowing a soil's CEC. In general a soil with a low CEC value (1-10 meq/100 g) may have some, or all, of the following characteristics:

- High sand and low clay content
- Low organic matter content
- Low water holding capacity
- May have low pH value
- Lightly buffered and cannot easily resist changes in pH or other chemical changes
- Plant nutrients will be leached very easily (Ca^{2+}, NH$_4^{+}$, K^{+})
- Productivity may be low.

Soils with higher CEC values (11-50 meq/100g) may have some or all of the following characteristics:

- Low sand and high clay content
- Moderate to high organic matter content
- High water holding capacity

- Highly "buffered" and can resist changes in pH or other chemical properties
- Plant nutrients are retained and leaching losses are less than in low CEC soils.

How is the CEC determined or calculated?

The effective CEC, which is simply the summation of the meq of the principal cations that are extracted from a soil sample, can be readily calculated if the concentrations of the various cations are known. The following procedure is carried out to calculate the meqs of Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+} that exist in 100 g of soil. The meq of all these cations are summed up to calculate the CEC of the soil. For example, soil extraction was completed with 230 mg of Ca in a 100 g sample of soil. How many meq are there of Ca?

1. The mole equivalent of any cation is equal to its atomic weight divided by its valence or ionic charge. In the case of Ca^{2+}:

$$\frac{\text{Atomic weight of Ca}}{\text{Valence of Ca}} = \frac{40}{2} = 20 \text{ g}$$

Therefore, the equivalent weight of Ca is equal to 20 grams. The CEC values are expressed as meq. There are 1000 meq in one equivalent.

$$\frac{\text{Atomic weight of Ca}}{\text{Valence of Ca x 1000}} = \frac{40}{2000} = .02 \text{ g or } 20 \text{ mg}$$

The meq weight of Ca is equal to 20 mg. In the current example, there are 230 mg of Ca in a 100 g soil sample, but we would like to know how many meq of Ca are in the sample?

$$\frac{\text{230 mg Ca/100 g soil}}{\text{20 mg per meq}} = 11.5 \text{ meq Ca/100 g soil}$$

The following table includes the atomic weights and valences or ionic charges for each of the cations and their meq weights:

Element	Atomic Weight	÷	Valence	=	Meq weight (mg/meq)
Ca	40		2		20
Mg	24		2		12
K	39		1		39
Na	23		1		23
Al	27		3		9

With this information, it is now possible to calculate the effective CEC of any soil. The following information has been provided to calculate the theoretical CEC of "Soil A".

Element	mg/100 g soil	÷	mg/meq	=	meq/100 g soil
Ca	230		20		11.5
Mg	30		12		2.5
K	40		39		1.0
Na	5		23		0.2
Al	10		9		1.1
			CEC Total =		16.3 meq/100 g soil

Base Saturation and Nutrient Availability

Of the common soil bound cations, Ca, Mg, K and Na are considered to be "basic cations." The "base saturation" of the soil is considered that portion of the CEC which is being occupied by these cations (on a charge basis) as opposed to acid-forming Al. It is important to maintain a relatively high base saturation because it maintains availability of Ca, Mg and K and positively influences pH. Low base saturation levels indicate that the soil is probably very acid and there is a higher concentration of exchangeable aluminum which would be detrimental to plant growth.

With the data from the CEC calculation above, base saturation can be calculated as follows:

$$\% \; Base \; Saturation = \frac{Bases \; meq}{CEC \; meq} X100$$

$$\frac{11.5 + 2.5 + 1 + 0.2}{16.3 \, meq/100g} X100 = \frac{15.2 \, meq/100g}{16.3 \, meq/100g} X100 = 93.3\% BS$$

Many times it is important to know the proportion of each cation in the total CEC, this is often called "cation saturation of the CEC". This can be calculated in the following manner:

meq/100 g element of interest/ total CEC x 100 = % Saturation of element.

The saturation of each cation of the CEC in the above example is as follows:

Ca	11.5 meq / 16.3 meq total x 100	= 71%
Mg	2.5 meq / 16.3 meq total x 100	= 15%
K	1.0 meq / 16.3 meq total x 100	= 6%
Na	0.2 meq / 16.3 meq total x 100	= 1%
Al	1.1 meq / 16.3 meq total x 100	= 7%
		100%

Anion Retention in Soil

Most soils do contain a small amount of positively charged surface sites which exhibit anion exchange capacity (AEC). Nitrate, for example, is completely mobile and moves freely with soil moisture. Thus, under high rainfall, or during periods of low plant transpiration, nitrate moves downward. Under extremely dry weather, it moves upward with soil capillary moisture, causing nitrate to accumulate near the surface.

Sulfate (SO_4^{-2}) can be held rather loosely in some soils under certain conditions. At low pHs, positive charges can develop on broken edges of some clays. Soils containing hydrous iron (Fe) and aluminum (Al) oxides, either in topsoil or subsoil, hold some SO_4^{-2} through these positive charges, however, this small retention is of little consequence above pH 6.0. Large quantities of SO_4^{-2} can be retained through accumulations of gypsum in arid and semi-arid soils.

SOIL CLASSIFICATION AND SURVEY

Use of Soil Survey

Significance of Soil Survey Reports

Some kind of soil inventory has been made of most parts of the world, though in many of the non-industrialized nations, little more than broad reconnaissance work is available. In the United States, most counties have been surveyed separately and in great detail.

A Soil Survey Report tells what kinds of soil exist in a county (or other area covered by the report). The soils are described in terms of their location, their profile characteristics, their relation to each other, their suitability for various uses, and their needs for particular types of management. Each soil survey report contains information about soil morphology, soil genesis, soil conservation, and soil productivity.

There are two major parts to a soil survey report. One is the soil map. Usually this consists of many mapping sheets in the back of the report. In the newer reports, the soil map is printed on aerial photographs. In older reports it was printed on plain sheets or on contour maps. Soil mapping in the past was done at scales ranging from 1:10,000 to 1:50,000. USDA-NRCS mapping is now done at 1:24,000 to match USGS quads. Mapping units are soil series, consociations, complexes and occasionally associations.

Each soil area is delineated by a boundary line on the map. Soil boundaries sometimes approximately follow contour lines, but these two kinds of lines should be carefully distinguished. A contour line always remains at the same elevation. It cannot intersect other contour lines except where there is a vertical cliff. Soil boundaries, on the other hand, are drawn wherever there is a significant change in the type of soil. The boundaries may follow contour lines but they also cross contour lines. Soil boundaries intersect each other in complex patterns somewhat akin to a jig-saw puzzle.

The other major part of a soil survey report is the narrative portion. Without it, the soil maps would have little meaning. Soil symbols placed inside each soil area on the map are named and the soils are described in detail.

Terminology Used in Soil Surveys

1. Soil series - basic unit of soil classification
   - a subdivision of a family
   - consists of soils that are essentially alike in all main profile characteristics.

2. Soil phase - subdivision of a soil series or other unit of classification having characteristics that affect the use and management of the soil, but which do not vary enough to merit a separate series (variations in slope, erosion, gravel content, etc.).

3. Soil complex - a naturally occurring grouping of two or more soil series with different use and management requirements which occurs in a regular pattern on the landscape at such a scale that it is impossible to delineate out each series.

4. Soil association - a naturally occurring grouping of soil series which occur in a characteristic pattern on the landscape.

5. Map unit - this is the actual unit which is delineated on the soil map. Map units generally contain more than one soil series. If >50% of the area is a single soil phase or similar soils, then units are given the name of the dominant soil.

If the inclusions of similar use soils exceed 25% or dissimilar inclusions exceed 15%, then soil complexes are employed as the map unit and the unit is given the name of the series which comprise the complex.

Map units are given a symbol (numbers or letters) on the soil map; for example, 12A or Ma. The map unit designates the name of the soil series or complex being mapped; e.g., Frederick or Mattapeak. The following capital letter designates the slope phase, which may vary from one county survey to another.

Commonly used slope phases:

A = 0- 2%
B = 2- 7%
C = 7-15%
D = 15-25%
E = 25-50%
F = >50%

6. Capability classes - The NRCS groups soils into eight agricultural capability classes. Those with the least limitations are in class I, -those with the most limitations in class VIII.

Each capability class has four subclasses for limitations imposed by:

1. erosion hazard (e),
2. excessive wetness (w),
3. shallow root zone (s),
4. climatic problems (c).

Subclasses can be divided further into groups of soils which require similar management. For instance, in a particular soil survey, three II-e capability subclasses may be distinguished, which would be designated IIe-1, IIe-2, and IIe-3.

Soil Survey Reports are available from county NRCS and Cooperative Extension offices. A user interested in an overall picture of the soils in a county should probably turn first to the soil association section of the soil survey report. The general soil pattern of the county is discussed in this section. A user interested in the soils of a particular farm must first locate that farm on the soil map and determine what soils are present. Index sheets located with the soil maps help the user find the correct section of the map. The legend gives the soil names for each symbol and enables the location of descriptive and interpretive material in the report.

Within each soil survey report there are detailed soil descriptions that provides information to those who are primarily interested in the nature of the soils. Another section concerned with the use and management of the soils is most helpful to farmers and others who use the soil or give advice and assistance in its use (soil conservationists, etc.). Management needs and estimated yields are included in this section. The newer reports have engineering properties of soils listed in tables that are useful to highway engineers, sanitary engineers, and others who design water storage or drainage projects.

SOIL CONSERVATION

Erosion Types

Soils and land use activities are deeply involved with the struggle to protect the quality of our environment. Soils can sometimes be a cause of and sometimes a cure for pollution. In terms of shear tonnage, sediment is the leading water pollutant. How does it get into the streams, rivers, and the Bay? The process is called erosion. Geologic erosion is a natural process which continually wears away the soil. However, the very presence of the blanket of soil covering the land is evidence that geologic erosion is, in most locations, in dynamic equilibrium with soil formation, and a very slow process.

According to the Natural Resource Conservation Service the maximum tolerable rate of soil erosion is two to three tons per acre per year. This corresponds to a loss of about 1/32 of an inch of soil per year. In an average soil, this rate of soil loss may be compensated by a corresponding rate of soil formation. In the southeastern United States, the average erosion rate from cropland is 4 to 5 tons per acre per year. Erosion is the most insidious long-term danger to agricultural productivity facing the nation and the world today.

Wind

Conditions conducive to wind erosion exist when the soil is loose, dry, and finely granulated; when the soil surface is smooth and vegetation is sparse or absent; and when the wind is strong and turbulent enough to move the soil. The transport of soil particles by wind takes place by suspension, surface creep, and saltation. Suspension describes the movement of fine particles, usually less than 0.2 mm in diameter, high in the air and over long distances. Surface creep is the rolling of coarse grains along the ground surface. Saltation is the process of grain movement in a series of jumps and is caused by the pressure of the wind on the soil particles and their collision with other particles. Saltation is the major cause of aggregate breakdown during wind erosion.

Water

Accelerated erosion generally occurs as a result of human activities which leave the soil surface unprotected by natural vegetative cover. Both wind and water may be the agents of soil erosion. Accelerated erosion by water is classed into three types distinguished by their surface patterns.

1. Sheet erosion - soil is lost uniformly from the entire soil surface.
2. Rill erosion - erosion is concentrated in zones where small channels of water collect.
3. Gully erosion - soil loss is concentrated in ravines where large volumes of water collect and run off.

There are many factors which affect the type as well as the intensity of soil erosion. Among these are:

1. Soil texture - silts and fine sands are most erosive; coarser sands and well aggregated finer textured soils are less erosive because infiltration is greater (hence, less runoff) and because energy needed to move larger particles is greater.

2. Soil structure - well aggregated soils behave as coarse textured materials; if aggregates are not water stable, dispersion will occur and runoff and soil loss will increase.

3. Vegetation - the binding effect of roots; effects of organic matter on structure; diminishes raindrop impact energy.

4. Slope - the longer and steeper the slope, the higher the velocity of runoff and the greater the potential for erosion.

5. Rain intensity - the greater the rainfall intensity, the greater the potential for runoff and erosion.

6. Surface roughness - if the surface is rough and irregular, a buffer against runoff during high intensity storms occurs because water must fill surface depressions before runoff initiates. Irregular surfaces also offer greater resistance to surface flow thus decreasing the velocity and erosive power of runoff.

Control Practices and Factors

The principal reasons for soil erosion are: (1) insufficient vegetative cover, which is usually the result of inappropriate tillage and cropping practices for local site conditions, (2) overexposure through the use of cultivated crops on soils not suited to cultivation, and

(3) use of improper tillage implements and the methods used in preparation and tillage of the soil. Therefore, soil erosion can be held to a minimum by: (1) using the soil to produce crops to which it is suited, (2) using adequate fertilizer and lime to promote vigorous growth of plants, and (3) using appropriate soil preparation and tillage methods or conservation tillage.

Soils that have lost part or all of their surface horizon are usually harder to till and have lower productivity than those that have a desirable thickness of surface soil. However, in some cases, loss of surface soil increases productivity for certain crops. This would be the case where a very sandy (sand or loamy sand) surface was underlain by a thick subsoil of sandy loam or sandy clay loam texture. To compensate for surface soil losses, better crop management and tillage practices should be used. Increasing the organic matter content of an eroded soil often improves its tillage characteristics, as well as its water and nutrient capacity.

Site topography largely determines the amount of runoff and erosion. It also dictates irrigation methods, drainage, conservation measures and other best management practices (BMP) needed to conserve soil and water. The steeper the land, the more management is needed, thus increasing labor and equipment costs. At certain slopes, soil conditions become unsatisfactory for row crop production. The ease with which surface soils erode, along with percent slope, is a primary determinant in a soil's potential productivity.

BASIC HYDROLOGIC CYCLE AND SOIL WATER BALANCES

A basic understanding of the hydrologic cycle is necessary to understand nutrient loss mechanisms and to develop management strategies to reduce nutrient losses to ground and surface water. The hydrologic cycle is illustrated in Figure 2-5. The basic stages of the hydrologic cycle which are important to nutrient transport to ground and surface water include precipitation, runoff, leaching, and discharge of ground water into streams.

Although timing and amounts of precipitation will vary in each individual year, these deviations from the average cannot be reliably predicted in advance. Runoff from an area will be influenced by storm intensity, storm duration, slope, soil type, and vegetation or amount of residue. Leaching occurs when soluble nutrients percolate through the soil with water. Nutrients move into the ground water system via leaching and to surface water via runoff or ground water discharge.

Precipitation averages range from 35 to over 50 inches annually in various portions of the Chesapeake Bay Watershed. Evapotranspiration, the sum of evaporation of soil moisture and transpiration of moisture by vegetation, accounts for about 20 to 30 inches of the total precipitation. The remaining water is either leached below the root zone, eventually reaching ground water, or runs off as surface flow which enters streams. Ground water is connected to surface water via springs, seeps, wetlands, and recharge of streams.

Any contaminants dissolved in the ground water, such as nitrate, can contribute to surface water contamination. In addition, seepage of ground water into surface water often occurs in stream beds and tidal portions of the Chesapeake Bay and its tributaries.

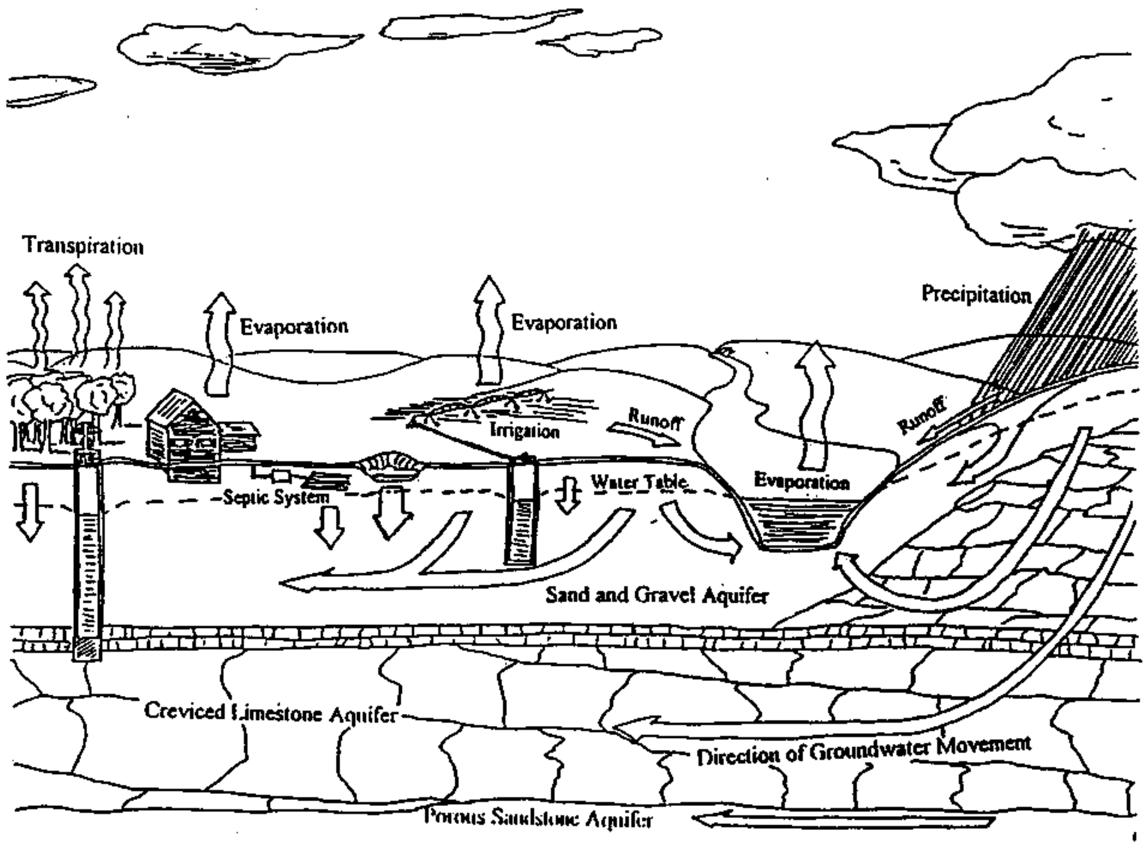


Figure 2-5. The Hydrologic Cycle.

Groundwater discharge into streams is termed "base flow." The base flow in the example watershed represented by Figure 2-6 accounts for about 5 inches per acre of watershed area, while direct surface flow accounts for 7 inches annually. Surface flow contribution to stream water occurs during and after rainfall events or snow melt and is therefore highly variable over time. In contrast, base flow is generally a continuous contributor to stream flow throughout the year. During dry periods, base flow is the only contributor to stream flow, which vividly demonstrates the interconnection of ground and surface waters.

In Piedmont areas, surface runoff of water is a larger contributor to surface water flow relative to base flow contributions due to the topography and geology of the area. Piedmont soils are generally more impermeable to water infiltration due to higher clay content as compared to other regions. In Coastal Plain areas, base flow and subsurface seepage of ground water into surface water bodies are more significant than surface runoff. In some areas of the Coastal Plain, ground water discharge may account for as much as 80% of total annual contributions to surface water due to the permeable soils and shallow ground water which are characteristic of the region. Ground water in the Coastal Plain typically moves laterally at a rate of several inches to as much as 2 feet per day. Flow direction of the ground water will usually follow the general slope of the overlying land and flow toward surface water in unconfined aquifers.

As previously mentioned, long term average rainfall by month does not vary significantly throughout the year in our region. However, since crops and other vegetation are actively growing during the late spring, summer, and early fall, evapotranspiration rates are much higher during this period than in late fall, winter, and early spring. Water use by corn on a monthly basis is shown in Figure 2-7.

Water losses to the atmosphere due to evapotranspiration during midsummer will exceed rainfall contribution to soil moisture. Consequently, the chance of significant leaching or runoff of water is much lower during the summer than during the winter. During periods of low evapotranspiration (due to cooler temperatures), significant leaching and runoff can occur. The use of timely planted small grain cover crops following summer annual crops such as corn are critical to minimizing nitrogen losses from soils during the fall and winter, particularly following a drought year when lower levels of nitrogen are removed by summer annual crops.

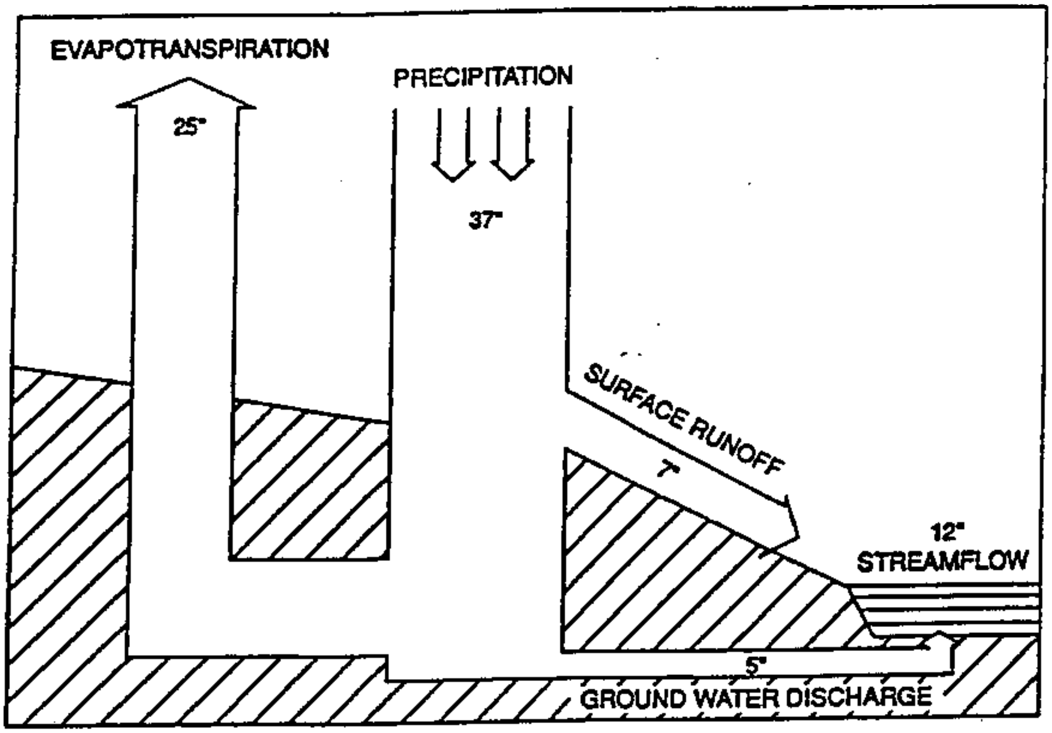


Figure 2-6. General water budget, Upper South Fork, Shenandoah River.

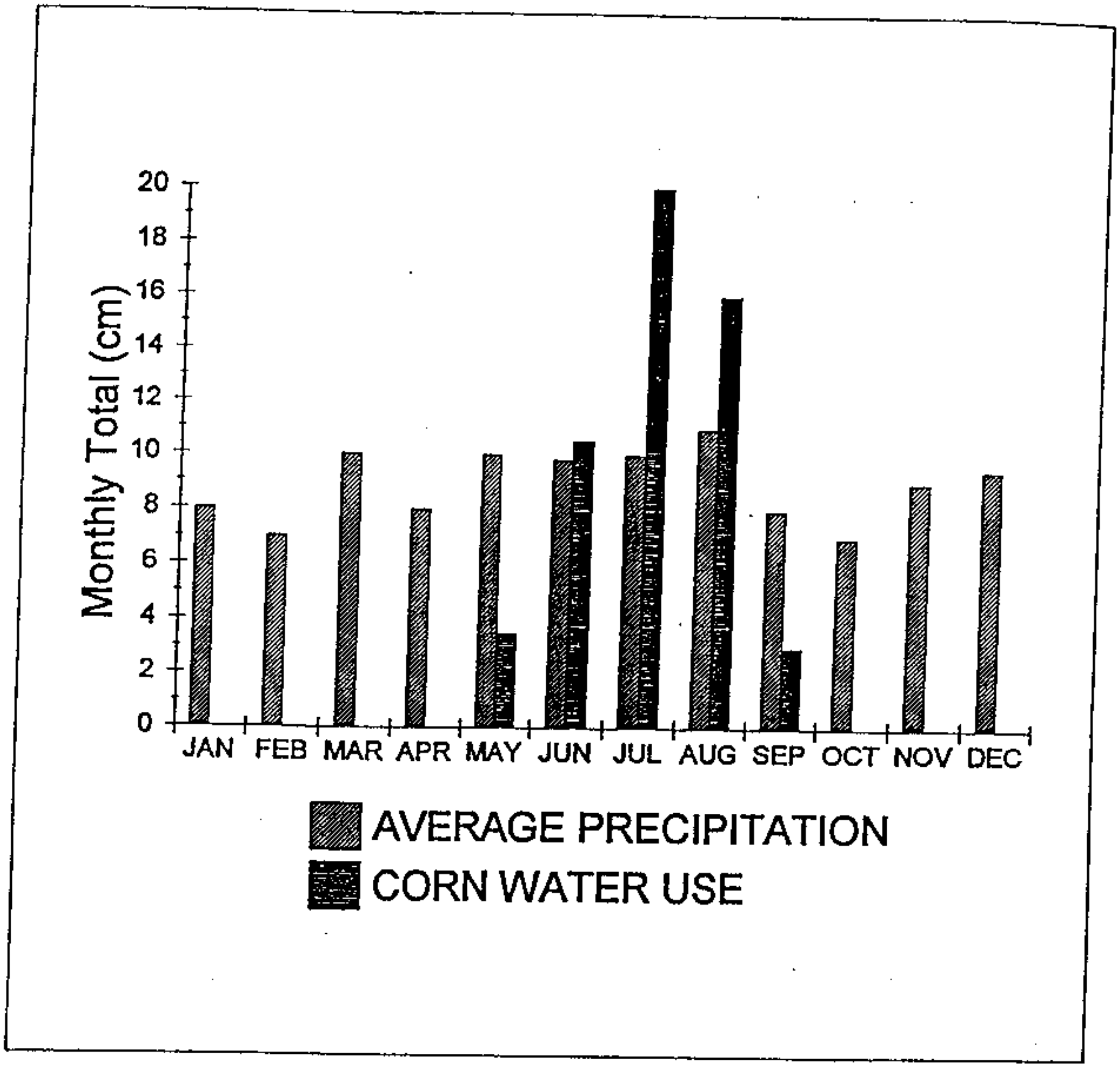


Figure 2-7. Monthly corn water use in the mid-Atlantic region. (Staver et al., 1988)

Chapter 3. BASIC SOIL FERTILITY

PLANT NUTRITION

Essential Elements

In order to grow and reproduce, a plant must be able to obtain certain elements, in the proper concentration, from its environment. Some of these elements come from the atmosphere, others from water and many from the soil. Furthermore, each of these elements are considered essential for plant life and one is just as important in the plant's physiological processes as another. However, the total amount of each element that the plant needs varies considerably from one element to another.

There are sixteen (16) elements (Table 3-1) that are considered essential for plant growth.

Table 3-1. Sixteen Essential Elements for Plant Growth.

Element	Symbol	Element	Symbol
Carbon	C	Iron	Fe
Hydrogen	H	Manganese	Mn
Oxygen	O	Boron	B
Nitrogen	N	Molybdenum	Mo
Phosphorus	P	Copper	Cu
Potassium	K	Zinc	Zn
Calcium	Ca	Chlorine	Cl
Magnesium	Mg	Sulfur	S

The essential elements can be grouped into four categories based on their origin (Table 3-2) or the relative amounts that the plants need in order to develop normally. The non-mineral essential elements are derived from the air or water rather than from the soil. The primary essential elements are the nutrients most often applied in commercial fertilizers or in manures and the secondary elements normally are applied as soil amendments or are components of fertilizers that carry primary nutrients. The micronutrients are required in very small or trace amounts by the plant and hence their name. Even though the micronutrients are required by plants in very small quantities, they are equally essential to plant growth.

Table 3-2. Essential Nutrient Elements And Their Sources

Used In Relatively Large Amounts			Used In Relatively Small Amounts
Mostly from Air and Water	From Soil		From Soil
Non-mineral	**Primary**	**Secondary**	**Micronutrient**
Carbon	Nitrogen	Calcium	Iron
Hydrogen	Phosphorus	Magnesium	Manganese
Oxygen	Potassium	Sulfur	Boron
			Molybdenum
			Copper
			Zinc
			Chlorine

Plant Available Forms of Essential Elements

Plants absorb essential elements through their leaves or roots in various forms. In general, the soil contains large amounts of all the elements, but only a small percentage of these total amounts are actually in a plant available form (Table 3-3). For example, the total Fe content of a soil may exceed 50,000 parts per million (ppm) or mg/kg; however, the plant available level in the soil may only be 5 ppm Fe. Many factors contribute to the availability of nutrients to plants. Some of these factors include: form of the element found in soil, pH, soil aeration, soil compaction, soil temperature and soil moisture.

Table 3-3. Plant Available Form of the Essential Elements.

Element	Available Form(s)	Element	Available Form(s)
Carbon	CO_2	Iron	Fe^{2+}, Fe^{3+}
Hydrogen	H^+, OH^-	Manganese	Mn^{2+}, Mn^{4+}
Oxygen	O_2	Boron	H_3BO_4
Nitrogen	NH_4^+, NO_3^-	Molybdenum	MoO_4^{-2}
Phosphorus	HPO_4^{-2}, $H_2PO_4^-$	Copper	Cu^{2+}
Potassium	K^+	Zinc	Zn^{2+}
Calcium	Ca^{2+}	Chlorine	Cl^-
Magnesium	Mg^{2+}		
Sulfur	SO_4^{-2}		

Non-mineral nutrients are carbon (C), hydrogen (H), and oxygen (O). These nutrients are found in the atmosphere and water. They are involved in photosynthesis in this manner:

$$6CO_2 + 12H_2O \xrightarrow{\text{Light}} 6O_2 + 6(CH_2O) + 6H_2O$$

Products of photosynthesis account for most of plant growth, therefore, insufficient carbon dioxide, water or light reduces growth. But the amount of water used in photosynthesis is so small that plants will show moisture stress before water is low enough to affect the rate of photosynthesis.

Nitrogen (N) is very important in the physiology of plants and is part of the chlorophyll molecule. Plants also require N in order to produce amino acids which are the building components of proteins. When plants are deficient in N, they become stunted and yellow in appearance. This yellowing, or chlorosis, usually appears on the lower leaves first while the upper leaves remain green because N is a mobile element within the plant.

Phosphorus (P) is very important for plant development and deficiencies of P are just as yield limiting as are other deficiencies. Phosphorus is important in developing healthy plant root systems, normal seed development, uniform crop maturation, photosynthesis, respiration, cell division and many other processes. Phosphorus tends to be concentrated in the seeds of many plants. Phosphorus deficient plants are generally stunted in growth and affected plants often exhibit some purple or reddish pigmentation in the stems, stalks or leaves. Phosphorus is a mobile element in plants, in other words the plant has the capacity to move this element from an older plant part to a younger plant part. Therefore, P deficiency should affect older leaves first. Many times the affected crop will have a darker green color than normal. Phosphorus deficiency is often difficult to visually diagnose, therefore soil and plant tissue samples should be taken to confirm this deficiency.

Potassium (K) is responsible for regulation of water usage in plants, disease resistance, stem strength, is involved in photosynthesis, and is essential in protein synthesis. This nutrient is often linked with improving overall crop quality, and improves handling and storage qualities. Like N and P, K is mobile within the plant. Plants which are deficient in K often exhibit scorching, or necrosis, of the margin of the lower leaves. Plants deficient in K develop very slowly and have poorly developed root systems. Plants, especially small grains and corn, are prone to lodging when they are deficient in K. Disease resistance and crop quality are often lowered by K deficiency.

Calcium (Ca) performs a number of functions in the plant: stimulates root and leaf development, strengthens plant structure through the formation of cell wall compounds, and helps to activate several plant enzyme systems.

Magnesium (Mg) serves many functions within the plant. Magnesium is the central atom in the chlorophyll molecule, so it is actively involved in photosynthesis. Magnesium and N are the only soil nutrients that are constituents of chlorophyll. Much of the Mg in plants is found in the chlorophyll. Seeds are also relatively high in Mg, though grain crops such as corn have low levels in the seed. Magnesium also aids in phosphate metabolism, plant respiration and the activation of many enzyme systems.

Sulfur (S) is absorbed primarily as the sulfate (SO_4^{-2}) anion. It can also enter plant leaves from the air as sulfur dioxide (SO_2) gas. Sulfur is a part of every living cell and is a constituent of two of the 21 amino acids which form proteins. Other functions of S in the plant include: development of enzymes and vitamins; promotion nodulation for N fixation by legumes; aid in seed production; chlorophyll formation although it is not a constituent of chlorophyll; and formation of several organic compounds which give the characteristic odors to garlic, mustard and onion.

Boron (B) is essential for germination of pollen grains and growth of pollen tubes, and for seed and cell wall formation. It also forms sugar/borate complexes associated with sugar translocation and is important in protein formation

Copper (Cu) is necessary to chlorophyll formation in plants and catalyzes several other plant reactions although it is not usually a part of the product(s) formed by those reactions. Iron is a catalyst to chlorophyll formation and acts as an oxygen carrier. It also helps form certain respiratory enzyme systems.

Iron (Fe) along with manganese serve as catalysts in chlorophyll synthesis. Iron deficiency shows up as a chlorosis (pale green leaf color) with sharp distinction between green veins and yellow interveinal tissues.

Manganese (Mn) functions primarily as a part of enzyme systems in plants. It activates several important metabolic reactions and plays a direct role in photosynthesis by aiding chlorophyll synthesis. Manganese accelerates germination and maturity, while increasing the availability of P and Ca.

Zinc (Zn) aids synthesis of plant growth substances and enzyme systems and is essential for promoting certain metabolic reactions. It is necessary for production of chlorophyll and carbohydrates. Zinc is not translocated within the plant, so symptoms first appear on the younger leaves and other plant parts.

Molybdenum (Mo) is required for the synthesis and activity of the enzyme nitrate reductase. This enzyme system reduces NO_3^- to NH_4^+ in the plant. Molybdenum is vital for the process of symbiotic N fixation by *Rhizobia* bacteria in legume root nodules. It is also needed to convert inorganic P to organic forms in the plant.

Chlorine (Cl) is involved in energy reactions in the plant. Specifically, it is involved in the chemical breakdown of water in the presence of sunlight and activates several enzyme systems. It is also involved in transporting several cations (K, Ca, Mg) within the plant, regulating the actions of stomatal guard cells, thus controlling water loss and moisture stress, and maintaining turgor. Research has shown that Cl diminishes the effects of fungal root diseases such as take-all and common root rot on small grains. It also helps suppress infections of small grain fungal leaf and head diseases. Lowered incidence of stalk rot in corn has been related to adequate Cl. It is speculated that Cl competes with NO_3^- uptake, tending to promote the use of ammonium N. Higher concentrations of NO_3^- in plants have been related to disease severity.

The amount of nitrogen, phosphate and potash (N, P_2O_5 and K_2O) taken up by various crops is shown in Table 3-4 and Table 3-5.

Table 3-4. Nitrogen, phosphate, and potash removal from soil by various crops.

	lb removed per unit production			
Crop	Units	N	P_2O_5	K_2O
Corn, grain	bu	1.0	0.4	0.3
Corn, stover	ton	20.6	7.5	37.2
Corn, silage	ton	7.4	2.9	8.9
Soybeans, grain	bu	—	1.0	1.5
Soybeans, residue	ton	—	6.5	15.8
Wheat, grain	bu	1.3	0.5	0.3
Wheat, straw	ton	13.0	3.6	24.6
Oats, grain	bu	0.7	0.3	0.2
Oats, straw	ton	12.4	4.6	32.9
Barley, grain	bu	1.0	0.4	0.3
Barley, straw	ton	13.5	4.7	31.0
Rye, grain	bu	1.0	0.5	0.3
Rye, straw	ton	10.0	6.0	16.9
Alfalfa	ton	—	11.0	50.0
Orchardgrass	ton	50.0	16.6	62.5
Bromegrass	ton	33.2	13.2	50.8
Tall fescue	ton	38.6	18.6	52.9
Bluegrass	ton	25.8	18.3	60.0
Clover-grass	ton	41.0	13.3	38.9
Timothy	ton	37.5	13.8	62.5
Sorghum-Sudangrass	ton	39.9	15.3	55.9

-Legumes fix a proportion of their required nitrogen depending on soil nitrogen status.

Table 3-5. Nutrient Removal by Row Crops.

Crop	Plant Part	Acre Yield	N	P as P_2O_5	K as K_2O	Ca	Mg	S	Cu	Mn	Zn
			lbs								
Barley											
	grain	80 bu	70	30	20	2	4	6	0.06	0.06.	0.12
	straw	2 ton	30	10	60	16	4	8	0.02	0.64	0.10
	TOTAL	100	40	80	18	8	14	0.08	0.70	0.22	
Corn											
	grain	150 bu	135	53	40	2	8	10	0.06	0.09	0.15
	stover	4.5 ton	100	37	145	26	20	14	0.05	1.50	0.30
	TOTAL		235	90	185	28	28	24	0.11	1.59	0.45
Cotton											
	seed & lint	1500 lb	40	20	15	2	4	3	0.06	0.11	0.32
	stalk, leaves, & burs	2000 lb	35	10	35	28	8	15	—	—	—
	TOTAL		75	30	50	30	12	18			
Oats											
	grain	80 bu	50	20	15	2	3	5	0.03	0.12	0.05
	straw	2 ton	25	15	80	8	8	9	0.03	—	0.29
	TOTAL		75	35	95	10	11	14	0.06	—	0.34
Peanuts											
	nuts	1.25 ton	90	10	15	1	3	6	0.02	0.01	—
	vines	4500 lb	105	25	95	—	—	—	—	—	—
	TOTAL		195	35	110						
Sorghum											
	grain	60 bu	50	25	15	4	5	5	0.01	0.04	0.04
	stover	3 tons	65	20	95	29	18	—	—	—	—
	TOTAL		115	45	110	33	23	—	—	—	—
Soybeans											
	grain	40 bu	150	35	57	7	7	4	0.04	0.05	0.04
	straw	30	10	25	—	—	—	—	—	—	—
	TOTAL		180	45	80						
Tobacco											
	leaves	2000 lb	75	15	120	75	18	14	0.03	0.55	0.07
	stalks	35	15	50	—	—	—	—	—	—	—
	TOTAL		110	30	170						
Wheat											
	grain	80 bu	100	45	49	2	16	8	0.06	0.18	0.28
	straw	2 ton	34	9	113	12	8	12	0.02	0.32	0.10
	TOTAL		134	54	162	14	24	20	0.08	0.50	0.38

Table 3-5. cont. Nutrient Removal by Crops

Crop	Plant part	Acre Yield	N	P_2O_5	P as K_2O	K as Ca	Mg	S	Cu	Mn	Zn
			lbs								
HAY											
Alfalfa		4 tons	180	40	180	112	12	19	0.06	0.44	0.42
Bluegrass		2 ton	60	20	60	16	7	5	0.02	0.30	0.08
Coastal Bermudagrass		8 ton	300	70	270	59	24	35	0.21	—	—
Red clover		2.5 ton	100	25	100	69	17	7	0.04	0.54	0.36
Soybean		2 ton	90	20	50	40	18	10	0.04	0.46	0.15
Timothy		2.5 ton	60	25	95	18	6	5	0.03	0.31	0.20
FRUITS, VEGETABLES											
Apples		500 bu	30	10	45	8	5	10	0.03	0.03	0.03
Cabbage		20 ton	130	35	130	20	8	44	0.04	0.10	0.08
Grapes											
	fruit	5 ton	15	10	25	—	—	—	—	—	—
	leaves & wood		20	5	20	—	—	—	—	—	—
	TOTAL		35	15	45	—	—	—	—	—	—
Muskmelon											
	fruit	7 tons	30	11	60	—	—	—	—	—	—
	vines	1.5 ton	20	5	30	—	—	—	—	—	—
	TOTAL		50	15	90	—	—	—	—	—	—
Peaches		600 bu	35	20	65	4	8	2	—	—	0.01
Potatoes											
	tubers	400 bu	80	30	150	3	6	6	0.04	0.09	0.05
Sweet Potatoes											
	roots	300 bu	45	15	75	4	9	6	0.03	0.06	0.03
Tomatoes											
	fruit	20 ton	120	40	160	7	11	14	0.07	0.13	0.16

NUTRIENT DEFICIENCY SYMPTOMS

Visual diagnosis of plant deficiencies is very risky due to the great probability of error. Many times there is more than one deficiency present which cause confusing symptoms. Before any recommendations are made concerning the application of fertilizer materials; soil and tissue samples should be taken, analyzed and interpreted prior to the investment in fertilizer application. Deficiency symptoms of elements are discussed individually in the following section.

In the description of plant deficiency symptoms, certain terminology is used to describe the appearance of the plants which exhibit those deficiencies. In order to better understand the following deficiency symptoms, it is necessary to review the meaning of those terms:

Chlorosis: yellowing or lighter shade of green.
Necrosis: browning or drying of plant tissue.
Interveinal: between the veins.
Meristem: the growing point of a plant.
Internode: distance of the stem between the leafs.
Mobile: if an element is mobile within the plant, the plant has the capacity to translocate, or move, this element from one part of the plant to another depending on the need of the plant. If elements are mobile in the plant, they are generally moved from older parts of the plant to the growing point (meristem) of the plant in order to permit proper plant development.

Nitrogen

Nitrogen is mobile within plants; therefore, lower leaves show chlorosis first. Plants are stunted and pale green in color. In grass species, the deficiency occurs at the tip of the lower leaves and proceeds along the mid-rib. With increasing severity of deficiency the lower leaves dry or "fire-up" early in the growing season. Yields are reduced and plants are susceptible to weather stress and disease. Slow growth and stunted plants are also indications of N deficiency. Small grains and other grass-type plants tiller less when N is in short supply.

Inadequate N leads to low protein in seed and plant vegetative parts. Deficient plants usually have fewer leaves and certain crops such as cotton may reach maturity earlier than plants with adequate N. Corn adequately fertilized with N will have a lower moisture content in the grain than corn supplied with insufficient N. Nitrogen is sometimes blamed for delayed maturity. Excess N can increase vegetative growth, reduce fruit set and adversely affect quality. Delayed maturity, however, is usually caused by deficiencies of other nutrients, not too much N.

Phosphorus

Phosphorus is mobile within plants; therefore, lower leaves tend to indicate deficiency first. Plants are stunted and the root system has poor development.

The first sign of P deficiency is an over-all stunted plant. Leaf shape may be distorted. With severe deficiency, dead areas may develop on the leaves, fruit and stems. Older leaves will be affected before younger ones. A purple or reddish color associated with accumulation of sugars is often seen on deficient corn plants and on some other crops, especially during low temperatures. Phosphorus deficiencies result in delayed maturity. Small grains grown on soils without adequate P tiller less.

Visual deficiency symptoms, other than stunted growth and reduced yield, are not as clear as are those for N and K. Phosphorus deficiency is difficult to detect in many field crops. At some growth stages, P deficiency may cause the crop to look darker green. One should always be alert for the characteristic stunted condition and, when possible, confirm what the eye sees with soil and/or plant analysis.

Phosphorus can be deficient in plant tissue in situations where the amount of plant available P is low, and in higher P soils with low soil temperatures, soils that are either too acid or too alkaline where the P is tied up as aluminum, iron or calcium phosphates, soils that are compacted, or any other condition that limits root development.

Potassium

Potassium is mobile within plants; therefore, lower leaves tend to exhibit the deficiency first. One of the most common K deficiency signs is scorching or firing along leaf margins. Firing first appears on older leaves in most plants, especially grasses. Potassium deficient plants grow slowly, are poorly developed, root systems, stalks are weak, and lodging is common. Seed and fruit are small and shriveled, and plants possess low resistance to disease. Some specific crop deficiency symptoms are listed below.

- Corn -firing or scorching on the outer edge of the leaf while the midrib remains green; unfilled, chaffy ears.
- Soybeans -firing or scorching begins on the outer edge of the leaf, edges becoming broken and ragged as the leaf dies; shriveled, non-uniform seeds.
- Alfalfa -small white or yellowish dots around outer edges of leaves; leaf then turns yellow and tissue dies.
- Fruit tree crops -yellowish green leaves curl upward along margins; scorched areas develop along edges which become ragged; small fruit which drop prematurely; poor storage, shipping and canning qualities.
- Potatoes -upper leaves usually smaller, crinkled and darker green than normal.

Potassium deficiencies are most common on acid sandy soils and on soils which have had large amounts of Ca and/or Mg applied.

Calcium

Calcium is not mobile within plants; therefore, upper leaves and the growing point tend to exhibit deficiency first. Poor root growth is a common symptom of Ca deficiency. In severe cases, the growing point dies. Calcium deficient roots often turn black and rot. Young leaves and other new tissue develop symptoms because Ca is not translocated within the plant. New tissue needs Ca for cell wall formation, so Ca deficiencies cause gelatinous leaf tips and growing points. Fruit quality is poor. Calcium deficiencies seldom show up in the field because secondary deficiency effects such as high acidity usually limit growth first. Deficiencies are most likely to occur on crops such as peanuts and vegetables. Calcium deficiency most often occurs on very acid soils where Ca levels are very low. High amounts of K fertilizers could induce Ca deficiencies.

Magnesium

Magnesium deficiency symptoms first appear on lower (older) leaves, generally, because Mg is translocated within the plant. They show a yellowish, bronze or reddish color, while leaf veins remain green. Corn leaves are yellow-striped, with green veins. Crops such as potatoes, tomatoes, soybeans and cabbage also show the orange-yellow color and green veins.

Sulfur

Sulfur is mobile within plants, but to a lesser degree than N. Even though the deficiency symptoms tend to develop on the lower leaves first, the entire plant generally is pale green in color. Plants deficient in S show a pale green coloring of the younger leaves, although the entire plant can be pale green and stunted in severe cases. Leaves tend to shrivel as the deficiency progresses.

Sulfur, like N, is a constituent of proteins, so deficiency symptoms are similar to those of N. Nitrogen deficiency symptoms are more severe on older leaves, however, because N is a mobile plant nutrient and moves to new growth. Sulfur, on the other hand, is less mobile in the plant, so new growth suffers first when S levels are not adequate to meet crop need. Often, broad light green streaks develop on upper leaves of grasses. This difference is important in distinguishing between the two, particularly in early stages of a deficiency. However, it is difficult to distinguish between N and S deficiencies because the symptoms are very similar. Many times an improper diagnosis is made based on visual diagnosis in the field and the wrong fertilizer is often applied. Confirmation of the deficiency through tissue testing should be done prior to fertilizer application.

Plants deficient in S can be thin-stemmed and spindly. Crops such as cabbage and canola may develop a reddish color, first appearing on the underside of leaves and on stems. On alfalfa, leaves are long and slender and branching is reduced. Corn exhibiting S deficiency symptoms can be identified by the general yellowing of the upper leaves, often with some broad, lighter colored streaks. These symptoms usually occur before the plants are knee-high. Sulfur deficiencies occur most often on soils with low organic material, sandy soils with high annual rainfall and areas with low atmospheric contamination. Crops may "grow out" of S deficiencies observed early in the season as root systems develop and intercept S reserves deeper in the soil.

Boron

Boron is not mobile within the plant; therefore; deficiency symptoms are exhibited at the meristem and new leaves. Symptoms include reduced leaf size and deformation of new leaves. With severe deficiency, the leaves often exhibit interveinal chlorosis. The distance between internodes is greatly reduced causing a "witch's broom" effect. Boron is often related to flower and/or fruit abortion, poor grain fill and stunted growth. Boron can be confused with zinc deficiency on some crops.

Boron deficiency can occur on very acid sandy textured soils or alkaline soils. High levels of exchangeable Ca can inhibit B uptake. Some specific B hunger signs are:

- Celery - crooked stem,
- Peanuts - hollow heart,
- Apples - corky core,
- Alfalfa - rosetting, yellow top, death of terminal bud, and
- Table beets and sugar beets - black heart.
- Cotton - ringed or banded leaf petioles, with die back of terminal buds, causing resetting effect at the top of the plant (seldom seen in the field). Ruptured squares and thick, green leaves that stay green until frost and are difficult to defoliate.

Copper

Copper is not mobile within the plant; therefore, deficiency symptoms are exhibited at the meristem and new leaves. Symptoms include reduced leaf size, uniformly pale yellow new leaves, and the leaves may wilt and wither without chlorosis. Common symptoms of Cu deficiency include dieback in citrus and blasting of onions and truck crops. Many vegetable crops show Cu deficiency with leaves that lose turgor and develop a bluish-green shade before becoming chlorotic and curling. And, plants fail to flower.

Organic soils are most likely to be Cu deficient. Such soils usually contain plenty of Cu, but bind it so tightly that only small amounts are available to the crop. Sandy soils, low in organic matter content, may also become deficient in Cu because of leaching losses. Soils with very high soil P levels or soils with a high pH may be Cu deficient. Heavy, clay type soils are least likely to be Cu deficient.

Iron

Iron is not mobile within the plant; therefore, deficiency symptoms are exhibited on the new leaves. Symptoms include very chlorotic young leaves with prominent green veins which also eventually turn chlorotic. Plants remain stunted.

Severe deficiency may turn the entire plant yellow-to-bleached white. Iron deficiency may be caused by an imbalance with other metals such as Mo, Cu or Mn. Other factors that may trigger Fe deficiency include:

- Excessive P in the soil,
- Combination of high pH, high lime, wet, cold soils and high bicarbonate levels,
- Plant genetic differences, and
- Low soil organic matter levels.

Manganese

Because Mn is not translocated in the plant, deficiency symptoms appear first on younger leaves with yellowing between the veins. Sometimes a series of brownish-black specks appears. In small grains, grayish areas appear near the base of younger leaves. Manganese deficiencies occur frequently on high organic matter soils. Soils with neutral-to-alkaline pH and naturally low in Mn content (leached, light-colored soils) are also frequently Mn deficient. It is often difficult to distinguish between iron and manganese deficiency symptoms.

Zinc

Zinc is not mobile within the plant; therefore, deficiency symptoms are exhibited on the new leaves first. Symptoms include shortened internodes between new leaves, death of meristematic tissue, deformed new leaves, interveinal chlorosis and bronzing of leaf tissue. Zinc deficiency in corn is called "white bud" because the young bud turns white or light yellow in early growth. Leaves may develop broad yellow bands (chlorosis) on one or both sides of the center mid-rib. Other symptoms include bronzing of rice, rosette of pecans, "little leaf" of fruit trees and severe stunting of corn and beans. Deficiency symptoms occur most often on alkaline soils, or soils with high available P levels.

Molybdenum

Molybdenum is an immobile element and symptoms occur on the younger leaves first. Symptoms may include interveinal chlorosis, wilting and marginal necrosis of younger leaves. Legumes which are deficient in molybdenum usually turn pale yellow and become stunted, similar to N deficiency.

Molybdenum deficiency occurs principally on very acid soils. Molybdenum deficiency symptoms show up as a general yellowing and stunting of the plant. A deficiency can cause N deficiency symptoms in legume crops such as soybeans and alfalfa, because soil bacteria on legumes must have Mo to help fix N from the air. Molybdenum becomes more available as soil pH goes up, the opposite of most other micronutrients. So, deficiencies are more likely to occur on acid soils. Sandy soils are deficient more often than finer-textured soils.

Chlorine

Chlorine is a mobile element. However, symptoms usually appear on the younger leaves first. The younger leaves wilt then become chlorotic. Deficiency may occur in well drained soils under high rainfall conditions, especially where there has not been applications of chlorine containing fertilizers. Fertilizers which contain muriate of potash (KCl) contain ample quantities of chlorine

SOIL PROPERTIES THAT INFLUENCE NUTRIENT AVAILABILITY

Cation Exchange Capacity

The capacity for a soil to retain nutrients varies among individual soils. This capacity is directly related to the cation exchange capacity (CEC) of the soil (see section 2). Many of the important plant nutrients are cations, or in other words, are positively charged ions. The most important cations which are retained by the negative charges in the soil include:

$$NH_4^+, \ Ca^{2+}, \ Mg^{2+}, \ K^+, \ Na^+, \ Al^{3+}, \ H^+$$

The soil behaves similar to a type of magnet, attracting and retaining positively charged cations against the leaching. This retention is of extreme importance to plant production because those cations that are being retained by the soil are available for plant absorption and are not being lost from the soil system by leaching. Cations that are retained in this manner are called "exchangeable cations". They may be exchanged or replaced by other cations or they may be absorbed by plants. As the CEC of the soil increases, the capacity the soil has to retain and provide cations in a form available to plants increases. Generally, the fertility and productivity of a soil are greatly influenced by its CEC.

Where soils are highly weathered and organic matter levels are low, CEC values are low. Where less weathering has occurred and organic matter levels are usually higher, CEC values can be quite high. Clay soils with high CEC can retain large amounts of cations against loss by leaching. Sandy soils, with low CEC, retain smaller quantities. This makes timing and application rates important in planning a fertilizer program. For example, it may not be wise to apply K on very sandy soils in the fall to serve next spring's crops, especially where fall and winter rainfall is high. But enough fall K for one or more future crops can be safely applied in a single application on clayey soils.

Percent base saturation is the percent of total CEC occupied by basic cations (K^+, Ca^{2+}, Mg^{2+}). The concept of base saturation has been used in the past to develop fertilizer programs. A commonly held belief is that certain nutrient ratios or "balances" are needed to insure proper uptake by the crop for optimum yields. Research has shown, however, that cation saturation ranges have little or no utility in the vast majority of agricultural soils. Under field conditions, ranges of nutrients can vary widely with no detrimental effects, as long as individual nutrients are present in sufficient levels in the soil to support optimum plant growth.

Nutrient Mobility in Soils

Nutrient mobility in the soil is dependent on various factors. Two very important factors are the charge of the ion and the size or diameter of the ion. Generally, the greater the positive charge and the smaller the ionic diameter of a cation, the more difficult it is for the cation to move through the soil profile. Clay and organic matter in the soil have negative charges and tend to attract positively charged cations. For example: Al is a cation which has a positive charge of three and a very small ionic diameter. For that reason, it is very difficult for Al to move through the soil profile. In the advanced stages of soil formation the more easily leached anions and cations are encountered at very low levels while Al is encountered at relatively high levels. The degree of strength with which cations are held by the soil can be depicted in the following manner:

$$Al^{3+} >> Ca^{2+} = Mg^{2+} >> K^{+} > Na^{+}$$

Essential nutrients, due to differences in their chemical properties, move through the soil profile at varying rates with excess drainage water. These differences are of paramount importance in understanding how to properly apply fertilizers, biosolids or manures in agronomic systems in order to effectively supply plant nutrients to the crop. Understanding these properties and their proper management are also important to avoid unnecessary expense and to reduce the possibility of surface and groundwater contamination.

Anions (negatively charge ions) in general are more easily leached than cations. For example, NO_3^- due to its negative charge and relatively large ionic radius, is not readily retained in the soil and is easily removed from the soil system by leaching with the drainage of excess soil water. Even though the plant available sources of P are anions, they are not easily leached through the soil profile due to their specific complexing (fixation) with various soil components. Applications of P, without incorporation, will undoubtedly result in the accumulation of this nutrient on the soil surface. Estimates of phosphate movement in most agricultural soils are on the order of 0.5 or 1 inch per year with an average rainfall of approximately 36 inches. Phosphate movement in sandier textured soils is considerably higher than in finer textured soils. However, leaching is not the principal mechanism of P movement. Due to the fact that P is readily complexed at the soil surface, the loss of P from an agricultural system is usually related closely to the erosion of the top layer of soil and the P concentration within that layer of soil.

pH Affect on Nutrient Availability and Uptake

Soil pH is a measure of the active acidity or alkalinity, i.e., a measure of H^+ concentration in solution which is a very small part of the total acidity. It does not indicate how much total acidity or alkalinity is present. Therefore, pH alone cannot be used to determine the lime requirement of a soil. Other factors such as soil type, crop to be grown, and kind of liming material to be used, must also be considered.

Soil pH and lime requirement are probably the most important tests made by soil test laboratories. A pH value of 7 is neutral. Those values below 7 are in the acid range while values above 7 are in the alkaline range. As pH decreases in the acid range, the degree of acidity increases rapidly (logarithmically). For example, a pH value of 5.5 is ten times more acid than 6.5 while a pH of 4.5 is 100 times more acid than 6.5.

Soil pH greatly influences plant nutrient availability and is largely responsible for the solubility of the various elements. Several essential elements tend to become less available as the pH is raised from 5.0 to 8.0. Figure 3-1 illustrates the relationship between soil pH and the plant availability of nutrients.

Most crops grow well in the pH range 6.0 to 6.5. Legumes generally grow better in soils limed to pH values of 6.2 to 6.8. Alfalfa and sweet clover are less tolerant of acid soil conditions than are other legumes. Most of the common horticultural crops grow best in soils limed to pH 5.8 to 6.2. Some crops or plants grow best in strongly acid soils (below pH 5.2). These include such plants as blueberries, mountain laurel, and rhododendron. Tobacco, on the other hand, grows well in the pH range of 5.6 to 6.0.

Potassium, Ca and Mg generally are not as available for plant uptake in acid soils because these basic cations have been leached out of the soil profile during the soil formation process. Generally, these cations are found in greater concentration and therefore, more available, in soils with pH levels greater than 6.0.

Phosphorus availability is related to many complex reactions in the soil and its availability to plants is dependent on many factors. Plant availability of this nutrient is generally greatest in the pH range of 5.5 to 7.0. At pH values less than 5.5, the solubility and reactivity of Fe and Al are greater, which can react with P forming iron and Al phosphates, which are not readily available for plant uptake. At pH values greater than 7.0, Ca exists at greater concentrations, and P can easily react with Ca to form relatively insoluble Ca phosphates which are not readily plant available.

In general, micronutrients are more readily plant available at pH values of less than 6.0. Notable exceptions to this are Mo and B which become less available as soil pH decreases. Conversely, B also becomes less available in soils where the pH exceeds 7.0 which is primarily due to the fact that at higher pH levels there tends to be higher Ca levels in the soil which can interfere with B uptake.

At pH values less than 5.0, Al, Fe and Mn are often soluble in sufficient quantities to be toxic to the growth of some plants. In the case of Al, this element generally exists as some form of Al hydroxide at pH values greater than 5.0. Aluminum hydroxides are relatively insoluble and pose limited danger to the normal development of plants. However, at pH values less than 5.0, the aluminum hydroxides degrade and exchangeable Al^{+3} can exist in significant amounts. High concentrations of exchangeable Al are toxic and highly detrimental to proper plant root development.

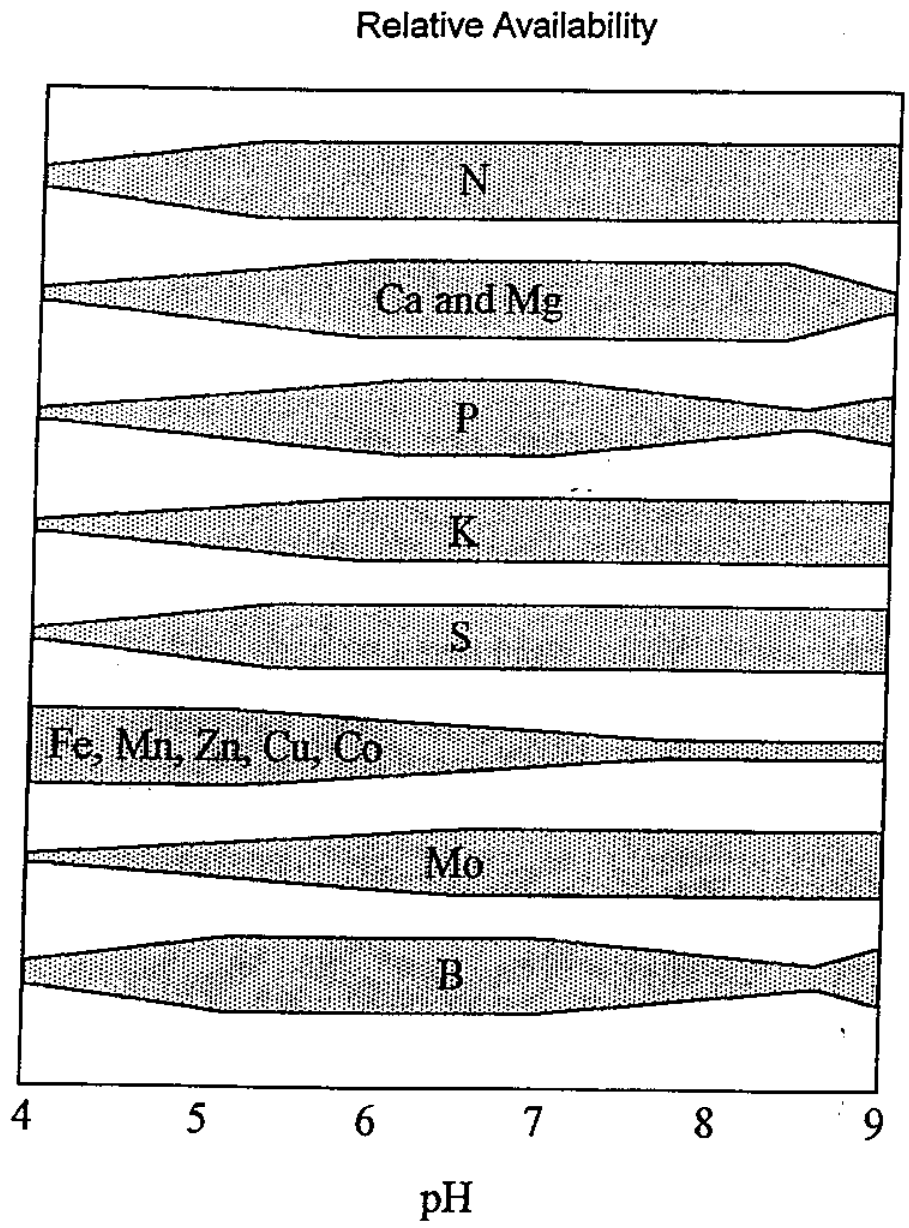


Figure 3-1. Effect of pH on Nutrient Availabilities for Plant Uptake

As pH values increase, the potential for micronutrient deficiencies increase. Molybdenum and Cl are the exceptions. As pH increases, Mo availability goes up, while Cl availability is unaffected. This is one reason liming acid soils can affect soybean yields as much or more than Mo seed treatment does. Relative amounts of micronutrients in the soil, especially metals, determine their availability and may be more important than absolute amounts of each. This relationship can make soil test results misleading, unless the levels of other micronutrients (and major and secondary nutrients) are considered.

LIMING

Acidification is a natural process which occurs continuously in our soils and other regions of similar climate. It is caused by the decomposition of soil organic matter, the movement of acidified rain water through the soil, erosion of surface topsoils, and plant growth processes. The movement of water through soils slowly leaches basic elements such as Ca, Mg, and K below the plant root zone and increases the concentration of Al in the soil system. Soluble Al reacts with water to form hydrogen which makes the soil acid. Erosion removes topsoil and, in so doing, removes basic elements. Hydrogen (H^+) is also released into the soil by the root system of plants during respiration and ion uptake. Harvesting all or part of a crop, either directly or through livestock, may also remove basic or acid-opposing elements.

Crop yields have been limited by acid soil conditions on many farms in the Chesapeake Bay Region. With few exceptions, a Mid-Atlantic Region soil which has never been limed will be moderately, to strongly acidic. In fact, many soils that have not been limed within the past several years may be too acidic for optimum growth of many crops or plants. On the other hand, crops will grow well on organic soils (soils with more than 20% organic matter) when the soil pH is in the range of 5.0 to 5.5 because much of its acidity is derived from non-toxic organic matter functional group charges rather than toxic Al.

Liming benefits are both direct and indirect. Direct benefits of liming include the reduction in the activity or solubility of Al and Mn. Both of these ions in anything other than very low concentrations are toxic to most plants. Another direct benefit would be due to the application of Ca and/or Mg, both of which are plant nutrients and their concentrations are generally low in very acid soils.

Indirect benefits of liming are numerous. They include increased P availability on soils with extremely low soil pH values, increased availability of some micronutrients such as Mo, increased microbial activity (e.g. nitrifying and N fixing bacteria) and increased N fixation by leguminous plants. Increasing the soil Ca levels also helps to improve soil structure in many cases. Maintaining a proper soil pH also helps to improve the efficiency of some herbicides.

While liming has many beneficial effects, over liming can create several problems. Over liming can easily induce micronutrient deficiencies, especially with Fe, Zn, and Mn, in many crops adapted to low or moderate pH conditions.

Lime Requirement

Although soil pH is an excellent single indicator of soil acidity, it does not determine lime requirement. Lime requirement is the amount of agricultural limestone needed to establish the desired pH range for the cropping system being used. When pH is measured, only active acidity in the soil water is determined. Reserve acidity held by soil clay and organic matter must also be considered. Some method of relating a change in soil pH to the addition of a known amount of acid or base is necessary. Such a method is called lime requirement determination.

The lime requirement of a soil is not only related to the pH of that soil, but also to its buffer capacity which is controlled primarily by its CEC. Total amounts of clay and organic matter in a soil, as well as the kind of clay, will determine how strongly soils are buffered or how strongly they resist a pH change. Buffering capacity increases with the amounts of clay and organic matter. Such soils require more lime to increase pH than soils with a lower buffer capacity. Sandy soils, with small amounts of clay and organic matter, are weakly buffered. So they require less lime to change the pH.

The quantity of limestone that should be applied to any given area should be determined by a soil test. Many laboratories use special solutions to extract and then determine the amount of reserve acidity that exists in the soil. The known quantities of active and reserve acidity are then used to determine the amount of limestone necessary to be applied to cause an increase in soil pH. Often the proper amount of lime is determined (soil test) and then a poor job is done in selecting and applying lime. Factors to consider in selecting a liming material include the length of time between application of lime and planting of the crop, degree of soil acidity, value of the crop, and intensity of cropping.

Whether to use a quick-acting or slower-acting liming material frequently is a difficult or confusing decision. The time between application of lime and planting of the crop can be helpful in answering this question. If lime can be applied three to six months ahead of planting, then one of the more coarsely ground limestones can be used. Agricultural ground limestone (GL) or agricultural coarse ground limestone (CGL) perform best when applied in this manner. If lime is being applied just prior to planting, agricultural ground limestone, pulverized limestone (PL), or one of the burned or hydrated limes should be considered.

The degree of soil acidity can be important in deciding which liming material to use, especially for acid-sensitive crops such as alfalfa, sweet clover, trellis tomatoes, and certain other vegetables. In strongly acid soils it may be desirable to use pulverized lime or one of the burned or hydrated limes. These liming materials will benefit crops and reduce the level of soil acidity more quickly. The cost per acre may be somewhat more, however, improved crop performance may result in a higher net income.

The value of the crop should be considered in determining what lime to use, especially those crops that are acid-sensitive or have a critical pH requirement. The medium to coarse limestones have their maximum effect in a period of one to three years whereas the burned and hydrated limes have their maximum effect in three to six months, provided, of course, the lime is properly mixed with the soil.

Intensity of cropping is a factor in a liming program as it usually influences the frequency of liming. If more crops and/or greater yields are being produced, this results in increased removal of the basic elements, Ca and Mg. Also higher rates of ammonium and urea forms of N may be used. Such N forms increase the rate of acidification of soils. A soil test every two or three years will reveal the effect of intensive cropping practices and whether or not lime is needed.

Amount and Timing

The frequency of lime application varies with soil characteristics, intensity of cropping, and fertilization practices. Soil textures vary from loamy fine sand to clay loam. Sandy soils generally require less lime at any one time than silt or clay soils to decrease soil acidity a given amount. Sandy soils, however, usually need to be limed more frequently.

The procedure used in applying lime is perhaps as important as determining the correct amount and best type of lime for a given situation. The careless application of lime can result in loss of income and may lead to other soil difficulties. Soils are limed to correct the acid condition which has developed over time. However, soil can be over limed. This often happens when applications overlap too much in the spreading operation or if there is uneven distribution for other reasons. Factors that affect the pattern of distribution by bulk lime spreaders include the rate of application per acre, rate of speed over the ground, steadiness of the speed, and equal distribution of the lime by the spinners (or other spreading devices) to each side and behind the spreader.

Another important factor determining the effectiveness of lime is placement. Placement for maximum contact with the soil in the tilled layer is essential. To begin with, most common liming materials are only slightly soluble in water, so distribution in the soil is a must for lime reaction. Even when properly mixed with the soil, lime will have little effect on pH if the soil is dry. Moisture is essential for lime-soil reaction to occur. When applying large amounts of lime to clay soils, best mixing results from applying part before primary tillage and the rest after. On sandy soils, one application, incorporated by primary tillage will do.

Tillage affects

Lime moves slowly in soil from point of application; therefore, it should be mixed with the entire plow layer. Also, as acidity is reduced, the lime particles dissolve more slowly. Consequently, for lime to efficiently neutralize soil acidity in the primary root zone it should be mixed to plow depth. One exception to this is "no-tillage" corn. Research with this tillage method has shown that surface-applied lime has been effective in reducing soil acidity in the surface two to four inches of soil, especially those fields that have been limed to plow depth in previous years. The system of mulching used for this type of corn production more nearly maintains optimum moisture conditions in the surface soil, which has a favorable effect on the dissolution of lime and neutralization of soil acidity in the surface layer.

When possible, such as in the case of conventional tillage methods, lime should be mixed to plow depth. On moderately acid soils (pH 5.2 - 5.7), a single application of lime made either before or after plowing will usually give good results. Lime applied before plowing should be disked into the soil, then plowed. Similarly, lime applied after plowing should be mixed with the soil to a depth of 4 to 6 inches.

In some cropping systems, such as perennial sods, mixing is only possible before seeding. Once the sod is established, the lime must be topdressed. Surface applied lime reacts more slowly and not as completely as lime mixed with the soil. So fields should be re-limed before pH drops below the desired range to avoid excess acidity in the root zone.

NITROGEN

N Cycle

Modern agriculture has been developed with a large dependence on N fertilization. Nitrogen is one of the primary nutrients, and plants commonly contain between 2 and 4% N on a dry weight basis. In order for a plant to absorb so much N, it must be available in adequate amounts from the soil solution. However, this nutrient is not found as a constituent of rocks or minerals, but is found in large concentrations in the atmosphere in the form of inert N_2 gas. Approximately 78% of the earth's atmosphere is composed of N, but it is unavailable to plants in this form and must be transformed by biological or industrial processes into forms which are plant available. The N cycle is illustrated by Figure 3-2.

Nitrogen Fixation

Nitrogen can be fixed from the atmosphere either by natural or by synthetic processes. In either case, inert N_2 gas is transformed into forms which are plant available such as NH_4^+ or NO_3^-.

Biological processes:

Biological N fixation may be symbiotic or non-symbiotic. Symbiotic N fixation refers to microorganisms fixing N while growing in association with a host plant. It benefits both the microorganisms and the plant.

The most widely known example of such a symbiotic association is between *Rhizobium* bacteria and leguminous plants. These bacteria infect the plant's roots and form nodules. The bacteria within these nodules fix N_2 from the atmosphere and make it available to the legume. The legume contributes to the welfare of the bacteria by providing them with carbohydrates which they use as an energy source to fix the N. The quantity of N which may be fixed by *Rhizobium* are estimated to be between a few pounds in some cases to over 500 lbs/acre/year. This upper value was encountered in optimal conditions in some clover/grassland systems in New Zealand. Under our conditions, the quantity of N fixed by most leguminous crops is probably less than 150 lbs/acre/year.

From an agronomic point of view, it is very important to take into account or credit, a certain amount of residual N left in the soil from a previous legume crop (Table 3-6). Farmers can economize on N fertilizer costs and also reduce the potential for NO_3^- contamination of surface and groundwater resources.

Non-symbiotic N fixation is carried out by free-living bacteria and blue-green algae in the soil. The amount of N fixed by these organisms is much less than the amount fixed symbiotically. Some estimates of the N fixed by these organisms range from 20 to 45 lb/A, but a generally accepted figure is about 5 lb/A. From an agronomic standpoint, these sources of N are not very significant.

Table 3-6. Residual nitrogen provided by legumes.

Legume	Time passed and density of legume	Residual nitrogen (lb/acre)
Alfalfa	First year after alfalfa	
	50%-75% stand	110
	25%-49% stand	80
	0%-25% stand	40
	Second year after alfalfa	
	50%-75% stand	50
Red clover and trefoil	First year after clover or trefoil 25%-75% stand	40
Soybeans	First year after soybeans for grain	25

Source: PSU, 1990.

Atmospheric Additions:

Nitrogen may be fixed by the electrical discharge of lightening in the atmosphere. The heat from the lightening can form NO_3-N, which is then brought to the earth through rainfall. Industrial pollution may also contribute to the N level of rain or snow, which may be important at the local level. However, the amounts of N generally brought to the soil through these processes is probably on the order of 5 to 15 lbs/acre/year.

Synthetic or Industrial Processes of Nitrogen Fixation:

Industrial processes can fix N in plant available forms. The most important process synthesizes ammonia (NH_3) from N and hydrogen (H), shown as follows:

$$N_2 + 3H_2 \text{ ———— } > 2NH_3$$

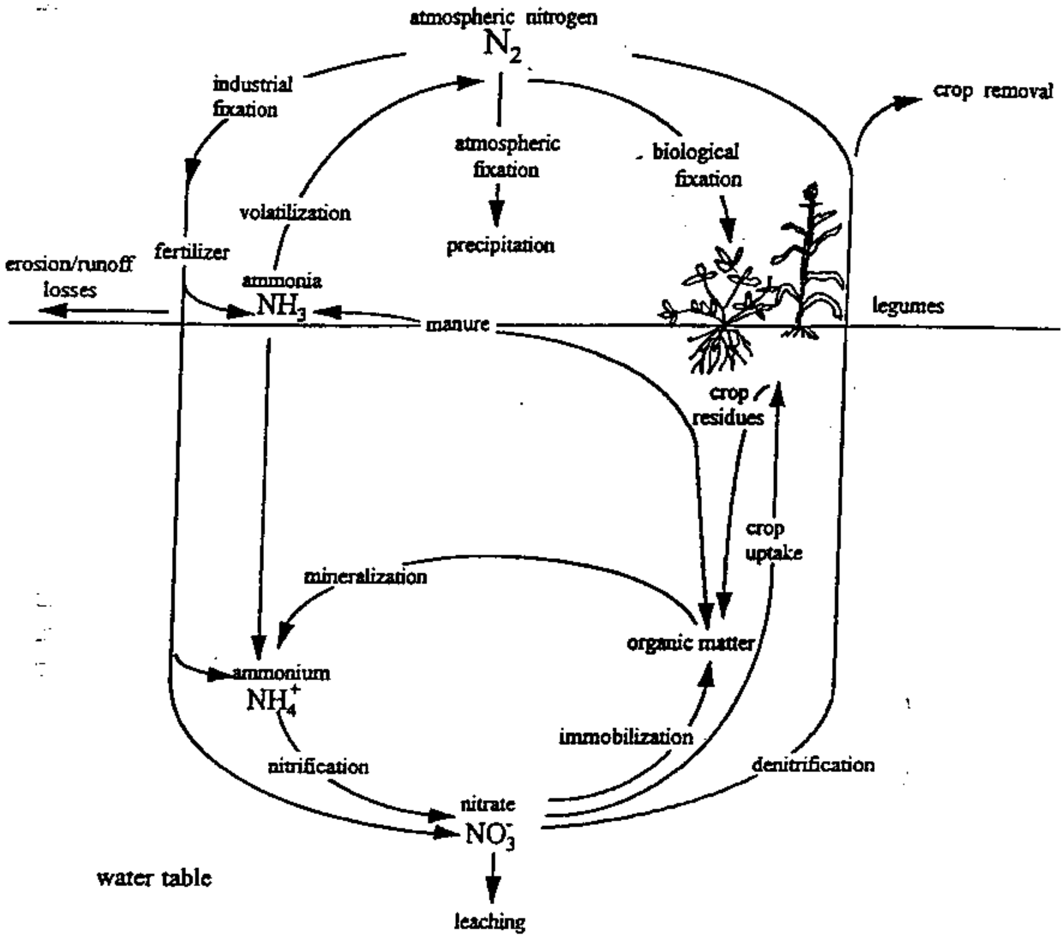


Figure 3-2. The Nitrogen Cycle.

Hydrogen (H_2) is usually obtained from natural gas and nitrogen (N_2) comes directly from the atmosphere. Once in the ammonia form (NH_3), it serves as the raw material for many other materials that contain N, such as ammonium nitrate, ammonium sulfate, sodium nitrate, urea, aqua ammonia, N solutions and ammonium phosphates.

Immobilization and Mineralization of Soil Nitrogen

The "immobilization" of N refers to the absorption of plant available N forms (NH_4^+ and NO_3^-) by soil microorganisms and their transformation into amino acids and proteins. This form of N is no longer available for plant uptake and has been "immobilized" within the microbial biomass. At some future time, this microbial biomass will decompose. A by-product of the decomposition process is the breakdown of organic N sources and the liberation of plant available inorganic N forms (NH_4^+, NO_2^- and NO_3^-). The decomposition and liberation of NH_4^+, NO_2^- and NO_3^- from soil organic matter is known as "mineralization" because mineral forms of N are liberated. Plant uptake of available soil N results in removal of N from the soil system.

The soil contains a relatively large proportion of unavailable (organic) N and a small proportion of available (inorganic) N, illustrated in Figure 3-3. Organic N may represent 90 to 98 percent of the total N in the soil. Inorganic N usually represents only 2 to 10 percent. So the process by which unavailable organic forms are converted to available forms is important to plant growth.

Both immobilization and mineralization are ongoing processes in the soil and generally are in balance with one another (Figure 3-3). This is to say that just as much N is being liberated into the soil by mineralization (organic matter decomposition) as is being immobilized (absorbed by plants and microbes). However, this balance can easily be disrupted by the incorporation into the soil system of organic residues which have high carbon to nitrogen ratios (C:N).

When immobilization of soil N exceeds mineralization, there may be very little N available for growing crops unless N fertilizers have been applied in a band near the roots. This is called the NO_3^- depression period. It is a critical time for crops. How long it lasts depends on three factors: 1) the C:N ratio of the decomposing material, 2) the quantity of crop residue added to the soil, and 3) the environmental conditions in the soil. Adding more crop residue generally lengthens the period. Supplying adequate N generally shortens the period. To avoid the problem or to minimize its impact, residues should be incorporated well ahead of planting to allow early decomposition.

C:N Ratio

Shortly after the soil incorporation of organic residues which have a high C:N ratio, soil microorganisms begin to attack and decompose the material. The soil microorganisms utilize the carbon components of the residue as an energy source and require available N in order to form proteins for their bodies. There is extreme competition between the microorganisms for a limited amount of soil N. Microorganisms compete among themselves and against crops for N. During the decomposition process, available soil N levels drastically decrease and the carbon in the organic material is liberated as CO_2 into the atmosphere. Once the materials are decomposed, the microorganisms no longer have a food source and begin to die off. The decomposition of these microorganisms once again mineralizes the protein in their bodies and liberates plant available NH_4^+ and NO_3^-. This biological process can take a great deal of time and is dependent on soil temperature, soil moisture levels, soil chemical and fertility conditions, and the quantity of residues incorporated into the soil. The process can be accelerated by applying N fertilizer sources at the time of incorporation of these residues to supply sufficient N to maintain the activity of the microorganisms.

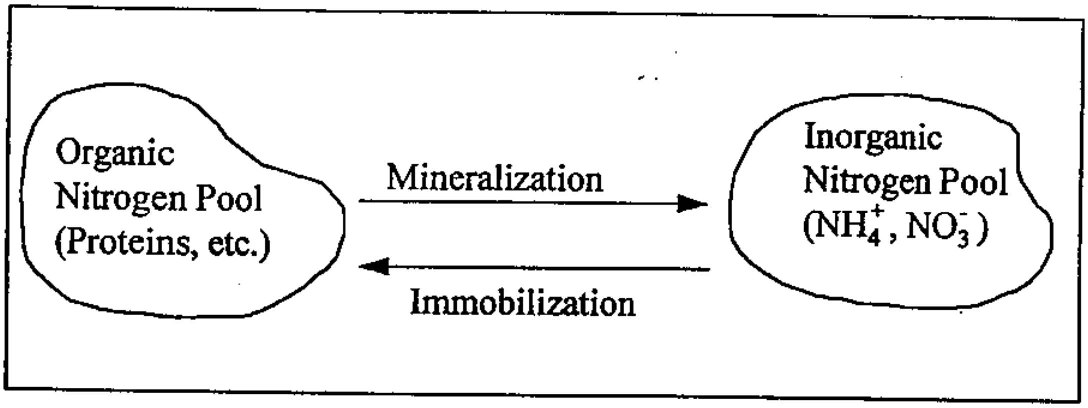


Figure 3-3. Forms of Soil Nitrogen.

Mineralization and immobilization occur simultaneously in soils. Whether the soil shifts toward an organic or inorganic N pool depends largely on the C:N ratio of the decomposing organic materials. Materials with wide C:N ratios (above 30:1) favor immobilization. These residues include materials such as hay, straw, pine needles, cornstalks, dry leaves, and sawdust. Materials with narrow C:N ratios (less than 20:1) favor more rapid mineralization. Organic materials having this C:N rate include alfalfa, clover, manures, biosolids, and immature grasses. At C:N ratios in the range of 20 to 30:1, the two processes are about equal.

Nitrification

Nitrification refers to the biochemical oxidation in the soil of the ammonium (NH_4^+) form of N to the nitrate (NO_3^-) form. The ammonium may originally come from the application of fertilizers or from the mineralization of organic residues. Basically, this is a two step process that requires the presence of soil dwelling bacteria (*Nitrosomonas* and *Nitrobacter*) to oxidize the ammonium:

$$2NH_4^+ + 3O_2 \xrightarrow[\textit{Nitrosomonas}]{} 2NO_2^- + 2H_2O + 4H^+$$

$$2NO_2^- + O_2 \xrightarrow[\textit{Nitrobacter}]{} 2NO_3^-$$

The resulting NO_3^- is highly mobile in soils and is easy lost from the soil with water that moves downward or laterally through a soil profile. Nitrate is a potential pollutant if excessive quantities reach surface and groundwater supplies.

Nitrification is important for several reasons:

1) Nitrate is readily available for use by crops and microorganisms. Organisms also use NH_4^+, under aerated conditions.

2) Nitrates are highly mobile in the soil. They move freely with soil water. Much NO_3^--N may leach through the soil profile, more on deep, sandy soils than on fine-textured soils with moderate drainage and high rainfall. Nitrogen management, though, can control leaching into groundwater.

3) Nitrates can be lost through denitrification, a process whereby NO_3^- is reduced to gaseous nitrous oxide (N_2O) or elemental N (N_2) and lost to the atmosphere.

Often there is much confusion in the terminology used to express NO_3^- concentration in the soil and water. Generally, the proper way to express NO_3^- concentration is based on the N equivalency and should be expressed as NO_3-N, or in the concentration of elemental N that was encountered in the NO_3^- form. If NO_3^- is expressed as NO_3^-, it refers only to the concentration of the NO_3^- anion.

The following conversions are based upon molecular weights:

To convert NO_3^--N to NO_3^-:

$$NO_3^- \text{-N} \times 4.4 = NO_3^-$$

To convert NO_3^- to NO_3^--N:

$$NO_3^- \times 0.23 = NO_3^- \text{-N}$$

During the nitrification process two H^+ ions are produced for every NH_4^+ cation involved in the process. The H^+ cations accumulate and significantly reduce the pH of the soil. The application of any fertilizer which carries part of its N in the ammonium form will ultimately decrease the soil pH due to the nitrification process. Ammonium sulfate, for example, will therefore drastically reduce the soil pH of agricultural soils. In order to not induce problems with soil acidity through the use of ammonium fertilizers, it is recommended that a well planned liming program be an integral part of the farming enterprise.

Leaching and Runoff

An important source of N loss is through leaching and runoff. Leaching occurs when inorganic forms of N, particularly NO_3^- are solubilized and carried with water through the soil profile or with surface waters. Apart from being an economic loss to the farmer, NO_2^- and NO_3^- are potential pollutants to groundwater and surface water resources. Factors which contribute to NO_3^- leaching or runoff include the following:

- Heavy, one-time applications of N fertilizers on sandy textured soils.
- Over applications of manures or sludge to land.
- Improperly timed applications of N fertilizers.
- Poorly designed or non-existent soil conservation measures.
- Periods of exceptionally heavy rain.

Volatilization

Volatilization, or the gaseous loss of ammonia (NH_3), may occur under certain conditions with ammonium fertilizers. In situations where the soil pH is alkaline, or where limestone has recently been applied on acid soils, applications of ammonium sulfate, urea or ammonium nitrate may result in the transformation of the ammonium (NH_4^+) to ammonia (NH_3) which may be lost to the atmosphere. This situation can be avoided by incorporating these fertilizers into the soil or waiting a least a month after limestone applications to surface apply ammonium fertilizers. Volatilization of ammonia may also be a significant pathway for N loss from surface-applied manures and, sometimes, biosolids, whose primary inorganic form of N is ammonia.

Denitrification

Denitrification is the microbial reduction of soil NO_3^- under anaerobic conditions. If nitrates are present in waterlogged soil there can be a transformation of NO_3^- into gaseous forms of N, such as N_2 and N_2O which can then be lost from the soil to the atmosphere. The losses of soil NO_3^- through denitrification are related to the degree of soil saturation, the duration of saturation and soil pH. Obviously, the greater the soil saturation and the longer the time of saturation favors denitrification. Alkaline soil pH also favors the denitrification process. From a practical viewpoint, the best way to prevent NO_3^- losses from denitrification is to promote farming practices that encourage adequate soil aeration, reduce soil waterlogging, and maintain soil pH in the 5.5 to 7.0 range.

Timing and Placement

The efficiency of N fertilizer is greatly influenced by the time of application. Factors determining the optimum time of fertilization are the crop grown, climate, and soil properties. Economic advantages from applying all the N fertilizer in the fall or early spring at planting are often offset by the lower yields obtained. The most common reason for the reduction in yield is the loss of N by leaching as NO_3^-. These leaching losses are more prevalent on sandy soils under warm, humid conditions than on fine-textured soils in cooler regions with lower rainfall.

Fall application of N for corn in the Midwest is only slightly less effective than spring application. However, on several soils of the Southeast, fall application of N was found to be only 49% as effective as spring application in increasing corn yields.

Winter small grain crops in the Southeast produce higher forage and grain yields when the N fertilizer is applied in split application. Yields of summer forage crops are increased by split application of N as compared with applying all the N in fall or spring.

Time of application can greatly affect the efficiency of N for crops grown with no-tillage. Crops grown with conventional tillage responded equally well to N applied in April or June. However, corn grown with no-tillage produced higher yields with June application than with April application of N. This difference in efficiency was a result of immobilization of the early applied N by soil micro-organism in the organic matter in the top few inches of soil.

PHOSPHORUS

Elemental P is very reactive chemically, so it is not present in the pure state in nature. It is found only in chemical combinations with other elements. Soil P comes largely from the weathering of apatite rock, a mineral containing P and Ca, along with other elements such as F and Cl. As apatite breaks down and releases P into the soil, several

P compounds are formed. The two orthophosphate ions taken up by plant roots are subsequently released. Orthophosphate ions are present in very small amounts in the soil solution.

Soluble P in the soil will form highly insoluble compounds with Ca, Fe and Al, whether it comes from apatite, fertilizer, manure or organic matter. Most of these compounds are not available to plants, and are said to be in residual or fixed forms. However, compounds such as dicalcium phosphate and octacalcium phosphate are relatively available to plants. Other plant available sources of P include decomposing organic matter, humus, and other forms of decomposing plants and animals. Research shows that organic compounds in the soil can help offset P fixation reactions.

The plow layer of most agricultural soils contains 800 to 1,600 lb of P per acre in combination with other elements, most of it in forms not available to plants. Only a very small amount of total P in the soil is in solution at any one time, usually less than 4 lb/A. The key to P fertility, then, is not large quantities of P in the soil solution, but the soil's ability to replenish that solution P. The P cycle is shown in Figure 3-4.

Availability

Phosphorus, of all the primary plant nutrients, is one of the most difficult to manage from an agronomic standpoint. This nutrient has very little mobility within soils due to the fact that it is readily bound by many different compounds and by the clay fraction of many soils.

Plant available forms of P are HPO_4^{-2} and $H_2PO_4^-$. The form of P that predominates in the soil solution is pH dependent. In soils with pH values greater than 7.2 the HPO_4^{-2} form predominates, while in soils with pH between 5.0 and 7.2, the $H_2PO_4^-$ form predominates. Regardless of the form, the concentration of HPO_4^{-2} or $H_2PO_4^-$, in soil solution is very low due to the reactivity of these P forms with other soil components.

In acid soils, available P tends to be fixed by Fe, Al and Mn into forms which are not plant available. In alkaline soils, P readily reacts with Ca to form relatively insoluble calcium phosphates. Soil P is most available in the pH range of 5.5 to 6.5 where there is a minimum of soluble Al, Fe, Mn and Ca to react with the P.

As root uptake exhausts the soil solution P, it must be replaced on a continuous basis. Phosphorus in soil solution is replaced about twice a day or some 300 times or more during the growing season of such crops as corn and soybeans. A soil must replenish or maintain sufficient levels of solution P to insure high yields. Figure 3-5 shows (1) how P is replenished in soil solution, (2) how it is made unavailable and (3) how it is removed (or lost) from the soil. Note the double arrow between "Phosphorus in Soil Solution" and "Minerals," indicating that a dynamic equilibrium exists.

Nearly all P in solution moves from the soil solids to the root in solution by diffusion, a slow and short-ranged process that depends on soil moisture. Dry conditions reduce diffusion sharply. How little does P actually move? If the P in a loamy soil is more than one-fourth inch from a root, it will never move close enough to be taken up by the root. It has been estimated that roots of a growing crop contact only 1 to 3% of the soil in the surface 6 to 7 inches. In practical terms, this means the soil P level throughout the root zone should be high enough to insure available P during every stage of growth.

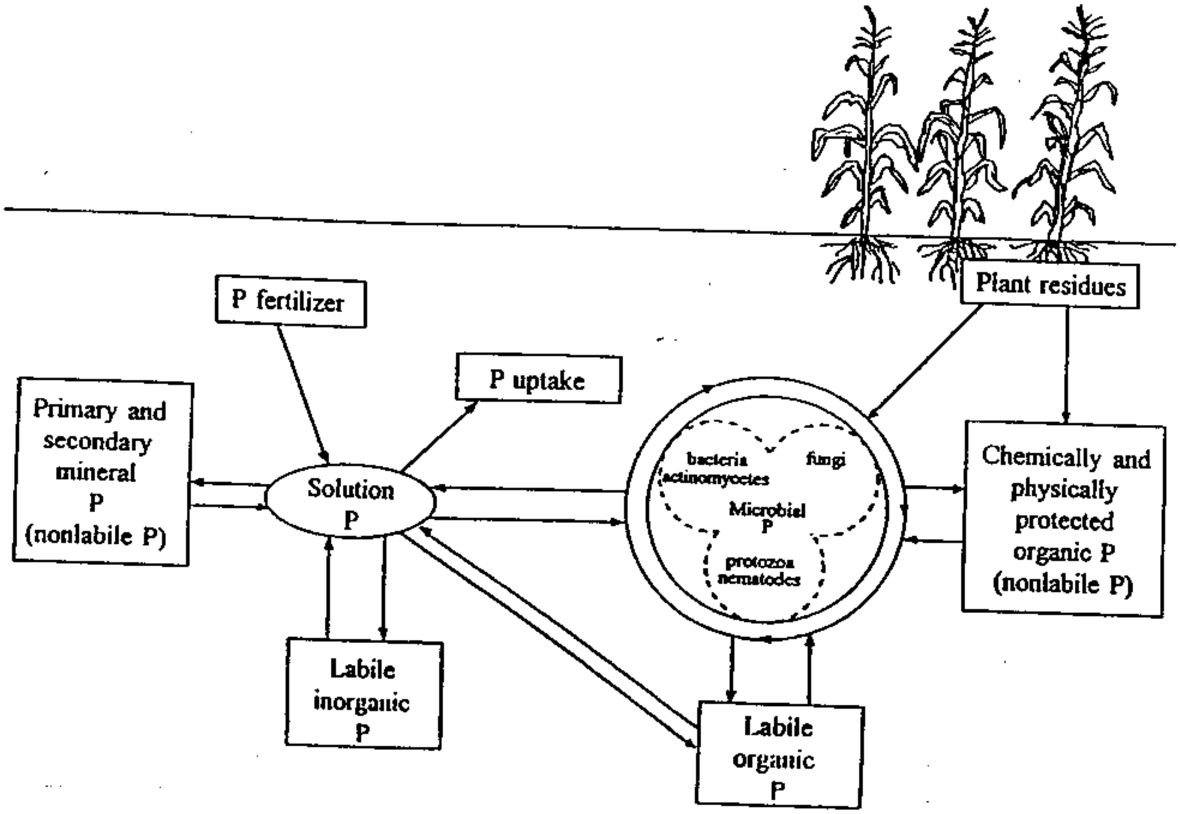


Figure 3-4. The Phosphorus Cycle.

Most crops recover only 10 to 30 percent of fertilizer P during the first year following application. Recovery percentage varies widely, depending on P source, soil type, crop grown, application method and weather. But much of the residual P will be available to succeeding crops.

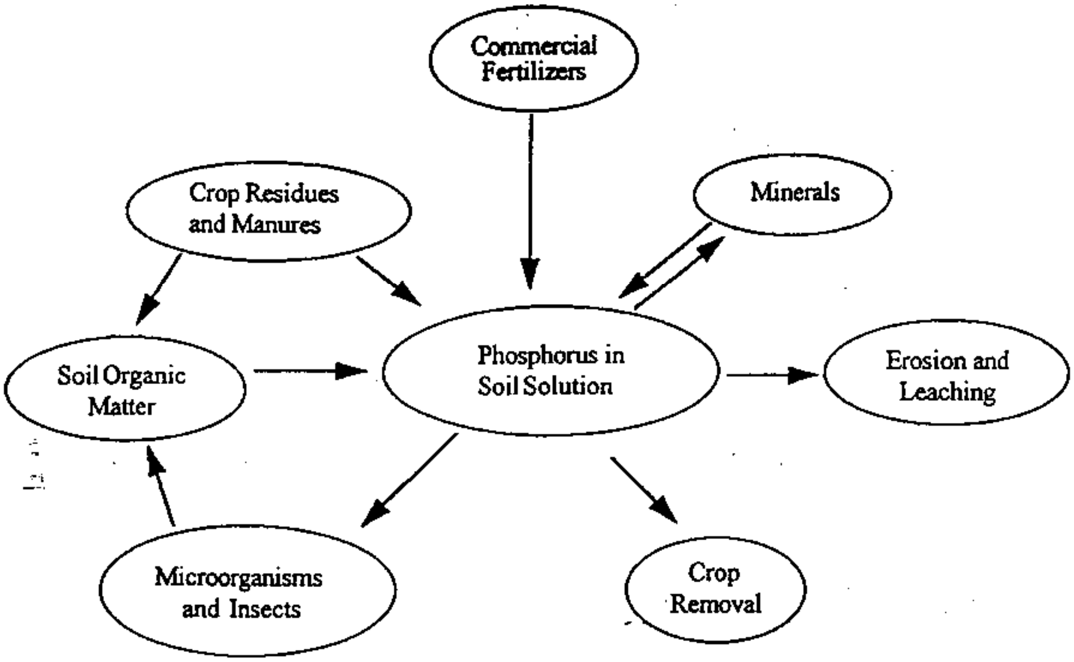


Figure 3-5. Phosphorus content of the soil solution.

Timing and Placement

Historically, most agriculturally important soils have had low native amounts of available soil P; however, through the years of intensive fertilization and sludge and manure application, many soils now test high in available P levels. In these cases, broadcast applications of fertilizers which contain P should be suspended. At most, a small amount of a banded starter fertilizer which contains P should be applied. Newly planted crops need a highly available P source in order to establish a vigorous root system early in the season, but once the root system begins to explore the entire soil volume, there should be adequate amounts of plant available P to maintain the crop. Sludge and manure applications should be made to satisfy the P requirement of the soil and should not exceed this amount whenever possible.

There is no set method of applying phosphate fertilizer. Many factors must be considered, including soil fertility levels, crop(s) to be grown, tillage methods, equipment, timing, and other management factors. Phosphorus fixation is an important point to consider when deciding how to apply P. More P fertilizer contacts more soil when it is broadcast and plowed down or disked in than when it is banded. So the amount of fixation is higher. Crops usually respond more to banded than to broadcast P on low fertility soils. Fixation is greater when fertilizer is broadcast. Further, banding puts a readily accessible P source in the root zone, making it positionally more available. Banding also concentrates other nutrients with the P, such as ammonium-N, which can slow fixation reactions and enhance P uptake.

Phosphorus Loss Mechanisms to Surface Waters

Phosphorus moves very little in most soils. It generally stays where it is placed by mineral weathering or fertilization, but can be a potential pollutant of surface waters. Phosphorus can easily enter surface water through dislocation and erosion of soil particles that maintain this nutrient tightly bound. Surface erosion (run-off) can remove soil particles containing P. Surface soils, which are the most susceptible to erosion, generally have much higher P levels than deeper soil horizons due to applications of fertilizers, manures and sludges that contain this nutrient. The Higher the P content of the soil, the more P will erode per ton of soil lost. Once into the surface water system, P is a major contributor to excessive algae growth which can have detrimental environmental consequences. Little P is lost by leaching, though it moves more freely in sandy than in clay soils. Erosion and crop removal are the primary pathways for P loss from most soils. Phosphorus dissolved in run-off water may be an additional P loss pathway for very high P amended soils.

POTASSIUM

The third primary plant nutrient is K. Potassium is required in approximately the same quantity as N. Plants absorb K in the cation form (K^+). It is vital to maintain adequate K fertility levels in the soil because soil K does not move much, except in sandy or organic soils. Unlike N and some other nutrients, K tends to remain where fertilization puts it. When K does move, it is usually by diffusion on slow, short trips through water films surrounding soil particles. Dry conditions slow this movement. High soil K levels speed it up.

Availability

Potassium exists in the soil in various forms: unavailable, slowly available and available. Unavailable soil K is chemically bound in rocks and minerals and becomes available only after intense weathering of these materials. Slowly available K is found "fixed" in the internal structure of clays and is only slowly available to the plant. This fixed K can be released when the clay fraction of the soil goes through wetting and drying cycles. Available K refers to the portion of K that is encountered in the soil solution or held on the exchange complex of clays and organic matter. Available K can be readily absorbed by plant roots. Soil colloids have negative charges and attract cations, such as K. Soil colloids repel anions, such as NO_3^-. These exchangeable cations are in equilibrium with those in the soil solution. This equilibrium may be represented as follows:

Exchangeable K <====> Solution K

Most soils contain 10 lb/A or less of solution K. This will supply an actively growing crop barely a day or two. But as the crop removes solution K, some of the exchangeable K moves into solution. It is replaced on the soil colloid by a different cation. This movement continues until a new equilibrium is established. So, through the cation exchange process, K is continuously available for plant growth, if the soil contains enough K at the beginning of the growing season to supply the crop's needs. Figure 3-6 illustrates the three forms of soil K unavailable, slowly available, readily available. It also shows how they relate to each other and to plant availability.

After being applied to the soil, K can have various fates:

1) The potassium cation (K^+) can be attracted to the exchange phase of the soil and organic matter where it is held in an exchangeable form for plant uptake.
2) Part of the K will remain in the soil solution.
3) The K which is present in the soil solution or in the exchangeable form may be absorbed by the plant.
4) In some soils, the K may become "fixed" in a slowly available form by the clay fraction of the soil.
5) Applied K may leach on sandy soils during periods of heavy rainfall.

At this time, K contamination of surface and groundwater is not considered a major environmental problem. However, techniques which limit the loss of K from agricultural soils should be used due to the economic loss of this primary plant nutrient. Techniques which reduce the loss of K from agricultural soils are based principally on the improvement of the CEC of the soil. Some of those techniques include:

1) Liming acid soils to increase the overall negative charge of the soil.
2) Incorporation of plant residues to the soil which will improve soil organic matter and also increase the CEC of the soil.
3) On sandy soils, total K applications should be split into two or more smaller applications during the growth cycle. Providing smaller quantities of K will improve plant uptake and reduce leaching losses.

Timing and Placement

Potassium fertilizers are completely water-soluble and have a high salt index. Consequently, when placed too close to seed or transplants, they can decrease seed germination and plant survival. This fertilizer injury is most severe on sandy soils, under dry conditions, and with high rates of fertilization - especially N and K. Some crops such as soybeans, cotton, and peanuts are much more sensitive to fertilizer injury than corn. Placement of the fertilizer in a band approximately three inches to the side and two inches below the seed is an effective method of preventing fertilizer injury. Row placement of K fertilizer is generally more efficient than broadcast application when the rate of application is low or soil levels of K are low.

Broadcasting and mixing with the soil before planting is usually a convenient and effective method of applying K fertilizers. Fertilizer injury is minimized by this method but on sandy soils some K may be lost by leaching, especially if considerable time elapses between application and planting time and heavy rainfall occurs. Plant-available K may accumulate in the subsoil of sandy Coastal Plain soils that are underlain by subsurface soil horizons of increasing clay concentrations. In some soils that contain clay minerals that fix K (2:1 type clays), some fertilizer may become unavailable.

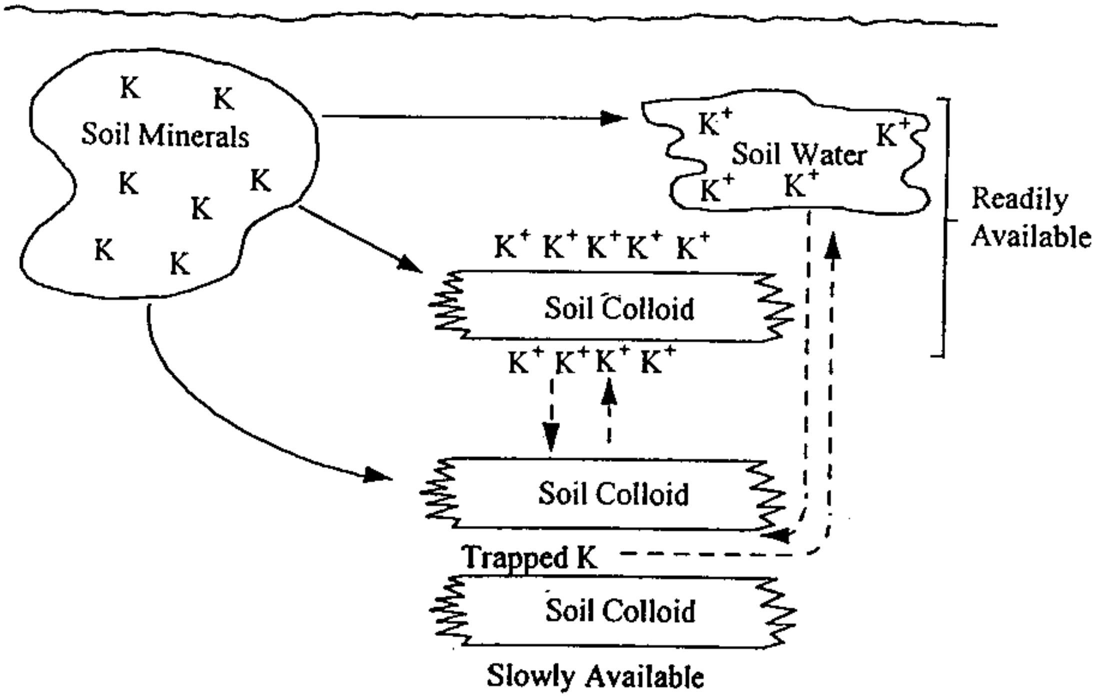


Figure 3-6. Forms of soil potassium.

Split application of K fertilizers on long season crops such as alfalfa or grass crops that are harvested several times during the growing season is often recommended. This practice prevents the crop from absorbing more K than is needed for maximum growth during the early growing season (luxury consumption) and provides adequate available K during the latter part of the growing season.

SECONDARY PLANT NUTRIENTS

The secondary plant nutrients include Ca, Mg and S. These nutrients are usually applied as soil amendments or applied along with materials which contain primary nutrients. Secondary nutrients are as important to plant nutrition as major nutrients, though plants don't usually require as much of them. Many crops contain as much S as P, sometimes more. Secondary nutrient deficiencies can depress plant growth as much as major nutrient deficiencies do.

Calcium and Magnesium

Calcium and Mg behave very much alike in the soil due to similar chemical properties. Both are cations, both have the same amount of positive charge (Ca^{+2}, Mg^{+2}), and their ionic radius is about the same. The mobility of both Ca and Mg is relatively low, especially compared to anions or even other cations such as sodium or K. Therefore, the amount of loss of these two cations through leaching is relatively low.

One problem concerning the application of carbonates, hydroxides and oxides of either Ca or Mg is the insolubility of these compounds in water. Surface applications of these compounds to the soil are not efficient ways of supplying Ca or Mg to established crops. These materials must be mixed with acid soils, with several weeks lead time, in order to liberate the Ca and Mg which they contain. One should not use these materials to try and correct a deficiency of either of these nutrients on an established crop. The sulfate and NO_3^- forms of Ca and Mg are quite water soluble and may be used to correct nutrient deficiencies of these nutrients. They are sufficiently soluble to apply through irrigation systems, granular soil applications or foliar applications.

Total amounts of Ca in the soil range from less than 0.1 percent to as much as 25 percent. Arid, calcareous soils contain the highest levels of Ca. Newly drained organic soils often contain very little Ca and may have extremely low pH values. Clay soils usually contain more Ca than sandy soils. Since Ca exists as a cation, it is governed by cation exchange phenomena just as other cations are, and is held as exchangeable Ca^{2+} on the negatively charged surfaces of soil clay and organic matter. It is usually the most dominant cation in the soil at moderate pHs, and normally occupies 70 to 90 percent of the sites on the soil's cation exchange complex in soils above pH 6.0. Like other cations, Ca is also present in the soil solution. It is part of the structure of several soil minerals. In fact, such soil minerals as dolomite, calcite, apatite, and Ca feldspars are a major soil source of Ca.

Soil Mg, other than that added in fertilizer or liming materials, comes from the weathering of rocks containing such minerals as biotite, hornblende, dolomite and chlorite. Being a cation, Mg^{2+} is subject to cation exchange. It is found in the soil solution and is adsorbed to clay and organic matter surfaces. Soils usually contain less Mg than Ca because Mg is not adsorbed as tightly by clay and organic matter and is more subject to leaching. Also, most parent materials contain less Mg than Ca. Although many soils contain enough Mg to support plant growth, Mg deficiencies frequently occur, most often on coarse-textured, acid soils developed under high rainfall conditions. Deficiencies can also develop on calcareous soils where irrigation water contains high bicarbonate or on alkali soils.

Sulfur

Sulfur is generally encountered in the sulfate (SO_4^{-2}) form in the soil. Elemental S may be used as a source of this nutrient, but it must first undergo a biological oxidation process that is dependent upon the *Thiobacillus* bacteria to produce sulfate. This process is extremely acid generating and occasionally elemental S is added as a soil amendment to decrease soil pH. The S cycle is illustrated in Figure 3-7.

In general, once in the sulfate form, such as gypsum ($CaSO_4$), potassium sulfate (K_2SO_4), magnesium sulfate ($MgSO_4$) and potassium magnesium sulfate (K-Mag), the sulfate does not contribute to soil acidity. However, there are other sulfate compounds which contribute greatly to soil acidity such as ammonium sulfate ($(NH_4)_2SO_4$), aluminum sulfate ($(Al_2(SO_4)_3$) and iron sulfate ($FeSO_4$). Ammonium sulfate has a very acidic soil reaction principally due to the nitrification of its ammonium component. Aluminum and iron sulfate are also very acidic due to the hydrolysis of the Al and Fe components of these materials. Unfortunately, many individuals believe that the "sulfate" is the source of the soil acidity and will refrain from applying gypsum or even potassium sulfate for fear of lowering the soil pH. These materials are neutral salts and will have little, if any, effect on the soil pH.

Sulfate, being an anion (SO_4^{-2}), is not strongly retained and can readily be leached from most soils. In well-weathered, naturally acidic soils, sulfate often accumulates in subsurface horizons, where positively charged colloids attract the negatively charged sulfate ion. Residual subsoil SO_4^{-2} from long term gypsum application on peanut fields can meet the S requirements of crops years after gypsum application has ceased.

Until recently, deficiencies of S were relatively uncommon because the burning of coal and oil contributed SO_4^{-2} to soil through atmospheric deposition. Also, commercial fertilizers previously contained significant amounts of S in their chemical composition. However, recently with the increased use of high analysis fertilizers such as urea and triple superphosphate, which contain little or no S, there has been much less application of this important plant nutrient. There have been reports of S response in some areas where previously the nutrient was available in sufficient quantities.

Much of the soil S in humid regions is associated with organic matter. Through biological transformations, similar to those of N, sulfate and sulfate compounds are produced that are available to the plant. More than 95 percent of the S found in the soil is tied up in organic matter. Other natural sources include animal manures, irrigation water and the atmosphere.

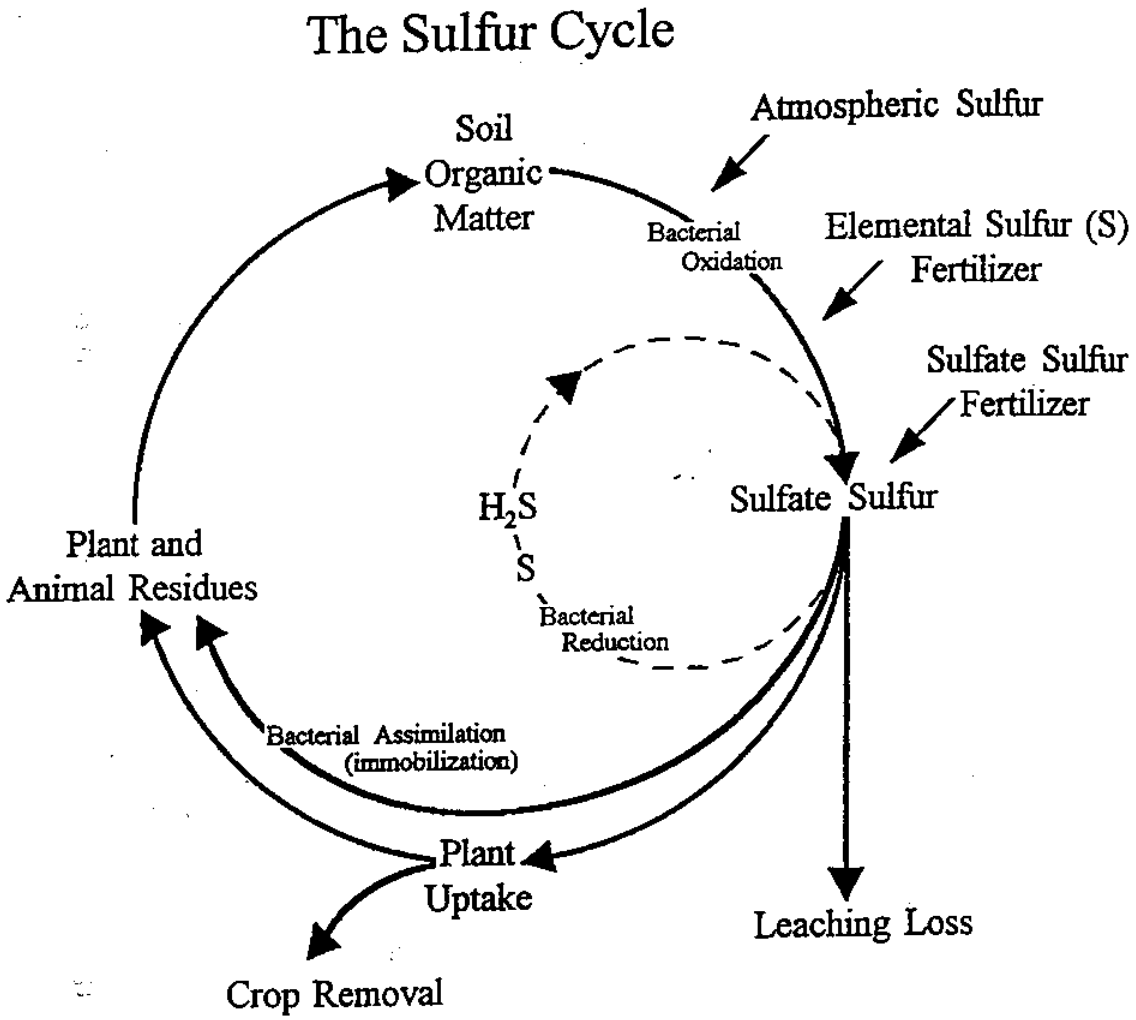


Figure 3-7. The Sulfur Cycle.

MICRONUTRIENTS

Seven of the 16 essential plant nutrients are called micronutrients: B, Cu, Cl, Fe, Mn, Mo, and Zn. Cobalt (Co) has not been proven essential for higher plant growth, but nodulating bacteria need it for fixing atmospheric N in legumes.

They are as important to plant nutrition as major and secondary nutrients, though plants don't require as much of them. A lack of any one of the micronutrients in the soil can limit plant growth, even when all other essential nutrients are present in adequate amounts.

The need for micronutrients has been known for many years. But their broad use in fertilizers is a fairly recent practice. Micronutrients become so important in recent years for several reasons:

1) Crop yields-Increasing per-acre crop yields remove higher amounts of micronutrients. As more and more micronutrients are removed from the soil, some soils cannot release enough of them to meet today's high-yield crop demands.

2) Past fertilizer practices-When crop yields were not so high and NPK fertilization was not as common as it is today, one of the three major nutrients usually was the first limiting growth factor.

3) Fertilizer technology-Today's high analysis production removes impurities much better than older manufacturing processes. So micronutrients are not commonly provided as "incidental" ingredients in fertilizers.

Micronutrient fertilization should be treated as any other production input. If a micronutrient deficiency is suspected, it can be pinpointed through soil tests, plant analyses, and/or local field demonstrations. One should develop the habit of closely observing the growing crop for potential problem areas. Field diagnosis is one of the most effective tools available in production management.

Soils vary in micronutrient content, and they usually contain lower amounts of micronutrients than major and secondary nutrients. Total soil content of micronutrients does not indicate amounts available for plant growth during a single growing season; however, it does indicate relative abundance and potential supplying power for a particular nutrient. Soil pH sharply affects micronutrient availability. Availability decreases as pH increases for all micronutrients except Mo and Cl. Figure 3-1 shows the soil pH range where each micronutrient is most available. Each micronutrient is discussed individually below.

Boron

Organic matter is the most important soil source of B. In hot, dry weather, decomposition slows down in the soil surface where most of the organic matter is found.

This can lead to a B deficiency. In cold weather, organic matter decomposition also slows, and low B release affects many cold crops (i.e., Brussel sprouts, radishes) and other early planted species. Plant availability of B is maximum between pH 5.0 and 7.0. At higher pH values, B uptake is reduced. Dry weather restricts root activity in the surface soil and can cause temporary B deficiency. Symptoms may tend to disappear as soon as the surface soil receives rainfall, and root growth continues, but yield potential is often cut.

Coarse-textured (sandy) soils, which are composed largely of quartz, are typically low in minerals that contain B. Plants growing on such soils commonly show B deficiencies. Boron is mobile in the soil and is subject to leaching. Leaching is of greater concern on sandy soils and/or in areas of high rainfall. Crops vary widely in their needs for and tolerance to B. Yet, the line between deficient and toxic amounts is more narrow than for any other essential nutrient. So B should be used very carefully, especially in a rotation involving crops with different sensitivities to B. It is important that B fertilizers are applied uniformly because of the narrow range between deficiency and toxicity. Rates of B fertilization depend on several factors including: soil tests, plant analysis, plant species, crop rotation, weather conditions, cultural practices and soil organic matter.

Copper

Organic soils are most likely to be Cu deficient. Such soils usually contain plenty of Cu, but hold it so tightly that only small amounts are available to the crop. Sandy soils, low in organic matter content, may also become deficient in Cu because of leaching losses. Heavy, clay-type soils are least likely to be Cu deficient.

Like most other micronutrients, large quantities of Cu can be toxic to plants. Excessive amounts depress the Fe activity and may cause Fe deficiency symptoms to appear in plants. Such toxicities are not common. Other metals in the soil, Fe, Mn, and Al, affect the availability of Cu for plant growth. This effect is independent of soil type.

Iron

Iron deficiency may be caused by an imbalance with other metals such as Mo, Cu or Mn. Other factors that may trigger Fe deficiency include:

1) Excessive P in the soil.
2) A combination of high pH, high lime, wet, cold soils and high bicarbonate levels.
3) Plant genetic differences.
4) Low soil organic matter levels.

Altering soil pH in a narrow band in the root zone can correct Fe deficiencies. Several S products will lower soil pH and convert insoluble soil Fe to a form the plant can use.

Manganese

Manganese deficiencies occur most often on high organic matter soils, and on those soils with neutral-to-alkaline pH and naturally low in Mn content. Although deficiencies are often associated with high soil pH, they may result from an imbalance with other nutrients such as Ca, Mg and Fe. Soil moisture also affects Mn availability. In organic soils, waterlogging favors Mn availability because reducing conditions convert Mn^{4+} to Mn^{2+} which is plant available. Manganese deficiency is often observed on sandy Coastal Plain soils under dry conditions that have previously been wet.

Molybdenum

Molybdenum becomes more available as soil pH goes up, the opposite of most other micronutrients. So, deficiencies are more likely to occur on acid soils. Sandy soils are deficient more often than finer-textured soils. Since Mo becomes more available with increasing pH, liming will correct a deficiency if the soil contains enough of the nutrient. Heavy P applications increase Mo uptake by plants, while heavy S applications decrease Mo uptake. Applying heavy amounts of S-containing fertilizer on soils with a borderline Mo level may induce Mo deficiency.

Zinc

Soils can contain from a few to several hundred pounds of Zn per acre. Fine-textured soils usually contain more Zn than sandy soils. But the soil's total Zn content does not indicate how much Zn is available. Several factors determine its availability. Zinc becomes less available as soil pH increases. Some soils limed above pH 6.0 can develop Zn deficiency, especially sandy soils. Zinc concentration in the soil can decrease 30-fold for every pH unit increase between 5.0 and 7.0. Zinc deficiency may occur on soils with very high P availability. Several plant species have shown Zn-P interactions. High levels of either Zn or P may reduce plant uptake of the other. Applying one on soils marginal in both may induce a deficiency of the other. Soil pH further complicates Zn-P interactions. Applying P to a soil with sufficient Zn levels will not produce a Zn deficiency. Consultants and laboratories caution that when P soil tests are high and annual P applications are still needed for maximum yields, Zn fertilization may be recommended.

Much Zn may be fixed in the organic fraction of high organic matter soils. It may also be temporarily immobilized in the bodies of soil microorganisms, especially when animal manures are added to the soil. At the opposite extreme, much of a mineral soil's available Zn is associated with organic matter. Low organic matter levels in mineral soils are frequently indicative of low Zn availability

Zinc deficiencies tend to occur early in the growing season when soils are cold and wet. This is due to slow root growth. The slow growing root system is unable to take up enough Zn to supply the upper portions of the plant. Plants sometimes appear to out grow this deficiency but the damage has already been done and yields can still be significantly reduced. Zinc availability is also affected by the presence of certain soil fungi, called microrhizae, which form symbiotic relationships with plant roots. Removal of surface soil in land leveling may remove the beneficial fungi and limit plants' ability to absorb Zn.

Chloride

About 60 lb/A of Cl per surface 2 feet of soil seems to be adequate for top yields of small grains. It can be provided by fertilizer or the soil. The most practical source is potassium chloride (KCl) which contains about 47 percent Cl. Preplant, at seeding and top-dressed applications have all been effective. Higher rates should be applied preplant or topdress. Chloride is highly mobile in the soil and should be managed accordingly.

Chapter 4. SOIL MANAGEMENT FOR CROP PRODUCTION

NUTRIENT NEEDS

Plants require 16 nutrients to complete the metabolic processes necessary for growth and reproduction (see Chapter 3). A deficiency in any of these nutrients will reduce yield, providing other factors, e.g., disease, weeds, insect pests, climate, are not more limiting.

Most nutrients are obtained from residual sources such as soil minerals and organic matter. Fertilizer is necessary only as a supplement for optimum growth. Fertilizer recommendations have been developed to provide the minimum amount of nutrient required without limiting yields under optimal cultural (management) and average climatic conditions. In order to produce high-yielding, profitable crops, fertilization, and liming should be carried out according to appropriate soil test results.

The timing and placement of nutrients directly affects crop utilization and potential losses of nutrients to the environment. Since N is the primary concern in timing decisions due to leaching potential, this section will deal primarily with major non-leguminous crops.

CORN

Nitrogen Uptake

Efficient fertility management of corn is critical to water quality because corn has among the highest N requirements of all crops. During the first 25 days after emergence, corn will utilize only 10 percent of its total N requirements (Figure 4-1). If all the N is applied at planting, significant portions that are not utilized can be lost through leaching, surface runoff, soil erosion, and denitrification. By applying approximately 30 lb/A of N at planting, and delaying the larger application until the corn is about 12 to 18 inches tall, a greater portion of the applied N will be used by the crop and less will be lost to surface and ground water. On fine textured soils, applying the sidedress N shortly after the 12 inch stage is suggested so rainfall will position the N in the corn rooting area by the time of maximum crop demand for N. Thus, on a farm with contrasting soil textures, one should begin sidedressing soils with the most clay, followed by sandier soils. By efficiently applying N in split applications, corn can generally be grown on approximately one pound of N per bushel of expected yield.

An additional reason for recommending that the total N application for corn be divided between an at-planting and a sidedressing application is that soils used in corn production differ in leaching potentials and can be subdivided into four N management groups. Sandy-textured soils, have a high potential for nitrate leaching into groundwater.

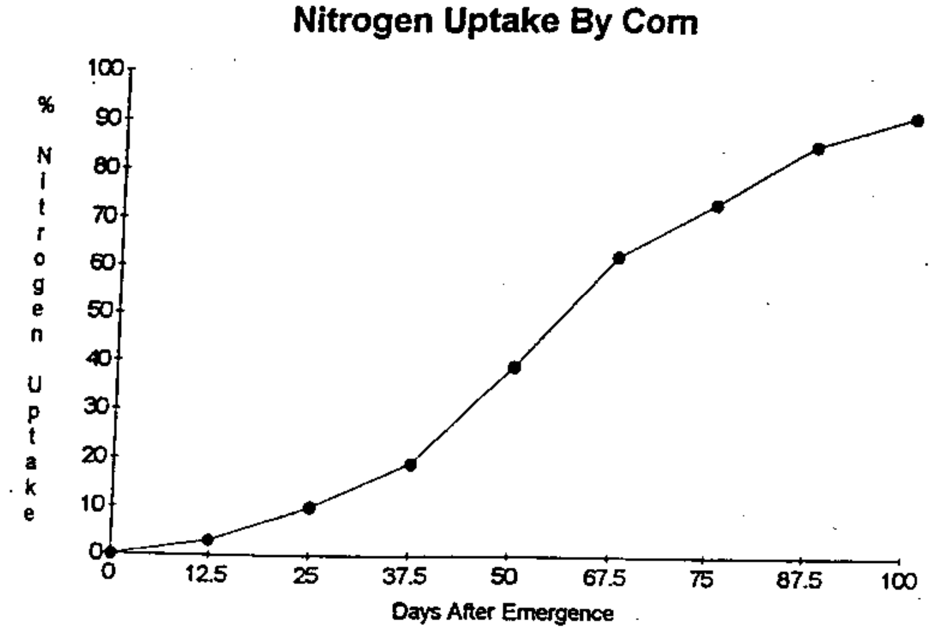


Figure 4-1. Nitrogen Uptake by Corn.

When all the N is applied at planting on these soils, there is a high probability that it will be leached below the rooting zone before it is taken up by the crop.

A second group of soils includes those with shallow profiles and those in which fragipans and clay pans restrict root penetration. In all cases, N applied at planting could very likely be moved beyond the reach of the shallow root systems of plants growing in these soils. Sidedressing will help avoid this.

Poorly drained soils must be drained before they can be cultivated and they may be sufficiently wet to cause significant N loss through denitrification. The likelihood of this happening is greater in early spring than it is later in the season.

A fourth group would include the deep, well-drained and moderately well drained soils with loam, silt loam and clay loam textures. They have a much lower nitrate leaching potential, permit much deeper root penetration and have a much lower potential for denitrification. For these reasons, there would be less reason for sidedressing the N. However, these are the soils most likely to contain residual N at sidedressing time at levels that would significantly reduce the total amount of N needed to finish the crop. This would be particularly true if the corn were following a legume such as alfalfa, red clover, a pasture sod that contained clover, or applications of manure or sewage sludge. If all the N is applied at planting; there is no opportunity to adjust the rate based on a nitrate soil test taken when the corn is about 12 inches tall.

Nitrogen at Planting

For most efficient use, N applied at planting time should be banded two inches beside and two inches below the row at the rate of 20 to 40 pounds per acre. Alternatively, if N must be broadcast at planting due to the lack of a starter fertilizer attachment, 50 to 70 pounds should be applied at planting, or no more than 50% of the total crop needs, particularly on environmentally sensitive sites such as high leaching index soils.

The use of low N, high P banded fertilizers should be avoided since not enough N will be concentrated near the young corn plant for optimum growth. Banded fertilizer grades which achieve application rates of 30-0-0, 30-15-0, or 30-30-0 (lb/A N-P_2O_5-K_2O) are recommended depending on the P soil test needs.

Phosphorus

Because P is relatively insoluble, timing of applications is not as critical to plant growth. However, P is susceptible to surface losses by direct runoff as dissolved P or attached to sediment particles. Significant P applications should not be left on the surface of bare soil. Small annual applications with no-till or minimum till systems should then be limited to starter and/or band applications. No-tillage systems offer many water quality benefits; however, the concentration of P at or near the soil surface can become very high under continuous no-till and runoff is likely to contain higher phosphate concentrations than if fertilizers have been subsurface or band-applied.

Band applied P reduces P fixation to soil particles and makes the P more available to growing plants. All applications should be made in a band, if possible for soils that have high soil test P concentrations. If soils test low in P, a combination of broadcast and band applications is preferred.

Potassium

Potassium applications are normally broadcast. If only small applications are needed, a band application may be used if placed at least two inches beside and two inches below the seed. If band application is used, it is important not to exceed a total of more than 80 pounds of N plus potash per acre to avoid salt injury to seedlings.

If significant broadcast applications are necessary, it is possible to supply the crop needs for the next crop in the rotation on soils with low leaching potentials. On soils subject to substantial leaching and on irrigated soils, split applications of potash may be beneficial.

Sulfur

Sulfur is contained primarily in the soil organic matter and as soluble sulfates in the soil solution. In low organic matter, sandy soils of the Coastal Plain, S deficiencies can occur in corn, especially when excess rainfall leaches the sulfate out of the sandy surface horizons and into the finer textured subsoil where the sulfate accumulates. Rates of 20-50 lbs/A are sufficient for high corn yields where S deficiencies exist.

Micronutrients

Micronutrients, if determined to be necessary by a soil test, are most efficiently applied in the starter fertilizer. If deficiency symptoms are present in the crop, foliar applications are generally the preferred method of application.

COTTON

Cotton is very sensitive to deficiencies of N, K, S , and B . These nutrients can be removed by leaching rains, especially in sandy soils. Of these elements, soil K is least subject to leaching and is the only one of the nutrients analyzed in a routine soil test sample. Recommended rates of N, S, and B are based on long-term field trials over a wide range of conditions. Annual applications of these nutrients are usually recommended for most soils. On soils subject to leaching, two or more applications may be required to improve fertilizer efficiency and ensure adequate availability throughout the growing season.

Liming

Cotton is among the most sensitive of the crops grown in the east to soil acidity. Marked growth and yield increases have repeatedly occurred when lime was applied to acidic soils. When the soil pH drops below 5.5, aluminum and manganese in Piedmont soils severely decrease early plant growth and results in fewer and smaller bolls with poor lint quality. The optimum pH for cotton ranges from 6.2 to 6.5.

Nitrogen Fertilization

More than any other nutrient, N can increase or decrease yields of cotton. Apply too little N, and yields drop sharply. Apply too much N or apply at the wrong time and plants will be slow to fruit, more attractive to insect pests, late to mature, more difficult to cover with crop protection chemicals, quick to develop boll rot, more troublesome and expensive to defoliate and control regrowth.

Rate

The recommended rate of N ranges from 50 to 70 pounds N per acre. The best rate for a particular field depends on soil texture, the previous crop, expected rainfall patterns or irrigation, and grower experience in that field. Without knowledge of the field and the specific management practices used, it is difficult to give specific recommendations, but some guidelines are available. Uptake studies across the cotton belt suggest that cotton needs approximately 60 pounds of fertilizer N per acre to produce one bale of lint. Following soybeans or peanuts, use a total N rate of 40 to 50 pounds per acre. Soils with more than 16 inches to the subsoil will require the highest rates of N, while loams and finer textured soils will require the lowest rates of N.

Timing

Fertilizer timing is important for cotton. Unlike crops such as corn and tobacco, only a small portion of the N is taken up before fruiting or flowering. About 45 days after emergence, nutrient uptake increases rapidly until it reaches a prolonged peak about two weeks after first bloom, when the processes of flower production, boll filling, and boll maturation create a heavy demand for nutrients. All too frequently, all the N is applied early in the season, or even before planting. While this may be the most convenient means of application, it makes little sense in an area subject to unpredictable leaching rains. The applied N remains exposed to leaching rains for more than 60 days before demand begins to peak. Leaching losses during this period will need to be accounted for and replaced to attain optimum yield. Heavy applications early in the season can also lead to excessive vegetative growth and delayed fruiting.

Cotton needs about 20 to 25 pounds N per acre to get the plant through sidedress time. If following peanuts or soybeans, no initial N may be required. The ideal time to sidedress would be just prior to first bloom, but uncertainty with rainfall dictates that N should be applied between first square and first bloom. On sandy soils subject to rapid leaching, the sidedress N can be split, with half applied about four weeks after emergence and the remainder in three to four weeks. The potential to reduce vegetative growth with Pix (a plant growth regulator) has led some growers to increase N rates with the hope of increasing yields. On-farm tests in North Carolina consistently show that cotton yield response to N is not affected by Pix applications. Additional N is not justified just because Pix will be applied.

Potassium and Sulfur

Although K is retained by soils more strongly than N, it can be lost through winter leaching. On sandy soils where this can occur, K should be applied in the spring rather than the fall.

In recent years, K deficiency symptoms have been reported even when soil K levels appear to be adequate. One reason for this deficiency is the use of very high yielding, determinate-type cultivars that set a heavy fruit load over a very short period. In these cases, application of foliar K (as potassium nitrate, KNO_3, at mid-bloom) has improved yield and quality. Where deficiencies from leaching are likely, sidedress applications of K have frequently solved the problem..

A two bale/acre crop will take up 20 to 30 pounds of S. Some S is supplied by the decomposition of organic matter and some is supplied by rainfall. Deficiencies are most likely to occur in highly leached, sandy soils with low organic matter content. If sufficient S is present in the subsoil and root growth is not restricted, older plants can take up enough for normal development. Additional S may still be needed for early growth. As a general rule, annual applications of 15 to 20 pounds of S per acre are suggested. Additional S probably will not be needed if cotton follows peanuts that received gypsum (landplaster). Foliar application of S to correct a deficiency is not recommended.

Liming To Supply Calcium and Magnesium

Lime is the primary source of Ca and Mg for cotton. A two-bale crop will take up 14 pounds of Ca and 23 pounds of Mg. Calcium deficiencies are seldom seen because acidity (low pH) and aluminum toxicity usually limit growth first. The Mg content of soils is usually less than that of Ca because less Mg is added, and it is more easily leached than Ca. Magnesium deficiencies are most likely to occur on sandy soils. Heavy gypsum or K applications can also result Mg deficiencies.

Boron

Boron is needed throughout the life of a cotton plant, but adequate supplies are especially crucial during flowering and boll development. Boron occurs in the soil as an anion and leaches readily. Boron that is held by the soil is associated primarily with organic matter and is released as the organic matter decomposes. Dry weather can trigger a temporary deficiency as organic matter decomposition slows. Also, dry weather slows root growth and limits B uptake. Thus, cotton grown on well-drained, sandy, low-organic-matter soils is more prone to B deficiencies, especially in years of high rainfall or in drought periods. Deficiencies can sometimes be induced by a soil pH greater than 6.5 or a heavy lime application in the recent past.

In many cases, the first real indication of a problem may be excessive growth. A close look at the plant will usually reveal abnormal fruit shed as the reason for this problem. If plants are not carefully monitored, the problem may not be noticed until harvest reveals an unexpectedly poor response to N and K applications.

Because availability of B is difficult to assess, but essential to successful production, annual application of B to cotton is recommended. Boron can be applied to the soil or foliage. The suggested rate of soil application is 1 pound of actual B per acre broadcast before or during seedbed preparation or 0.2 to 0.4 pound of actual B if a borated fertilizer is banded. Only a soluble B source, such as Solubor, should be used for foliar applications. For foliar application, use 0.5 pound of actual B applied at early bloom or 0.25 pound at early bloom and another 0.25 pound about two weeks later. Split applications are more efficiently taken up by the plant, and ensure availability during the critical bloom and boll-filling periods. If cotton is under drought stress during the fruiting period, a third foliar application may be justified. On light sandy soils that receive the preplant B applications, foliar application may be needed also if significant leaching occurs during the prebloom stage.

Manganese , Zinc and Copper

Deficiencies of copper, manganese, and zinc are seldom seen in cotton. Base applications of these elements on soil test reports.

Foliar Fertilization

Foliar-applied nutrients such as urea N, K and certain micronutrients can be absorbed through the leaf to increase yields only when deficiencies occur. The amounts of nutrients absorbed will not meet the full daily demands for these nutrients, but can supplement the soil-supplied nutrients. When deficiencies are detected using tissue analysis or petiole monitoring, foliar fertilization can improve yields. The real key is knowing when deficiencies are present, and the only way to be sure is to monitor plant nutrient levels.

Foliar applications for N or K are usually made using either urea (43-0-0) or potassium nitrate (13-0-44) as the source. Generally, the solution is made by mixing 10 pounds of the fertilizer material with 10 to 20 gallons of water for each acre to be treated.

The petiole (leaf stem) nutrient levels have proven to be the most effective indicator of plant-available nutrients. Petiole monitoring has been used primarily to monitor the status of N and K. To be successful, a petiole monitoring program requires an established "track record" of results, consistent sampling, an estimate of the fruiting rate, good insect control, and timely application of recommended treatments. By tracking the change in nutrient levels from week to week, deficiencies can be predicted before they occur. Petiole monitoring programs are most effective when soil moisture is good to adequate since drought causes a drop in petiole levels.

Starter Fertilizers

In a high management situation, starter fertilizers can enhance early season growth, promote earlier fruiting, and increase yields. Responses are usually greatest in cool, wet soils with low P levels, but are not limited to these conditions. Replicated trials in North Carolina with soils testing high in P have shown an average increase in cotton lint yield of 60 pounds per acre. The most consistent responses have occurred when the starter is placed in narrow band 2 inches below and 2 inches to the side of the seed.

PASTURE

Grass and Mixed Grass-Legume

Managing pastures so that they provide year-round grazing in the quantity and of the quality needed requires sound planning and an understanding of how to handle the plant-animal relationship so both will benefit. Pastures on productive soils should be given highest priority for fertilizer inputs.

Nitrogen

Mixed grass-legume pastures containing at least 25% legume do not require fertilizer N inputs because the N fixed by the legumes should meet the requirements of the grass. In some instances, particularly for stockpiling tall fescue for winter grazing, N fertilization is practical and economically advantageous. In deciding how much N to apply, the decision should be governed by the need for early and late grazing, the stocking pressure on the pasture, and type of livestock grazing the pasture. A good general recommendation is to apply half of the N in early spring and the other half in late summer or early fall.

Liming and Fertilizing

A common fertility problem in mixed grass-legume pastures is low P_2O_5. Applying P_2O_5 to soils containing low levels of this nutrient, but capable of high production, encourages growth of legumes. Grass growth will be stimulated by N fixed by legumes. Since very small amounts of P_2O_5 and K_2O are actually removed from the pasture by grazing animals, soil fertility levels remain fairly constant once they are built up by fertilization.

Lime to maintain a soil pH of at least 6.0. Response to fertilizer will be small if the soil pH is below 5.4; therefore, such areas should have a low priority for fertilization unless lime can also be applied. If the pH is below 5.0, do not fertilize unless lime is applied. It is especially difficult to keep clover in the stand if the soil is acid. Fertilizer and lime can be effectively applied any time of the year, but fall or spring applications are ideal.

On marginal soils, priority should be given to fertilizing slopes with a northern rather than a southern exposure. Slopes facing south green-up earlier in spring and grow longer in fall than slopes facing north. However, southern slopes are first to turn brown during dry periods because of higher summer temperatures. Cool season plants such as bluegrass often cannot survive these higher temperatures and the dry conditions that often accompany them.

Alfalfa

Soils Adapted to Alfalfa Production

Select deep, well-drained soils for growing alfalfa. Friable or crumbly clays, silt loams, and sandy loams are preferable, but alfalfa will grow well on most well-drained soils if properly limed and fertilized. Avoid soils that are subject to flooding and those likely to remain wet. Even when first-terrace soils are well-drained, they are not generally suited to alfalfa. Better and longer-lasting stands occur on second terraces and on uplands where drainage is adequate.

Lime Requirements

Alfalfa grows best and maintains stands longest at a soil pH of 6.5 to 7.0. Nitrogen fixation in the root nodules is reduced as pH decreases. Alfalfa is especially sensitive to aluminum toxicity and B deficiency in acid soils, therefore, have your soil tested frequently. If the pH is 6.0 or below apply lime at least 6 months before the alfalfa is seeded. In tilled seedbeds a sound practice is to plow-down half the lime and disk the remaining half into the seedbed after plowing. Applying needed lime on the soil surface at the time of no-till seeding is effective.

Fertilization for Establishment

Results from a soil test are necessary to determine the analysis and amount of fertilizer required to successfully establish a stand of alfalfa. Apply B at the rate of 2-4 lbs per acre. Alfalfa may respond to S application in some instances. Phosphate (P_2O_5) promotes seedling establishment, but excessive amounts of N and potash (K_2O) applied at seeding may reduce germination and the number of plants that survive the seedling stage. Where possible, apply fertilizer 6 months before seeding. This is particularly important for P_2O_5, since this nutrient does not readily move in the soil.

Fertilizing Established Stands

Adequate quantities of plant nutrients must be available in order to maintain vigorous, high-yielding stands of alfalfa. Each ton of alfalfa hay contains on a per acre basis about 60 lbs of N, 12 lbs of phosphate (P_2O_5) and 45 lbs of potash (K_2O). A 5-ton alfalfa crop removes on a per acre basis about 300 lbs of N, 60 lbs of P_2O_5 and 225 lbs of K_2O from the soil. Properly nodulated alfalfa fixes its N from the air, so additional N is not needed. Phosphate and potash, however, must be supplied. Apply B at the rate of 2-4 lbs per acre.

Fertilizer rates based on soil test results and applied at seeding will normally be adequate for the first productive year. The fertilizer program should begin following the first harvest season and continue each year as long as the stand is productive. Fertilizer may be applied during fall, the dormant season, or after the first or second cutting. Fertilizing during the fall helps the plants survive the winter and make a vigorous early start next spring. While research results indicate no advantage from split applications, producers with excellent stands seeking top production often apply fertilizer in the fall and again after the first cutting.

PEANUTS

Peanut plants have the ability to utilize fertilizer P and K from previous crops and often do not respond to additional fertilizer on fertile soils. Peanuts are legumes and do not require N fertilizer; however, they must be carefully managed for Mn, B, and Ca.

Manganese

Manganese is needed in small amounts for peanut production. Manganese availability to plants most commonly becomes critical with a soil pH of 6.2 to 6.5 or higher. Since peanut yields are not increased by pH values which exceed 6.2, it is recommended that peanut soils retain a pH value of 5.8 - 6.2. One or more foliar applications of the nutrient will be required if soil testing indicates insufficient concentrations of the nutrient or if visual plant deficiency symptoms appear. Soil application of manganese is ineffective in providing this element to the crop.

Apply 1-3 applications of manganese inorganic salts [Tecmangam, $MnSO_4$, $MnCl_2$ or $Mn(NO_3)_2$] as a foliar spray as needed between July 1 and August 15 at the rate of 1.0 lb/A elemental manganese per application. If other manganese materials are available, spray the material to deliver 1.0 lb elemental manganese per acre. Do not mix Solubor with the inorganic salts of manganese. Manganese EDTA chelate may be used; in which case, apply enough material to give 0.1 to 0.2 lbs/A of elemental manganese per application. When soil tests for manganese are 3.0 ppm or below, three preventative applications should be made at 2 week intervals, beginning mid June. Do not mix any manganese source with cupric hydroxide.

A number of liquid formulations containing manganese are available for use on peanuts. When used according to label instructions many of these products provide less than 1.0 lb elemental manganese per acre. Recent Virginia research results have shown that liquid manganese formulations should be applied in multiple applications, which supply a total of at least 0.5 to 1.0 lb/A elemental manganese per application. With manganese EDTA chelate the material should supply 0.1 to 0.2 lbs of elemental manganese per application. Application of manganese to the soil in fertilizer has been ineffective in providing this element to the crop.

Boron

Boron is needed during kernel development; hence, it should be applied about the time of, or immediately following, flowering. Boron is generally applied as a wettable powder or liquid spray with the leafspot fungicides. When plants are under water stress or if the recommended rates are exceeded leaf burning will occur. Excessive use of B can cause severely reduced yields even when foliage burning is not obvious. Boron can be applied satisfactorily as a soil application in fertilizer. Apply 0.5 lb elemental B per acre at the early bloom stage to prevent kernel damage. The application of B is especially important on light, sandy soils.

Landplaster-Calcium Recommendations

Peanut production requires supplemental Ca beyond what liming provides. Landplaster (or gypsum) is the most common source of soluble Ca for peanuts. Table 4-1 below shows the types, Ca content, and amounts to apply.

Table 4-1 Calcium Recommendations for Peanuts.

Source	% Calcium	Band 16-18	Broadcast
		———lb/A	———
US Gypsum Bagged	25	600	
US Gypsum Bulk 420 (gran.)	25		900-1200
US Gypsum Bulk 500 (gran.)	21		900-1200
Texas gulf Gypsum (Phosphogypsum)	17	—	1500-1800
Mineral By-Products			
Peanut Maker (Semi-Granular)	21	—	1100-1500

Time of application: June 10 - July 15.

Special Recommendation for Peanut Seed Production:

It is essential that peanuts being grown for seed receive a continuous available supply of Ca from pegging through seed development to insure high germination. This can be accomplished by either using two (2) applications or by increasing the amount used at the first application by 50%; being certain to apply it after June 10th. Specific recommendations are:

1. a) June 10 - June 30 - Apply 75% of recommended amounts above for non-seed crop.

   b) July 1 - July 20- Apply 400-500 lb/A of bagged or dry USG 420 or USG 500 landplaster in a band over the row.

OR

2. June 10 - June 30 - Apply the higher rate of the above rate ranges. <u>CAUTION:</u> If soil potash level is relatively low, this choice could cause a potash deficiency to occur unless potash is applied prior to planting.

SMALL GRAINS

<u>Nitrogen</u>

Small grain crops (wheat, barley, and rye) utilize relatively small amounts of N in the fall. Most uptake begins in late winter at the time of jointing. Figure 4-2 shows the N uptake curve for winter wheat, and Figure 4-3 shows the growth stages of wheat.

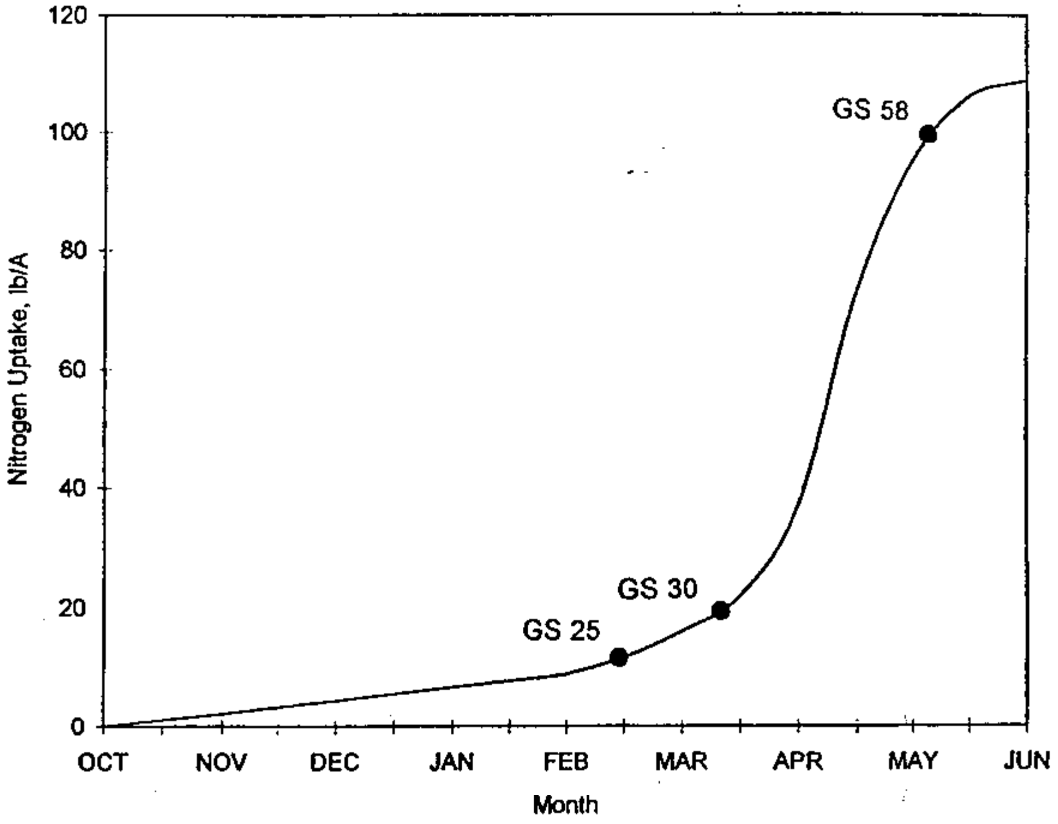


Figure 4-2. Nitrogen Uptake by Winter Wheat.

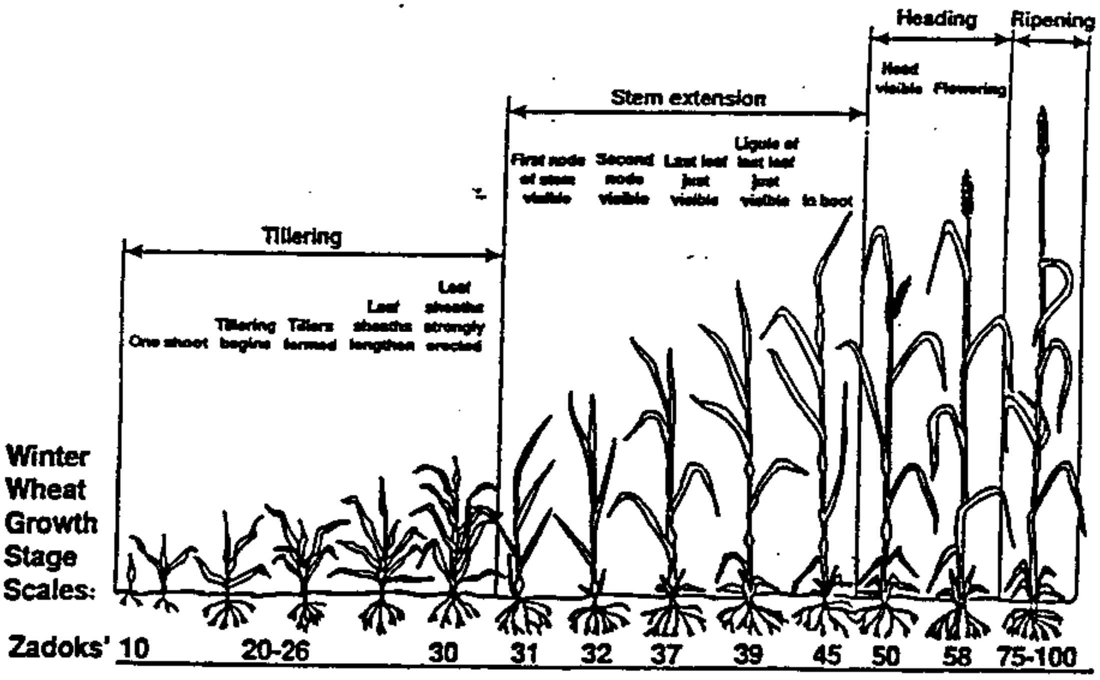


Figure 4-3. Zadoks Growth Stages of Wheat.

At Planting Application

With conventional tillage broadcast and incorporate up to 30 pounds N per acre during land preparation for planting. If no-till is used, broadcast up to 30 pounds N per acre shortly after planting. A nitrate soil test is often recommended in Virginia as the basis for modifying N rate given above. If the nitrate N in the top six inches is above 30 ppm, no fall N is needed. If nitrate N is below 30 ppm, apply 15-30 pounds of N.

Midwinter Application

In the southern portion of the Chesapeake Bay region (e.g., Virginia), a midwinter (December - January) N application may be needed if the crop is developing slowly. Three conditions should be met before this application is made. These are:

(1) Two or more rainfall events each of two or more inches have occurred during the October-December period;
(2) there are less than three tillers per plant and the crop has a pale green color, and
(3) the long range weather outlook indicates there may be several days during December and January in which maximum temperature will exceed 50° F.

If these conditions are met, apply 30 pounds of N per acre.

Late Winter Applications (February - Early March)

Research on N management in small grain production continues to show advantages to dividing this application between Zadoks growth stage 25 and at Zadoks growth stage 30 (Figure 4-3).

Phosphorus and Potassium Applications

Phosphorus and K applications to small grain are generally broadcast prior to planting. These applications should be large enough to supply nutrients to the succeeding crop if the small grain will be double cropped. However, on soils with high leaching potential, split applications of K are preferred.

Sulfur

Sulfur deficiencies will occur most often on coarse textured-soils with low organic matter contents. The entire S requirement should not be applied at planting due to loss potential. Apply 10 to 15 lb S/ acre to S deficient soils with the first N application in late winter/early spring. Determine GS 30 S tissue content, and if the N:S ratio is greater than 15:1, apply recommended S with the GS 30 N application.

Micronutrients

Micronutrient deficiencies can be identified with soil analysis, plant tissue testing, and historical field records that indicate previous micronutrient deficiencies. Generally, micronutrient deficiencies occur in fields with very high or low pH's. Careful monitoring of the crop can detect deficiencies and recommended rates of the nutrients can be applied to correct deficiencies.

SOYBEANS

Nitrogen

The soybean plant, being a legume, obtains its required N from symbiotic N fixation in root nodules when inoculated with soybean N fixing bacteria (*Rhizobia*). These bacteria have the capability to convert atmospheric N into forms usable by the soybean plant. *Rhizobial* inoculant should be mixed with the seed at planting in soils where soybeans have not been grown in three years. The recommended inoculation practice involves: a) purchase of fresh inoculant only, b) storage of inoculant in cool place, and c) thorough mixing of inoculant with slightly moistened seeds just before planting.

Producers sometimes use small amounts of N fertilizer (up to 20 lbs N/Acre), as a starter. Nitrogen fertilizer for soybeans is not recommended because response to fertilizer N additions of soybeans that are properly inoculated is unlikely, and N fertilizers inhibit *Rhizobial* activity.

Phosphorus and Potassium

Little or no yield response to added P can be expected from soybeans grown on soils testing high in P. If soil tests show a low or, sometimes, a medium level, P application will usually increase yields. Soil P may build up to high levels since it does not leach to any appreciable extent where land has been repeatedly fertilized for years. In such situations, top soybean yields can be produced without direct P application.

Yield response to added K when soil test levels are medium or above is rare, and direct K application may not always be needed. Potassium can be leached from sandy Coastal Plain soils and more frequent, light K fertilizer applications may be more efficient on these soils. Under conservation tillage, P and K accumulation near the soil surface has caused concern that these nutrients may become positionally unavailable. Most research has indicated that the availabilities of P and K are not adversely affected by surface accumulation which occurs in conservation tillage systems.

Liming, Ca, Mg, and S

Soybean growth and yield may be adversely affected by both low and high soil pH. When the soil pH is below 5.8, liming may improve soybean yield potential because the growth of nodule-forming N-fixing bacteria (*Rhizobia*) are favored and the availability of soil residual Mo and P are increased. Indiscriminate limestone applications may result in excessively high soil pH values (pH > 6.5), which can induce micronutrient deficiencies.

For most situations adequate levels of Ca and Mg can be maintained by using dolomitic lime. Where soil pH is above 6.0 and soil Mg is still low, it is generally advisable to apply needed Mg with a fertilizer material rather than by adding extra lime.

Soybeans also need 20-25 lbs per acre of S for top yields. Some S is present in organic matter and a sizeable quantity (1-15 lbs/A) is supplied through rainfall. Soil testing or plant analysis should be used to ascertain whether supplemental S additions should be made.

Micronutrients

Direct application of micronutrients to soybeans probably is not needed for most soils provided that they are adequately, but not excessively, limed. The average farm soil has inherent trace amounts of micronutrients and their availability to the soybean plant is closely related to soil pH. Researchers have found that a soil pH in the range of 5.6-6.3 is generally satisfactory for supplying micronutrients for normal soybean nutrition in most situations. One exception may be molybdenum (Mo). At low soil pH, reduction in Mo availability may cause Mo deficiency in beans.

Over-liming (pH > 6.5) can induce deficiencies of manganese (Mn), iron (Fe), zinc (Zn), and copper (Cu), particularly on very sandy soils. Where such deficiencies occur, soil or foliar applications of these micronutrients may be necessary for attaining normal growth and yield. On these soil types, manganese (Mn) deficiencies have been reported on coarse-textured, light-colored, sandy soils at pH levels as low as 6.2. To overcome Mn deficiency, apply 3/4 lb chelated Mn (elemental basis) or 1 lb inorganic Mn (elemental basis) per acre foliarly upon appearance of symptoms and prior to bloom. More than one application may be needed to correct the deficiency.

TOBACCO

Flue-Cured

Transplant Starter Solutions

The use of soluble fertilizer materials in the transplant water has historically resulted in reductions in plant stand and stunted growth. The probability of such an effect is great enough to discourage the use of starter solutions. If any benefit is to be expected from their use, it would be the ready availability of P to the transplant when soil availability may be lacking. This would be most important in years with a cool, wet spring. In recent years, new materials with relatively high P levels have become available.

Nitrogen

Flue-cured tobacco is very exacting in its N requirement. Inadequate N results in low yield and quality of tobacco. Excess N delays maturity and results in poor quality cured leaf. Excess N will also increase sucker growth which may lead to excessive use of maleic hydrazide (MH) and increase the severity of some diseases and insect problems.

It is well recognized that soils differ in their ability to hold N. Some of the more important soil characteristics affecting this are organic matter content, texture of the surface, and depth to subsoil. Fields with deeper, sandy topsoils require more N than those with shallower, heavier textured topsoils. For sandy loam soils of average fertility, suggested N rates for different topsoil depths are as follows:

Topsoil depth in inches	Nitrogen rate lbs/acre
0 to 12	50 to 60
12 to 18	60 to 70
18 to 24	70 to 80

At least 50% of the total N in the base fertilizers should be in the nitrate form.

Adjustment for Leaching

When leaching occurs, N and K in addition to the base amounts recommended may be necessary. The quantity of N and K required will depend on the amount of water that percolates through the plow layer and the stage of plant growth at the time this occurs. Although research information on nutrient replacement from leaching is limited, the information in the Table 4-2 may be used as a general guide for making leaching adjustments.

Applications of N and potash materials to replace elements lost through leaching should be made as soon as possible after heavy, slow rains. Waiting until deficiency symptoms develop before applying supplemental fertilizer is not recommended.

Phosphorus and Potassium

Repeated applications of larger quantities of P than plants can absorb, with essentially no loss from leaching, has resulted in a general buildup of this element. On soils with a medium soil-test P level, 40 lbs of P_2O_5 per acre are adequate to give maximum production and maintain the soil P level. Growth responses of tobacco to P application are observed more frequently early in the growing season than they are in final yield and quality.

Potassium requirements of tobacco are relatively high. Soils vary in their supply of available K, depending upon the parent material, previous fertilization and cropping history. Approximately 100-175 lbs of K_2O per acre are adequate for most soil conditions. Sources of N or K should not be those that contain chloride, which causes poor curing and adversely affects leaf burning.

Table 4-2. Nitrogen Adjustment for Excess Water[a]

Topsoil depth (to clay) in inches	Est. inches of excess[b] water percolated through soil	% of applied N to replace after transplanting weeks		
		1-3	4-5	6-7
Less than 10	1	0	0	0
	2	20	10	0
	3 or more	30	20	0
10 to 6	1	30	20	0
	2	45	30	10
	3 or more	60	40	15
17 or more	1	50	25	15
	2	75	35	20
	3 or more	100	45	25

[a] For each pound of N used as an adjustment for leaching, use about 1 pound of potash (K_2O) where recommended potash levels as a base application have been used.

[b] Excess water is that quantity percolating through the soil after the water-holding capacity of the soil has been satisfied.

Liming, Calcium and Magnesium

If the soil pH is maintained within the desirable range of 5.5 to 6.0 with dolomitic limestone, the available levels of Ca and Mg will generally be sufficient to meet the needs of the crop. Otherwise, 40 to 50 lbs/A of Ca and about 30 lbs/A of available Mg oxide (MgO) are needed from the mixed fertilizer.

Micronutrients

The need for the application of micronutrients such as B, Cu, Mn, and Zn has not been demonstrated sufficiently for tobacco to warrant general applications. It is definitely known that if applied at excessive rates, these elements am toxic to tobacco. Boron is the micronutrient most likely to be deficient for tobacco. Generally, 0.25 lb of elemental B per acre is sufficient to correct or prevent such deficiencies.

Time and Method of Application

The preplant fertilizer rates should not exceed 40 lbs N and 120 lbs K_2O per acre. Additional N and K_2O can be applied as a side application to obtain the total amount of nutrients desired. Side-dressing applications of the base rate of nutrients should be made as soon an the stand is established.

Burley

Most burley tobacco producers have practiced long term usage of complete fertilizer such as 5-10-15 and have built very high fertility levels in the soil. Soil test summaries over the past five years have shown that 70-80 % of soils analyzed for burley tobacco contain high levels of P and K and require little or no additional P or K for maximum yields.

Lime and Fertilizer Recommendations

Research results have shown no benefit of N application rates above 160-175 lbs N/A on fields producing yields less than 2,500 lbs/A. Whereas, on fields producing over 2,500 lbs per acre 200 lbs N/A is required. On many soils the recommended N may be broadcast and disked in prior to setting. However, on sandy textured well drained soils greater efficiency of fertilizer may be achieved by reducing the preplant applications to a maximum of 100 lbs N/A and topdressing the remainder at 30 days after setting. Increasing rates of N above the recommended rates significantly reduces use efficiency.

The recommended rate of P (P_2O_5) to be applied per acre should be based on the level present in the soil and the amount required to raise the soil test P to adequate concentration for maximum yields. Although low levels of P may severely stunt tobacco growth, there is no advantage in exceeding the recommended rates. Any P source may be used and should be thoroughly incorporated. This is especially important if the soil test level was low.

For burley tobacco, potassium sulfate (0-0-50) or potassium nitrate (13-0-44) should be used as a source of K. Also, do not use muriate of potash (0-0-60) as a K source as it contains chloride which causes poor curing and adversely affects burning of the tobacco product. For this reason, complete fertilizer such as 5-10-10, 8-8-8, etc., which are usually blended with muriate of potash (0-0-60), should not be substituted for either of the two materials listed or for a tobacco grade fertilizer.

Micronutrients will normally be adequate and no deficiencies of these have been identified in burley tobacco.

CONSERVATION TILLAGE AND RESIDUE MANAGEMENT

Conservation tillage has become an accepted cultural practice for many seeded row crops since its introduction in the 1950's. Acceptance can be attributed to a combination of events occurring concurrently including herbicide development and use, concern for soil erosion, and innovative equipment modifications.

Management practices that control storm runoff and soil erosion from agricultural land are often essential to the maintenance of soil productivity and to improved downstream water quality. Many cropped fields are losing soil to runoff at a much faster rate than it can be formed from the parent material or underlying rock layers. As topsoil is lost, soil tilth or structure becomes less friable, rainfall infiltration into the soil slows, and soil depth gradually decreases. The eventual result is a decline in soil productivity.

Runoff and soil erosion are the combined result of several factors including rainfall rate, soil cover, soil properties, length of slope, percent slope, and conservation practices used to conserve water and soil. Of these, percent slope, some soil properties, and rainfall rate are essentially uncontrollable. Changes to reduce the percent slope, for example, are not feasible. Soil properties such as the proportions of sand, silt, and clay cannot be altered. The given rainfall rate affects the amount of energy available for soil particle detachment. The factors affecting erosion that are controllable include the tilth of a soil, crop or plant cover, and length of slope. The erosion control practices in use today are based on modification of the controllable factors to reduce runoff and resulting soil loss.

Vegetative soil cover is the most significant factor in the control of runoff and soil erosion. A dense cover absorbs the energy of rainfall, decreases the flow and velocity of runoff, improves infiltration rate and soil moisture storage, and decreases soil particle separation and movement.

The tilth or friability of a soil affects its erodibility by influencing the rate and the amount of rainfall infiltration. The use of cropping and tillage systems that increase the organic matter content of soils generally improves soil friability and its resistance to forces of erosion.

Preventing or slowing runoff conserves water for the production of crops and, in turn, reduces soil erosion and the sedimentation of waterways. There are a number of practices for reducing runoff that are suitable for present-day agriculture. Most fit into the short-run framework of farming operations; nearly all have long-term benefits for the farm family and the general public. Effective conservation practices that can be adapted to different crops are discussed below.

Row Crops

Row crops are a major part of Chesapeake Bay region farming operations. Runoff and soil erosion are more difficult to manage on sloping land planted to row crops. Perhaps the most important factor contributing to erosion and soil loss on such lands is tillage. Tillage that turns the soil and buries plant residue exposes the soil to the erosive forces of wind and rain. Cropping systems that greatly reduce such exposure include no-till and minimum till.

No-till eliminates tillage of the soil except for that required to cover the seed. A cover crop may be grown and retained as a surface mulch. Herbicides are used to kill vegetative cover and to control weeds. This essentially eliminates the need for tillage in most years. The residue left on the surface greatly reduces the erosive forces of rainfall, conserves moisture, increases the efficiency of moisture usage by the crop, and makes it possible to row-crop moderately sloping land with very little soil loss (Table 4-3).

An additional benefit in the control of erosion is that the soil has vegetative cover the entire year except for a short time in the fall during establishment of a new seeding of small grain or cover crop (usually rye). This system can be used for growing corn, soybeans, and other row crops in rotation with or without forage crops.

Table 4-3. Effect of No-till and Conventional Tillage Systems on Soil Loss in Southern Illinois (4-year average).

Tillage System	Soil Loss (tons/acre/year)	
	5% slope	9% slope
Conventional tillage, wheat and corn double-cropped	3.04	8.42
No-till, wheat and corn double-cropped	0.34	0.54
No-till, continuous corn	0.25	0.36

Source: Rasnake, 1983.

Minimum tillage is a cropping system in which most of the soil surface is covered by plant residue or mulch. Some tillage, such as chisel plowing, is used to prepare the land for planting. Some runoff and erosion may occur, the amount being dependent upon the amount of tillage and soil exposure. Minimum tillage is best suited for gently sloping land, though in combination with strip cropping, filter strips, and contour planting, it can be used on moderately sloping land.

Contour farming involves the planting of crops on the contour. The rows are usually sloped to a small degree to permit drainage to a grassed waterway. Contour farming is best practiced on gently sloping land. In combination with terraces or strip cropping, steeper slopes can be cropped with effective control of erosion.

Strip cropping is the alternate production of row crops and forage crops, either planted on the contour or parallel. Strip cropping is very effective in the control of runoff and erosion, is economical and easy to establish. Such a cropping system is especially well suited in farming operations where some forage is needed for livestock or marketing.

Grassed waterways are drainageways that have been seeded to a sod crop to concentrate, slow, and filter runoff and to prevent gullying. Grassed filter strips in addition to their use in strip cropping, can be located along the banks of water courses to filter runoff, anchor soil particles, and protect stream banks against erosion. Used for this purpose, the minimum width of the grassed strip should be 12 feet, with the average being 20 feet. Such strips help to keep sediment out of streams and otherwise improve water quality by filtering out plant nutrients, pesticides, and microorganisms.

Crop rotation is an established practice that makes soils more resistant to erosion by its favorable effect on soil tilth and aggregation, provided the rotation includes a forage crop. Frequently, whole fields are planted to a particular crop. The number of years in a crop rotation and the number of years devoted to forage crops in the rotation is influenced by the steepness of the terrain and erodibility of the soil. The data in Table 4-4 show the effect of fallow and different cropping systems on runoff and soil loss.

Table 4-4. The Effect of Cropping Systems on Runoff and Soil Loss (14-year average).

Cropping System	Percent of Total Rainfall Lost To Runoff	Soil Loss (tons/acre/year)
Fallow (cultivated)	30	41.0
Continuous corn	29	19.7
Continuous wheat	23	10.1
Corn-wheat-clover rotation	14	2.7
Continuous bluegrass	12	0.3

Source: Miller, 1936.

Forage Crops

Forage crops represent an aspect of farming that is much less subject to erosion except during the period of establishment if conventional seeding methods are used. No-till seeding of forages, a relatively new practice, essentially does away with the need to till land for new seedings. Forage crops protect and improve soils because of their favorable effect on humus content and soil tilth. If such fields are overgrazed and under fertilized, i.e., poorly managed, they also can become severely eroded.

YIELD LIMITING FACTORS

The ideal soil for crop production can be characterized as follows:

- Loamy texture and organic matter in the surface for air and water movement.
- Sufficient clay to hold reserve soil moisture
- Deep, permeable subsoil with adequate fertility levels.
- Suitable chemical and physical environment for roots to go deep for moisture and nutrients.

Soil is a determinate of crop yield because it provides an environment for root growth. Figure 4-4 from Kiniry et al. (1983) shows the concept of a productivity index. For any combination of plant species, climate, and level of management, root growth and yield are determined by the soil environment as described in terms of five soil properties. Those soil properties are:

PAWC - Potential available water capacity, a property related to soil texture and aggregation.
Bulk Density - A measure of aggregation, porosity, and root impedance.
pH - A measure of soil acidity and indicator of aluminum toxicity to root growth.
Aeration - A measure of oxygen movement to roots that is related to wetness.
Conductivity - A measure of the salt content of the soil. Salt content is not a factor in most soils of the Chesapeake Bay region.

Potential productivity of the soil can be modified by a number of practices. If density or poor aggregation is a problem, then tillage methods, cropping systems or organic matter additions to promote aggregation could change the potential. If low pH is a problem, liming could improve the potential. If low potential available water capacity is a problem, modifications may be difficult. However, if materials with high available water capacity are in the profile, then methods of soil mixing that place the best materials at the surface may be feasible.

CROP PRODUCTION ECONOMICS

A basic understanding of crop production economics is essential to be able to make sound nutrient application recommendations. Farm production decisions should include consideration of what practices will return the highest level of expected profits to the farmer in the long run, the level of risk inherent in the farm enterprise, and the balance of farm practices with environmental and regulatory constraints.

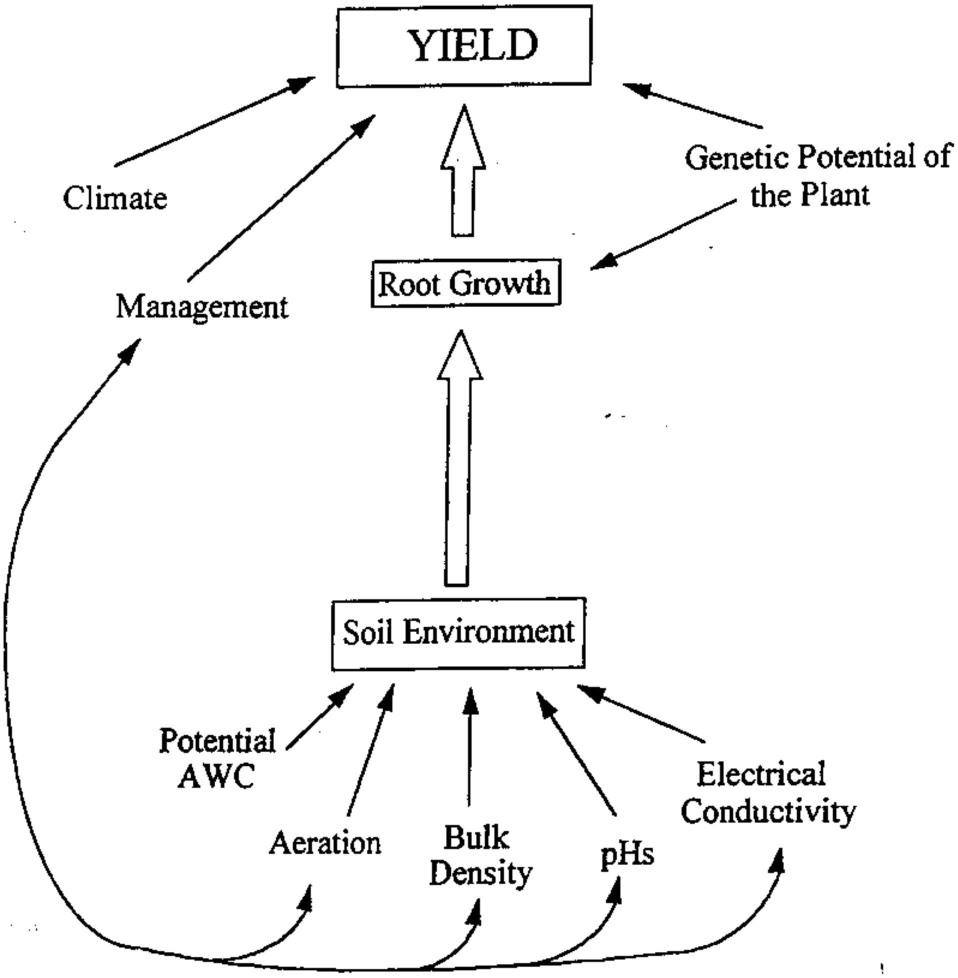


Figure 4-4. Conceptual model for the study by Kiniry et al. (1983).

Smaller gains in output per unit of input will occur as the input is increased according to the "Law of Diminishing Returns." For example, small amounts of nutrients applied to deficient soils may increase corn yields substantially; however, as greater amounts of nutrients are applied, yield increases will be less dramatic and eventually will level off or even decline. The maximum economic yield (MEY) concept is based upon the law of diminishing returns. To achieve the MEY in a given year, the level of inputs should be increased to the level where the expected value of the yield increase will be more than the additional input cost. Table 4-5 and Figure 4-5 illustrate this point by assuming a $2.00 value per bushel of corn, a twenty cent cost per pound of N, and a crop response curve for a specific field in one year.

In this example, the appropriate rate necessary to achieve MEY in this specific field and during this year would be 120 pounds of N, since higher rates would lead to a smaller gain in yield value than the cost to obtain the increase.

Table 4-5. MEY Example.

N Rate	Increase in N Rate	Additional N Cost	Yield	Increase in Yield	Additional Yield Value
0				34	
40	40	$8	73	39	$78
80	40	$8	107	34	$62
120	40	$8	122	15	$30
160	40	$8	125	3	$ 6
200	40	$8	127	2	$ 4

A weakness of the MEY concept is that it oversimplifies the problem of selecting the most profitable fertilization rate. Unfortunately, the yield response curve on a given field is not known with certainty at the time of fertilizer application since the response curve can vary with the seasonal weather conditions. This could be overcome if a long term average response curve could be obtained which incorporates a wide variety of growing conditions for each major soil type and management practice. Few, if any, farmers have this data.

Without long term response data, the MEY concept fails to account for risk, and farming is a risky business. Farmers can control many crop inputs such as fertilizer, seed varieties and planting rates; however, some production factors are largely beyond the control of the producer. These uncontrollable factors include the type of soil on the farm, price fluctuations in farm products and supplies, and the amount and timing of water (rainfall) for efficient crop growth.

Yields in any given year may be limited by either controllable factors like soil fertility, or uncontrollable factors like the weather. If nutrient levels limit yields in most years, the level of applied nutrients are too low relative to maximization of returns. However, if enough nutrients were applied to insure that the nutrients were never the limiting factor to maximum yields, at least two adverse affects would occur. First, farmers would not be managing yields for maximum profits since money would be wasted on nutrients not fully utilized in most years. Second, excessive losses of nutrients to the environment could occur since crop utilization efficiencies would not approach the level of nutrients applied in all but the very best years, however, plant nutrient application rates can be controlled, and plant nutrients have economic value. True long term maximum economic yields will be limited by available nutrients in some years, and by rainfall patterns in other years. Each soil series has differing physical and chemical properties and will react differently to various weather patterns.

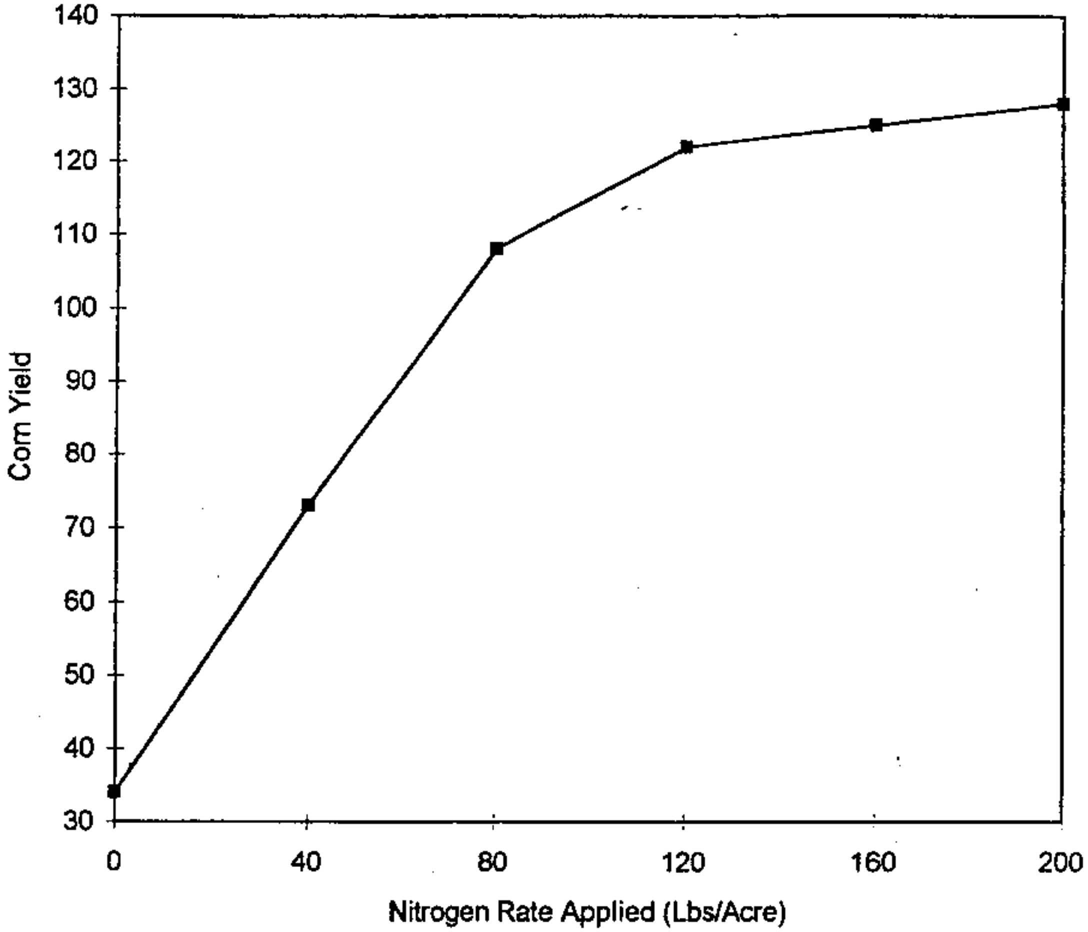


Figure 4-5. Example corn response curve to nitrogen applications.

If we knew at the beginning of each year what the weather patterns would be, we would fertilize differently each year to achieve maximum economic yields. Since in reality there is significant risk involved, a planning yield must be chosen based upon past yields on a given soil. It is not sufficient to look at an average yield for a soil series over time. The planning yield should also be based upon yield variability over time for a given soil. Figure 4-6 presents long term yield variability for corn yields at a Virginia research station. The average yield over time in Figure 4-6 was 119 bushels of corn per acre, however, in most years the actual yield was significantly higher or lower than the average. The maximum profit in the long run is greater with fertilizer applications based on the average response rather than the modal response.

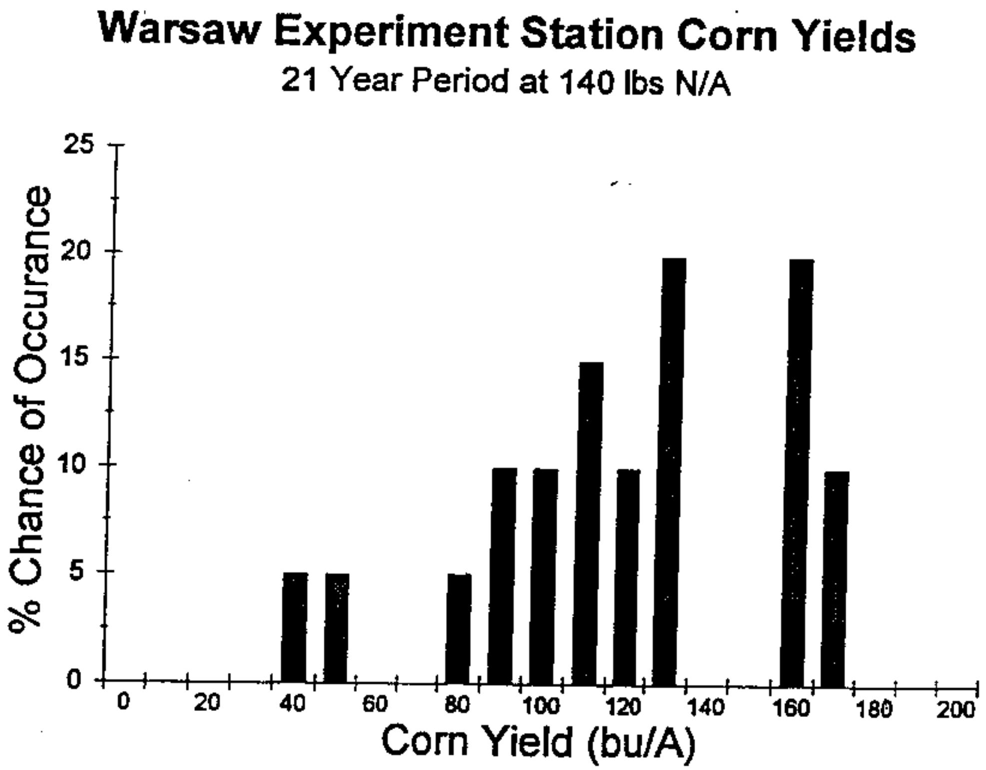


Figure 4-6. Corn yield variability.

Chapter 5: Nutrient Testing, Analysis, and Assessment

SOIL TESTING

There are four major components to a soil testing program: sampling, analysis, interpretation, and recommendation. To maximize the effectiveness of soil testing it is important to understand each of these components.

Routine Soil Testing

Sampling

Generally the largest source of errors in soil testing is in obtaining a representative sample. Many of these errors are due to the variability of soils. This can be natural variability or man-made variability caused by farming practices. Natural variability in nutrient levels is due to on going soil forming processes and is characterized by soil properties such as soil texture, mineralogy, depth, drainage, slope, aspect, landscape location. For example, there are often major differences in nutrient concentrations with depth due to horizonation of the soil profile. Sandy-textured soils have a lower cation exchange capacity (CEC) and thus will hold fewer cations like calcium (Ca), magnesium (Mg), and potassium (K). Low nitrogen (N) concentrations, due to denitrification, may be found in low lying, wet soils.

Superimposed over this natural variation is man made variation due to farming practices. The most obvious source of man made variation in soil nutrients is the uneven application of nutrients as fertilizers or manures. Uneven application may be intentional, such as when fertilizer is banded or manure is injected. It may also be unintentionally caused (e.g., by improper adjustment or operation of application equipment).

Tillage is a very important factor in nutrient variation in the soil. The repeated mixing of the surface layer of soil by conventional tillage reduces the effects of man-made variation due to nutrient application; however, cultural practices applied after tillage (e.g., banding a starter fertilizer) can result in variation for the rest of the growing season (Figure 5-1). This variation will remain until the fall or early spring and must be taken into account when soil testing is preformed for the next year's fertilizer recommendations. Conventional tillage can also increase variability of soil test levels over time if the tillage is not performed consistently. For example, the depth of plowing can alter soil nutrient concentrations. Occasionally, plowing deeper may mix low fertility subsoil material with the plow layer and thus, lower the soil test levels for nutrients samples from this soil layer.

The increased emphasis on residue management and reduced tillage has resulted in even more soil nutrient variation. There is no mechanical mixing of the soil in no-tillage

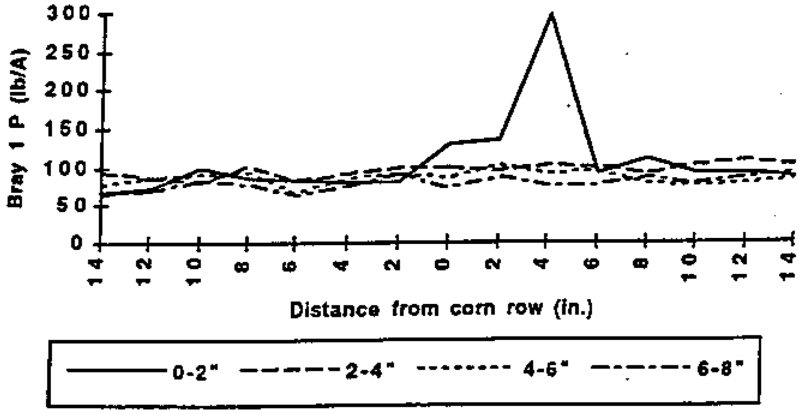


Figure 5-1. Variation in P across the row and with depth in a long term conventional till corn field.

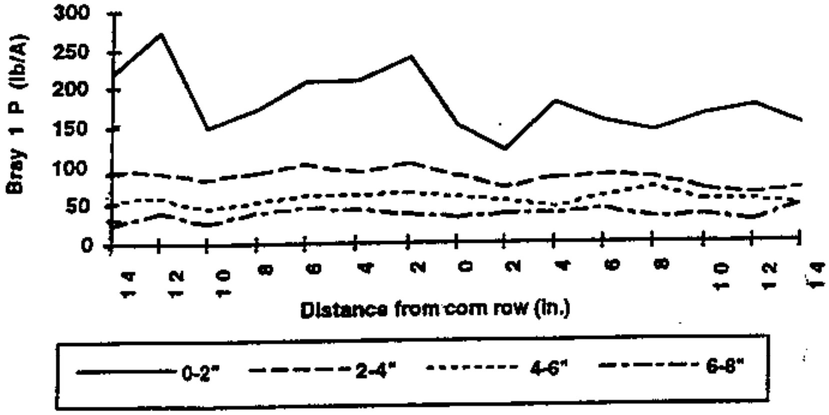


Figure 5-2. Variation in P across the row and with depth in a long term no-till corn field.

systems; therefore, natural or man-made variation in soil nutrient levels tend to become amplified over time. Application of immobile nutrients like P in fertilizer or manure will result in higher soil test levels near the surface and a decline in soil test level with distance down through the plow layer (Figure 5-2). Nutrients and organic matter released from crop residues also accumulate at the soil surface.

Variation in soil pH with depth is a likely result of no-tillage systems. Nitrification of surface-applied fertilizer and manure N causes lower soil pH at the surface of no-till fields (Figure 5-3). The effects of limestone application will be greatest where it is applied because limestone is immobile in the soil. Thus, limestone application will usually result in a higher pH near to the soil surface. Figure 5-4 shows that there is little effect below the surface 2 inches even after 7 years in a continuous no-till field where the lime is applied to the soil surface.

With all of this variation in field soils it is easy to see why collecting a representative soil sample is a major potential source of error in soil testing. There are several general guidelines that should be kept in mind when collecting soil samples. First, think "representative sample". In a 10 acre field there are approximately 20 million lbs of soil in the plow layer, of which you must collect about 1/4 of a pound of soil that represents all of the soil in the field. A handful of soil grabbed from the surface along the road at the edge of the field is not likely to be representative of the rest of the field. Thus a rigorous procedure for obtaining a representative soil sample must be followed. Two main questions that must be considered when developing the sampling plan for a field are: (1) How deep should the samples be taken? (2) What pattern should be followed for selecting where to take the samples?

Sampling Depth

Depth is an important factor that must be considered in developing a sampling plan for a field. Traditionally, soil sampling recommendations for P, K, Ca, Mg, micronutrients, pH, and lime requirement for soil testing have been to sample to plow depth. Under conventional tillage, nutrients and pH in this layer of soil are most impacted by nutrient additions and have the greatest impact on crop nutrition. For these reasons, this is still the sampling depth recommended by most labs for conventional tillage systems. In addition, shallower sampling will not usually affect fertilization recommendations because the plow layer is uniform throughout under conventional tillage.

In reduced and no-tillage systems the correct sampling depth is less clearly defined and the depth sampled has a much greater impact on the soil test result than in conventional tillage systems because nutrients concentrate near the surface in these tillage systems. Root systems and nutrient uptake also concentrated near the surface in conservation tillage systems; thus shallower sampling than the plow layer may be more appropriate. Some soil testing labs now recommend that minimum and no-till fields be

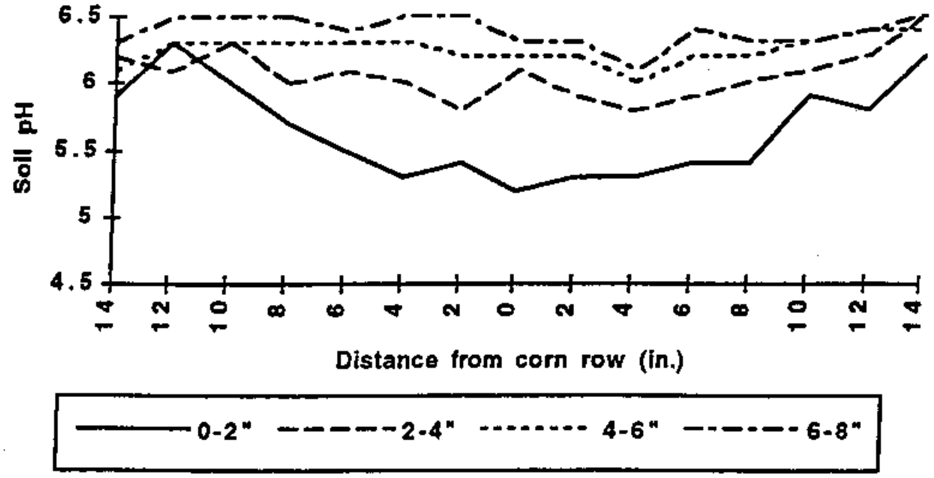


Figure 5-3. Variation in pH across the row and with depth in a long term no-till corn field.

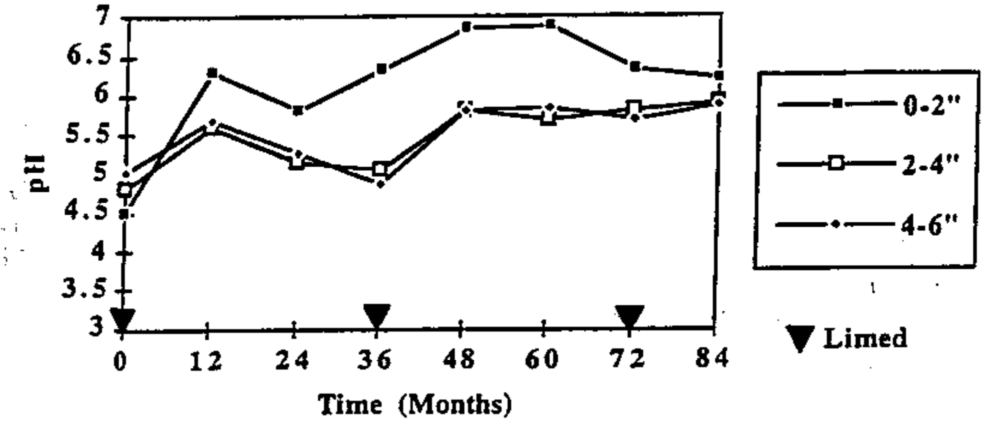


Figure 5-4. Soil pH vs. Time for a no-till soil limed at 6000 lb/A every third year.

sampled to "plow depth", but an additional shallow sample of 1 to 2 inches be taken primarily for measurement of soil pH. It is usually recommended that soil be sampled to a depth of 2 to 4 inches for routine soil tests under permanent sod crops.

Recommended sampling depth for nitrogen is deeper than for the routine soil tests because of the greater mobility of nitrogen. The most common soil test for nitrogen in the humid region of the U.S. is the presidedress soil nitrate test (PSNT) for corn. The recommended sampling depth is 1 foot for this soil test .

Sampling Pattern

At the field scale there are two general patterns for sampling a field: random and systematic. The best approach for a uniform field is to randomly select locations in the field to take soil cores, which are thoroughly mixed and subsampled for lab analysis. The result is an average soil test level for the field. It is usually recommended that 15 to 20 cores be taken at random locations to make up the composite sample. Usually the locations for taking cores are not totally random but are selected by walking a zig-zag pattern that covers the whole field and randomly stopping to collect a core (Figure 5-5).

An average soil test level from a composite sample may not be very useful for a non-uniform field. In this situation, the field is comprised of several distinctly different soil test levels; thus, the average soil test level from a randomly collected composite sample may not actually exist anywhere in the field. Ideally the variability in a non-uniform field should be determined and mapped to permit the various areas of the field to be managed differently. The usefulness of characterizing the variability in a field will depend on the ability to change management based on this variability.

A systematic or grid sampling approach is often used to map the variability of a field. To accomplish this, a grid is superimposed on the field. A common grid size is 100 feet on a side. At each intersection of grid lines, 5 to 10 soil cores are taken within a 3 foot circle and composited to make up the sample for that point. This sampling pattern is illustrated in Figure 5-6.

Analysis of the composite samples is used to make of map of the variation in soil fertility. A simple example of such a map is shown in Figure 5-7. Notice the generally high P levels along the north side of the field. The east end of the field has low soil test P levels and the southwest part of the field has medium soil test P levels. Ideally, P rates would be adjusted accordingly when fertilizer or manure is applied to this field.

This grid sampling approach is best suited for large regularly shaped fields. Small and irregularly shaped fields make grid sampling and variable management very difficult. A common compromise is to systematically sample on the basis of known or suspected

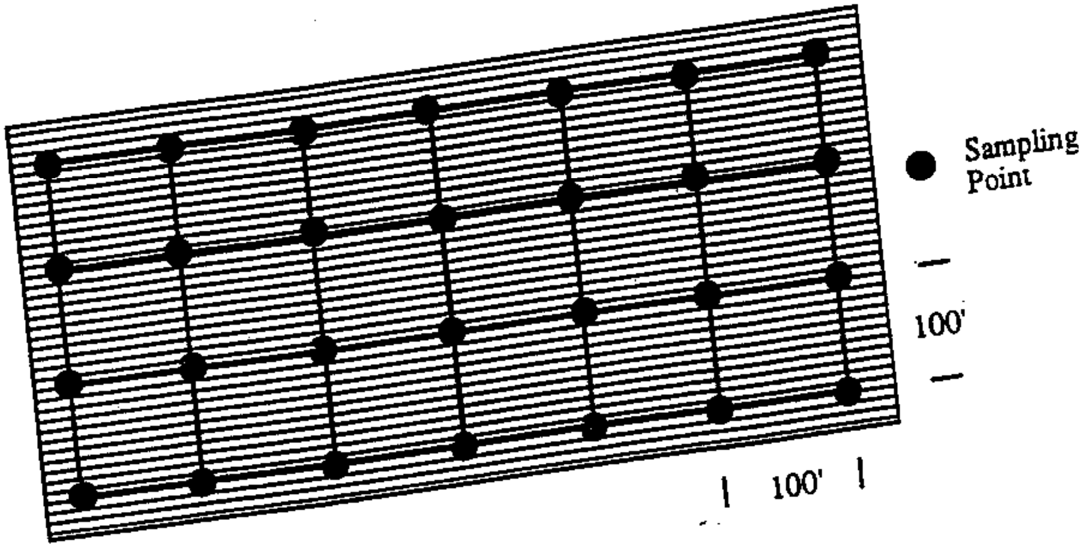


Figure 5-5. Example of a random sampling pattern in a field.

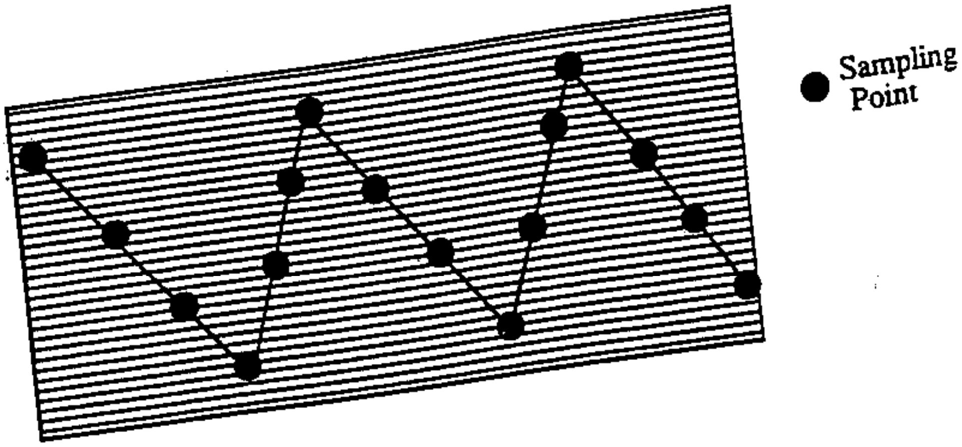


Figure 5-6. Example of a grid sampling pattern in a field.

gross variability in the field. Examples might include: historical manure or fertilizer spreading patterns, soil drainage, soil type, slope, etc. An example is illustrated in Figure 5-8. In this field, three areas that could be sampled and managed separately include an old barnyard area that has historically had heavy manure applications and is expected to contain high organic matter and nutrients concentrations; a small area of wet soil that is not productive and has not received much manure; and a well-drained unmanured area.

One should not attempt to take a random composite sample that represents the whole field depicted in Figure 5-8. The result of the soil tests on that composite sample will be useless in most cases. If the field can't be divided, sampled and managed separately, it is probably best to sample the largest and/or most productive section of the field and not sample the odd areas at all.

A good soil sampling plan must account for soil variability for the results to be valid. Always check with the soil testing lab to determine the recommended sampling procedures for their tests. An important factor to consider is that the same sampling procedures should be followed in the collecting samples that was used to calibrate the soil. Table 5-1 provides some general guidelines that should be followed for taking soil samples.

Table 5-1. Guidelines for taking soil samples.

1. Do not wait until the last minute. The best time to sample is in the fall.
2. Take cores from at least 15 to 20 spots over the field to obtain a representative sample. One sample should represent one management unit.
3. Sample between rows. Avoid old fence rows, dead furrows, and other spots that are not representative of the whole field.
4. Take separate samples from areas that differ significantly if they can and will be managed as different management units.
5. In cultivated fields, sample to plow depth.
6. In no-till fields some labs recommend a 2 - 4 inch deep sample while others recommend taking two samples: one to plow depth for lime and fertilizer recommendations, and one to a 1 - 2 inch depth to monitor surface acidity .
7. Sample permanent pastures to a 2 to 4 inch depth.
8. Collect the samples in a clean container. (DO NOT use a galvanized bucket.)
9. Mix the core samples, allow to air dry, and remove roots and stones.
10. Fill the soil test mailing container.
11. Complete the information sheet that accompanies the sample to the lab, giving all of the information requested. Remember the recommendations can only be as good as the sample collected and information supplied.

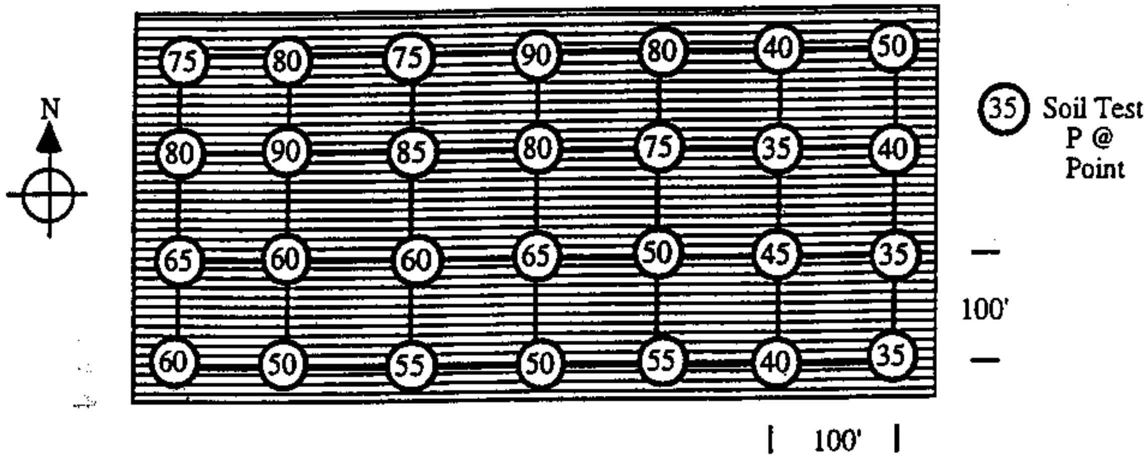


Figure 5-7. Example of grid map of soil test P levels.

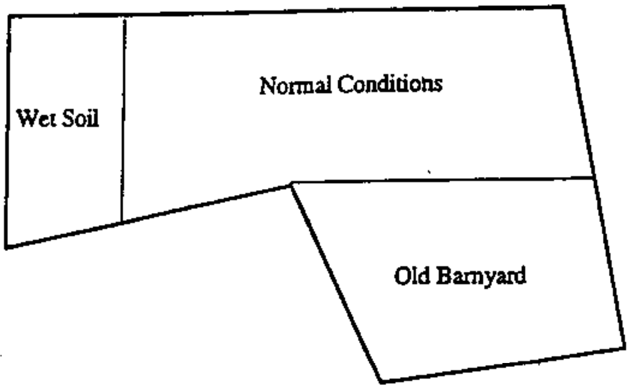


Figure 5-8. Example of systematically dividing a field for soil sampling on the basis of known or suspected variability.

Analysis

Laboratory analysis of a properly sampled soil provides the basis for assessing the nutrient status of soil. With a few exceptions, such as the measurement of NO_3^--N, most soil test extractants do not directly measure the total amount of available nutrients in the soil. Soil tests generally extract a fraction of the nutrient from the soil that is correlated to the plant-available portion of that nutrient. Consequently, soil extractants differ in their utility to correlate various soil nutrients with plant-availability. Different methods often extract different amounts of the nutrients and provide different soil test results. An example of how three different extractants might extract different fractions from the same soil, which results in three different soil test results is illustrated in Figure 5-9.

Generally, the soil test user need not be concerned with the details of the soil test methods. It is most important that the testing lab is using standard procedures that are recommended for the region where the samples were collected or the results and/or interpretations may be misleading. It is also important to know what methods are used when comparing results from different labs. If the tests being compared are both valid for the area where the sample was taken, the interpretation of the results should be the same even though the numerical analytical results from the two tests might be different.

The units employed to express soil teat results sometime cause confusion. Some soil tests results are presented on a volume basis. In this system, a fixed volume of soil is analyzed and the results are presented as the amount of a nutrient extracted per unit volume of soil. The common units used in this system are mg dm^{-3}.

A more common system is based on an actual or assumed weight for the soil. Results in this system are presented as parts per million (ppm) or pounds per acre (lb/A). As a further complication, some results present nutrients as pure elements (i.e. N, P, K) while others use the fertilizer oxide (P_2O_5, K_2O). These units can all be easily converted back and forth. Some common conversion factors are given in Table 5-2.

Table 5-2. Common conversions for soil test units.

$P \times 2.3 = P_2O_5$	$P_2O_5 \div 2.3 = P$
$K \times 1.2 = K_2O$	$K_2O \div 1.2 = K$
$NO_3^-\text{-N} \times 4.4 = NO_3^-$	$NO_3^- \div 4.4 = NO_3^-\text{-N}$

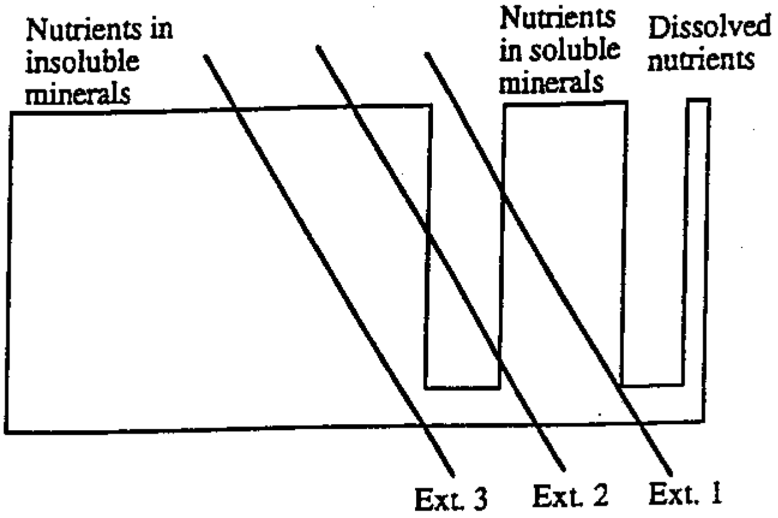


Figure 5-9. Illustration of how different soil test extractants might extract different fractions of the nutrient in the soil.

Interpretation

The analytical results from a soil test extraction are relatively meaningless by themselves. Soil nutrient levels must be interpreted in terms of the soil's ability to supply the nutrients to crops. To make this interpretation the soil test level must be calibrated against crop response to the nutrient. This is accomplished by conducting fertilizer response experiments at different soil test levels covering the range of interest for use of the soil test. These experiments must be conducted for all crops and under all of the conditions that the test will be used.

Examples from such experiments of relationships that have been developed between percent yield and yield increase and soil test P concentrations are illustrated in Figure 5-10. In Figure 5-10a, percent yield represents the ratio of the yield in the unfertilized soil to the yield where P is non-limiting. For example, 70% yield means that the crop yield with the unfertilized soil is 70% of the yield at optimum concentration of P. Similarly, yield increase represents the yield increase with optimum fertilization (Figure 5-10b). Thus, as soil test P increases, percent calibration is yield increases to 100%, which represents the soil test concentration where there is no difference in yield between fertilized and unfertilized soil. Alternatively, as soil test P increases, the yield increases as P fertilization decreases to 0 (Figure 5-10b).

Generally, when percent yield reaches 95 to 100% when yield increase reaches 0 to 5%, the soil test critical level (CL) is obtained. The CL represents soil test level above which no yield response to fertilization will be obtained. Soil test CLs can vary among crops, climatic regions, and extractants.

Most soil test laboratories indicate the interpretation of the results by use of qualitative terms such as "Low", "Optimum", and "High" or "Low", "Medium", "High", and "Very High". These qualitative terms are related to quantities of nutrients extracted but may have different absolute meanings depending on the laboratory employing them. An example of an interpretation in the form of a chart that has been adapted from the Penn State Soil Test report is shown in Figure 5-11.

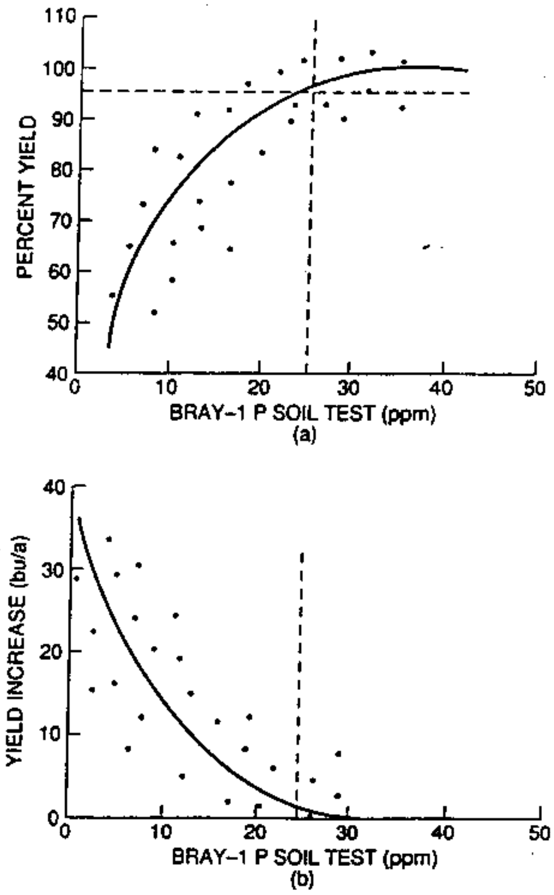


Figure 5-10. Relationship between percent yield (a) and yield increase (b) and Bray-1 P soil test level.

Some labs report their results in the form of an index number. A common index system would assign an index of 100 to the optimum level. With this system index numbers less than 100 would indicate the degree of sufficiency and numbers above 100 would indicate an excess of nutrient over the optimum for the crop. Regardless of the system used to indicate the interpretation on a soil test report, if an equally valid but different soil test method were used for a given soil, the numbers might be different but the interpretations should be similar.

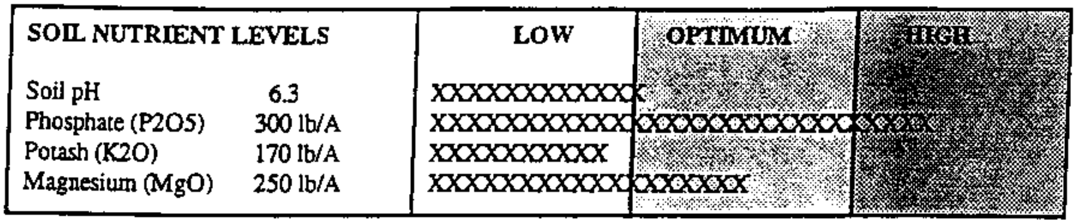


Figure 5-11. Example of a bar chart for displaying the soil test interpretation on a soil test report.

Soil test results are most commonly interpreted on the basis of the probability of an economic response to adding additional nutrients. Because of the increasing concern about the potential impact of nutrients on the environment, soil tests are being considered in terms of predicting potential environmental impact from nutrients. However, it is not possible to directly use conventional soil test interpretation for crop response to make an environmental interpretation. The soil test level will need to be interpreted in the context of the characteristics of the soil and the site. An example of this approach is the Phosphorus Index. The Phosphorus Index provides a site vulnerability index for potential P loss based on the soil test level in addition to the following site characteristics: soil erosion, irrigation erosion, runoff class, P fertilizer application rate, method of P fertilizer application, organic P (manure, sludge, compost, etc.) application rate and organic P application method.

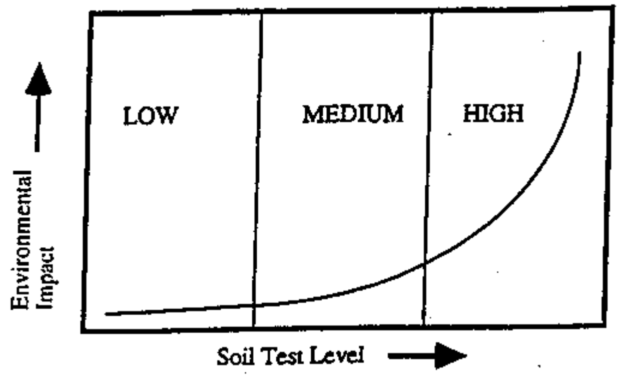


Figure 5-12. Hypothetical soil test calibration based on environmental impact.

Recommendations

The final step in the soil testing process is making a recommendation. Soil test calibration studies depicted in Figure 5-12 can provide the data to establish fertilizer recommendations. For example, at each location, the P rate required for optimum yield can be determined and the results used to make fertilizer P recommendations.

A factor that results in different recommendations is related to the philosophy of fertilization goals. One philosophy calls for fertilization for maximum economic yield while another attempts to maintain concentrations of soil nutrients that will be removed by crop uptake. At low soil test concentrations, recommendations are usually based on the expected response of the crop to added nutrients. Recommendations may be based on the minimum amount needed for the optimum economic yield or on an amount to either rapidly or gradually build the soil concentrations into the optimum range.

There are generally two common approaches to making recommendations in the optimum range. Because there is a low probability of an economic yield response to adding a nutrient that is adequate, the sufficiency level approach, recommends no additional nutrient. Crop removal may decrease the soil test level by the end of the growing season. Therefore, an alternative approach for soil in the optimum range is to include an amount of nutrient equal to the expected crop removal. The objective of this type of recommendation is to offset the crop removal and thus maintain the soil in the optimum range over time. No nutrient addition is recommended for soils testing high or very high because there is no change of an economic response.

Pre-Sidedress Soil Nitrate Test for Corn

Theory

Soil testing has been effectively used for years to determine the availability of P and K in agricultural soils and for determining fertilizer recommendations for these nutrients. Due to the complex behavior of nitrogen in the soil, development of a reliable soil test for availability of N in humid regions of the country has been more difficult. In humid regions, a soil test taken before the growing season would not accurately reflect the availability of N later when it is most important to the crop. This is shown in Figure 5-13 which illustrates the large change in soil NO_3^--N that can occur from early in the season until the major demand for N by a corn crop occurs. If the early season soil NO_3^--N level were used to predict availability in this example, the manured field would have been predicted to have the highest level and the field following alfalfa would have been predicted to have the lowest. However, nitrogen availability in the alfalfa field is higher than from the manure by the time major uptake by the corn occurs. Thus, an at planting NO_3^--N test would have been misleading and attempts to develop a reliable soil test for N as part of a traditional soil testing program have not been successful. Since corn has the greatest need for N several weeks after emergence, a successful soil test for N should reflect N availability at that time. A new approach to N soil testing called the pre-sidedress soil nitrate test (PSNT), which involves soil sampling during the growing season, has been successfully implemented in the Mid-Atlantic region.

The basis for the PSNT involves taking soil samples just before sidedressing - after the spring wet period but before the period of major N demand by corn - and determining the NO_3^--N in the soil sample. The NO_3^--N concentration in the soil at this point in the season is the result of the integration of the many factors that influence the soil N transformation from organic forms of NH_4^+ to NO_3^- has been found to be related to the soil's nitrogen supplying capability. The results of the test are used as an index of N availability for corn production and thus to make sidedress N recommendations.

Data from field research experiments conducted in Pennsylvania, Maryland, and Delaware with the PSNT shown in Figure 5-14, indicated that the NO_3^--N level from this test was very good for identifying soils where there would be no yield increase from fertilizing with N (a relative yield near to 1 in Figure 5-14). The vertical line in this chart at 21 ppm soil NO_3^--N is the critical level that separates the sites where additional N is needed for maximum yield from those where there is no yield increase when N is added. Almost all of the points with soil NO_3^--N levels above this critical level did not respond to added N.

In most states, this test is primarily recommended for use on fields where there are significant organic N contributions such as a history of manure or biosolids applications or forage legumes in rotation because these are traditionally the most difficult sites to determine a sound N recommendation. In Figure 5-14, the open circles are the fields which had a history of organic N additions. This test is of limited value on most fields without organic N contributions, because these sites had low levels where the standard recommendations are usually adequate. These fields are the squares in Figure 5-14. Notice that most of these are in the low range. Problems have also been noted in using the test following a forage legume particularly in no-till situations. This is due to the slow release of NO_3^--N as the legume residue is mineralized. Generally, it has been found that this release is slow and there is not a large accumulation of NO_3^--N in the soil by the time the PSNT is conducted. Nitrate mineralization is usually fast enough to keep up with the demands of the crop so that there is often little or no response to added fertilizer N even though the PSNT is low. The best use of the PSNT is to confirm the adequacy of N to meet the needs of a corn crop where it is expected that applied and residual manure nitrogen should be adequate. If the estimate of N available from the manure is found to be inadequate there is still time to make a sidedress application of N fertilizer. Thus this test can reduce some of the uncertainty associated with utilizing manure N to meet the needs of a corn crop and also reduce the use of unnecessary fertilization.

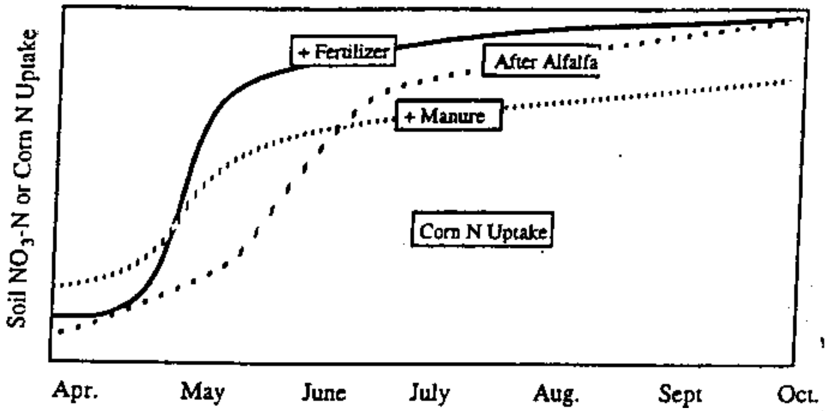


Figure 5-13. Relative levels of nitrate-N in the soil in a corn field with different management systems vs. corn N uptake.

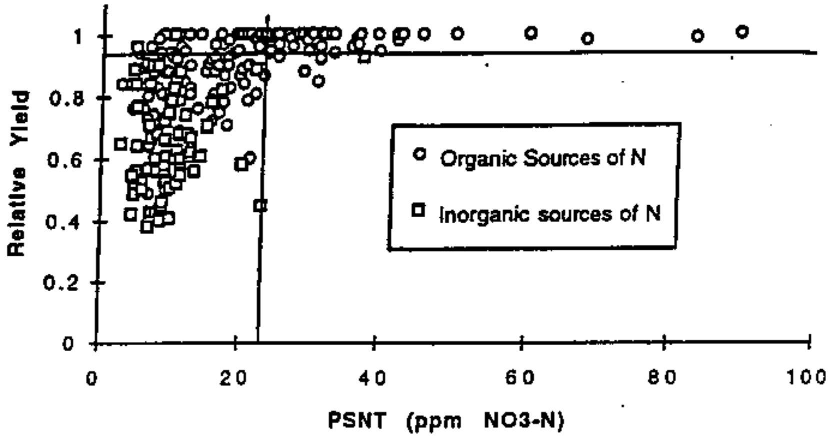


Figure 5-14. Pre-sidedress Soil Nitrate Test Calibration data combined from Pennsylvania, Maryland, and Delaware (Fox et al.).

Procedure

Following is the general procedure for the PSNT. While there may be minor modifications in different states this procedure has been fairly well standardized across the country.

1. A minimum of fertilizer N (usually less than 50 lb N/A) is applied in the spring. (Starter fertilizer banded at planting, pre-plant broadcast fertilizer, and/or a small amount of N used as a herbicide carrier.)

2. Manure is applied based on the history of the field, a manure analysis, how the manure will be handled, and on crop requirements for N estimated from the expected yield and crop history.

3. Soil samples are taken when the corn is 12" tall or at least a week before planned sidedressing.

4. Fields with uniform fertilization history and soil properties are sampled by taking 20 to 25 cores to a 12 inch depth. Starter bands and other atypical areas must be avoided. Because of sampling problems this test cannot be used on fields that received injected fertilizer or manure.

5. The cores are combined, crumbled, and air-dried as quickly as possible. The samples should be microwaved, spread out in the sun, or under a heat lamp in a well ventilated area to dry.

6. The sample is then sent to a reputable soil testing lab for soil NO_3^--N analysis. A reliable field test kit for NO_3^--N can also be used to determine the NO_3^--N level in the sample.

7. The adequacy of soil nitrogen for the crop is determined from the results and if needed, a sidedress N recommendation may be estimated.

Calibration research with the PSNT has resulted in a remarkable consistency in critical levels used to interpret this test. Most critical levels from Vermont to Iowa have fallen between 20 and 25 ppm NO_3^--N. The data combined from three states shown in Figure 5-14 indicated a critical level of around 21 ppm NO_3^--N. Above this level there is a very high probability that no additional nitrogen fertilizer will be needed.

Below the critical level, the PSNT can also give some guidance for adjusting N recommendations. However, there is considerable scatter in the data below the critical level (Figure 5-14). As a result different approaches to making recommendations based on the PSNT have been developed. Most everyone agrees that above the critical level no sidedress N should be recommended. When the test level is below the critical level there are several general approaches to making recommendations. In the first approach, if the test level is below the critical level, the full rate of N is recommended. A second approach is to fall back on traditional methods of adjusting N recommendations based on field history, manure applications, previous legumes, etc. to make an adjusted recommendation when the test level is below the critical level. The third approach is to use the PSNT level as a guide for adjusting recommendations when the test is below the critical level. A final approach is a combination approach which uses the test level in combination with some of the traditional factors to come up with a recommendation.

TISSUE TESTING

Sampling Plant Tissue For Elemental Analysis

Plant analysis is the laboratory determination of several elements on a single sample of plant tissue. This technique is most commonly used to diagnose nutritional problems related to soil fertility or to monitor the effectiveness of fertilizer practices on growing crops. Plant analysis is not a substitute for soil testing, but is most effective when used in conjunction with a regular soil testing program.

The number of elements that are measured depends on the laboratory to which the samples are sent for analysis. The most common elements analyzed in the sample are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), boron (B), copper (Cu), zinc (Zn), and aluminum (Al). Others that may be measured either routinely or upon request include sulfur (S), sodium (Na), molybdenum (Mo), cobalt (Co), silicon (Si), cadmium (Cd), nickel (Ni), lead (Pb), chromium (Cr), arsenic (As), and selenium (Se). Although some of these are not essential for plant growth, the results may be used to identify elemental toxicities.

In order for plant analysis to be effective, considerable care must be given to collecting, preparing and sending plant tissue to the laboratory for analysis.

What to Sample

Proper sampling requires that a specific plant part be taken such as a particular leaf, group of leaves or portion of the plant. Instructions also include number of individual parts, as well as the number of plants to sample. This will ensure that a sufficient quantity of plant tissue is submitted for analysis and that the collected sample is statistically representative of the area under study. When sampling mixed stands, particularly forages and pastures, separate plant species. Similarly, the sample should be of only leaves or petioles or whole tops and not mixtures.

When no specific sampling instructions are given for a particular crop, the general rule of thumb is to sample the uppermost recently mature leaves. Young emerging leaves, older mature leaves and seed are not usually suitable plant tissues for analysis since they do not ordinarily reflect the general nutrient status of the whole plant. The recommended time to sample usually occurs just prior to the beginning of the reproductive stage for many plants. However, sampling earlier or even later than specified may be recommended for specific plants or circumstances. Sample plants which are showing a suspected nutrient deficiency symptom at the time or shortly after the visual symptoms appear. Do not sample or include in a sample plants under a nutrient stress for an extended period of time, dead plant tissue or plants or tissue mechanically injured, diseased or insect damaged.

Multiple Sampling

When a nutrient deficiency is suspected at a time other than specified for sampling, also collect similar plant parts from normal plants growing in the immediate or adjacent areas. Take care to ensure that the two sets of plants are at approximately the same stage of growth and have been treated the same. Comparative analyses are questionable when the two sets of plants are not at the same stage of growth, have not received the same treatment or are not the same variety or hybrid. If the soil type varies between the two sites, tissue analyses would not be comparable. If all the proper conditions have been met, then a comparison of results between two sets of plant tissue samples can be invaluable to the interpreter. Do not mix or place the collected tissues in the same mailing kit. When soil test data are not available, take soil samples from both areas.

Washing to Remove Contaminates

Avoid dusty or soil-covered leaves and plants whenever possible. Under normal conditions, rainfall is frequent enough to keep leaf surfaces fairly free from dust and soil particles. However, when leaves are dusty, brush or wipe with a damp cloth to remove the contaminates. If this is not effective or when leaves are covered with spray materials, wash in a mild detergent solution (0.30 percent) and rinse in running water to remove most attached substances. Do not prolong the washing procedure or allow the plant material to "stand" in either the washing or rinsing baths. Wash and rinse briskly. Wash leaves which have been sprayed with nutrient solutions while they are still fresh. If iron is of primary interest, wash leaves regardless of their outward appearance. Wash whole plants sampled shortly after emergence to remove soil particles which are frequently attached to the new tissue.

What Not to Sample

Do not include diseased or dead plant material in a sample. Do not sample or include plants or leaf tissue which have been damaged by insects or mechanically injured in a sample. When whole plants are sampled, remove the roots and wash the upper portion to remove soil particles. Do not sample plants which have been stressed extensively by cold, heat, moisture deficiency or by excess moisture. Examine both the below ground as well as the above ground portion of the plant. The presence of nematodes or roots damaged by other insects or diseases should preclude the need to sample.

Packaging Plant Tissue

Air dry plant tissue samples before shipment to the laboratory. Package samples in clean paper bags or envelopes for mailing to a laboratory. Never place fresh samples in a plastic bag.

Interpretation

Plant Analysis Interpretation

The use of plant analyses is an effective management strategy for a sustainable soil fertility program because it provides a direct measure of nutrient concentrations and balance within the plant. Principles and procedures used for plant analyses have evolved over many years and changed as knowledge increased about each element that is essential for a plant to complete its life cycle. As such, use of plant analyses has become an integral part of most agronomic research and a tool for crop consultants and fertilizer dealers to monitor production fields.

Principles for Basic Plant Analyses

The basis for plant analyses is a determination of the concentration of an element that is essential for a plant to survive and reproduce. These measurements can be made using whole plants or an individual part which has been shown to be responsive to the medium in which the plant is being grown and proportional to the growth or yield of the plant. The results of these measurements can be interpreted using several techniques including critical levels or sufficiency ranges, the Diagnosis and Recommendation Integrated System (DRIS), total amounts and rates of accumulation, and nutrient use efficiencies.

Some have based plant analysis interpretations on "critical" or "standard values." A critical value is that concentration below which deficiency occurs. Critical values have been widely published and used, although they have limited value since they only designate the lower end of the sufficiency range.

The effects of time of sampling, variety or hybrid and environmental factors, such as soil moisture, temperature, light quality and intensity may significantly affect the relationship between nutrient concentration and plant response. A defined sufficiency range may not apply to all situations or environments. Nutrient uptake and internal mobility, as well as dry matter changes, can affect the nutrient concentrations in plant tissues. Concentration and dilution occur due to the difference between plant growth and nutrient absorption as well as movement of the nutrients within and between plant parts. Under normal growing conditions, nutrient absorption and plant growth closely parallel each other during most of the vegetative growth period. Exceptions occur during the very early growth period shortly after germination, after seed set and at the beginning of senescence. However, if the normal rate of growth is interrupted, nutrient accumulation or dilution can occur.

DRIS Approach

The DRIS concept was developed to determine (1) the concentrations and interrelations of essential elements in plants, and (2) the soil nutrient levels, conditions, and cultural practices associated with optimum plant growth and the highest attainable yields. The basis for this approach is that with optimum concentrations of one or more elements, yield levels will be low, medium, or high depending upon one or more factors which also influence plant growth. These factors include: availability of other nutrients, soil characteristics, water availability, temperature, plant population, weeds, insects, diseases, and cultural practices. The DRIS approach allows the user to determine a relative ranking from the most to the least deficient nutrient. It is also less sensitive to dry matter dilution than critical values because nutrient ratios rather than concentrations are used for interpretation. Originally, a common data base for interpretation of DRIS norms was thought to be feasible, but studies with corn, soybean *(Glycine max* L. Merr.), alfalfa *(Medicago sativa* L.), wheat *(Triticum aestivum L.),* and potato *(Solanum tuberosum* L.)

have indicated that local or regional norms provide more accurate deficiency diagnosis than those developed in other regions.

Total Nutrient Accumulation

Use of plant analyses to determine amounts and rates of nutrient uptake is a useful management strategy for sustainable soil fertility. The information can be used to anticipate when high plant nutrient concentrations must be made available for rapid uptake and assimilation and when they would be more vulnerable to loss through processes such as leaching. This approach identifies periods of intra-seasonal variation in accumulation which could be used as a sustainable soil fertility management tool to schedule fertilizer applications to provide a minimum nutrient stress environment during both vegetative and reproductive plant growth stages.

Nutrient Use Efficiencies

Use of plant analyses data to determine relative nutrient use efficiencies for various crop and soil management practices is one of the most important applications of the information relative to sustainable soil fertility management. Measuring total dry matter and nutrient concentrations provides the needed information to compute total uptake in the entire plant or harvested portion. By dividing these values by the amount of fertilizer applied or the amount of nutrient available in the soil, nutrient use efficiency (NUE) values can be determined. These efficiency values can then be used to determine the recovery of applied fertilizer and the uptake of residual nutrients.

LEGUME and NON-LEGUME NITROGEN CREDITS FROM COVER CROP RESIDUALS

The major factor limiting the establishment of legume cover crops and subsequent N availability is climate. Temperature varies greatly throughout the Chesapeake Bay basin, which ranges from New York state to southeastern Virginia. Winter legumes must put on adequate fall growth and to produce biomass before summer crops are planted.

Hairy vetch and crimson clover appear to be the best winter legume covers for the mid-Atlantic region. They are easily established and winter-hardy, and they break dormancy early in spring. They also produce large amounts of N, resulting in good yield response by summer cash crops. Hairy vetch typically is more winter-hardy and produces more dry matter than crimson clover.

Mid-Atlantic researchers have evaluated many legume-grass mixtures, with most research focusing on cereal rye plus hairy vetch. Such mixtures do a good job conserving soil moisture. They also allow for efficient N fixation and uptake of leftover soil N. Fifty to one hundred pounds of added N may be required to maintain corn yields after a rye-vetch mix. In general, when seeding legume-grass mixtures, use low to medium seeding rates for the grasses, and medium to high rates for the legumes. Adjust rates of the respective crops depending on whether your goal is N production (increase legume rate) or faster and more thorough ground cover (increase grass rate).

Legume Cover Crop N Contributions

Table 5-3 summarizes the results of research reports from the lower Northeast to the upper Southeast that estimate fertilizer N replacement value for various crops.

Table 5-3. Nitrogen fertilizer equivalents from various cover crops.

COVER CROP	N FERTILIZER EQUIVALENT (lbs/A)	SUBSEQUENT CASH CROP
Arrowleaf Clover	50	Corn (2 observations)
Austrian Winter Pea	67	Corn (8 observations)
Bigflower Clover	53	Corn (7 observations)
Hairy Vetch	84	Corn (22 observations)
Crimson Clover	60	Corn (14 observations)
Common Vetch	79	Corn (2 observations)
Subterranean Clover	4	Corn (2 observations)
Crimson Clover + Rye	100	Corn
Crimson Clover + Oats	100	Corn
Common Vetch + Wheat	70	Corn
Bigflower Vetch + Wheat	---	Corn
Hairy Vetch + Rye	100	Corn
Hairy Vetch + Oats	100	Corn
Hairy Vetch + Wheat	50	Corn
Austrian Winter Pea + Wheat	16	Corn
Bigflower Vetch	67	Sorghum
Crimson Clover	30-60	Cotton
Crimson Clover	17-114	Sorghum
Hairy Vetch	60-90	Cotton
Hairy Vetch	44-114	Sorghum
Subterranean Clover	11-92	Sorghum

Chapter 6. Commercial Fertilizer

The conversion of ammunition factories to N fertilizer production following World War II resulted in a plentiful supply of N fertilizers at very affordable prices. Its low cost compared to the value of the resulting yield increases stimulated rapid adoption of increasing rates of N fertilizer application on most farms. It was also no longer necessary for farmers to have legumes in their crop rotations to contribute the N necessary to produce grain crops nor was it necessary to depend on the recycling of nutrients on the farm through the soil application of livestock manures.

FERTILIZER MATERIALS

Nitrogen

Inorganic N fertilizers are produced by fixing N from the atmosphere. Natural gas is used as the energy source and is a major component of the cost of N fertilizers. The following is a listing of the primary N materials used by the fertilizer industry.

A. **Urea** [$CO(NH_2)_2$] (46-0-0)

- Produced by reacting ammonia with carbon dioxide under pressure and at an elevated temperature.
- Dry source having highest percentage N.
- Rapid hydrolysis to ammonium carbonate (unstable) can cause significant N losses as ammonia gas (NH_3) when applied to bare soil or sod covers.

$$CO(NH_2)_2 + H_2O \Rightarrow 2(NH_3)\uparrow + CO_2$$

- Timely soil incorporation or injection is important to avoid volatilization losses.
- A soluble, readily available N source.

Urea does not contain NH_4^+-N in the form in which it is marketed and used. However, in the soil it can quickly hydrolyze in the presence of the urease enzyme to produce NH_4^+ and bicarbonate ions. Urea normally hydrolyses rapidly. Significant quantities of NH_3 may be lost by volatilization when urea or urea-containing solutions are applied to bare soil surfaces which are rapidly evaporating water or to soils with large amounts of surface residues, including sod. Application during cold weather, soil incorporation or surface band applications of urea-containing fertilizers (e.g., UAN solutions) can help control the problem.

Rapid urea hydrolysis in soils may be responsible for NH_3 injury to seedlings when large quantities are placed too close to the seed or banded with the seed in narrow rows. A good rule of thumb is to avoid direct seed contact in row crops and narrow row-seeded small grains. Urea is an excellent fertilizer for foliar application, but some grades may contain small amounts of a condensation product known as biuret. Biuret is toxic when applied to the foliage but has no effect when applied to the soil.

B. **Ammonium Nitrate** (NH_4NO_3) (34-0-0)

- Readily available plant food as nitrate or ammonium.
- Used with oil for blasting (explosive).
- Natural affinity to absorb moisture limits bulk storage during summer months.

Ammonium nitrate contains 33.5 to 34.0 percent N. Half the N in ammonium nitrate is NH_4^+ and half is NO_3^-. Although solid ammonium nitrate has excellent handling qualities, it is hygroscopic (absorbs moisture) and should not be left in open sacks or bins for long periods in humid climates. For that reason, it is coated during manufacturing with materials such as diatomaceous earth to prevent absorption of water. Ammonium nitrate is well suited to bulk blending and to crops requiring sidedress N applications.

C. **Aqua Ammonia** (NH_4OH) (29-0-0)

- Produced by dissolving ammonia gas in water.
- Must be stored and handled under pressure because of free ammonia content.
- Used to neutralize acidity in fertilizer mixes.
- Inexpensive source of N.
- If used as a N fertilizer, it must be injected into the soil to avoid ammonia losses.

Aqua ammonia and N solutions have properties similar to anhydrous ammonia and must be placed beneath the soil surface to prevent NH_3 loss. Nitrogen solutions are manufactured by blending concentrated liquors of ammonium nitrate, urea and sometimes aqua ammonia. Nitrogen solutions are sometimes produced by dissolving solid urea and/or ammonium nitrate. All N solutions are classed either as pressure or non-pressure solutions.

D. **Non-pressure Nitrogen Solutions** (28 - 32% N)

- Produced by dissolving N salts (urea and ammonium nitrate) in water.
- "Salting Out" - lower temperatures cause dissolved salts to precipitate.
- Lowering salt content lowers the salting out temperature.
- Example: UAN solution containing 30% N is made up of 42% ammonium nitrate, 34% urea, and 24% water.

Non-pressure solutions usually contain ammonium nitrate, urea and water. These solutions can be handled without the use of high-pressure tanks and equipment. They contain essentially no free NH_3. Nitrogen solutions containing both urea and ammonium nitrate (UAN) have higher N concentrations than solutions of either material alone. The presence of both compounds lowers the "salt out" temperatures and allows the solutions to be used at lower temperatures without formation of precipitates. However, even in UAN solutions, as the N concentration increases, the salt-out temperature increases: 28% N salt out is -5°F (-21°C), 30% N salt out is 20°F (-7°C), 32% N salt out is 29°F (-2°C).

Pressure solutions, on the other hand, have an appreciable vapor pressure of free NH_3. They may require specialized tanks and equipment, especially if their vapor pressure is high at operating temperatures. Pressure solutions must be applied below the soil surface to avoid NH_3 loss. Do not apply pressure solutions in direct seed contact because of NH_3 damage to germination.

E. Anhydrous Ammonia

Anhydrous NH_3 contains more N than any other N fertilizer (82%). It is stored under pressure as a liquid. It is applied to the soil from high-pressure tanks by injection through tubes running down the rear of a blade-type applicator or by metering into irrigation water for flood or furrow irrigation (not sprinkler irrigation). Applying anhydrous NH_3 can be difficult on rocky, wet or dry, or cloddy soils. On sod crops, it can cause temporary injury to roots and results in rough surface conditions.

A gas at normal temperatures and atmospheric pressure, some ammonia can be lost during and after application. Soil physical and chemical conditions affect the amount of loss. Soil moisture content, depth of application, spacing of applicator knives or release points (on a sweep) and soil CEC affect how well the soil retains ammonia. Low CEC soils such as sands may require deeper ammonia application to avoid volatilization losses.

If a soil is very dry and cloddy during ammonia application, the slit behind the applicator knife will not seal and NH_3 may volatilize. Soil moisture content near field capacity is ideal for ammonia retention. Water-logged conditions also increase loss possibilities because of difficulty in sealing behind the knives. Narrow applicator knife spacings or release points tend to reduce NH_3 losses because of reduced ammonia concentrations at the point of injection. Lower rates of application also reduce ammonia concentrations at release points and reduce possibilities of loss. Cold-Flo (reduced pressure) application of NH_3 results in NH_3 release as a liquid below the soil surface, lowering the possibility of volatilization losses. Less soil cover is then required to retain the NH_3. Everything considered, volatilization losses of NH_3 are usually quite low and are not a large economic factor.

F. Other Forms

Ammonium sulphate contains 21 percent N and 24 percent S. It is often produced as a by-product in the manufacturing of coke and nylon. Increasing frequency of S deficiencies is resulting in its wider use as a N and S source.

Ammonium phosphates- Monoammonium phosphate (MAP: $NH_4H_2PO_4$; 11-13% N; 21-24% P) and diammonium phosphate (DAP: $[(NH_4)_2HPO_4]$; 18-21% N; 20-35% P) are generally considered more important sources of P than N.

FERTILIZER CATEGORIES

Commercial fertilizers are generally classed into four categories: ammoniated dry granular, dry bulk blend, clear liquid, and liquid suspension. If blended and applied properly, all are equally effective in providing nutrients to crops.

Ammoniated Dry Granular

These fertilizers are manufactured by reacting NH_3 with a superphosphate slurry followed by the addition of muriate of potash and fillers. The resulting mixture is subsequently granulated during the drying process and each granule contains a known percentage of nutrients. In the past, this was one of the major means of mixed fertilizer production. However, the advent of less expensive bulk blends has caused the dramatic reduction in the production of mixed fertilizers by this process.

Dry Bulk Blends

Dry bulk blended fertilizers are produced by mechanically blending various granular fertilizer materials in a mixing drum. Materials such as ammonium nitrate, ammonium sulfate, urea, diammonium phosphate (DAP) and muriate of potash are used. Matching particle size and, to a lesser extent, particle density of the various materials is important to avoid material segregation during blending and transport to the farm. Larger or less dense ingredients tend to segregate and migrate to the top of the spreader truck. Also, more dense ingredients are thrown farther from the truck during the spreading, and less dense materials are spread closer to the truck, resulting in uneven distribution. These fertilizers are widely used and are less expensive than ammoniated dry granular products when compared on a cost per pound of plant nutrient.

Clear Liquids

Hot Mix Process: In this process, NH_3 or aqua ammonia (ammonia hydroxide) is reacted with phosphoric acid. Water is used as a filler and muriate of potash is dissolved in the solution to produce a specific grade. If additional N is needed to formulate the grade it may be supplied by adding a UAN solution. A great deal of heat is generated during the neutralization of phosphoric acid. Following mixing, the fertilizer must be cooled before being placed in storage. This process has not been as popular with liquid blenders because of the need for storing and handling phosphoric acid at the dealership and the need to cool the resulting fertilizer before placing it in storage.

Cold Mix Process: Superphosphoric acid is neutralized by anhydrous ammonia by either the basic supplier or the liquid blender. The resulting 10-34-0 liquid becomes the basic material in making a complete liquid fertilizer. Any additional N needed to formulate the grade will come from a UAN solution. Muriate of potash is dissolved in the mix to supply the desired K. Water is used as the filler.

Since phosphoric acid is neutralized as the first step in the production of these fertilizers and N materials are the least expensive materials to use, clear liquid fertilizers will almost always contain N. This could be a disadvantage when one is fertilizing legumes. Due to limits on the solubility of the materials being used to formulate these fertilizers, the analysis and ratios that can be formulated as clear liquids is limited.

Liquid Suspensions

Liquid suspension fertilizers were developed to make high analysis liquid fertilizers and to overcome the solubility limits of clear liquids. A particular kind of clay, that is relatively easy to maintain in suspension, is added to the mix. The clay provides a large surface on which the fertilizer salt crystals may form as the solution becomes saturated. Crystal formation on the clay surface helps to maintain the nutrient in suspension. This makes it possible to formulate higher analyses grades such as 4-12-24. Periodic agitation of suspensions while they are being held in storage is necessary to prevent settling of the clay and fertilizer crystals. Agitation with a sprayer type system is also required during transport and application.

COMMON FERTILIZER GRADES

Clear Liquids and Dry Ammoniated

Clear Liquids and Ammoniated or Granulated fertilizers are alike in that reactions producing heat occur when mixed. Nutrient contents or grades are limited and usually contain lower amounts of N-P_2O_5-K_2O (6-1).

Table 6-1. Examples of some common nutrient contents.

2-6-12	10- 5-10
3-9-12	10-10-10
4-6-12	5-10-10
6-6-12	10-20-20
8-8- 8	12- 6- 6
8-5-12	15- 5- 5

Dry Bulk Blends and Liquid Suspensions

Dry blends and suspensions are alike in that the mixing principle involves blending raw materials. No chemical reactions occur, therefore the grades are infinite and can contain high amounts of nutrients (Table 6-2).

Table 6-2. Starter Fertilizer Grades

Liquid		Dry
30- 0-0	5-10-10	34- 0- 0
10-34-0	8- 8- 8	18-46- 0
10-29-0	7-22- 7	5-10-10
18-18-0	18-12- 0	10-20-20
9-18-9		8-24-24
4-10-8		8-30-20
3-12-6		10-20-10

Note: Liquid Starters are Hot-Mix Liquid or Clear

Phosphorus

Traditionally the P content of P fertilizer materials and mixed fertilizers is expressed as the pentoxide P_2O_5. With the exception of a very few specially fertilizer materials such as calcium metaphosphate ($Ca_3(PO_4)_2$), which are seldom if ever used in crop fertilization, P occurs in fertilizers as salts of either the monovalent or divalent anion $H_2PO_4^-$ or HPO_4^{-2}. Phosphorus also exists in the soil solution as these two anions with their relative concentrations being determined by the pH of the solution. These are also the two forms absorbed by plants from the soil solution.

Phosphate rock is the basic material used in all P fertilizer production. The most important deposits are sedimentary materials, laid down in beds under the ocean and later lifted up into land masses. Known world reserves of phosphate rock are enormous, approaching 40 billion tons. About 35 to 40 percent of the reserve can be economically recovered under today's conditions. This tonnage represents enough phosphate to meet present consumption for hundreds of years. As the economy changes, even greater amounts can be recovered.

Almost all phosphate rock is surface mined. It usually contains about 15 percent P and must be upgraded for use as fertilizer. Upgrading removes clay and other impurities. This process is called benification. Following benification, the rock phosphate is finely ground. Although some is applied directly as fertilizers on acid soils in some countries, the P in it is slowly available and seldom increases crop yields during the first two or three years after application. Usually, the rock is treated to make the P more soluble.

Fertilizer phosphates are classed as either acid-treated or thermal-processed. Acid-treated P is by far the most important. Sulfuric (H_2SO_4) and phosphoric (H_3PO_4) acids are used in producing acid-treated phosphate fertilizers. Sulfuric acid is produced from elemental S or from sulphur dioxide. More than 60 percent of this industrial acid is used to produce fertilizers. Treating rock phosphate with concentrated (about 90 to 93 percent) sulphuric acid produces a mixture of phosphoric acid and gypsum. Filtration removes the gypsum to leave green, wet-process, or merchant grade (MG) phosphoric acid containing about 54 percent P_2O_5. Wet process acid can be further concentrated to form superphosphoric acid. In this process, water is driven off and molecules with two or more P atoms are formed. Such molecules are called polyphosphates.

Wet process sulphuric acid acidulation is the most commonly used technique for solubilizing P in phosphate rock. The majority of P fertilizers used in North America are based on wet process phosphoric acid (52-55 percent P_2O_5) resulting from the reaction of phosphate rock with sulphuric acid. Common P-containing fertilizers and their manufacturing processes are listed below.

A. **Phosphoric Acid** - 55 % P_2O_5 (H_3PO_4)

- Manufactured by dissolving rock phosphate in sulfuric acid.
- Also known as "wet process or green acid".
- Used as a P source in the production of hot mix complete liquid fertilizers. Reacted with ammonia to produce liquid N & P fertilizer materials and dry granular MAP and DAP. Reacted with rock phosphate to produce concentrated superphosphate (0-46-0).

B. **Superphosphoric Acid** - 76-85% P_2O_5 ($H_4P_2O_7$ and H_3PO_4)

- Produced by dehydrating wet process phosphoric acid.

C. **Ammonium Phosphates** -

Monoammonium phosphate	- MAP (11-52-0)
Diammonium phosphate	- DAP (18-46-0)

- Produced by reacting ammonia with phosphoric acid and then granulated & dried.
- Completely water soluble P (but not suitable for use in irrigation systems or for formulating liquid fertilizers).
- Used for direct application as starters; however, care should be taken to avoid seedling injury caused by free ammonia formation.
- High analysis, easy handling and storing, and cost-effective.

D. **Ammonium Polyphosphate** APP (10-34-0) - liquid

- Fluid sources of P produced by ammoniating superphosphoric acid.
- Neutral solution pH.
- Used as a true "pop-up" starter.

E. **Concentrated Superphosphate** (0-46-0)

- Produced by reacting rock phosphate with wet process phosphoric acid.
- A dry granular product in which the P is about 85% water soluble and 100% available.
- May also be called triple superphosphate (TSP).

Potassium

Potassium content of K fertilizer materials and mixed fertilizers is expressed as the oxide K_2O even though it does not exist in fertilizers or the soil solution nor is it taken up by plants in this form. In natural deposits and in fertilizers it commonly occurs as the K salt of either chlorine (KCl, or muriate of potash), sulfur (K_2SO_4) or nitrogen (KNO_3). Potassium is absorbed by plants from the soil solution as the monovalent cation K^+.

Potassium Fertilizer Sources

Elemental K is not found in nature because of its chemical reactivity. Potash deposits occur as beds of solid salts beneath the earth's surface and brines in dying lakes and seas. Potash is mined four major ways:

- Conventional underground mining method. This under cuts the face, drills and blasts.
- Continuous mining method. This uses specially-developed mining machines that take the ore directly from the vein, without blasting.
- Solution mining. A hot salt brine is pumped down to the potash bed, dissolving mainly K salts and returning the potash brine to the surface for refining.
- Surface brine recovery. Potassium and other minerals are harvested by solar evaporation from natural surface brines in the Great Salt Lake in the U.S. and the Dead Sea in Israel and Jordan.

Potassium is mined from a number of minerals. Sylvinite, sylvite and langbeinite are the most important.

- Sylvinite is composed primarily of potassium chloride (KCl) and sodium chloride (NaCl)-containing 20 to 30 percent K_2O.
- Sylvite is composed mainly of KCl-containing about 63 percent K_2O.

- Langbeinite is composed largely of potassium sulphate (K_2SO_4) and magnesium sulphate ($MgSO_4$) containing about 23 percent K_2O. (Brines containing K are about two-thirds water and contain about three percent K_2O.)

A. **Potassium chloride** (KCl)

Potassium Chloride, or muriate of potash, accounts for more than 90 percent of the K sold in the U.S. and Canada. It is water soluble and contains 60 to 62 percent K_2O. Most North American KCl is produced from sylvinite, but some comes from brines. The raw, impure ore is refined to fertilizer by crystallization or flotation processes. Most agricultural KCl is produced by the flotation process.

Fertilizer grade KCl is available in five particle sizes:

(1) white soluble,
(2) special standard,
(3) standard,
(4) coarse,
(5) granular.

Granular is very suited to bulk blending. The white soluble grade is ideal for clear liquids.

B. **Potassium sulphate** (K_2SO_4)

Also called sulphate of potash (SOP), it contains about 50 percent K_2O and 18 percent sulphur (S). Because its chloride (Cl) content is below 2.5 percent, it is used for Cl-sensitive crops such as tree fruits and tobacco, and to supply S. It accounts for about six percent of total agricultural K sales. Potassium sulphate can be used where Cl buildup becomes a problem.

C. **Sulphate of potash-magnesia** ($K_2SO_4 \cdot 2MgSO_4$)

It is also called potassium-magnesium sulphate, "Sul-Po-Mag" and "K-Mag." It contains about 22 percent K_2O, 11 percent Mg and 22 percent S. It occurs in nature as the mineral, langbeinite, which is refined to the commercial fertilizer product. It is a good source of water-soluble K and Mg, and is very important where Mg and/or S is deficient.

D. **Potassium nitrate** (KNO_3)

Potassium nitrate contains little or no Cl or S. It contains about 44 percent K_2O and 13 percent N.

SECONDARY PLANT NUTRIENTS: SULFUR, CALCIUM, and MAGNESIUM

Secondary plant nutrients include Ca, Mg and S (Table 6-3). These nutrients are usually applied as soil amendments or applied along with materials which contain primary nutrients. Secondary nutrients are as important to plant nutrition as major nutrients, though plants don't usually require as much of them. Many crops contain as much S as P, sometimes more. And secondary nutrient deficiencies can depress plant growth as much as major nutrient deficiencies do.

Table 6-3. Secondary Plant Nutrient Chemical Composition

	Element Material	Chemical Composition	% Element	CCE[1]
S	Elemental Sulfur	S	100.0	none
S	Ammonium Bisulfate	$(NH_4)HSO_4$	17.0	none
S	Ammonium Polysulphide	$(NH_4)_2S_x$	40-50	none
S	Aluminum Sulfate	$Al_2(SO_4)_3$	14.0	none
S	Ammonium Sulfate	$(NH_4)_2SO_4$	24.2	none
S	Ammonium Thiosulfate	$(NH_4)_2S_2O_3$-$5H_2O$	26.0	none
S	Gypsum	$CaSO_4$	18.6	none
S	K-Mag	$K_2SO_4 \cdot 2MgSO_4$	22.0	none
S	Potassium Sulfate	K_2SO_4	18.0	none
S	Magnesium Sulfate	$MgSO_4$	13.0	none
Ca	Calcitic Limestone	$CaCO_3$	32.0	85-100
Ca	Dolomitic Limestone	$CaMg(CO_3)_2$	22.0	95-108
Ca	Hydrated Lime	$Ca(OH)_2$	45.0	120-135
Ca	Calcium Oxide	CaO	55.0	150-175
Ca	Gypsum	$CaSO_4$	22.3	none
Ca	Calcium nitrate	$Ca(NO_3)_2$	19.4	none
Ca	Basic Slag		29	50-70
Mg	Dolomitic Limestone	$CaMg(CO_3)_2$	3-12	95-108
Mg	Epsom Salts	$MgSO_4 \cdot 7H_2O$	9.6	none
Mg	Kiserite	$MgSO_4 \cdot H_2O$	18.3	none
Mg	K-Mag	$K_2SO_4 \cdot 2MgSO_4$	11.0	none
Mg	Magnesium Nitrate	$Mg(NO_3)_2$	19.0	none
Mg	Magnesia	MgO	55-60	none
Mg	Basic slag		3	none

---

[1] Calcium carbonate equivalent - Relative neutralizing value based on pure calcium carbonate at 100%.

Sulfur

Elemental S, sulfides, and thiosulfates must be oxidized to SO_4^{-2} by S oxidizing bacteria in the soil before S can be taken up by plants..

Most fertilizer S sources are sulfates (Table 6-3) and are moderately to highly water soluble. Soluble forms also include bisulphites, thiosulphates and polysulphides. The most important water insoluble S fertilizer is elemental S, which must be oxidized to the sulphate-S form before plants can use it. Bacterial oxidation of S in the soil is favored by:

- Warm soil temperatures,
- Adequate soil moisture,
- Soil aeration,
- Fine particle sizes.

Table 6-3 lists the common S fertilizer sources, along with their chemical formulae and percent S.

The water soluble sulfates are immediately available to plants and should be used when S is needed quickly. They are commonly used in dry fertilizers, although ammonium sulphate solutions are also common. Ammonium thiosulfate (ATS: 12-0-0-26) is a clear, odorless, non-corrosive liquid well-suited for use in fluid fertilizers or addition to irrigation water. It should not be seed placed and, if band applied, should be at least 1 inch from the seed. Ammonium polysulphide (APS) is a red fluid S source with a strong odor of ammonia, commonly applied in irrigation water. Sulphur in APS must be oxidized to the sulphate form to be available to plants.

Although gypsum (calcium sulphate) is less water soluble than the other sulfates, it is an effective and inexpensive S source. Elemental S, sulfides, and thiosulfates must be oxidized to SO_4^{-2} by S oxidizing bacteria in the soil before S can be taken up by plants. This causes a reduction in soil pH which may be an undesirable result. Fertilization with elemental S results in a slower crop response than sulphate sources because it is water insoluble. To be effective, it should be incorporated into the soil well in advance of crop needs. Used properly, however, elemental S is an agronomically effective and economically efficient S source. One objection to the use of finely ground S is discomfort to the user. It is dusty and can be a fire hazard under confined conditions. The problem is usually avoided by granulating the S with bentonite clay.

Calcium

Calcium can be supplied in several ways. Because most Ca deficient soils are acid, a good liming program can add Ca most efficiently. Both calcitic and dolomitic limestones are excellent sources (Table 6-3). Gypsum can also supply Ca when soil pH is high enough not to need lime, but (in the unlikely event) where Ca might be deficient. Normal superphosphate which is 50 percent gypsum and to a lesser extent, triple superphosphate, can also add Ca to the soil.

When using Ca sources other than ground calcitic and dolomitic limestone, apply with caution. Excess hydrated lime and burned lime can partially sterilize the soil. Adding large amounts of Ca and Mg to K-deficient soils or adding Ca to a Mg-deficient soil can cause nutrient imbalances and poor crop growth. Supply all needed nutrients to alleviate growth-limiting conditions.

Magnesium

The most common source of Mg is dolomitic limestone, an excellent material which provides both Ca and Mg while neutralizing soil acidity. Other sources include potassium-magnesium sulphate, magnesium sulphate, magnesium oxide and basic slag. Table 6-3 shows common Mg sources and the percent Mg they contain. The sulphate Mg forms are more soluble than dolomitic lime and may be the preferred Mg source on those soils where a quick crop response is required.

Micronutrients

Seven of the 16 essential plant nutrients are called micronutrients: B , Cu, Cl, Fe, Mn, Mo, and Zn (Table 6-4). They are as important to plant nutrition as major and secondary nutrients, though plants don't require as much of them. Relative amounts of micronutrients in the soil, especially metals, determine their availability and may be more important than absolute amounts of each. This relationship can make soil test results misleading, unless the levels of other micronutrients (and major and secondary nutrients) are considered. Refer to Chapter 3, for more information concerning the micronutrients.

Micronutrients can be applied in several different ways and the chosen method many times dictates the micronutrient source to be applied. Each material has its own chemical and physical properties which makes each one suited for soil or foliar applications. Some materials are suited for both soil and foliar application. For example, sulfates, chelates and most organics are soluble and better adapted for foliar applications than are frits and oxides.

In general, most micronutrients can be supplied at quantities sufficient to meet the crop's need through repeated foliar applications. Foliar applications are useful in maintaining or increasing crop yields, but it is a temporary solution. The soil factors which induced the foliar deficiency of the nutrient continue to exist and must be remedied in order to achieve a long lasting correction. Great care should be taken when adding micronutrients and primary nutrients in the same solution. There are incompatibility problems between P and most of the micronutrients, particularly with Zn, Cu, Mn and Fe.

Fertilizer materials which contain significant amounts of micronutrients generally should be banded into the soil for maximum efficiency. Micronutrients can be mixed into bulk blends or incorporated into the chemical composition of many commercial fertilizers.

Table 6-4. Sources of micronutrients

ELEMENT	MATERIAL	% ELEMENT
B	Borax	11.3
B	Borate 46	14.0
B	Borate 65	20.0
B	Boric Acid	17.0
B	Solubor	20.0
B	Boron Frits	2.0 - 6.0
Cu	Copper Sulfate	22.5
Cu	Copper Frits	Variable
Cu	Copper Chelates	Variable
Cu	Other Organics	Variable
Fe	Iron Sulfates	19-23
Fe	Iron Oxides	69-73
Fe	Iron Ammonium Sulfate	14.0
Fe	Iron Frits	Variable
Fe	Iron Chelates	5-14
Fe	Other Organics	5-10
Mn	Manganese Sulfates	26-28
Mn	Manganese Oxides	41-68
Mn	Manganese Chelates	12
Mn	Manganese Chloride	17
Mn	Manganese Frits	10-25
Zn	Zinc Sulfates	23-35
Zn	Zinc Oxides	78
Zn	Zinc Carbonate	52
Zn	Zinc Frits	Variable
Zn	Zinc Phosphate	51
Zn	Zinc Chelates	9-14
Zn	Other Organics	5-10
Mo	Sodium Molybdate	39-41
Mo	Molybdic Acid	47.5

Due to the small amounts of element which are needed, it is generally impractical to make soil applications of individual micronutrients. Extreme care should be taken when making micronutrient applications to the soil due to the fact that the difference between an adequate amount and a toxic amount of many of these nutrients is very small. Once over applied, a toxic level of many of these micronutrients can exist for many years.

AGRONOMIC ASPECTS OF FLUID AND DRY FERTILIZERS

Questions frequently arise concerning the relative agronomic merits of various physical and chemical forms of fertilizers. Two common questions center on whether fluid fertilizers are agronomically better than their dry counterparts and whether polyphosphates are agronomically better than orthophosphates. The polyphosphate question is pertinent to a discussion of fluid fertilizers because polyphosphates are most often encountered in fluids. The answers to these questions are often confusing because responders tend to include non-agronomic factors such as ease of application, uniformity of application, and economics in their agronomic evaluations. The answer should be based solely on crop yield obtained when materials are compared using similar rates of plant nutrients under similar methods of application.

Comparisons of Fluid and Dry Fertilizers

Although numerous field studies have been performed comparing fluid and dry fertilizers under similar conditions, very little of this research is in reports which are widely available. The comparisons most often made have been among solid urea, solid ammonium nitrate, and urea-ammonium nitrate (UAN) fluids; between dry ammonium phosphates and fluid ammonium phosphates; and between ammonium orthophosphates and ammonium polyphosphates.

Experimental data from a wide range of studies overwhelmingly support the conclusion that there are essentially no differences among the liquid, suspension, and dry fertilizers when they are compared over the long term under conditions of similar nutrient rates, placements, and chemical forms. The latter is particularly important when comparing phosphate fertilizers. For instance, it would not be valid to compare a highly water-soluble phosphate in fluids with a solid phosphate of low water solubility. However, when solids such as diammonium phosphate (DAP), monoammonium phosphate, or ammonium polyphosphate were compared with fluids such as 10-34-0, 8-24-0, or 11-37-0 under similar conditions, long-term studies have shown these to be essentially equal in nutritive value. Similarly, long-term studies have shown solid urea or ammonium nitrate to be essentially equal to N solutions, such as urea-ammonium nitrate. Essentially the same conclusions would be reached with dry and fluid NPK mixes.

The relative equality of fluid and dry fertilizers should not be too surprising in light of the fact that the chemical constituents of the two physical forms are usually identical. For example, UAN solution or suspension contains both urea and ammonium nitrate, both popular dry materials. Likewise, 8-24-0 solution is an ammonium orthophosphate material, just as MAP and DAP are. Some of the ammonium phosphate fluids may contain ammonium polyphosphates; but this does not confuse the issue too much, as discussed below.

The matter of equality of various physical forms is even more predictable when one considers the limited variety of chemical forms presented to the plant root. Although a farmer may apply fertilizer N as anhydrous ammonia, urea, ammonium nitrate, UAN, calcium nitrate, or several other forms, the same farmer may be assured that, within a fairly short time, the roots of his crops will be confronted mainly with N in the nitrate form (NO_3^-). This is because various soil enzymes rapidly convert urea N to ammonium forms, and then soil microbiological processes fairly rapidly convert the ammonium forms to nitrate. So, for most of the growing season, plant roots "see" mainly nitrates.

Despite the fact that farmers are offered a wide array of P-containing fertilizers, these farmers are assured that their crops are really confronted with a very limited variety of chemical forms of P. First, the P in most fertilizers is present in the orthophosphate form. When an orthophosphate-containing fluid fertilizer is applied or an orthophosphate containing dry fertilizer dissolves in the soil solution, the plant roots are confronted mainly with two phosphate species ($H_2PO_4^-$ and HPO_4^{-2}). Polyphosphate is fairly rapidly converted in most agricultural soils to the orthophosphate form if a fertilizer material containing polyphosphates is applied. So, regardless of the physical or chemical form of P fertilizer, after a short while in the soil, plant roots "see" only two very similar forms of P.

Potassium fertilizers are even more uniform than either N or P fertilizers. The dominant source of K for both fluid and dry fertilizers is KCl. Even when other sources, such as potassium phosphate or potassium nitrate, are used, it is the potassium ion (K^+) which the plant root deals with in the soil solution.

In summary, fluid and dry fertilizers of comparable chemical constituency are essentially equal agronomically when applied at equivalent nutrient rates under similar placements. This equality gives farmers a large number of options in choosing fertilizer materials based on economics, convenience, compatibility with other operations, dealer services, or regional availability.

FERTILIZER PLACEMENT SYSTEMS

There are many placement systems available to put the fertilizer material anywhere you want it. Many factors must be considered, including soil fertility levels, crop(s) to be grown, tillage methods, equipment, timing, and other management factors. It is impossible to discuss all of them here, but a few general categories will illustrate the key points to be considered. We can first consider the main types of placement systems: BROADCAST, BAND, STRIP. Most systems involve variations or combinations of these.

Broadcast Application

Material, either fluid or dry, is spread uniformly over the soil surface. This provides for the most even distribution of nutrients over the field. It has the advantage of the most roots being in contact with the fertilizer material. In most cases, it will be the least cost method of application. Disadvantages of broadcast placement are that it increases the probability of nutrients being fixed in unavailable forms, because more soil surface area is in contact with the applied fertilizer. This is a problem only in soils with a high tendency to fix nutrients, in cases of relatively low soil test, and in cases of relatively low application rates. Even distribution is critical if the fertilizer is to be left on the surface, as is in the case of top-dressing wheat. If it is to be incorporated with one or more tillage operations, uniform distribution is still desirable, but the tillage operations can help somewhat.

Band Application

Generally, band application refers to application in a concentrated band at some point below the soil surface. Starter application 2" below and 2" to the side of the seed with a corn planter is one example. Sidedress injection of N materials is another. The fertilizer is mixed with only a small volume of soil. Phosphorus and K fertilizers applied in a band will remain in that band until they are disturbed by subsequent tillage operations. The nutrients are available to only those roots that intercept the band, therefore, there is often a proliferation of root growth around the band.

If rates are high, the salt content in the band may be high enough to inhibit root growth, so that the fertilizer in the center of the band may not be available to the plant. Nitrogen will move gradually away from the band in the soil solution, but there still may be an advantage to having it concentrated for a period of time. In the case of anhydrous ammonia, the concentration of ammonia helps slow the conversion to nitrate and thus helps keep the N in the free ammonia form for a short time.

The location may range from surface to deep injection, but the common feature of band application systems is that the fertilizer material is kept in a concentrated area, so that the roots which come in contact with the band have a high concentration of nutrients available. Deep banding of fertilizer may help to ensure an adequate supply of nutrients during later periods of the growing season when moisture in the plow layer becomes limiting. Deep placement of fertilizer helps encourage deeper root development and thus helps the crop to withstand moisture stress. The clear advantage to banding is for low testing soils where you want to get the most direct benefit from the fertilizer material for the crop to which it is applied. If the objective is merely to apply a maintenance supply, there may not be an advantage of banding over broadcasting. For soils with a high tendency to fix P and K in unavailable forms, banding also has some advantages. There is only a small amount of soil surface area in contact with the fertilizer material, so fixation is minimized.

Dual placement is a variation of band application, in which two different fertilizer materials are applied in the same band. An example is the application of anhydrous ammonia in a band with P fertilizer. Research in the Great Plains has shown some advantages to this system for small grains and corn. Again, to the advantage is greatest where soil P levels are low, or where there is a high tendency for P to be tied up in unavailable forms.

Strip Application

Strip application is intermediate between broadcast and band application systems in amount of mixing with the soil and in the degree of fixation. Generally, by strip application, we refer to the application of materials in a strip 3-5 inches wide on the surface of the soil, with or without subsequent incorporation with tillage operations. Tillage helps to further spread out the material from the band, but it usually will result in less mixing than broadcast and incorporated applications. Early studies at Purdue University showed a decided yield advantage to strip application over band or broadcast applications for corn grown on soils testing low in P and K. There was little difference among application systems where soil test levels were high.

Foliar Application

There has been some interest in foliar application of nutrients, but yield responses have not been consistent. With the exception of some micronutrient materials, most nutrients are not readily absorbed by leaves. The fertilizer materials used must be low analysis materials to avoid burning of the leaves. To get a substantial amount of macronutrients into the plant in this manner is rarely cost effective, even where physiologically possible. The most useful application for foliar-fertilization seems to be for field specific treatment of micronutrient deficiencies.

As research continues on foliar applications, we may learn more about how to get the nutrients into the leaves to help improve nutrition during grain filling, when roots are generally declining in effectiveness. For the present, foliar feeding does not appear to be a dependable or economically efficient system.

Tillage operations after band and strip applications will tend to increase the amount of mixing of nutrients with soil. The more tillage that is done, the less likely you will be to see any of the benefits of the concentrated application system. It would also be expected that after several years of fertilization with any of these application systems, there would be a tendency for the fertility level to even out throughout the profile and any relative advantages for band or strip application over broadcast would disappear.

Fertigation

Fertigation is another fertilizer placement system defined as "the application of nutrients using an irrigation system by injection of the desired nutrients into the water flowing through the system". In most cases, fertigation supplements the overall fertility program and is not intended to replace soil application and incorporation of plant nutrients.

Fertigation can be used to decrease the losses of mobile nutrients (e.g., NO_3^--N, K, B, Mg, SO_4^{-2}) on sandy soils by applying the nutrients as they are needed by the crop and at rates relative to the plants' requirements. Nitrogen applications on corn are a good example; weekly fertigations of 30 to 40 lb/A N from the time corn is 18 inches tall until tasseling will assure supplying N when it is in greatest demand by the crop.

Fertigation is also useful when special nutrient applications are required according to visual symptoms and/or according to tissue analyses. A range of soluble nutrient compounds are available for applications of this type. Fertigation can normally be performed even when other types of applications are not possible, such as when soils are wet or when airplanes cannot fly due to bad weather.

Fertigation should, with some care, result in very uniform application of nutrients, especially micronutrients. Of course, the degree of uniformity depends on the type of irrigation system being used. Likewise, fertigation offers flexibility in fertilizer application. Since the irrigation system is essentially dedicated to the land, there is no wait for equipment which may be committed to another farm task or for the availability of an aerial applicator.

There are also some potential disadvantages with fertigation. For example, the fertilizer sources for fertigation are limited to those that are completely soluble. This is generally not a problem with N, since solutions are widely available. However, aqua and anhydrous ammonia are not generally injected because of special problems with volatilization losses and corrosion.

Fertigations can be non-uniform. Uneven applications can result from poor irrigation patterns and are particularly apparent on the ends of center-pivot systems. Another problem occurs when fertilizers are injected into a system either already in operation or full of water. Considerable time, depending on the length of the system, will lapse before a uniform application is made at the perimeter. Therefore, it is best to begin injection with the first water that passes the point of injection.

FERTILIZATION TIMING

Proper timing of fertilizer applications may be important in providing adequate plant nutrition in some situations. Usually timing is not a major concern for K and P, but it is sometimes critical for N. Phosphorus and K move very little in the soil, so applications may be made for two or three years at a time in many soils. Soil texture, clay mineral make-up, and cation exchange capacity are among the factors to be considered in deciding whether annual applications are necessary. Of course when soil test levels are low, it is important that the P and K be applied before they are needed by the crop.

Nitrogen, being much more mobile in the soil, must be applied directly for the crop when it is needed. For lighter textured soils (high sand and/or silt content), split applications may be essential. Where high yield goals are involved, split applications may also show an advantage. Some recent studies indicate a response to free ammonia-N during grain filling in corn. If continuing research supports these early findings, changes in current methods and timing of N applications may be warranted.

Again the overall objective of a fertilizer program is to provide adequate nutrients to meet the needs of the growing crop, but not to excessive levels. Where timing considerations help to meet that objective, special attention to timing is needed.

LIMING

The acidification of soils can be reversed and a favorable pH maintained by applying lime. The amount and frequency of liming depends largely on soil characteristics, fertilization practices, and cropping. Interruption of a proper liming program will eventually lead to an acid soil condition and its adverse effects on crop production. In other words, it will always be necessary to lime periodically if the soil pH is to be maintained in the range most desirable for plant growth and efficient use of plant nutrients.

Major sources

There are many materials that can be used to increase the pH of a soil. These materials have differing physical and chemical characteristics which influence the application rates and the reactivity of the material. Two factors which must be considered in the evaluation of a liming material are: chemical composition and fineness of grind. Some of the most common liming materials are listed below in Table 6-3.

Limestone is a naturally occurring mineral that is the result of the deposition and compression of the skeletal remains of marine organisms (coral, shellfish, etc.) that contain high amounts of Ca and Mg carbonates. Due to the fact it is a naturally occurring mineral there are varying degrees of purity and chemical composition. For example, pure calcium carbonate ($CaCO_3$) has been assigned an arbitrary index number of 100 to define its neutralizing value. Other liming materials are compared to $CaCO_3$ and rated on their neutralizing abilities relative to pure $CaCO_3$ known as calcium carbonate equivalent (CCE). A CCE greater than 100 indicates that the material is capable of neutralizing more acidity on a weight basis than pure $CaCO_3$ and vice versa. Pure, or relatively pure $CaCO_3$ is known as calcitic limestone.

Liming Materials

The characteristic or property that distinguishes lime from other Ca- and Mg- bearing materials is that lime contains Ca and/or Mg in forms, which, when dissolved, will neutralize acidity. Lime components which reduce acidity are the carbonates contained in limestone and marl, the oxides contained in burned lime, and the hydroxides found in slaked lime. Not all materials that contain Ca and Mg can be used for liming purposes. For example, Ca and Mg sulfates and chlorides are capable of supplying Ca and Mg but cannot reduce soil acidity.

The carbonates, oxides and hydroxides of Ca and Mg are only sparingly soluble in water. These materials require soil acidity in order to react. Burned lime and hydrated lime are highly reactive and react very quickly with soil acidity while the carbonates are slower reacting. In order to obtain the greatest benefit from these materials, especially at higher rates of application, they must be thoroughly mixed with the soil by disking and/or plowing.

There are several materials that can be used for lime. All will neutralize soil acidity, but they have different characteristics and properties which influence their use and value. The more common liming materials used are discussed below.

A. Calcitic and Dolomitic Lime

These liming materials are made by grinding or crushing mined limestone rock to a certain fineness. The product is distributed in bulk or bags. The degree of fineness must be specified when sold. Crushed limestone, to be useful as an agricultural liming material, must react with soil acids in a reasonable length of time. The rate of reaction or dissolution of crushed limestone is largely determined by its fineness or mesh size.

Calcitic lime reacts somewhat faster than dolomitic lime of the same mesh size. However, the factor to consider in deciding which to use is the need for Mg and its relative cost. Dolomitic lime contains an appreciable quantity of both Mg and Ca which are essential nutrient elements in plant growth; whereas calcitic lime contains mostly Ca. They have essentially the same capacity for neutralizing soil acidity as indicated by their CCE (Table 6-3).

B. Calcium Oxide (Burned Lime)

Burned lime is made by roasting crushed limestone in an oven or furnace. This changes the chemical form from a carbonate to an oxide. Burned lime is also known as unslaked or quick lime. The CCE of burned lime depends on the purity of the limestone from which it is made and usually ranges between 150-175. No other liming material has such a high neutralization value. Approximately 1140 lbs of burned lime with a CCE of 175 is equivalent to 2000 lbs of calcitic lime with a CCE of 100. Burned lime is sold in bags because of its powdery nature, unpleasant handling properties, and reactivity with moisture in the air. This liming material neutralizes soil acids rapidly but may be somewhat difficult to mix with the soil. Thorough mixing at the time of application is necessary due to a tendency to absorb moisture, which results in the formation of lime granules or aggregates.

C. Hydrated Lime

Hydrated lime is calcium hydroxide, but is frequently called slaked or builders' lime. The manufacture of hydrated lime involves the reaction of burned lime with water, drying of the calcium hydroxide that is formed, and then bagging. Hydrated lime is similar to burned lime in that it is powdery, quick-acting, and somewhat unpleasant to handle. The CCE ranges between 110 and 135, depending on the purity of the burned lime from which it is made. Fifteen hundred pounds of hydrated lime with a CCE of 135 is equivalent to 2,000 lbs of agricultural limestone with a CCE of 100.

D. Marl

Marls are found in beds, mixed with earthen materials, in the form of calcium carbonate. These calcite deposits are often found in the eastern or coastal plain region of Virginia, limestone valleys in the Appalachian region, and other Atlantic Coast states. Their usefulness as a liming material depends on their CCE, which ranges from 70 to 90, and the cost of processing. They are often plastic and lumpy and must be dried and pulverized before application to the soil. Marls are usually low in Mg. Their reaction with the soil is the same as that of calcitic lime.

E. Slags

Slags that can be used for liming purposes include blast-furnace, electric-furnace, and basic. All are by-products of manufacturing processes. Blast-furnace slag is a by-product in the manufacture of pig iron. The slag is ground, screened, and distributed in bulk. Blast-furnace slag is a calcium silicate and reacts with soil acids in a manner similar to ground limestone. It has a CCE of 75 to 90. These slags contain appreciable quantities of Mg. As agricultural liming materials, they are comparable to ground limestone when applied in equivalent amounts based on CCE and fineness.

Basic slag is a by-product of the open hearth process for making steel from pig iron. This slag is finely ground and marketed in bags. Basic slag has a CCE of 60 to 70 and contains from 10 to 25% phosphate (P_2O_5). This product is particularly useful for acid soils that are low in P.

Electric-furnace slag is a waste material of the electric-furnace process for separating elemental P from rock phosphate. The product is largely calcium silicate, has a CCE of 60 to 80 and ranges from 1.0 to 2.3% phosphate. Its reaction with soil acids is similar to that for blast-furnace slag.

F. Ground Oyster Shells

Oyster shells and other sea shells are largely calcium carbonate. They make a very satisfactory liming material when finely ground and have a CCE of 90 to 110. Sometimes oyster shell lime is burned and used in the calcium oxide form. In general, oyster shell lime is used on farms located near the source of supply.

Particle Size

Fineness, or mesh size, is the main factor influencing the rate of reaction of applied lime. This does not mean, however, that lime should immediately react with the soil to be of maximum value. Usually a certain amount should be sufficiently fine (pass an 80 mesh sieve) to react rapidly with the soil acidity and supply the nutrient elements Ca and Mg. Another part should be sufficiently fine (approximately 40-60 mesh) to react within one to two years with the remainder (approximately 20 mesh) reacting in a period of two to three years. For a liming material to react in this manner it must be composed of lime particles of different mesh sizes. Research has shown that limestone pulverized to 100 mesh, or finer, reacts rapidly with soil acids. On the other hand, 10 to 20 mesh limestone dissolves very slowly and therefore is only slightly effective in reducing soil acidity.

Burned and hydrated limes are frequently used in agriculture and also in urban areas. These lime materials have a much finer mesh than the ground limestones and are therefore quicker acting. All lime particles in these materials are 100 mesh or finer. The quick-acting characteristics of these lime materials can be an advantage in certain situations. Conversely, it is often desirable to use lime containing a variety of mesh sizes. The coarser mesh sizes dissolve over a longer period of time and in so doing, tend to maintain soil pH.

Ca:Mg Ratio

Research has shown that plant growth is optimum when the balance between soil Ca and Mg is in favor of Ca, that is, more exchangeable Ca than Mg. However, the ratio of Ca to Mg can be nearly one to one before plant growth is adversely affected. Acid soils that are deficient in Mg should be treated with dolomitic limestone. Calcitic lime should be used on acid soils where the ratio of soil test Ca and Mg is 1.4 or less. Either dolomitic or calcitic lime may be used in all other situations. The lime to be used is generally determined by availability.

Chapter 7. MANURE AS A NUTRIENT SOURCE

Manure is a valuable agricultural by-product that contains the three major plant nutrients-nitrogen (N), phosphorus (P), and potassium (K) and other essential elements such as calcium (Ca), sulfur (S), boron (B), magnesium (Mg), manganese (Mn), copper (Cu), and zinc (Zn). Properly applying manure to fields may also improve soil tilth, aeration, and water-holding capacity of soil; decrease soil erosion potential; and promote the growth of beneficial soil organisms.

On a typical livestock farm about 75% of the N, 60-70% of the P, and 80-85% of the K fed to animals are excreted in the manure. Applying manure in excess or at the wrong time of the growing season, or improperly handling manure releases the nutrients into surface waters, groundwater, and the air. Instead of nourishing crops, the nutrients may become pollutants. A common misuse of manure is to apply it to a field, and then to supply a crop's entire nutrient requirements with commercial fertilizer without accounting for the nutrients contained in the manure.

ANIMAL WASTE MANAGEMENT BASICS

An animal-based agricultural operation must have a comprehensive waste management plan to reap the benefits and to reduce the risks associated with the use and disposal of animal manures. Manures have several potential end uses including land application, production of "biogas" for on-site heating, and off-site use as fuel or feed. The most common practice at present is land application.

A sound waste management plan requires careful attention to detail. It uses principles from agricultural engineering, agricultural economics, animal science, and crop and soil sciences to maximize the economic value of wastes and minimize the potential for environmental damage. An effective waste management plan for land application purposes has three key components:

- site selection,
- storage, and
- land application.

Site Selection

Natural land features should be carefully considered in selecting sites for farm waste management practices, including storage facilities and disposal or use areas. Slopes, soils, vegetation, and proximity to streams and drainage ways are traditional considerations when evaluating the effects of waste management practices on nearby surface water quality. One should also consider visual impact, odor, health and safety implications, as well as economic costs and benefits, when locating a waste management facilities.

Evaluate site and soil conditions carefully to avoid contaminating ground and surface waters. Avoid putting unlined storages over shallow creviced bedrock or below the water table. Also avoid storage in sandy or gravelly soils or other areas where serious leakage can cause groundwater pollution. Consider the soil characteristics to a depth of at least three feet below the proposed storage bottom.

Storage

Manure can be handled as a solid, a semi-solid, or liquid. The amount of bedding or dilution water influences the form. In turn, the form influences the selection of collection and spreading equipment and the choice of storage system.

Manures and wastewaters must be properly stored to maintain good physical condition, to provide ease of handling, and to avoid loss of nutrients to ground or surface waters. Storage facilities include basins, lagoons, plastic-covered stacks or wind rowed piles, and permanent roofed structures with earthen or concrete floors. All facilities must have these essential features:

- sufficient capacity to store manure until proper time of disposal or application to cropland,
- proper location - to avoid runoff to surface waters, or percolation to groundwater,
- measures that ensure effective odor and fly control.

Consider all farming operations, building locations and prevailing winds when locating storage facilities. Allow at least 100 feet between a water supply and the nearest part of a storage facility. Remember to construct storage facilities in a location for convenient filling and emptying, to keep out surface runoff and to provide all-weather access.

Required storage capacity depends on regulations, number and size of animals, amounts of dilution by spilled and cleaning water, amounts of stored runoff, and desired length of time between clean outs. Provide enough storage capacity so that manure is spread only when field conditions, labor availability, and weather conditions permit application to land supporting an actively growing crop or land soon to be planted.

Land Application

Prepare a farm-wide nutrient budget to determine if the available land and intended crops have the capacity to use the nutrients provided by the manure. If sufficient land is available, determine crop yield potential and fertilizer requirements as indicated by soil tests and yields goals.

Waste application rates should balance nutrient content in the waste with crop nutrient demands based on realistic yield goals. Because of the variability in nutrient composition of manures and wastewaters, regular analysis of wastes for N, P, K, S and micronutrients is essential. Application timing is critical as well. Wastes should be applied as closely as possible to the time of maximum crop nutrient uptake.

Solid and semi-solid manure can be collected with tractor scrapers, front-end loaders or mechanical scrapers. Solid and semi-solid wastes are usually applied with conventional manure spreaders. Wastewaters may be delivered to the land by a variety of irrigation systems. In either case, calibrate the application equipment frequently. One of the greatest problems in land application of organic wastes is over-application caused by improperly calibrated equipment. This not only reduces the total fertilizer value of the waste and results in excessive concentrations of soil N and P, which can subsequently be lost to groundwater by leaching or to surface waters through runoff.

Liquid manure can be collected with scrapers, flushing systems, gravity flow gutters or slotted floors. Application of liquid manure from pits is typically done with liquid manure tank wagons and is either broadcast or injected. It may also be applied with irrigation equipment specially developed for manure handling. Land application from earth basins is usually done with liquid manure tank wagons. They are usually loaded by the agitation pumps that go in the basin.

VOLUME OF MANURE PRODUCED AND STORAGE REQUIREMENTS

The determination of volume of manure produced on a farm is critical for efficient nutrient management. Only by determining volume produced, can one decide to which fields manure should be applied, how much land is required for application, when manure will be applied, and how much storage is necessary based upon the cropping system.

Dry or Semi-solid Manures

For animal systems determine the number of animals managed in confinement for the year. Total animal manure volume can be roughly calculated using Table 7-1 for dry or semi-solid manures.

Broiler houses generate approximately 1.25 tons of litter per 1000 birds during each cycle. Six cycles per year are average. Houses are cleaned out at variable intervals ranging from after each cycle to once every two years. Turkey Tom production generates about 10 tons of litter per 1000 birds during each cycle for four cycles per year. Turkey hens produce about 8 tons per 1000 birds during each of five cycles per year. Complete clean-outs of poultry houses should be scheduled during spring or summer, unless covered storage is available, to minimize water quality impacts and maximize agronomic efficiency.

Liquid Manures

Variability in volume produced and nutrient content is much more significant between similar livestock farms producing liquid manures than for dry manures. The amount of wash water and lot runoff of rain water entering storage facilities have a direct impact on the volume of manure available for land application. Water inputs into the system dilutes the nutrient content per 1000 gallons of manure as does rain water falling directly into the storage structure. For liquid manures, either the following form should be used to estimate annual volume of manure, or producer records of number of loads hauled in past years should be used. The following worksheet is designed to calculate liquid animal waste volume production.

Table 7-1. Animal Production Rates of Manures

	Daily Manure Production per 1,000 lb				
Animal	Animal Size	lb	cu ft	gal	%Dry Matter
Cattle					
Dairy	150 - 1,500	82	1.4	10.0	13
Beef	400 - 1,400	60	1.0	7.5	12
Veal	100 - 350	63	1.0	7.5	1.6
Swine					
Pigs	35 - 200	65	1.1	7.5	9
Gestation Sow	275	32	0.5	4.0	9
Sow and 8 pigs	375	88	1.4	10.6	9
Boar	350	31	0.5	4.0	9
Sheep	100	40	0.6	4.6	25
Horse	1,000	45	0.7	5.6	20
Poultry[1]					
Liquid	—	300	—	—	5
Fresh, wet, sticky and caked	—	61	—	—	25
Moist, crumbly to sticky	—	32	—	—	50
Crumbly	—	22	—	—	70
Dry	—	18	—	—	85

---

[1] Storage losses already deducted.

Source: Adapted from Midwest Plan Service, 1985.

WORK SHEET FOR DETERMINATION OF ANNUAL LIQUID ANIMAL WASTE VOLUME AVAILABLE FOR LAND APPLICATION

A. Manure Production

Animal Type	Ave. Wt	Gal/Yr/lb	# Animals	% Confined	Volume (Gal)
Feeder Swine	______	X 2.74 X	__________	X __.___ =	________
Sow & Litter	______	X 3.84 X	__________	X __.___ =	________
Gestation Sow	______	X 1.46 X	__________	X __.___ =	________
Boar	______	X 1.46 X	__________	X __.___ =	________
Beef Cattle	______	X 2.74 X	__________	X __.___ =	________
Dairy Cattle	______	X 3.65 X	__________	X __.___ =	________
Laying Hen	______	X 2.46 X	__________	X __.___ =	________

Subtotal Annual Manure Production Gallons ________

	Typical Weights Lbs.
Feeder Swine	145
Sow & Litter	375
Gestation Sow	275
Boar	350
Beef Cattle (Finishing)	1000
Dairy Cattle	
Mature	1400
Heifers 16-24 Mo	1050
9-16 Mo	680
2-9 Mo	350
Calves 0-2 Mo	150
Laying Hen	4

B. Process Wastewater[1]

Type	# Animals		Gal/Day		365 Days/Yr		Total Wastewater
Dairy	______	X	________	X	365	=	__________
Hogs	______	X	________	X	365	=	__________
Other	______	X	________	X	365	=	__________

[1] Typical Wastewater, excludes flushing systems

Dairy Cows Milked	Wastewater (Gal/Cow-Day)
0 - 50	5 - 8
50 - 150	4 - 6
150 +	2 - 4

Note: Most modern swine operations using lagoons use recirculated flush water for production areas; therefore, wastewater should consider only the clean water used.

C. Feedlot Runoff

$$\frac{(A \text{ X } ROF \text{ X } AnnPrec \text{ X } 7.48)}{12} = \text{Feedlot Runoff}$$

where:

A = lot area in square feet,
ROF = runoff factor,
ROF for paved lot = .60,
ROF for unpaved lot = .25,
AnnPrec = annual average precipitation.

$$\left(\frac{\rule{3cm}{0.4pt}}{12}\right) \text{ X } 7.48 = \rule{3cm}{0.4pt}$$

D. Net Precipitation Excess Over Pit or Lagoon (Precip. less Evaporation)

Lagoons: NPE[1] = Rainfall - (Lake Evaporation X .9)

NPE = ______ - (______ X ______)

NPE = ______

Pits: NPE = Rainfall - (Lake Evaporation X .3)

NPE = ______ - (______ X ______)

NPE = ______

$$\frac{SA \times NPE}{12} \times 7.48 = \text{Total NPE}$$

where: SA = storage area of pit or lagoon at the top, NPE = net precipitation excess as calculated above, Total NPE = volume of NPE produced

$$\frac{(\underline{\qquad\qquad\qquad})}{12} \times 7.48 = \underline{\qquad\qquad}$$

Total Annual Liquid Animal Waste Volume Produced (A + B + C + D) ____________

Storage Requirements

Manure storage requirements should be based upon daily manure production, nutrient management, and cropping plans. Times when applications are not possible due to physical limitations must be considered. For example, manure application to established row crops is difficult unless irrigation equipment is used. Land in other crops such as grass hay would need to be used during periods when row crop land is unavailable. Another example of a physical limitation could include the use of irrigation equipment to land apply manure during the winter when the pipes and equipment could freeze.

NUTRIENT CONTENT OF MANURE

Plant nutrient levels in manure varies with animal type, age, ration, feed consumption, amount of dilution wastewater and runoff entering the manure storage facility. Methods of storing the manure and length of time the manure is stored before field application also affect nutrient levels. Generally, if manure is stored for long periods, more atmospheric losses of N will occur. While this can reduce the acres of land necessary for utilization of N in manures, P and K are not lost to the atmosphere. When such manures are applied at rates that supply the necessary amounts of N, higher amounts of P than required for crop needs are also supplied.

Nutrient management plans should be based upon manure tests from each farm due to the inherent variability from farm to farm. A minimum manure analysis should include the percentage of dry matter, ammonium N (NH_4^+-N), total N (NH_4^+-N + organic N), P (P or P_2O_5) and K (K or K_2O). The manure sample must be representative. Average nutrient values for manures can be found in Table 7-2. Additional representative analyses of secondary and micronutrients are presented in Tables 7-3 (swine) and 7-4 (poultry).

Table 7-2. Average Nutrient Values[1] for Various Manures

Manure Type	Total N	NH_4^+	P_2O_5	K_2O	Ca	Mg	% Moisture
Liquid Dairy	22.61	9.57	12.07	18.92	10.90	4.55	94.30
Dry Broiler Litter	62.58	11.75	62.12	28.57	40.97	8.44	28.43
Dry Turkey Litter	61.75	15.18	63.68	24.36	43.11	7.02	34.72
Layer or Breeder	36.46	8.98	65.06	24.22	123.38	7.67	43.28
Liquid Poultry	51.08	32.95	41.01	30.53	40.05	5.19	93.49
Semi-Solid Dairy	10.54	3.16	6.12	8.67	6.90	2.50	82.56
Semi-Solid Beef	12.79	2.57	6.67	11.30	7.43	2.69	73.08
Swine Lagoon	10.04	5.34	5.68	5.72	2.49	0.89	99.01
Mixed Swine	1.13	26.93	29.75	18.18	16.44	4.86	94.97

[1] Values presented in lbs/1000 gallons. All other values in lbs/ton.

The above table is a compilation of average values for 1090 manure samples.

Table 7-3. Secondary and Micronutrient Content of Swine Manures

Manure Type	Ca	Mg	S	Na	Fe	Mn	B	Mo	Zn	Cu
	lb/ton									
Fresh	7.9	1.7	1.8	1.6	0.39	.04	.074	.00066	.12	.029
Paved lot scraped	12.0	2.3	2.2	1.6	1.03	.19	.015	.00007	.35	.15
	lb/1000 gallons									
Liquid slurry	8.6	2.9	4.7	3.7	0.69	.15	.069	.0011	.39	.11
Lagoon sludge	15.8	4.5	8.3	2.9	1.8	.28	.023	.0095	.67	.23
	lb/acre-inch									
Lagoon liquid	25.5	8.3	10.0	57.7	2.4	.34	.18	.0045	1.5	.3

Source: Zublena, et al. 1990a.

Table 7-4. Average Secondary and Micronutrient Content of Poultry Manures

Manure Type	Ca	Mg	S	Na	Fe	Mn	B	Mo	Zn	Cu
						lb/ton				
Layer										
Undercage scraped	43.0	6.1	7.1	4.5	0.52	0.27	0.050	0.00390	0.32	0.036
Highrise stored	86.0	6.0	8.8	5.0	1.8	0.52	0.046	0.00038	0.37	0.043
Broiler Litter										
Broiler house	41.0	8.0	15.0	13.0	1.3	0.67	0.054	0.00085	0.63	0.45
Roaster house	43.0	8.5	14.0	13.0	1.6	0.74	0.049	0.00082	0.68	0.51
Breeder house	94.0	6.8	8.5	8.6	1.3	0.57	0.035	0.00048	0.52	0.21
Stockpiled	54.0	8.0	12.0	6.2	1.5	0.59	0.041	0.00069	0.55	0.27
Turkey Litter										
Brooder house	28.0	5.7	7.6	5.9	1.4	0.52	0.047	0.00081	0.46	0.36
Grower house	42.0	7.0	10.0	8.4	1.3	0.65	0.048	0.00092	0.64	0.51
Stockpiled	42.0	6.8	9.5	6.4	1.5	0.62	0.047	0.00095	0.56	0.34
Duck Litter										
Duck house	22.0	2.7	3.1	2.8	.98	0.31	0.021	0.00040	0.26	0.056
Stockpiled	27.0	4.4	5.6	8.8	1.2	0.47	0.030	0.00030	0.47	0.050
					lbs/1000 gallons					
Layer										
Liquid slurry	35.0	6.8	8.2	5.3	2.9	0.42	0.040	0.018	0.43	0.080
Lagoon sludge	71.0	7.2	12.0	4.2	2.2	2.3	0.082	0.014	0.80	0.14
					lbs/acre-inch					
Layer										
Lagoon liquid	25.0	7.4	52.0	51.0	2.0	0.24	0.37	0.020	0.70	0.19

Source: Zublena, et al. 1990b.

NUTRIENT LOSS DURING STORAGE

The greatest impact on N content of manures is loss of ammonia (NH_3) through volatilization during handling and storage of manure. As seen in the data in Table 7-5, as much as 50-60% of the original N may be lost during handling and storage.

Table 7-5. Nitrogen loss and retention from manure storage and handling systems (not including loss from field application).

Storage and handling system	Amount Lost (%)	Amount remaining (%)
1. Manure liquids and solids hauled daily[a]	15-25	75-85
2. Manure liquids and solids held in a covered, essentially watertight structure	20-30	70-80
3. Manure liquids and solids held in an uncovered, essentially watertight structure	30-40	60-70
4. Manure liquids and solids held in a storage pond; contents are agitated before spreading	30-40	60-70
5. Manure and bedding held in roofed storages	30-40	60-70
6. Manure without bedding held in unroofed storages; leachate is lost; solids are spread	45-55	45-55
7. Manure stored on open feedlot surface; only the solids are spread	50-60	40-50
8. Poultry layer manure stored in roofed shallow pit cleaned every 3 to 6 months	30-40	60-70
9. Broiler manure on sawdust or shavings in warm, humid climate; house cleaned every 4 months	45-55	45-55
10.Poultry layer manure in cool humid climate; stored in roofed, fan-ventilated pits cleaned yearly	50-60	40-50

Source: Vanderholm, 1975.

Note: A storage structure that is loaded from the bottom will have N losses as low as 0 to 20 percent.

MANURE TESTING

To manage nutrients in manure efficiently, having an analysis of the manure, an estimate of its nutrient availability, and a soil test to determine the nutrient requirements of the crop are desirable.

Manure Analysis

Once soils have been tested, the planner will have an idea about what the "account balance" is for nutrients in the "soil bank." It is most reasonable then to assess nutrient availability in manures available on the farm or from other farmers at low cost. Care should be taken to collect a representative sample. More specific sampling directions are explained below:

I. SAMPLE COLLECTING

A. Semi-Solid Lot Manure

Semi-solid manures may be sampled by digging under the crusted layer in several locations, or by using a probe. Mix about five pounds of manure in a bucket. Fill the sample bottle to the ½ level. If manures will be supplemented with commercial fertilizers, or with additional manure applications, collecting samples from application equipment when the manure is being applied is practical. Collect about five lbs of manure from at least 10 subsamples. Once the sample results are returned, adjustments may be made in future nutrient applications to compensate for nutrients already applied.

1. Scraped directly from lot into spreader

   a. After manure has been loaded into the spreader, collect manure from several different locations within the spreader. Thoroughly mix and fill sample container one-half full.

2. From storage

   a. Collect a representative sample of fresh manure under the surface crust. Thoroughly mix and fill sample container one-half full.

B. Liquid Manure Slurry

Samples should be taken from at least six locations in the storage pit or tank and mixed in a bucket after agitation of the storage structure by pump or propeller. This method will allow for test results to be available before spreading. If this is not possible, at least six subsamples should be taken and combined from the discharge pipe when the spreader is being loaded. Since the results will arrive after spreading has occurred, supplemental nutrient applications should be adjusted to reflect the nutrients supplied in the manure.

1. Under-slotted-floor pit

   a. Use a length of ½ inch conduit open on one end and that can be easily sealed on the other end (e.g., by placing one's thumb over the end of the conduit).

b. With both ends of the conduit open extend it into the manure to the pit floor.

c. Seal the upper end of the conduit trapping the mixture that has entered the lower end, remove and empty into a bucket or container.

d. Collect samples from at least five locations or at least enough for a total of one quart of slurry.

c. Thoroughly mix this slurry and fill sample container one-half full.

2. Exterior storage basin or tank

   a. Make sure the manure has been well mixed or homogenized with a liquid manure chopper-agitator pump or propeller agitator.

   b. Take samples from approximately five locations in the pit, from the agitator pump, or from the manure spreader and place in a bucket.

   c. Thoroughly mix and fill sample container one-half full.

C. Lagoon Liquid

Two methods are available to sample lagoon manure. If lagoon effluent is recycled as flush water for production facilities, a sample may be taken from the recycle inflow pipe. An alternative method is to tape or tie a bottle to the end of a long pole. Samples should be taken approximately one to two feet below the lagoon surface to avoid the layer of surface scum. Samples should be taken from at least six locations around the lagoon and mixed before consolidating an in sample container.

1. Collect approximately ½ pint of recycled lagoon liquid from the inflow pipe to the flush tanks.

2. From lagoon

   a. Place a small bottle (½ pint or less) on the end of a 10-15 ft long pole.

   b. Extend the bottle 10-15 ft away from bank edge.

   c. Brush away any floating scum or debris so it is not collected with sample.

   d. Submerge the bottle within one foot of the liquid surface.

e. Repeat at approximately five locations around the lagoon, place into a bucket, thoroughly mix, and fill sample container one-half full.

3. From a multistage lagoon system collect sample from the main irrigation lagoon.

D. Broiler or Turkey Litter

1. In-house litter.

The sampler should make an inspection tour of the house to identify and estimate the percentage of floor area with varying litter quality. Areas around waterers and feeders should be sampled in proportion to the floor area they represent. If the house will only be caked, all samples should come from the areas around waterers and feeders. At least ten subsamples should be taken from 6" by 6" areas down to the floor level, and mixed to fill the sample bottle or bag.

a. Visually inspect the litter for areas of varying quality, e.g., areas around feeders and waterers, and estimate the percentage of floor surfaces in each of these areas.

b. Take approximately five samples of litter at locations proportionate to item a, above. For example, if 20% of the litter of a certain visual quality is around feeders and waterers, take one sample from these areas and the other four samples from the remainder of the floor surface.

c. At each location, collect litter from a 6" by 6" area down to the earth floor and place in a bucket or container.

d. After the five samples have been collected, mix the contents of the bucket thoroughly, fill sample container about one-half full.

2. From stockpiled litter

a. Collect samples from approximately five locations around the pile at least 18 inches into the pile.

b. Thoroughly mix and fill sample container one-half full.

II. SAMPLE PREPARATION AND TRANSFER

A. Place the sample for analysis into the sample container (plastic bottles are best). Fill the container about one-half full leaving ½ inch for expansion. (They will expand so never use glass containers.) The bottle should be rinsed clean with water and free of any residues but should not be chlorinated or treated in any other way.

B. Complete sample identification form and place it in the mailer with the sample container.

C. The sample should be refrigerated or mailed to the lab as soon as possible.

NUTRIENT FORMS

A crop's utilization of nutrients depends on the management of the land application program, as well as the rate of biological breakdown of the organic material and release of plant-available nutrients. Some background about the N, P, and K in manures is necessary to fully appreciate their fertilizer replacement value.

Nitrogen

Because of its chemical nature, the N in manure is more difficult to manage than the other nutrients. Manure contains two forms of N: the unstable and the stable organic form (Figure 7-1). In either form, the organic N must be decomposed (mineralized) by microorganisms before it is available to plants. The resulting inorganic forms are available to the crop as ammonium (NH_4^+) and nitrate (NO_3^-).

The unstable organic N is present in urine as urea in dairy and swine manure and as uric acid in poultry manure. It may account for 50 to 60% of the total N in dairy and swine manure and 70% in poultry manure. Urea in manure is no different from urea in commercial fertilizer.

Urea or uric acid mineralizes rapidly to plant-available ammonium N (NH_4^+-N) and, in turn, converts very rapidly to ammonia (NH_3) as the pH increases and the manure begins to dry. Ammonia N is extremely volatile (Figure 7-2), so increased exposure of manure on the barn floor in storage, or after spreading, increases N loss. If manure is left exposed in the field, about 50% of the total N can be lost in a short time. The total N loss through volatilization from a combination of handling, storage and field application can be as high as 80-90% (Table 7-6).

The remaining N is contained in the feces. In this form, organic N is more stable and more slowly released than N from urea. Mineralization rate to a plant-available form occurs in two phases. The first phase includes the less resistant organic N, which mineralizes during the first year of application. The second phase includes the more resistant residual organic N, which mineralizes very slowly in future years. Repeated yearly applications to the same field result in an accumulation of a slow-release manure N source from present and past applications.

Phosphorus and Potassium

Manure is an excellent source of P and K. When manure is applied over a long period or at a high application rate, these nutrients will accumulate in the soil. Essentially all of the K is available during the year applied. On the other hand, some P is present as insoluble inorganic compounds or as organic P that, like organic N, must mineralize before it is available.

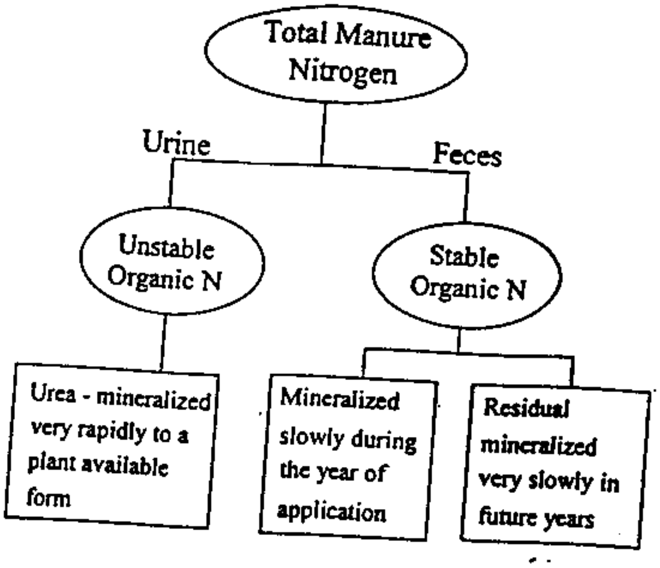


Figure 7-1. Form and degree of N availability in manure

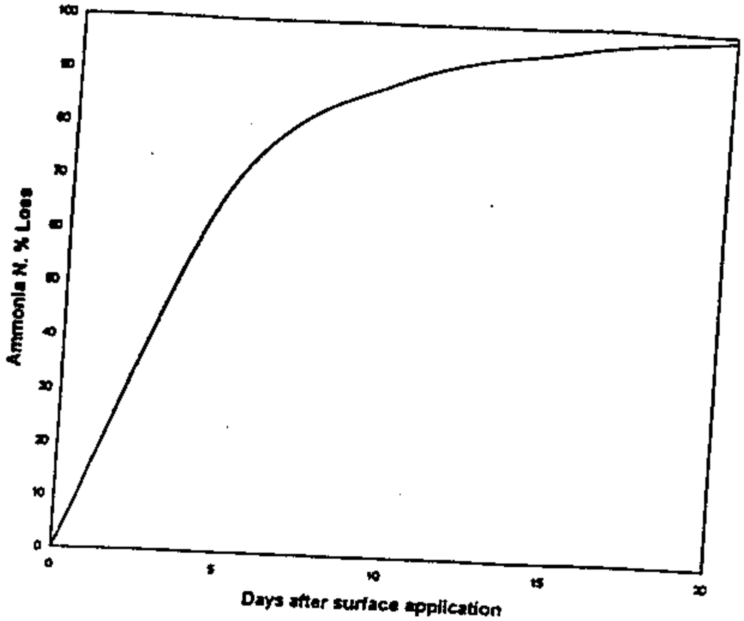


Figure 7-2. Loss of NH_4^+-N by volatilization after a surface application of dairy manure from Klausner and Bouldin (1983).

Table 7-6. Nitrogen loss and retention from manure treatment and handling systems (including loss as a result of field application).

Treatment and handling system	Amount lost (%)	Amount remaining (%)
1. Manure treated by anaerobic lagoon; applied on surface by irrigating or liquid spreading	55-65	45-35
2. Manure treated by anaerobic lagoon or stored in waste-storage pond (if diluted more than 50 percent); applied on surface by irrigating or liquid spreading	70-80	30-20
3. Manure treated by aerobic lagoon or oxidation ditch followed by anaerobic storage of effluent; applied on surface by irrigating or liquid spreading	80-90	20-10

Source: Vanderholm, 1975.
Note: Includes volatilization losses from manure left on soil surface.

FORMS AND PLANT AVAILABILITY OF NUTRIENTS CONTAINED IN MANURES

Nitrogen

In manure, the two primary forms of N present are ammonium N (NH_4^+-N) and organic N. Nitrate (NO_3^-) concentrations in fresh or stored manure are usually low and are generally not determined in routine manure tests. The NH_4^+-N is immediately available to crops, as from ammonium fertilizers. Ammonium (NH_4^+) can be converted to ammonia gas (NH_3) which is readily lost to the atmosphere. Organic N is not immediately available to crops. It must be mineralized into NH_4^+ by microorganisms in the soil to be made available to crops. The NH_4^+ can then nitrify into nitrite (NO_2^-) which is not utilized by crops and then to NO_3^- which is plant available.

Several factors determine the rate and timing of N availability to crops from manure applications which include:

- Amount of NH_4^+-N in the manure;
- Application method and resulting atmospheric loss of NH_3;
- Rate of mineralization of organic N to available forms.

Ammonium Nitrogen

In determining the immediate plant availability of N in manures, the relative amount of the immediately available NH_4^+-N in comparison to the slowly available organic N must be considered. The common means of reporting manure N content by testing labs is the NH_4^+-N and total N (TN) or Kjeldahl N (TKN). Total N and TKN are totals of total organic N and total NH_4^+-N, but do not include NO_3^--N, which is usually negligible in manures. The organic N in manures can be determined by subtracting NH_4^+-N from TN or TKN.

$$\text{Total Organic Manure N} = \text{TKN} - NH_4^+\text{-N} \quad \text{or} \quad \text{TN} - NH_4^+\text{-N}$$

The ratio of organic N to total N varies by the type of manure and is given below based on Virginia averages (Table 7-7).

Table 7-7. Forms of Nitrogen in Different Manure Types

	Organic N	NH_4^+-N
Dry Poultry	77%	23%
Liquid Poultry	36%	64%
Semi-solid Dairy	70%	30%
Liquid Dairy	58%	42%
Semi-solid Beef	80%	20%
Swine Lagoon	47%	53%
Mixed Swine	35%	65%

On average, swine manure contains a much higher percentage of NH_4^+-N relative to organic N than does beef or dairy manure. As a result, swine manure will behave more like a commercial fertilizer in that more of the N is in plant available form when applied than would beef manure.

Organic Nitrogen

The amount of organic N in solid manure that mineralizes into NH_4^+-N is largely determined by C:N ratio of the manure. Greater amounts of N are mineralized at lower C:N ratios. The rate of mineralization is determined by both C:N ratio and environmental effects such as temperature and moisture. In poultry manures, the C:N ratio is approximately 7:1 or less, resulting in rapid mineralization, with most occurring in the first eight weeks after application. For dairy manures, the C:N ratio is approximately 13:1, so mineralization is slower. Swine manure is intermediate in mineralization rate.

Once applied to land, the decomposition of organic manure N is greatest during the first year after manure is applied. The proper scheduling of manure applications is critical to insure the N will be available to crops rather than lost to surface water, ground water, or atmosphere. Manure applied far in advance of crop planting will result in higher losses of nutrients to the environment. Manure applied too late in the growing season can result in significant mineralization of organic N into available forms after crop removal has diminished, resulting in significant inorganic forms of N available for leaching or runoff. If manure is applied in the spring, summer, or early fall; organic N in poultry manure will be converted to the plant available inorganic N forms rapidly as compared to dairy and beef manures. Residual N also becomes available for plants during succeeding years.

Phosphorus

The P content of most manures is high relative to crop requirements. Unlike N, P is not lost to the atmosphere during manure storage. Phosphorus in manure is contained primarily in organic forms. It becomes available to plants when the organic matter is broken down. Phosphorus from manure is used as efficiently by plants as P from fertilizer. Nearly all P in manures should be considered plant-available for nutrient management planning purposes.

Potassium

Manure K, chiefly present in the urine as inorganic K, is chemically equivalent to fertilizer K It is available for plant growth in the year it is applied. In the soil, K is intermediate in mobility. It accumulates in the soil, which is generally desirable because it helps supply plant needs. Potassium may be leached from soil, especially sandy soil, but K leaching is not currently considered to be a pollution problem.

Secondary and Micronutrients

Manure can supply S, Ca, Mg and micronutrients to soils. The amount of these nutrients in manure is generally related to the nutrient content of the feed ration. In general, manure should not be utilized as a short term means to correct deficiencies of these nutrients in crops; however, the mean concentrations in Tables 7-1 to 7-3 show that considerable amounts of these may be supplied to soils. Sulfur is primarily contained in the readily mineralized amino acids and becomes rapidly available upon land application. Due to the micronutrient content, manure may help prevent micronutrient deficiencies from occurring.

MANURE APPLICATION TO LAND

Manure use efficiency can be maximized and water pollution minimized if basic principles are applied when utilizing manure. As with fertilizers, manure application timing affects primarily N and placement and application rates affects N and P. Crop rotations and soil test levels should affect manure routing decisions to fields.

Overall, the most important factors in preventing nutrient loss are the field application methods, timing, and application rate. Manure should always be spread uniformly on fields at specified rates. Nutrient losses, pollution, and odor are also reduced if manure is incorporated into the soil as soon as possible after it is spread if conventional or minimum tillage is used, and if it is spread as near as possible to the time when plants will use the nutrients. Incorporation captures more of the NH_4^+-N contained in manures to avoid NH_3 losses to the atmosphere.

The first priority of a well-managed land application program is to develop a soil fertility program that ensures that manure is used as the basis for supplying plant nutrients. Commercial fertilizer should be used only to supplement additional needs.

APPLICATION TIMING

Application timing is an important consideration for nutrient availability because the longer manure is in the soil before crops take up its nutrients, the more those nutrients, especially N, can be lost through volatilization, denitrification, leaching and erosion. Spring application is best for conserving nutrients for summer annuals or fall-planted small grains. Water contamination is greater in areas of high rainfall when manures for spring and summer crops are applied in fall or early winter.

Summer application of manure is suitable for small-grain stubble, non-crop fields or little-used pastures. Manure should not be spread on young stands of legume forage because legumes fix atmospheric N, and additional fertilizer N will stimulate competitive grasses and broadleaf weeds. It may be applied effectively to pure grass stands or to old legume-grass mixtures with low legume percentages (less than 25%).

Fall application of manure generally results in greater nutrient loss than does spring application, regardless of the application method, but especially if the manure is not incorporated into the soil. If manure is incorporated immediately, the soil will immobilize some of the nutrients, especially at soil temperatures above 50° F. In fall, manure is best applied at low rates to fields to be planted in winter grains or cover crops. If winter crops are not to be planted, manure should be applied to the fields containing the most vegetation or crop residues. Sod fields to be plowed the next spring are also acceptable, but fields where corn silage was removed and a cover crop is not to be planted are undesirable sites.

Winter application of manure is the least desirable, from both a nutrient utilization and a pollution point of view, because the frozen soil surface prevents rain and melting snow from carrying nutrients into the soil. The result is nutrient loss and pollution through runoff water. If daily winter spreading is necessary, manure should be applied to the fields with the least runoff potential, and it should be applied to distant or limited-access fields in early winter, then to nearer fields later in the season when mud and snow make spreading more difficult. Manure applications should never exceed the N requirement of the current or following crop.

APPLICATION METHODS

Surface Application

If manure is simply applied to the surface of the soil, much of the unstable, rapidly mineralized organic N from the urine will be lost through the volatilization of NH_3 gas. Volatilization increases with time, temperature, wind and low humidity. Loss due to runoff, and the resulting water pollution, are particularly great when manure is spread on frozen or snow-covered ground or on fields that get flooded. In areas with long slopes and/or high erosion potential, strip cropping, diversions and other conservation practices will reduce runoff, nutrient loss and pollution. Manure should not be applied on the soil surface within 100 feet of wells, springs or sinkholes, or on slopes adjacent to lakes, rivers or streams.

Subsurface Application

Incorporating manure into the soil, either by tillage or subsurface injection, increases the amount of manure N available for use by crops and can reduce water pollution. A half-inch of soaking rain with no runoff has the same effect as incorporating manure. When tillage tools such as moldboard plows, chisel plows, and heavy discs are used to incorporate the manure, care must be taken to incorporate the manure completely before it dries, usually within two days or less.

Injection is probably the best method for incorporating manure in reduced-till or no-till cropping systems because crop residues are left on the surface to act as a mulch and exposed soil surface is minimal. Injection requires a liquid manure spreader and equipment to deposit manure below the soil surface. To be effective, the openings made by the injectors must be closed over the manure following application. It may be possible to inject manure into a growing row crop in order to supply nutrients nearer to the time when the crop needs them.

Injection probably does the least damage to the environment, but it may represent the largest investment in equipment for the farmer. Also, injection is usually slower than broadcasting and requires considerably more energy. Liquid-manure-handling systems require the addition of water to the manure, so there is more material to handle and apply.

APPLICATION RATE

The rate of application should be based on the capacity of the crop to utilize the applied nutrients. The ratio of N to P_2O_5 to K_2O in manure usually does not match the ratio of the nutrients needed by the crop, therefore, complete utilization is impossible. An appropriate rate can be calculated by basing it on the nutrient availability of the manure and the crop requirement for the nutrient having the highest priority. Generally, the nutrient that determines the overall application rate is N.

The forms of N that must be summed to determine plant-available N (PAN) include: 1) inorganic N, largely NH_4^+-N, 2) first year mineralizable N from quick decompositions of organic N, and 3) residual organic N or the N that mineralizes during the second and third years.

All inorganic N is immediately plant available; however, the percentage that can be credited toward plant requirement must be modified based on the application type and timing of incorporation. Injected NH_4^+ can be considered to be essentially all plant-available (95-100%). Nitrogen from manure that is broadcast will be lost by NH_3 volatilization. The longer the material lays on the soil surface before incorporation, the greater the amount of N lost. The relative yield data in Table 7-8 indirectly demonstrates the large volatilization loss of N that occurs during the first four days following broadcast application of manure.

Organic N mineralizes according to a "decay series," which is specific for each manure type and composition. This concept recognizes the gradual mineralization of the organic N over several years. In practice, a decay series is represented by several consecutive numbers such as 0.40, 0.15, 0.05 and 0.02, where the first number represents the fraction of organic N that mineralizes during the first year, the second number represents the fraction of the N residual from the first year that mineralizes during the second year, etc. The last number represents the fraction of the residual N that mineralizes during the last and all succeeding years. From the decay series for various animal manures, coefficients may be developed that permit calculations of organic N mineralized over several years.

Table 7-8. Relative effectiveness of manure in increasing crop yields as influenced by time between spreading and plowing under.

Treatment	Relative value in increasing crop yield (Average of 34 experiments)
Manure plowed under immediately	100
Manure plowed under 6 hr after spreading	85
Manure plowed under 24 hr after spreading	73
Manure plowed under 4 days after spreading	56

Source: Salter and Schollenberger, 1939.

In summary the amount of PAN may be calculated from a manure analysis by employing the following equation:

$$PAN = a(NH_4^+ - N) + b(Org - N) + c(Org - N) + \ldots + x(Org - N)$$

where:

a = NH_4^+-N availability coefficient based on expected NH_3 loss for different methods of application and timing of incorporation.
b...x = organic N availability coefficients for years one through x based on decay series.
NH_4^+-N= amount of NH_4^+-N per weight or volume of manure.
Org-N = amount of organic N per weight or volume of manure. Organic N is determined by subtracting NH_4^+-N from TKN.

CROP ROTATION CONSIDERATIONS

If manure is applied to meet the N needs of a grain crop, P and K eventually build up to excessive levels in the soil. Where sufficient land area is available, every effort should be made to apply manure based on crop P requirements. This will generally require supplemental applications of commercial N. Considering that the organic N content of manure is in slow release form a split between manure N and commercial N helps insure that enough N is readily available to the crop.

Manure applications on a particular field should be preferred when tillage will occur in the rotation. It is sometimes feasible, and is preferable to apply enough manure to supply the P needs of the entire crop rotation if tillage will occur soon after application, provided the next crop's N requirements are not exceeded and no other manure applications will occur during the rotation. For example, if a six-year rotation is practiced on a field consisting of two years of corn followed by four years of alfalfa, it would be preferable to apply rates of manure which exceed the corn's P requirements during the two years of corn, in order to avoid fertilizer P or manure applications to the alfalfa.

APPLICATION EQUIPMENT AND USE

Manure application equipment has been developed to handle manures differing in type and consistency (dry, liquid, semi-solid).

Dry Manure Application Equipment

Past feeding programs used loose housing for the animals, which subsequently presented a large amount of bedding material to be disposed of along with animal waste. The standard box spreader with a chain drag delivery to a fan or beater spreader mechanism was very efficient at handling this bulky material. The total confinement feeding systems today result in waste with less bedding material and, thus, higher manure concentration. Spreader design has changed to accommodate these differences, but little attention has been focused on controlling application rates.

Box spreaders provide a durable delivery system and facilitate fast unloading speeds. They are less effective when lower spreading rates are desired for more concentrated material such as poultry litter. Gear reduction kits can be added to lower the rate of application. Options such as top beaters, litter pans, and hydraulic end gates will improve the uniformity of application. Unfortunately, these spreaders will only spread a pattern up to eight feet wide which decreases efficiency.

Litter bodies can be either mounted on a truck or can be driven with a tractor P.T.O. They are similar to dry fertilizer spreaders in appearance, but are designed to accommodate larger volumes of less dense poultry litter. They can spread a swath of about 25 feet which makes them more efficient. With some overlap of spread patterns, reasonably accurate delivery can be achieved.

Effective utilization of manure is not possible if you don't know how much is being spread over a given area. Calibrating your spreader is a simple and effective way of improving utilization of nutrients in manure more effectively. Only by knowing the application rate of your spreader can you correctly apply manure to correspond to crop needs.

Calibration of Solid Manure Spreaders

In order to calibrate a spreader for solid (20% or more solids) manure, the following materials are needed.

1. Bucket
2. Plastic sheet, tarp, or old bed sheet (an even size, 8 ft. X 8 ft., 10 ft. X 10 ft.,10 ft. X 12 ft., etc., will make calculation easier)
3. Scales

To calibrate your spreader:

1. Locate a large and reasonably smooth, flat area where manure can be applied.
2. Spread the plastic sheet, tarp, or bed sheet smoothly and evenly on the surface of the test field.
3. Start driving the spreader at the normal application speed toward the sheet spread on the ground, allowing the manure to begin leaving the spreader at an even, normal rate.
4. Drive over the sheet at the normal application speed while continuing to apply manure.
5. Collect all manure spread on the sheet and pour it into the bucket.
6. Weigh bucket with manure, then subtract empty-bucket weight. This will give you the pounds of manure applied to the sheet.
7. Repeat the procedure three times to get a reliable average.
8. Determine average weight of the three manure applications.
9. Refer to the chart in Table 7-9 or the size of sheet, then read "Tons of Manure Applied Per Acre". To estimate the capacity of the manure spreader refer to Table 7-10.

If the size of your sheet is not listed, the following equation may be used to determine litter application per acre.

$$\frac{\text{Pounds of manure collected over sheet} \times 21.78}{\text{Area of sheet, ft}^2} = \text{Tons/acre}$$

This procedure is particularly suitable for dry waste such as broiler and turkey litter. Wet litter or manure is more difficult, but the basic procedure can still be used; a plastic sheet works well, with the main difference in procedure being that the sheet and the litter can be placed in the bucket together, and the dry weight of both bucket and sheet subtracted as in Step 6. The remaining steps are the same.

Liquid Manure Application Equipment

Liquid spreaders, those capable of handling manure at moisture levels greater than 87 percent, are by nature more accurate and effective in preventing spillage of manure during transport. They do require a positive discharge mechanism to maintain spreading width during unloading. Splash boards at the discharge do not maintain spreading width or pattern. The large application volumes make this system somewhat inefficient, and large equipment is necessary to pull the spreaders.

Side discharge or slinger spreaders are the newest addition to manure spreader designs. They can handle a variety of manures from dry to wet. They allow for a uniform spreading swath and the rate can be controlled by adjusting the opening at the discharge flail. This adjustment can be made with liquid manures better than dry manures or those with large amounts of bedding. These spreaders have a high horsepower requirement and have a smaller load capacity per unit cost.

Table 7-9. CALIBRATION OF MANURE SPREADERS

Pounds of Manure Applied to Sheet	Size of Plastic Sheet		
	8'x 8'	10' x 10'	12' x 12'
	Tons of Manure Applied/Acre		
1	0.34	0.22	0.18
2	0.68	0.44	0.36
3	1.02	0.65	0.54
4	1.36	0.87	0.73
5	1.70	1.09	0.91
6	2.04	1.31	1.09
7	2.38	1.52	1.27
8	2.72	1.74	1.45
9	3.06	1.96	1.63
10	3.40	2.18	1.82
11	3.74	2.40	2.00
12	4.08	2.61	2.18
13	4.42	2.83	2.36
14	4.76	3.05	2.54
15	5.10	3.27	2.72
16	5.45	3.48	2.90
17	5.79	3.70	3.09
18	6.13	3.92	3.27
19	6.47	4.14	3.45
20	6.81	4.36	3.63
21	7.15	4.57	3.81
22	7.49	4.79	3.99

Table 7-10. ESTIMATING MANURE SPREADER CAPACITY

Spreader Size, Bushels	Approximate Tons of Manure
70-75	1.5
90-100	2.0
125-130	2.5
180	3.5

Calibration of Liquid Manure Spreaders

The application rate for a liquid waste spreader can be determined by knowing: 1) the capacity of the tank in gallons; 2) the distance the spreader travels to empty the tank; and 3) the path width over which the waste is being spread. The path width can be paced off or measured with a tape. Determining the travel distance can be more difficult. One method is to measure and count the number of wheel rotations. Measure the tire from one side to the other - this is the tire's diameter. Multiply the diameter by 3.14 to determine the distance the spreader will travel in one tire rotation. Tie a piece of rope at the top of the tire and as the spreader moves through the field count the number of times the rope comes to the top of the tire until the tank is empty.

Multiply this number by the length of one revolution to determine the total travel distance. The waste application rate is equal to:

$$\frac{\text{Tank capacity (gallons)}}{\text{Travel distance (ft.) x Spreading width (ft).)}} \quad \text{X} \quad \frac{43{,}560\ \text{ft}^2}{\text{acre}} = \text{Application Rate, Gal/Acre}$$

Manure Application with Irrigation Systems

Three major systems are used for irrigating liquid manure: solid sets, center pivots, and travelling guns. Manure applied with irrigation equipment should be managed carefully to avoid any runoff of animal waste. Solids in liquid manures tend to clog soil pores near the surface, thus sealing the soil and reducing infiltration. As mentioned previously, enough manure storage volume must exist so that applications during freezing weather are unnecessary.

Solid set systems are series of sprinklers generally supplied by underground pipe. Advantages include the ability to irrigate odd shaped fields, application rates low enough to enable good infiltration of liquid manures, and uniform application which is beneficial to achieving high yields. Disadvantages include high installation cost, and the relative ease in using the system which, coupled with the high initial cost, may encourage the overloading of a fixed land area with nutrients.

Center pivot systems are generally used in large fields. To be cost effective, they must generally be large systems and able to travel a full circle. Advantages include low labor requirements, potential for relatively good infiltration at low to moderate rates of application, and uniform application characteristics capable of high yields. Disadvantages include loss of corners and odd shaped areas in the field outside the circle, and relatively high initial cost.

Travelling guns are high pressure, high output single nozzle systems which "crawl" down travel lanes in the field. Liquid manure or water applications are controlled by how fast the gun crawls. This system requires very careful management when utilized for applying manure. The primary advantages include relatively low initial cost, and the ability to irrigate somewhat irregularly shaped fields. Disadvantages of this system are numerous. Labor requirements are high since the gun must be moved to another travel lane after each pull, and pipe must be moved unless underground pipe is installed. A seven to ten foot wide travel lane is wasted if row crops are grown. Manure nutrients are not removed in grain or silage from the travel lanes which increases leaching potential. Due to the high operating pressure, projection height and distance, significant aerosol drift is possible. Most importantly, travelling guns are prone to cause surface runoff of manures due to high application rates per minute at the wetting front, resulting in poor infiltration. Application rates must be monitored closely to insure that no runoff of animal waste occurs.

A "full circle" configuration should be used with travelling guns. The term "full circle" means the gun nozzle pivots nearly 360 degrees as it moves down the field. It is acceptable, and recommended to set the stops on the gun to allow a small wedge shaped area in front of the gun to remain dry. This allows for less rutting and compaction of the travel lanes, and reduces the amount of manure applied to bare travel lanes.

APPLICATION RATES

Table 7-11 should be used to determine maximum application rates per hour for specific soil types and conditions when animal manures are applied with irrigation systems. These rates must be reduced if runoff occurs.

Table 7-11 Maximum Manure Irrigation Application Rates for Different Soil Types

Soil Characteristics	0%-5% Slope inches per hour Cover	Bare
Clay; very poorly drained	0.30	0.15
Silty Surface; poorly drained clay or claypan subsoil	0.40	0.25
Medium textured surface soil; moderate to imperfectly drained profile	0.50	0.30
Silt loam, loam, and very fine sandy loam; well to moderately well drained	0.60	0.40
Loamy sand, sandy loam, or peat; well drained	0.90	0.60

Reduce application rates on sloping ground:

Slope	Rate Reduction
0% - 5%	0%
6% - 8%	20%
9% - 12%	40%
13% - 20%	60%
Over 20%	75%

Caution: Check application rates to insure that desired nutrient levels are not exceeded, use the most restrictive criteria.

Source: Pennsylvania Department of Environmental Resources, 1990.

Chapter 8. INTRODUCTION TO LAND APPLICATION OF BIOSOLIDS

LAND USE OF BIOSOLIDS: INTERACTIONS WITH SOIL-CROP-WATER SYSTEMS

Biosolids are municipal wastewater sewage sludge treated in a way that permits its safe and beneficial application to soil for agricultural purposes. The management and disposal of biosolids in an economical and environmentally acceptable manner are one of society's most pressing problems. Most municipal sewage sludge is currently disposed of by landfilling and incineration; however, land application of biosolids for agricultural production and soil reclamation is becoming more popular. The growing preference for land application is due in part to economic, environmental, and regulatory constraints associated with alternative methods of biosolids disposal.

Biosolids, like animal wastes, are part of natural biological cycles (Figure 8-1). Although the benefits of using biosolids in agricultural production and land reclamation are well documented, land application of biosolids may lead to potential problems. Constraints associated with use of biosolids are generally related to biosolids composition, site characteristics, management limitations, and public acceptance. Appropriate biosolids utilization systems for agricultural production must ensure a proper balance between biosolids-applied nutrients and the nutrient needs of the particular crop being produced. Potentially harmful effects such as the inducement of crop micronutrient deficiencies and phytotoxicity must also be considered. Acceptable Biosolids management options must also minimize negative environmental impacts, such as degradation of the soil's capacity to sustain plant growth, and discharge of N, P, and other potentially harmful constituents to surface water and groundwater.

WASTEWATER PROCESSING

What are Biosolids?

Biosolids are the materials remaining after treatment facilities purify wastewater from homes, businesses and industries. In some communities, runoff from roads, lawns and fields is also included. Biosolids are composed of inorganic constituents, such as macro- and micro-nutrients and non-nutrient trace elements, organic compounds, and microbes and other biological entities, including pathogens and parasites.

With minor exceptions, such as pretreatment required by industrial wastewater and sewer ordinances, treatment plants have little control over the material they process. They must accept all incoming wastewater and purify it before discharging the effluent back into the environment. The wide variety of incoming wastewater and available treatment technologies determines the volume and make up of wastewater treatment plant biosolids.Biosolids management (removing or destroying pollutants, dewatering or drying,

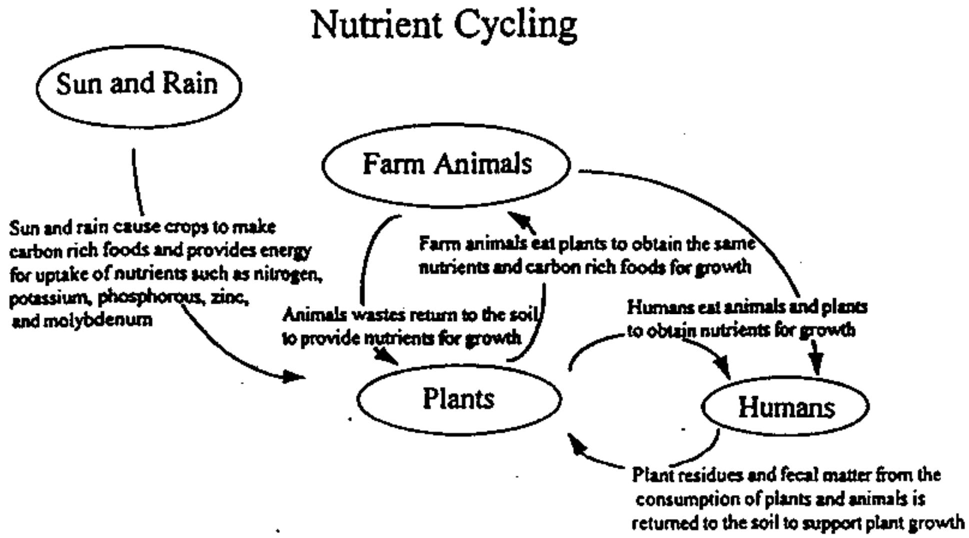


Figure 8-1. Natural cycling of nutrients.

and disposal) depends on the cleanliness of incoming wastewater and sewage treatment method use.

Wastewater Treatment

Figure 8-2 shows the wastewater treatment process generally used to produce biosolids. As wastewater enters the plant, a screen removes large objects and a settling chamber removes grit. The wastewater then travels through the primary sedimentation basin where much of the solid matter is separated from the liquid. The secondary treatment process then removes dissolved nutrients from the liquid. Advanced treatment further removes dissolved nutrients, then filters and disinfects the wastewater. Solids are combined, thickened, and stabilized. The stabilization process destroys harmful bacteria and readies the biosolids for dewatering. Once dewatered, the biosolids are ready to be used.

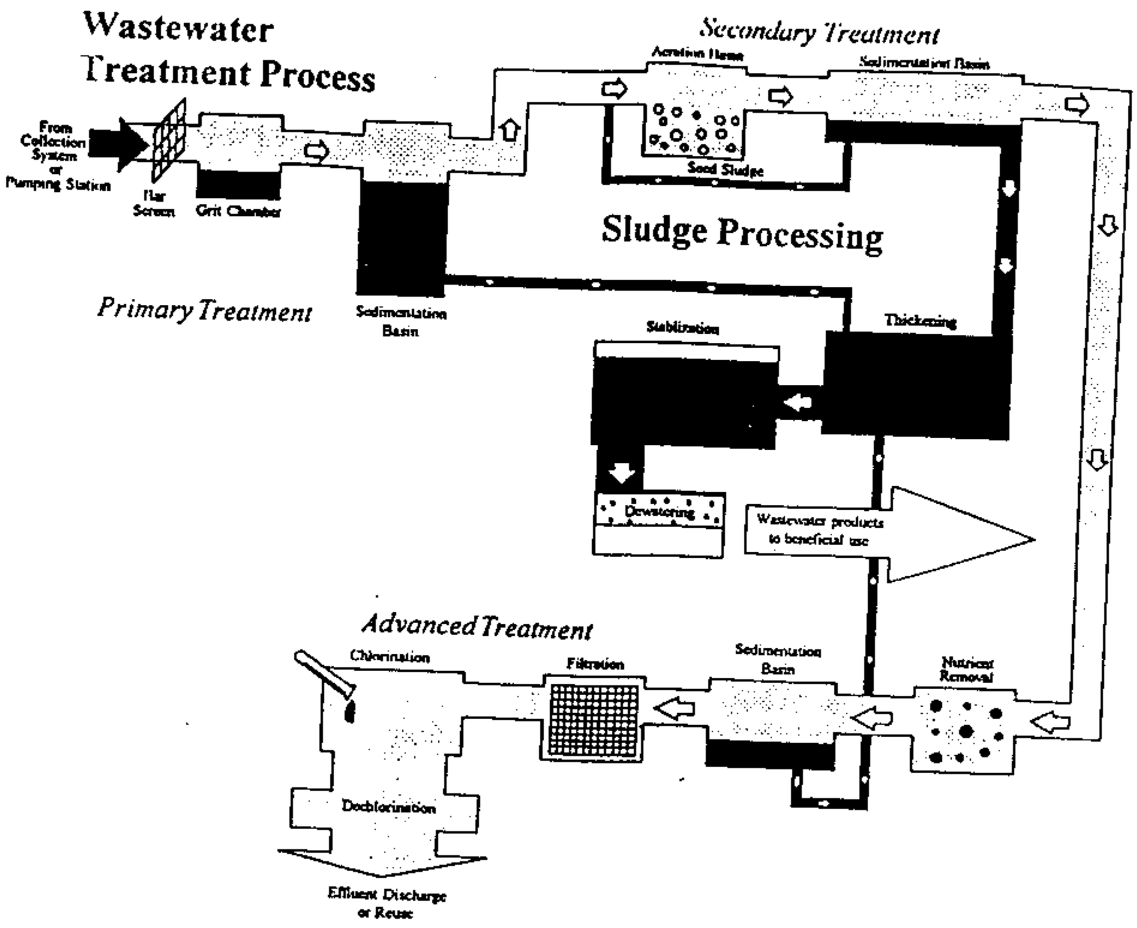


Figure 8-2. Schematic of typical wastewater treatment process.

Types of Biosolids

Treatment of municipal wastewater produces different types and volumes of biosolids. Raw primary biosolids are produced during the first phase of wastewater treatment. Primary treatment removes 40-50% of the solids in the water. They're removed by bar screens, grit chambers and primary sedimentation tanks. Primary biosolids contain solid organic material. Secondary biosolids are generated after the wastewater travels through an aeration tank and is allowed time to settle. They consist of microscopic material remaining after biological processes have removed dissolved organic matter. A third stage of water treatment generates tertiary biosolids by advanced processes such as chemical treatment and filtration. Since each treatment phase (primary, secondary, tertiary) add costs to the purification process, making water cleaner gets very expensive.

Biosolids must be treated or stabilized to make them safe for use or disposal. A typical goal of biosolids processing and stabilization is to increase the solids content by reducing the water content of the biosolids by separation and removal of liquid. Another goal is to stabilize the solid fraction through biochemical conversions that destroy disease causing organisms, called pathogens, and controls odors. To achieve these goals, various stabilization methods are used including anaerobic (without air) digestion, aerobic (with air) digestion, lime treatment, composting and heat drying (pelletization). Each of these methods reduces both the pathogen levels and odor potential of the biosolids. Types of biosolids derived from various treatment processes are summarized in Table 8-1.

Table 8-1. Types of biosolids treatment process.

Treatment	Description
Primary	Biosolids are obtained from the primary settling tank. It is that portion of the raw wastewater solids contained in the raw plant influent that is directly captured and removed in the primary sedimentation process.
Activated	Treated biosolids from secondary treatment that are recirculated into the primary sedimentation basins outflow to enhance organic decomposition.
Stabilized	Raw (untreated) biosolids are converted into a form that is less offensive in terms of odor and pathogenic organism content. Stabilization reduces the amount of solid matter and removes oxygen-demanding compounds. Aerobic and anaerobic digestion are the most common biological processes employed to stabilize these organic wastes. The result of these processes is a product that has an earthy odor and is without raw, undigested solids. Most of the pathogens have been destroyed, but the effluent remains high in nutrient content. Liquid sewage biosolids are blackish and contain colloidal and suspended materials of 2% to 5% solids. Most biosolids applied to agricultural land are of this type, but they may be mechanically or chemically dewatered to increase the solids content to 18-25% ("cake"). Lime treatment employs a chemical means (high pH) and composting employs a biologically mediated, thermophilic process as alternative stabilizing procedures.

Biosolids Management

Appropriate control is needed for the safe agricultural use of all fertilizers and soil conditioners–whether in the form of biosolids, other organic amendments, or chemically based fertilizers–to insure that the proper amounts of essential elements are provided and to avoid contamination of surface water and groundwater with N and P. Additional control is needed for biosolids and animal wastes because, depending upon the level of treatment, disease-causing organisms (pathogens) may be present and vectors such as flies and rodents can be attracted that may transmit disease. Wastewater treatment reduces pathogens to levels that are not harmful. Pretreatment by industry, mandated by law, prevents excessive levels of unwanted pollutants in wastewater and the resultant biosolids. Figure 8-3 shows that pretreatment and source control have been very successful in reducing the levels of pollutants in biosolids. Finally, compliance with the new Federal and existing state regulations requires the careful implementation of management practices and the use of biosolids application rates based on crop nutrient needs.

Federal and state regulations, based on more than 25 years of scientific and technical analysis, provide guidelines for municipal biosolids treatment and disposal to ensure the protection of human health and the environment. A primary goal in managing biosolids production is to generate the best quality biosolids possible. High quality biosolids (containing small amounts of metals, toxic chemicals and pathogens) are safer to the environment, of greater benefit to soil quality and crop production and can be marketed more successfully.

BIOSOLIDS CHARACTERISTICS

Biosolids vary widely in their chemical, biological, and physical properties. The determining factors include the source and composition of the sewage, the treatment system, the extent to which the material is digested and stabilized, and the handling method between processing and application to the soil. A major reason for considering the use of sewage biosolids in crop production is its nutrient value. The guiding principles in designing an effective nutrient management program for use of biosolids in cropping systems are to supply biosolids-derived nutrients when and where they are needed by the crop, and in the required quantities.

General Composition

Nineteen studies of municipal biosolids from 45 sites in seven southern states show enormous variability in composition. Data on solids, ash and macronutrients are summarized in Table 8-2.

Because composition varies greatly, each type of biosolid intended for use on agricultural land should be analyzed separately. The concentrations of N and P in biosolids are similar to those in animal manures, while K in biosolids is much lower than those in most animal wastes. Concentrations of all nutrients in biosolids from southern states are lower than those found in biosolids from the Midwest.

Composition of industrial wastes has also been determined by source: textile mills, fermentation processing, poultry processing, wood processing, and refinery/petrochemical. Data on solids, ash, and macronutrients are summarized by source in Table 8-3.

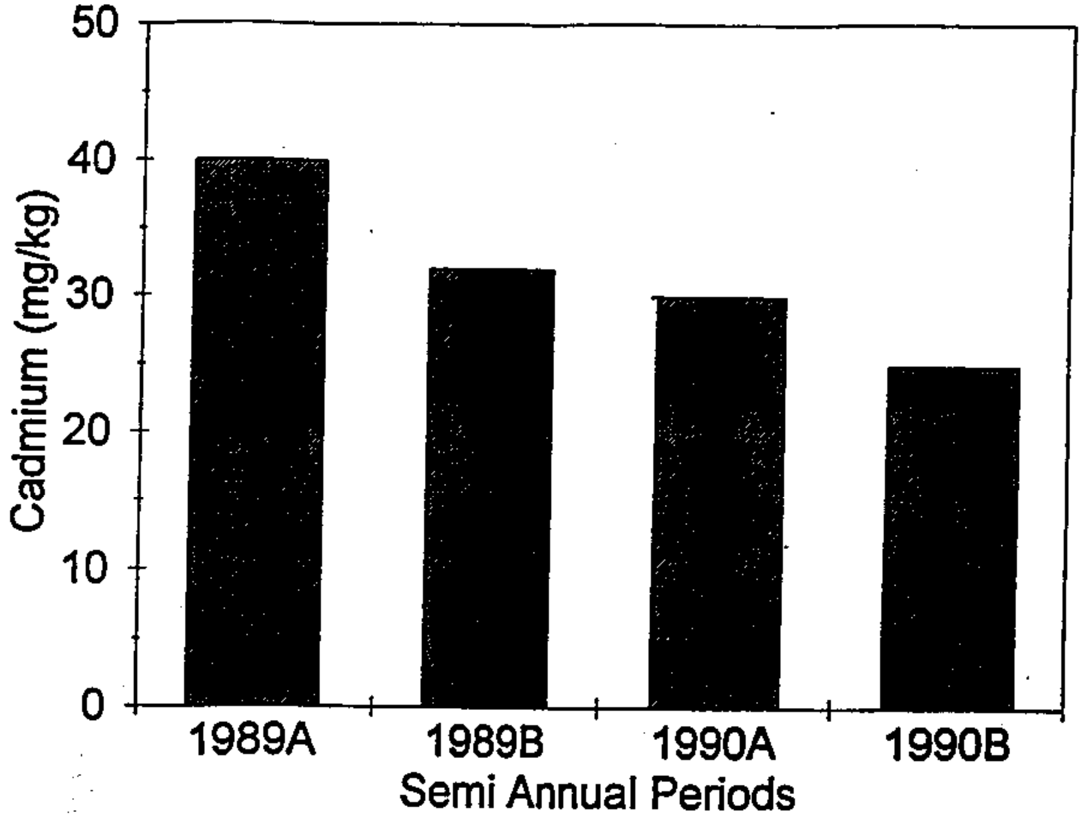


Figure 8-3. Pretreatment and source control success in reducing pollutant levels in biosolids.

Table 8-2. Properties of municipal biosolids from several southern states.

	Number of samples	Range	Mean	Median [a]
Solids content of liquid biosolids (%)	13	0.6-7.1	3.8	4.4
Ash (% of solids)	16	19-59	43.0	47.0
pH	8	5.4-7.0	6.1	5.9
Total N of solids	21	0.6-7.5	3.0	2.6 (3.3)
Total N [b] of liquid fraction (mg/L)	13	7-730	280	290
Total P of solids	40	0.4-5.3	1.8	1.6 (2.3)
Total K of solids	40	<0.1-1.0	0.2	0.2 (0.3)
Total Ca of solids (%)	39	<0.1-6.0	1.5	1.3 (3.9)
Total Mg of solids (%)	39	0.1-0.5	0.2	0.2 (0.45)

[a] Data in ( ) is for biosolids mainly from the Midwestern US.
[b] Predominantly NH_4^+-N.

The N content of textile and fermentation wastes is generally comparable to that of municipal biosolids, but N content of wood processing wastes is much lower. Except for Ca in fermentation wastes and Ca and K in wood processing wastes, concentrations of other macronutrients are relatively low.

Nitrogen

Although the source of the biosolids affects its N concentration, the type of biosolids treatment may be just as important a determining factor. Different biosolids treatment processes consist of various combinations of practices employed to treat wastewater that effect biosolids composition. Such practices include thickening, stabilization (reduction), conditioning, and dewatering. Different types of stabilization practices (i.e., aerobic and anaerobic digestion, lime treatment, and composting) cause significant variation in N composition. Typical average total N percentages present in biosolids subject to various types of treatment were 3.6% for primary, 4.9% for activated, and 2.9% for stabilized.

The treatment processes used also help estimate the N mineralization potential of biosolids. Biosolids processing effects the amounts of biodegradable material through decomposition, influencing the relative amount of microbial energy sources (C) and protein building blocks (N). The availability of N in biosolids decreases as the content of NH_4^+ and NO_3^- decreases and as the organic N becomes more stable because of digestion during biological waste treatment.

Table 8.3. Properties of industrial wastes from several southern states.

	Textile biosolids				Fermentation biosolids				Wood processing wastes			
	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median	No. of samples	Range	Mean	Median
Solids content of liquid wastes (%)	5	0.6-13.5	6.0	6.9	4	13-54	26	19	1	---	---	12.4
Ash (% of solids)	9	14-76	41	43	3	37-66	51	49	5	6-67	40	45
Total N of solids	9	1.0-7.9	4.1	2.8	6	2.0-7.0	4.1	3.5	6	0.3-2.3	0.8	0.4
Total N[a] of liquid fraction (mg/L)	5	16-112	42	22	3	19-680	350	340	0	---	---	---
Total P of solids (%)	9	0.3-2.0	1.1	0.9	5	0.1-0.7	0.4	0.2	5	<0.1-0.3	0.1	0.1
Total K of solids (%)	9	0.1-0.3	0.2	0.2	5	<0.1-0.2	0.1	0.1	5	<0.1-9.3	1.9	0.1
Total Ca of solids (%)	9	0.1-0.8	0.5	0.5	5	<0.1-9.8	4.5	5.2	5	0.3-9.8	3.3	0.8
Total Mg of solids (%)	9	0.1-0.4	0.2	0.2	5	<0.1-0.2	0.1	<0.1	5	<0.1-0.7	0.2	0.1

[a] Predominantly NH_4^+-N

Most wastes contain both organic and inorganic forms of N. Inorganic N is normally present as either NH_4^+ or NO_3^-, with the proportion of each being dependent on the waste treatment process employed. Aerobic digestion results in mineralization of organic N to NH_4^+ and nitrification of NH_4^+ to NO_3^-. In contrast, only NH_4^+ is present in anaerobically digested biosolids. In anaerobically digested biosolids with very little NO_3^--N, about 20 to 50% or more of the N is NH_4^+-N. If wastes are stored in a lagoon before application, inorganic N can be lost through NH_3 volatilization and denitrification. The inorganic N composition of biosolids is strongly influenced by waste processing, handling, and storage, and can make up <10% to >90% of the total N. The use of an average figure for total N should be discouraged because the variability of total N is high.

Phosphorus

In contrast to N, most of the P in biosolids is in the inorganic form. The inorganic P content of eight Indiana biosolids averaged 73% of the total P content. The availability of biosolids P to plants depends both on the rate at which it becomes available from the biosolids and the rate at which it reacts with the soil to form unavailable compounds.

NUTRIENT AVAILABILITY

A major reason for considering the use of biosolids in crop production is its nutrient value. The guiding principle in designing an effective nutrient management program for biosolids in cropping systems is to supply the proper amount of nutrients needed by the crop. The nutrient supplying capacity of biosolids has been difficult to predict due in a large part, to differences in biosolids quality and in experimental conditions.

Differences in the nutrient availability from various biosolids are generally related to differences in biosolids composition and the particular soil-water-management system in which the biosolids are used. To ensure a well-balanced fertility program, Biosolids application rates should reflect the inherent nutrient supplying capacity of the soil, any nutrient and organic matter additions from other sources (e.g., legumes, animal manures, commercial fertilizers), and the crop nutrient requirements for the yield potential of the specific soil. This helps ensure that sufficient nutrient levels are present to meet crop demand without application of excess N and P.

Nitrogen Availability

Biosolids should not be applied in excess of the agronomic rate. In general, the agronomic rate provides the N needed by the crop or vegetation. Therefore, lacking another limiting constituent in biosolids to be land applied, careful consideration must be given to calculating the application rate based on the kinds and amounts of N in the biosolids. A Biosolids analysis typically reports total Kjeldahl-N (TKN), NO_3^--N, and NH_4^+-N. Organic N is estimated as TKN minus NO_3^--N and NH_4^+-N.

The goal in N management of biosolids is to estimate of the amount of N in the biosolids that will be available to a crop after a Biosolids application. This value is sometimes called plant available N (PAN). It is generally assumed that 100% of the NO_3^--N is available for plant usage. Similarly, it is generally assumed that 100% of the NH_4^+-N is available for plant uptake unless the biosolids are surface applied. When surface applied, an estimate of the amount of N volatilized can be made and subtracted from the PAN value.

Available N from mineralization of organic N can be determined using incubation procedures or calculated with the use of mineralization coefficients estimated from experimentally-derived decay series (Chapter 7). The amount of N mineralized depends on the C:N ratio of the biosolids, which is influenced by the type of sludge treatment permitting the derivation of general mineralization coefficients for different sludge types (Table 8-4). The percentages listed in Table 8-4 are for the first year mineralization of organic N following biosolids application. Subsequent years' mineralization rates generally decrease to 10-15% for the second year, 5-10% for the third year, and less that 5% thereafter. Examples of mineralization rates used by various State Departments of Agriculture and/or Land Grant Universities to estimate available N from biosolids are presented in Table 8-5.

Using the information above, the concentration of PAN (typically expressed as percent by weight) in biosolids can be estimated with:

$$PAN = NO_3^-\text{-N} + x(NH_4^+\text{-N}) + y(\text{Organic N}).$$

Where x is the fraction of NH_4^+-N that does not volatilize and y is the fraction of organic N expected to mineralize. Given the potential variability in Biosolids composition and in the values of x and y, the most accurate application rates can be obtained through frequent biosolids analyses and incubation studies of each specific Biosolids source.

Table 8-4. Representative Values for Percent Organic N Mineralized.

Biosolids Type	Organic N Mineralized
waste activation process	40%
primary	30%
lime stabilized	30%
aerobically digested	30%
anaerobically digested	20%
composted	5 to 10%

Table 8-5. Rates used by mid-Atlantic states for proportion of initial organic N mineralized from biosolids by year.

State	Years After Application									
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Primary and waste activated										
Delaware	40%	20%	10%	5%	3%	3%	3%	3%	3%	3%
Maryland	40%	20%	10%	5%	-[1]	-	-	-	-	-
North Carolina[2]	40%	20%	10%	5%	3%	3%	3%	3%	3%	3%
Pennsylvania	40%	-	-	-	-	-	-	-	-	-
Virginia	30%	15%	7%	-	-	-	-	-	-	-
Aerobically digested										
Delaware	30%	15%	8%	4%	3%	3%	3%	3%	3%	3%
Maryland	40%	20%	10%	5%	-	-	-	-	-	-
North Carolina[2]	30%	15%	8%	4%	3%	3%	3%	3%	3%	3%
Pennsylvania	40%	-	-	-	-	-	-	-	-	-
Virginia	30%	15%	8%	-	-	-	-	-	-	-
Anaerobically digested										
Delaware	20%	10%	5%	3%	3%	3%	3%	3%	3%	3%
Maryland	20%	10%	5%	2%	-	-	-	-	-	-
North Carolina[2]	20%	10%	5%	3%	3%	3%	3%	3%	3%	3%
Pennsylvania	40%	-	-	-	-	-	-	-	-	-
Virginia	20%	10%	5%	-	-	-	-	-	-	-
Composted										
Delaware	10%	5%	3%	3%	3%	3%	3%	3%	3%	3%
Maryland	10%	5%	2%	1%	-	-	-	-	-	-
North Carolina[2]	10%	5%	3%	3%	3%	3%	3%	3%	3%	3%
Pennsylvania	10-15%	-	-	-	-	-	-	-	-	-
Virginia	10%	5%	3%	-	-	-	-	-	-	-

[1] Dashes indicate no mineralization rate recommendations.

[2] Recommends incubation studies to determine exact mineralization rates. Use mineralization rates in table if incubation data are not available.

While the total amount of organic N mineralized is largely dependent on the C:N ratio, the rate of mineralization can be increased or decreased by environmental factors such as soil texture, moisture and temperature.

One potential disadvantage to supplying N for crops with biosolids is the possibility of nitrate leaching, particularly after long-term biosolids applications. This possibility exists because the mineralization process occurs whenever soil conditions are favorable, which, on an annual basis, occurs over a longer period than N uptake by the crop. Thus, inorganic N produced in the soil when crop uptake is not occurring will be lost to leaching. Nitrate leaching potential can be minimized by taking into account contributions of available N from previous biosolids applications when calculating current application rates.

Phosphorus Availability

The P in biosolids exists in both inorganic and organic forms with the inorganic forms generally predominating. Organic P, like organic N, must undergo mineralization in the soil before the P is available for plant uptake. However, the critical C:P ratio for mineralization is between 200:1 and 300:1, thus most P in biosolids is easily mineralized and plant available. In addition, the total P application rates are generally much higher than crop needs when a Biosolids application rate is based on PAN. For example, biosolids having 1.3% PAN and 1.0% total P applied to supply 150 kg PAN/A would also apply 115 lbs P/A. The imbalance between N and P in biosolids can cause soil P levels to increase substantially, often to levels much higher than necessary for adequate P nutrition of crops, and may increase the potential for off-site movement of P.

It has been suggested that Biosolids application rates be based on the P content rather than on the N content. This would alleviate the increase in soil P that is common with long-term Biosolids applications but would greatly increase the land required for land application. Some states have compromised on this issue by requiring that P applications not exceed anticipated crop removal of P after soil test P has reached a certain level (usually quite high).

Potassium Availability

Biosolids are generally considered poor sources of plant available K, primarily due to the low concentrations of K in biosolids. Potassium is a soluble constituent in biosolids. When relatively high K concentrations (> 1.0%) are reported for biosolids, this often reflects biosolids with a low solids content dried down before analysis. The K in biosolids, however, is normally assumed to be 100% available for plant uptake.

pH Effects

Addition of biosolids to soil can decrease, increase, or have no effect on soil pH. The mineralization of organic C and N, nitrification of ammoniacal N forms, hydrolysis of Fe and Al compounds, and the oxidation of sulfides can decrease soil pH. The addition of lime in some alkaline stabilization treatment processes can provide calcium carbonate equivalences of 10-50%. It is possible that the lime potential of these biosolids can limit application rates on sandy soils having a high soil pH due to the possibility of inducing a micronutrient (primarily Mn) deficiencies.

TIMING OF APPLICATION

The timing of biosolids application to cropland is a critical component of a safe and effective Biosolids management program. Biosolids applications should be timed so that nutrient availability and uptake patterns of the crop are synchronous. Proper application timing helps to minimize any negative environmental impacts associated with nutrient loss to surface and groundwater.

Fall and winter applications of biosolids should be avoided unless actively growing winter cover crops are present. Without an actively growing crop, mineralized NO_3^--N may leach to groundwater or be transported over land to surface water. Surface applications of biosolids containing considerable amounts of NH_4^+-N, such as anaerobically-digested biosolids, during hot dry periods can result in large loss of ammonia. The same principles discussed under Manure Management should be used to rank fields to receive biosolids applications and the same principles may be applied to determine timing and placement of supplemental commercial fertilizers if they are necessary.

METHODS OF APPLICATION

The two primary application methods for biosolids are surface application, which may be followed by incorporation, and injection. Whenever possible, biosolids applications should be scheduled when tillage operations will occur in the rotation. Soil incorporation may speed the mineralization process, and will reduce surface transport of N and P. Biosolids runoff can detrimentally affect surface water quality through eutrophication. Since incorporation is preferred, Biosolids application to excessively sloped or highly erodible land should be discouraged unless the biosolids are injected.

Injection is generally preferred to protect surface water quality. The water content of the biosolids must be sufficient to allow the biosolids to be pumped through the injector. This method works best for wide row crops such as corn than for drilled crops such as small grains. In small grain or other drilled or solid seeded crops, variable crop growth can occur due to the wide spacing intervals of the injection shanks. This method is not agronomically sound for lime stabilized biosolids since very high pH bands in the soil will result.

Application Equipment

Various equipment is used to apply biosolids. Dry or "cake" biosolids are usually applied with a spreader truck similar to dry manure spreaders. Liquid biosolids can be irrigated using solid set, traveling gun, or center pivot equipment. Injection can also be accomplished on level land using overland flow, flooding, or ridge-and-furrow irrigation, although achieving acceptably low-loading rates with these methods may be difficult. Biosolids may be injected with an injector fitted spreader truck or pumped to the field through solid line, into the field using flexible line, and applied by a crawler tractor pulling a specially designed injector.

Major considerations for selecting application equipment include:

1. Solids' content of biosolids
2. Slope on the site
3. Need or desire for direct incorporation
4. Quantity of biosolids to apply.
5. Soil and weather conditions compared to biosolids storage volume.
6. Transport system to application site
7. Rate of application needed
8. Odor potential
9. Runoff potential.

SITE MANAGEMENT

Optimum Biosolids field management must begin at the unloading site. Soil compaction may occur due to the weight of the biosolids and trucks transporting the material. If soil moisture is high at the time of unloading, compaction will likely to occur. Material should be spread quickly to prevent accumulation of excessive concentrations of soluble salts in the soil at the unloading site.

Prevention of Erosion

Steps should be taken to prevent soil erosion as a direct result of land application practices. Detrimental water quality impacts from biosolids can be avoided by employing conservation tillage practices that reduce erosion and prevent the movement of sediment and Biosolids constituents to surface water. If land is left out of production to allow biosolids application during the normal crop growing season, it should be protected with a crop residue or a cover crop. For sloping land, alternating strips of cropped land with the strips left out of production would be wise.

Biosolids injection practices can affect the amount of soil erosion that occurs. Driving the applicator truck across the slope instead of up and down reduces erosion. Injecting biosolids up and down the slope provides channels for water and intensifies erosion potential in the same way as plowing or cultivating up and down the slope.

Prevention of Soil Structure Damage

Applicator trucks with high flotation tires reduce compaction damage in the upper zone of wet soils. However, since compaction in the 12 - 24" zone is a function of total axle weight rather than "foot print" pressure. Care must be exercised in using applicator trucks on wet soils. Also, using injectors in muddy soils results in much the same type of soil structural damage as plowing when the soil is too wet. Clay soils, in particular, become cloddy and adequate seedbed preparation is very difficult if stirred when wet. The problems are particularly bad when a second injection or a primary tillage pass is made across a field before previously injected biosolids are dry.

Prevention of Runoff

Besides preventing soil loss or damage, the environment must not be degraded by allowing biosolids to leave the site by overland flow. Biosolids should not be applied on frozen ground or applied on snow so that it is carried off in the melt water. Even sites with a very slight slope will show severe runoff problems from rain or melting snow on top of frozen ground.

Water pollution problems caused by movement of biosolids in runoff water can be minimized by use of grassed buffer strips along waterways adjacent to application sites. Grass has been shown to be an effective filter for various wastewater solids and water-borne soil particles.

INTERACTIONS WITH SOIL-CROP-WATER SYSTEMS

In developing Biosolids management strategies for soil improvement, think of the soil as a medium for plant growth and other biological activity at or below the soil surface. Biosolids additions to land will influence physical, chemical, and biological processes within the soil, and can lead to significant changes in soil-plant-water relations. Physical changes in soil associated with biosolids application to land includes increased soil organic matter, increased water holding capacity and improved soil structure, aggregation, and water infiltration. This can reduce runoff and erosion, restore soil productivity and quality, and provide a more favorable environment for plant growth. For these reasons, biosolids have been used in many areas for the reclamation and revegetation of disturbed lands, and for improvement of marginal soils. Addition of biosolids to marginal and disturbed soils can restore soil productivity and quality, and in general, provide a more favorable environment for plant growth. However, appropriate sites are not always available and biosolids must be applied to high quality farmland, often surrounded by sensitive natural resource areas.

Biosolids are particularly useful in the reclamation of surface-mined areas, sand tailings piles, borrow pits, and other disturbed land areas. These sites are lacking organic matter, very low in N, possibly low in pH and in P and K, and have poor physical structure. Because the soil strata may be disturbed well below the surface and vegetative cover may be sparse, the potential for groundwater pollution from biosolids application may be greater on surface-mined sites than on undisturbed sites, unless a vegetative cover is established. Some disturbed areas might be used as dedicated sites for biosolids application because these sites have limited usefulness for crop production.

Chemical changes in soil resulting from biosolids additions largely depend on the nature and amount of the chemical inputs from the biosolids material and the assimilative capacity of the soil. Because of the extreme variability in biosolids, it is critical to monitor the quality of biosolids being considered for land application. Careful management of Biosolids addition to control loading rates of nutrients and other chemical constituents such as metals, toxic organics, and salts is also important. Failure to do so may degrade soil quality, restrict the capacity of the soil to support plant growth, and lead to entry of toxic metals in the food chain.

Biological considerations in land application of biosolids are usually related to the presence of pathogens in the biosolids. Because of the potential for animal and human health effects from improper land application, pathogen removal is necessary before biosolids are suitable for agricultural use. The risk of exposure to pathogens can be further reduced by using buffer areas around application sites and placement of the biosolids below the soil surface.

In the end, the relative risks of all biosolids disposal options must be considered in arriving at policies and practices to manage biosolids use on land effectively. Awareness of the agricultural, health, and environmental benefits, costs, and impacts are critical to developing publicly acceptable biosolids management and disposal programs that are both economical and effective in protecting the food chain and the environment.

REFERENCES

Alley, M.M., P. Scharf, D.E. Brann, W.E. Baethgen and J.L. Hammons. 1994. Nitrogen Management for Winter Wheat: Principles and Recommendations. Virginia Cooperative Extension Service. Crop & Soil Environmental Sciences. Virginia Polytechnic Institute and State University. Blacksburg, VA. Pub. 424-026.

Baker, J.L. and J.M. Laflen. 1993. Water quality consequences of conservation tillage. J. Soil and Water Cons. 38:186-193.

Barczewski, R.A., J.N. Scarborough, and R. Graeber. 1989. Delaware Guidelines- Beef Manure Management. A Supplement to Delaware Guidelines~Manure Management for Environmental Protection. University of Delaware, Newark, DE. Cooperative Bulletin #22. pp. 4.

Brady, N.C. 1990. The Nature and Properties of Soils. Tenth Edition. MacMillian Publishing Co. New York. pp. 620.

Cera, K. 1989. Delaware Guidelines- Swine Manure Management. A Supplement to Delaware Guidelines~Manure Management for Environmental Protection. University of Delaware, Newark, DE. Cooperative Bulletin #26. pp. 31.

Collins, E.R. Jr.. 1994. Calibration of Solid Manure Spreaders. Extension Agricultural Engineer, Virginia Cooperative Extension Service. Virginia Polytechnic Institute and State University. Blacksburg, VA.

Cornell Cooperative Extension. Environmental Fact Sheets. The Production of Sludge. What is Sludge? Fact sheet #1. Cornell Cooperative Extension of Nassau County, Plainview, NY.

Cornell Cooperative Extension. Environmental Fact Sheets. The Beneficial Uses of Sludge. How Do We Dispose of Sludge? Fact sheet #3. Cornell Cooperative Extension of Nassau County, Plainview, NY.

Donohue, S.J., G.K. Evanylo, and D.W. Aho. 1993. Sampling instructions and nutrient sufficiency ranges for plant tissue analysis. Virginia Cooperative Extension Service. Crop & Soil Environmental Sciences. Virginia Polytechnic Institute and State University. Blacksburg, VA. Pub. 452-211.

Elliot, H.A. 1986. Land Application of Municipal Sewage Sludge. J. Soil Water Conserv. 41:5-10.

Givens, F. 1994. Aninal Wate Utilization. Agricultural Engineering Department, Virginia Polytechnic Institute and State University. Blacksburg, VA.

Kiniry, L.N., C.L. Scrivner, and M.E. Keener. 1983. A soil productivity index based upon predicted water depletion and root growth. Missouri Agric. Exp. Stn. Res. Bull. 1051.

Klausner, S. and D. Bouldin. 1983. Managing Animal Manure as a Resource Part I: Basic Principles. New York State Cooperative Extension Service, Cornell University, Ithaca, NY. pp. 4.

Laboratory Manual Basic Soils (CSES 3124). 1996. Virginia Polytechnic Institute and State University. Blacksburg, VA.

Manure Testing. 1994. Agricultural Engineering, Water Quality Lab, 400 Seitz Hall. Virginia Polytechnic Institute and State University. Blacksburg, VA.

McCart, G.D., G.W. Hawkins, and G.R. Epperson. 1970. Lime For Acid Soils-What to Use, How to Apply. Virginia Cooperative Extension Service. Virginia Polytechnic Institute and State University. Blacksburg, VA. Publication # 405. pp. 12.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, J.R. Williams, and V.W. Benson. 1991. Effect of cover crops on groundwater quality. p. 57-68. IN: W.L. Hargrove (ed.), Cover Crops for Clean Water, Soil & Water Cons. Soc., Ankeny, IA.

Midwest Plan Service. 1985. Livestock waste facilities handbook, Second Edition. Iowa State University, Ames, IA. MWPS-18.

Miller, M.F. 1936. *Cropping Systems in Relation to Erosion Control.* Missouri Agricultural Experiment Station Bul. 366.

NRC. 1978. Nitrates: An Environmental Assessment. National Research Council, National Academy of Sciences, Washington, DC. 435-84.

North Carolina Cooperative Extension Service. 1994. Cotton Information. North Carolina Cooperative Extension Service, North Carolina State University. Raleigh, NC. Publication AG-417. pp. 164.

Pennsylvania State University, 1990. Penn State Agronomy Guide. 1991-1992. IN: R.D. Chambers, ed. Agricultural information services. Pennsylvania State University Press, Pennsylvania State University, University Paark, PA. 26-36.

Pennsylvania Department of Environmental Resources. 1990. Assessment of Field Manure Nutrient Management with Regards to Surface and Groundwater Quality. Pennsylvania Department of Environmental Resources, Bureau of Soil and Water Conservation, Harrisburg, PA. REWAI Project No. 88232.

Rasnake, M. 1983. *Tillage and Residue Management.* University of Kentucky. Lexington, KY. Extension Publication AGR-99.

Reneau, R.B., Jr., D.F. Berry, and D.C. Martens. 1990. Fate and transport of selected pollutants in soils. pp. 14-44. IN: Proceedings, International Symposium: Environmental Pollution and Agriculture, Seoul Nat. University, Seoul, Korea.

Salter, R.M. and C.J. Schollenberger. 1939. Farm manure. Ohio Agric. Exp. Stn. Bull. No. 605.

Scrivner, C.L., B.L. Conkling, and P.G. Koenig. 1985. Soil Productivity Indices and Soil Properties for Farm-Field Sites in Missouri. University of Missouri-Columbia, Columbia, MO. EC947 2/85/1.2M.

Sharpley, A.N. and S.J. Smith. 1991. Effect of Cover Crops on Surface Water Quality. pp. 41-49. IN: W.L. Hargrove (ed.), Cover Crops for Clean Water, Soil & Water Cons. Soc., Ankeny, IA.

Simpson, T.W., S.M. Nagle, and G.D. McCart. 1985. Land Application of Sewage Sludge for Agricultural Purposes. Virginia Cooperative Extension Service. Virginia Polytechnic Institute and State University. Blacksburg, VA.

Sims, J.T., D. Palmer, J.N. Scarborough, and R. Graeber. 1989. Delaware Guidelines-Poultry Manure Management. A Supplement to Delaware Guidelines~Manure Management for Environmental Protection. University of Delaware, Newark, DE. Cooperative Bulletin #24. pp. 4.

Sommers, L.E. 1977. Chemical Composition of Sewage Sludges and Analysis of Their Potential Use as Fertilizers. J. Environ. Qual. 6:225-232.

Starver, K.W., R.B. Brinsfield, and J.C. Stevenson. 1989. The Effect of Best Management Practices on Nitrogen Transport into Chesapeake Bay.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil Fertility and Fertilizers, Fifth Edition. MacMillian Publishing Co. New York. pp. 634.

Thomas, P.J. Characterization, Classification, and Productivity Studies of Typic Hapludult Mapping Units in the Southern Piedmont of Virginia. MS Thesis. Virginia Polytechnic Institute and State University. Blacksburg, VA. pp. 358.

US-EPA. 1994. Standards for the Use or Disposal of Sewage Sludge. Federal Register 58(32):9248-9415. U.S. Gov. Print. Office, Washington, DC.

US-EPA. 1993. Process Design Manual for Land Application of Municipal Sewage Sludge. USEPA Rep. EPA-625/l83-016. U.S. Gov. Print. Office, Washington, DC.

US-EPA, 1990. National Pesticide Survey, Phase I Report. EPA 570/9-90-015, U.S. Gov. Print. Office, Washington, DC.

US-EPA. 1983a. Chesapeake Bay Program: Findings and Recommendations. United Stated Environmental Protection Agency. Philadelphia, PA. pp. 48.

US-EPA. 1983b. Process Design Manual for Land Application of Municipal Sewage Sludge. USEPA Rep. EPA-625/183-016. U.S. Gov. Print. Office, Washington, DC.

Vanderholm, D.H. 1975. Nutrient Losses from Livestock Waste During Storage, Treatment, and Handling. In Proceedings Third International Symposium on Livestock Wastes. American Society of Agricultural Engineering.

Vaughn, G.F., M.S. Gates, R. Graeber, M.R. Graustein, and R.C. Jester. 1989. Delaware Guidelines-Manure Management for Environmental Protection. University of Delaware, Newark, DE. Cooperative Bulletin #27. pp. 20.

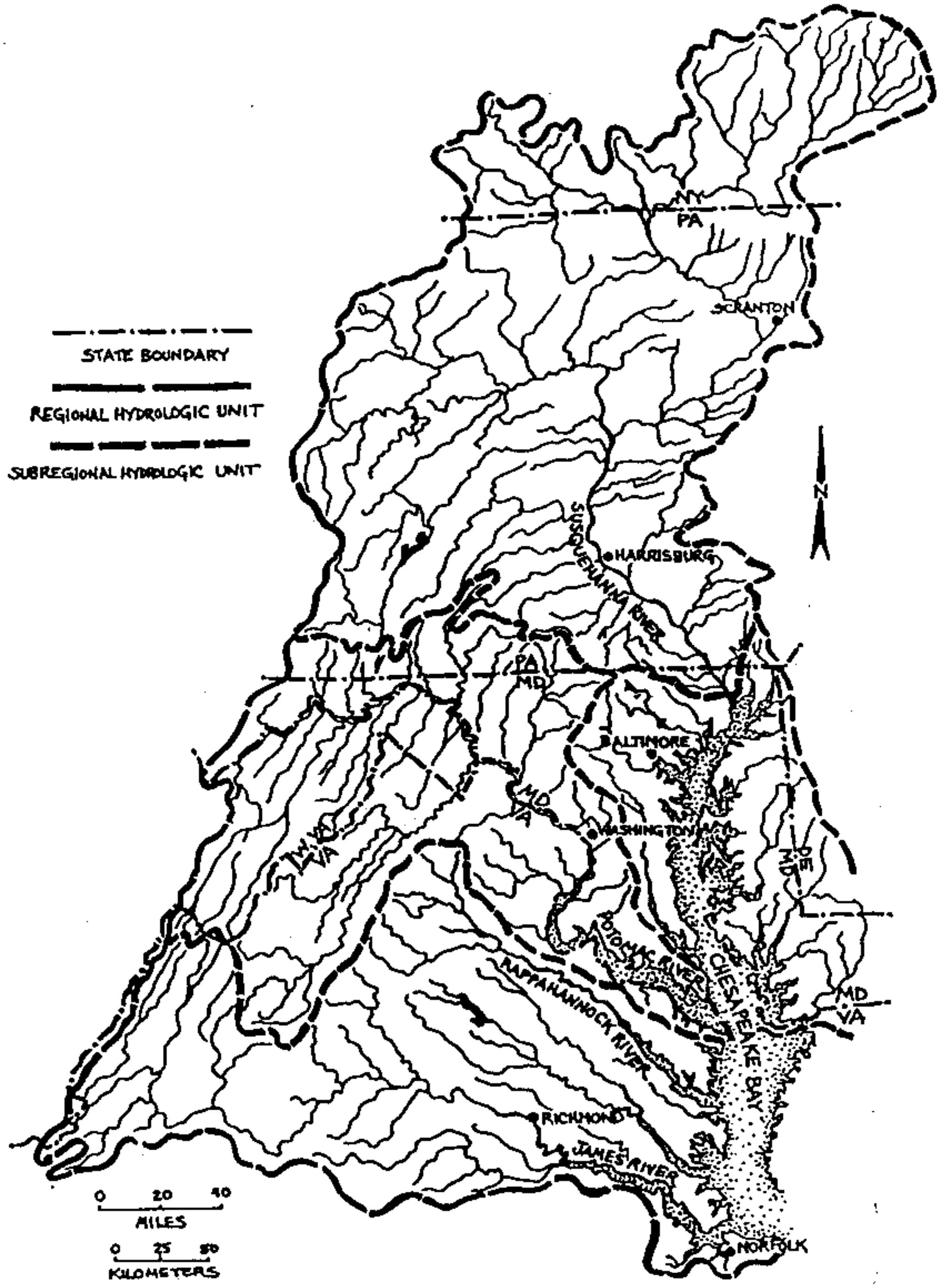
Virginia Cooperative Extension Service. 1987. A Handbook of Agronomy. Virginia Cooperative Extension Service. Virginia Polytechnic Institute and State University. Blacksburg, VA. Publication 424-100.

Washington Suburban Sanitary Commission (WSSC). Beneficial Use-The Successful Management of Wastewater Products. Booklet prepared by Hanifin Associates, Inc. for WSSC, Hyattsville, MD.

Williams, T. and R.W. Taylor. 1989. Delaware Guidelines-Field Application of Manure. A Supplement to Delaware Guidelines~Manure Management for Environmental Protection. University of Delaware, Newark, DE. Cooperative Bulletin #25. pp. 15.

Zublena, J.P., J.C. Barker, and J.W. Parker. 1990a. Soil Facts: Swine Manure as a Fertilizer Source. The North Carolina State Agricultural Extension Service. North Carolina State University, Raleigh, NC. 7/90-5M-TPM-200472/AG-439-4.

Zublena, J.P., J.C. Barker, and T.A. Carter. 1990b. Soil Facts: Poultry Manure as a Fertilizer Source. The North Carolina State Agricultural Extension Service. North Carolina State University, Raleigh, NC. 7/90-5M-TPM-200472/AG-439-5.



The **Chesapeake Bay watershed** encompasses approximately 64,000 square miles of land area and 5,000 square miles of water surface. The Chesapeake Bay is one of the largest estuaries in the world and has the most land area relative to water volume of any estuary. Because of this, our activities on the land are even more important. Nutrients, in particular nitrogen and phosphorus, are a major component of the pollution problem. Excess nutrients in the Bay can fertilize algae which reduces water clarity, preventing needed sunlight from reaching beneficial bottom grasses, and can result in decreased levels of dissolved oxygen contained in the water. Since 1983, the states of Maryland, Pennsylvania, Virginia, The District of Columbia, and the Federal government have been working to reduce nutrient inputs to the Bay. A major goal of nutrient management is to reduce environmental impacts from nutrients while maintaining a viable agricultural industry.