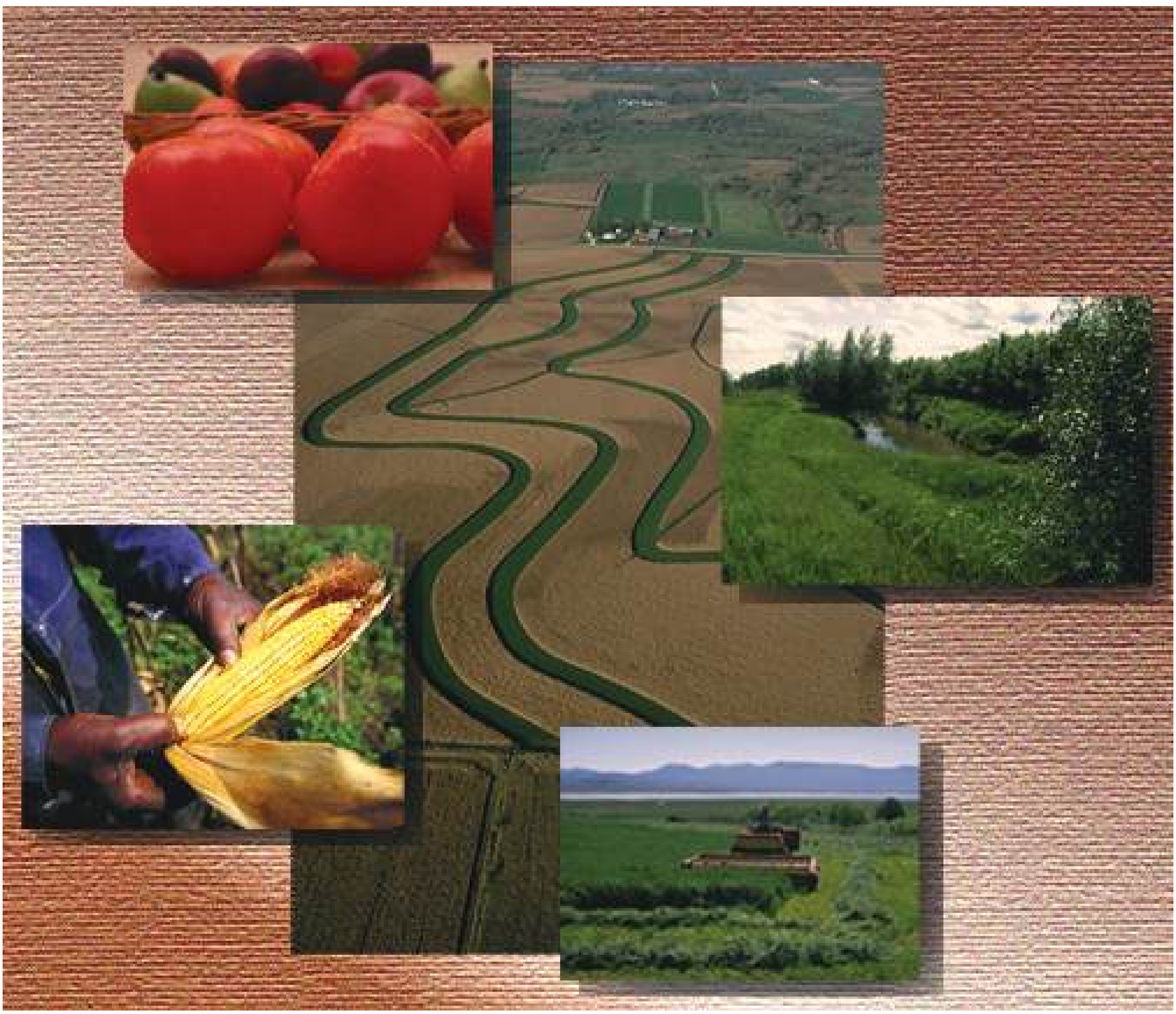
United States Department of Agriculture
Natural Resources Conservation Service

National Agronomy Manual



National Agronomy Manual

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National Agronomy Manual

Contents

Part 500 Authorities, Policies, and Responsibilities

Contents

Part 500 Authorities, Policies, and Responsibilities

Subpart 500A Authority

500.00 Description of authorities

The U.S. Department of Conservation (USDA) Soil Conservation Service (SCS) was renamed the Natural Resources Conservation Service (NRCS) by Secretary's Memorandum 101–1 of November 20, 1994. This action was authorized by the Federal Crop Insurance Reform and Department of Agriculture Reorganization Act of 1994 (Public Law 103–354). The SCS had been created in USDA by the Soil Conservation and Domestic Allotment Act of 1935 (Public Law 74–46).

Public Law 74–46 authorized a broad program of soil and water conservation, and it is still the basic authority for the Agency's work with farmers and conservation districts.

500.01 Purpose of the National Agronomy Manual

The National Agronomy Manual (NAM) contains policy for agronomy activities and provides technical procedures for uniform implementation of agronomy tools and applications. This manual is meant to complement all established USDA and NRCS policies and guidelines.

Subpart 500B Agronomic policies

500.10 Location of policy

Agronomic policies are contained in specific parts and subparts of the NAM as appropriate.

500.11 Amendments to NAM

The NAM will be amended as additional research is completed, existing methods or procedures are updated, or new technology is developed and approved for use in the NRCS. The national agronomist is responsible for updating this manual.

Subpart 500C Responsibilities of agronomists

500.20 Responsibilities of national, State, area, and field agronomists

The national agronomist, nutrient management specialists, and pest management specialists at the national level and agronomists on the center staffs and the National Technical Support Centers provide staff assistance in all NRCS programs and provide national leadership on NRCS agronomy-related activities. They are responsible for:

- assisting upper management in formulating and recommending national policies, procedures, and standards
- technical leadership and guidance; quality control
- national coordination of agronomy with other NRCS technical fields
- promoting and maintaining relations with groups and agencies that have common interest in agronomy
- technology transfer and direct technical support to States and State staff

State agronomists provide staff assistance to the State conservationist for all agronomy and related functions. They are responsible for:

- assisting in developing State policies, procedures, and instructions, and coordinating them with other States within the region
- providing technical leadership and guidance to other agronomists and appropriate personnel within the State
- collaborating with other State staff members to ensure interdisciplinary action in all NRCS programs
- training field personnel
- participating in agronomy components of appraisals and reviews
- maintaining working relations with research centers and other cooperating agencies
- developing and revising of all aspects of Field Office Technical Guides related to agronomy
- providing assistance in interdisciplinary technical reviews of project plans, environmental impact statements, and other technical materials
- coordinating agronomy functions with other States in the region and across regional boundaries as appropriate

Area, zone, or field level agronomists provide staff assistance in all NRCS programs. They are responsible for carrying out the requirements of conservation agronomy consistent with technical proficiency, training, interdisciplinary action, and quality control within their administrative area. In some cases, these agronomists may carry out some of the responsibilities of the State agronomists, if so delegated.

Agronomists in the mentioned positions may provide specific functions through team or ad hoc assignments at a National, regional, or State level. Each agronomist has the responsibility to develop a training needs inventory and to work with their supervisor to obtain technical training to improve the overall agronomic expertise.

500.21 Technical information—preparing, transferring, and training

Agronomists at all levels use technical information that has been developed by researchers, universities, institutes, and private sources to maintain technical materials for the administrative area they serve. Agronomists at all administrative levels develop and review field office technical guide materials and ensure materials are technically correct, comprehensive, and useful to the end user.

NRCS policy on preparing and maintaining technical guides is in General Manual (GM) Title 450, Part 401. In addition, State agronomists are responsible for technical notes and other agronomy technical materials that are applicable to the State.

Agronomists issue technical information at the area, State, or national level. This may include original information, research notes, papers, or excerpts of such material. All agronomists are encouraged to submit articles for publication or presentation at professional meetings. Technical information presented or prepared for publication shall have an appropriate technical and or administrative review and include crediting of appropriate references per GM450 Part 410, Subpart B, Scientific and Technical Publications Review Program.

Agronomists receive and provide training necessary to maintain technical competency at all administrative levels. Training includes, but is not limited to, National Employee Development Center courses, workshops, conferences, university courses, and on-the-job training.

500.22 Certification

Agronomists at all levels of the Agency are encouraged to obtain professional certification(s). Examples of certification programs include the Certified Crop Adviser (CCA), Certified Professional Agronomists (CPAg) under ARCPACS of the American Society of Agronomy, and Certified Professional in Erosion and Sediment Control (CPESC) of the Soil and Water Conservation Society. Continuing educational requirements of most certification programs provide excellent opportunities to stay abreast of advances in technology.

500.23 Affiliation with professional organizations

Agronomists at all levels are encouraged to be active members of professional scientific societies, such as the American Society of Agronomy, Soil Science Society of America, Crop Science Society of America, the Soil and Water Conservation Society. These organizations provide opportunities to interact with researchers at the national and State level and to stay current on the latest technology.

Part 501 Water Erosion

Contents

Part 501 Water Erosion

Subpart 501A Introduction

501.00 Overview of water erosion

This part presents United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) policy and procedures for estimating soil erosion by water. It explains the types, the method used to estimate, and the management of soil erosion by water. NRCS technical guidance related to water erosion shall conform to policy and procedures set forth in this part.

The Agricultural Research Service (ARS) has primary responsibility for erosion prediction research within the USDA. ARS is the lead agency for developing erosion prediction technology, including the Revised Universal Soil Loss Equation version 2 (RUSLE2). The majority of the technology in RUSLE2 is documented in the publication Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE), USDA Handbook 703, hereafter referred to as the Agriculture Handbook 703. The reader is referred to the Agriculture Handbook 703 for a detailed description of RUSLE2 technology and parameter effects on soil loss,

Subpart 501B Water Erosion

501.10 Forms of water erosion

Forms of soil erosion by water include sheet and rill, ephemeral gully, classical gully, and streambank. Each succeeding type is associated with the progressive concentration of runoff water into channels as it moves downslope. Sheet erosion, sometimes referred to as interrill erosion, is the detachment of soil particles by raindrop impact and the removal of thin layers of soil from the land surface by the action of rainfall and runoff. Rill erosion is the formation of small, generally parallel channels formed by runoff water. Rills usually do not re-occur in the same place. Ephemeral gullies are concentrated flow channels formed when rills converge to form shallow channels. They can easily be filled with soil by typical tillage operations and re-formed in the same general location by subsequent runoff events. Classical gullies are also concentrated flow channels formed when rills converge. These are well defined, permanent incised drainageways that cannot be crossed by ordinary farming operations.

Other forms of erosion that are related to soil erosion by water include stream channel and geologic. Stream channel erosion refers to the degradation of channels and waterways. Geologic erosion refers to long-term erosion effects, as opposed to accelerated erosion events described in this subpart.

No reliable methods exist for predicting the rate of ephemeral gully, classical gully, stream channel, or geologic erosion. However, the science is under development to add ephemeral gully erosion estimates to water erosion prediction models. The remainder of this part deals only with prediction and control of sheet and rill erosion.

501.11 The water erosion process

Detachment, transport, and deposition of soil particles caused by raindrop impact and surface runoff are known as the processes of sheet and rill erosion.

Detachment is the removal of particles from the soil mass and is expressed in units, such as tons per acre and is referred to as sediment.

The movement of sediment downslope is sediment transport. A measure of sediment transport is sediment load. Sediment load on a slope increases with distance downslope as long as detachment is occurring. That is, detachment adds to the sediment load.

Where runoff is slowed along the slope, at the base of a slope, or by dense vegetation, deposition occurs. Deposition is the transfer of sediment from the sediment load to the soil mass. That is, deposition removes sediment from the sediment load, and accumulates on the soil surface.

Two types of deposition, remote and local, occur. Remote deposition occurs some distance away from the origin of the sediment. Depositions at the toe of a concave slope, on the uphill side of vegetative strips, and in terrace channels are examples of remote deposition. Local deposition is where sediment is deposited near, within several inches, of where it is detached. Deposition in microdepressions and low gradient furrows are also examples of local deposition.

Subpart 501C Estimating sheet and rill erosion

501.20 How, why, and by whom water erosion is estimated

NRCS estimates soil erosion by water as part of its technical assistance to land users. In conservation planning, erosion estimates are made for an existing management system and compared with alternative systems and with soil loss tolerance (T) values.

In addition, soil loss estimates are used to inventory natural resources, evaluate the effectiveness of conservation programs and land treatment, and estimate sediment production from fields that might become sediment yield in watersheds.

Title 450 National Instruction Part 300 issued in July 2002 required that RUSLE2 be fully implemented in all NRCS field offices where water erosion is a resource issue by the end of calendar year 2002. In 2002, NRCS adopted RUSLE2 as the official tool for predicting soil erosion by water. NRCS continues to use some USLE components for certain provisions of Farm Bill programs, most notably it uses USLE soil factors in determining if fields are Highly Erodible Land.

501.21 Methods of estimating sheet and rill erosion

Efforts to predict soil erosion by water started in the 1930s. Cook (1936) identified the major variables that affect erosion by water. Zingg (1940) published the first equation for calculating field soil loss. Smith and Whitt (1947) presented an erosion-estimating equation that included most of the factors present in modern soil loss equations. The Musgrave equation (Musgrave 1947) was a soil loss equation developed for farm planning. Finally, an effort was initiated to develop a national equation from the various state and regional equations that existed in the 1950s. In 1954, the ARS established the National Runoff and Soil Loss Data Center at Purdue University in West Lafayette, Indiana, to consolidate all available erosion data. Using the data assembled at the Data Center, Wischmeier and

Smith (1965) developed the Universal Soil Loss Equation (USLE).

The USLE was a consolidation of several regional soil loss equations, and was based on summarizing and statistical analyses of more than 10,000 plot-years of basic runoff and soil loss data from 49 United States locations (Agriculture Handbook 703, 1997; Wischmeier and Smith 1965, 1978).

The USLE was designed to provide a convenient working tool for conservationists. It quantifies soil erosion as a product of six factors representing rainfall and runoff erosiveness, soil erodibility, slope length, slope steepness, cover-management practices, and supporting practices.

ARS released RUSLE in 1992 as a computer program in the DOS environment. The model calculates soil loss from a field slope using values for each factor and using data elements from climate, plant, and field operation databases.

501.22 The Revised Universal Soil Loss Equation version 2 (RUSLE2)

Since implementation during 2002, RUSLE2 has been used by NRCS to estimate soil loss by water. RUSLE2 predicts long-term average annual soil loss from sheet and rill erosion. RUSLE2 is an update of the Revised Universal Soil Loss Equation (RUSLE) as described in Agriculture Handbook 703. RUSLE2 utilizes a computer program to facilitate the calculations. RUSLE2 technology reflects the analysis of research data that were unavailable when Agricultural Handbook 282 (Wischmeier and Smith 1965), Agriculture Handbook 537, and Agriculture Handbook 703 were completed, including subsequent technology development.

The average annual soil loss from sheet and rill erosion is computed based on the following equation:

$$A = R \quad K \quad L \quad S \quad C \quad P$$

where

A = the computed spatial average soil loss and temporal average soil loss per unit of area (usually expressed in units of T/a/yr)

R = the rainfall-runoff erosivity factor (the rainfall erosion index value plus a factor for any significant snowmelt runoff)

K = the soil erodibility factor (the soil loss rate per erosion index unit for a specified soil as measured on a standard plot that is 22.1 meters long with a uniform 9 percent slope in continuous clean-tilled fallow)

L = the slope length factor (the ratio of soil loss from the field slope length and soil loss from standard plot length under otherwise identical conditions)

S = the slope steepness factor (the ratio of soil loss from the field slope gradient and soil loss from standard plot gradient under otherwise identical conditions)

C = the cover-management factor (the ratio of soil loss from an area with specified cover/management and soil loss from an otherwise identical area in continuous clean-tilled fallow)

P = the support practice factor (the ratio of soil loss with a support practice like contouring, strip cropping or terracing and soil loss with straight-row farming up and down the slope)

501.23 Limitations of the equation

The term Universal distinguishes the USLE, RUSLE and RUSLE2 from State and regionally based models that preceded them. However, the use of these equations is limited to situations where factors can be accurately evaluated and to conditions for which they can be reliably applied (Wischmeier 1978; Agriculture Handbook 703, 1997).

RUSLE2 predicts long-term average annual soil loss carried by runoff from specific field slopes under specified cover and management systems. It is not appropriate to use RUSLE2 to predict specific erosion events associated with single storms or short-term random fluctuations. RUSLE2 also estimates sediment yield for the amount of eroded soil leaving the end of a slope with certain support practices. It does not predict sediment yield for the amount of sediment that is delivered to a point in a watershed, such as the edge of a field that is remote from the origin of the detached soil particles. Nor does RUSLE2 predict erosion that occurs in concentrated flow channels.

501.25 Data needed to support RUSLE2

RUSLE2 uses soil erodibility, K, values from the NASIS Soils Database. The RUSLE2 user inputs the appropriate soil type/component for the defined slope being evaluated. Climatic data (R) is obtained from National Weather Service weather stations with reliable long-term data. State and area agronomists have developed management records for the different crops in their areas from which RUSLE2 calculates cover and management factors (C).

The crop database in RUSLE2 contains plant growth and residue production parameters. Values for many of these parameters are available in a database for a wide variety of plants.

The operations database in RUSLE2 contains the soil and residue disturbance parameters. Values are available for a very large number of field operations ranging from a spade to numerous types of harvesting equipment.

Development and maintenance of databases used by NRCS in erosion prediction models are the responsibility of NRCS agronomists at the State and national levels. Refer to part 509 in this manual for more detailed information on database management and instructions. The national database manager maintains a database management plan that identifies the process of developing and maintaining databases needed to support RUSLE2. Databases for all States are available in electronic format from the official RUSLE2 website (*http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm*). Length of slope (L) and steepness of slope (S) are entered by the user based on the slope and length being evaluated.

501.26 Tools for using RUSLE2

Most States and basin areas have developed county-based climatic maps for their areas. These contain the detail that is desired when applying RUSLE2 to specific field situations, and are available in NRCS State offices and, in many cases, from the Field Office Technical Guide.

Subpart 501D Principles of water erosion control

501.30 Overview of principles

The principle factors that influence soil erosion by water are climate, soil properties, topography, vegetative cover, and conservation practices. Climate and soil properties are conditions of the site and are not modified by ordinary management measures. Conservation treatment primarily involves manipulation of vegetative cover, modification of topography, and manipulation of soil conditions in the tillage zone.

The greatest deterrent to soil erosion by water is vegetative cover, living or dead, on the soil surface. Cover and cultural practices influence both the detachment of soil particles and their transport. Growing plants and plant residue absorb the energy of raindrops, decrease the velocity of runoff water, and help create soil conditions that resist erosion. Cultural practices that affect vegetative cover include crop rotations, cover crops, management of crop residue, and tillage practices.

501.31 Relation of soil loss values to RUSLE2 factors

In conservation planning, cover and management(C factor) and practice implementation (P factor) can be modified or selected in RUSLE2 to develop alternatives for erosion reduction. In addition, where slope length is reduced by installing terrace or diversion systems, the slope length and steepness factor (LS) will be reduced. Using RUSLE2 technology, estimates of erosion reduction are illustrated in the C subfactors. Benefits to erosion control are achieved in the:

- prior land use subfactor by increasing the mass of roots and buried residue and increasing periods since soil disturbance
- canopy cover subfactor by increasing the canopy cover of the field area and low raindrop fall height from the canopy

- surface cover subfactor by increasing the ground cover of plant residue, and by permanent cover such as rock fragments
- surface roughness subfactor by increasing the random surface roughness that ponds water, and thereby reduces the erosive effect of raindrops and traps sediment
- soil moisture subfactor by growing moisture-depleting crops. This benefit is only applied in RUSLE in the Northwest Wheat and Range Region of the western United States

When support practices are applied, they become integral parts of a resource management system for controlling soil erosion by water. Contour farming, contour stripcropping, and conservation buffers form ridges on or near the contour that slow runoff and trap sediment. Terraces and diversions intercept concentrated runoff flows and, in many cases, shorten the length of slope.

Some erosion control practices, such as grassed waterways and water control structures, do not substantially reduce sheet and rill erosion. While these can be effective erosion control practices for concentrated flow (in the case of grassed waterways) in a resource management system, they are not a part of the soil loss reduction that is estimated by RUSLE2.

Subpart 501E References

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Part 502 Wind Erosion

Contents

Figures

Tables

Part 502 Wind Erosion

Subpart 502A Introduction

502.00 Overview

This part presents U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) policy and procedures for estimating wind erosion. It explains the Wind Erosion Prediction System (WEPS) and provides guidance and reference on wind erosion processes, prediction, and control. NRCS technical guidance related to wind erosion conforms to policy and procedures in this part.

This part will be amended as additional research on wind erosion and its control is completed and published. The national agronomist is responsible for updating this chapter and coordinating wind erosion guidance with Agricultural Research Service (ARS).

Understanding the erosive forces of wind is essential to properly use WEPS and interpret wind erosion data. NRCS predicts erosion rates, assesses potential damage, and plans control systems to address wind erosion.

The ARS has primary responsibility for erosion prediction research within the USDA. Wind erosion research is conducted by the Wind Erosion Research Unit at Manhattan, Kansas, and the Cropping Systems Research Unit at Big Spring, Texas.

Subpart 502B Wind Erosion

502.10 The wind erosion problem

Wind is an erosive agent. It detaches and transports soil particles, sorts the finer from the coarser particles, and deposits them unevenly. Loss of the fertile topsoil in eroded areas reduces the rooting depth and, in many places, reduces crop yield. Abrasion by airborne soil particles damages plants and constructed structures. Drifting soil causes extensive damage to adjacent land, roads, and drainage features. Sand and dust in the air can harm animals, humans, and equipment. Wind erosion events have caused major highway accidents.

Some wind erosion has always occurred as a natural land-forming process, but it has become detrimental as a result of human activities. This accelerated erosion is primarily caused by improper use and management of the land (Stallings 1951).

Few regions are entirely safe from wind erosion. Wherever the soil surface is loose and dry, vegetation is sparse or absent, and the wind sufficiently strong, erosion will occur unless control measures are applied (1957 Yearbook of Agriculture). Soil erosion by wind in North America is generally most severe in the Great Plains. The NRCS annual report of wind erosion conditions in the Great Plains shows that wind erosion damages from 1 million to more than 15 million acres annually, averaging more than 4 million acres per year in the 10-State area. USDA estimated that nearly 95 percent of the 6.5 million acres put out of production during the 1930s suffered serious wind erosion damage (Woodruff 1975). Other major regions subject to damaging wind erosion are the Columbia River plains; some parts of the Southwest and the Colorado Basin, the muck and sandy areas of the Great Lakes region, and the sands of the Gulf, Pacific, and Atlantic seaboards.

In some areas, the primary problem caused by wind erosion is crop damage. Some crops are tolerant enough to withstand or recover from erosion damage. Other crops, including many vegetables and specialty crops, are especially vulnerable to wind erosion damage. Wind erosion may cause significant short-term economic loss in areas where erosion rates are below the soil loss tolerance (T) when the crops grown in that area are easily damaged by blowing soil (table 502–1).

502.11 The wind erosion process

The wind erosion process is complex. It involves detaching, transporting, sorting, abrading, avalanching, and depositing of soil particles. Turbulent winds blowing over erodible soils cause wind erosion. Field conditions conducive to erosion include:

- loose, dry, and finely granulated soil
- smooth soil surface that has little or no vegetation present
- sufficiently large area susceptible to erosion
- sufficient wind velocity to move soil

Winds are considered erosive when they reach 13 miles per hour at 1 foot above the ground or about 18 miles per hour at a 30 foot height. This is commonly referred to as the threshold wind velocity (Lyles and Krauss 1971).The WEPS model sets this threshold by the hourly conditions in the field. As the field or wind conditions change the threshold changes.

The wind transports single grain particles or stable aggregates, or both, in three ways (fig. 502–1):

Saltation—Individual particles/aggregates ranging from 0.1 to 0.5 millimeter in diameter lift off the surface at a 50- to 90-degree angle and follow distinct trajectories under the influence of air resistance and gravity. The particles/aggregates return to the surface at impact angles of 6 to 14 degrees from the horizontal. Whether they rebound or embed themselves, they initiate movement of other particles/aggregates to create the avalanching effect. Saltating particles are the abrading bullets that remove the protective soil crusts and clods. Most saltation occurs within 12 inches above the soil surface and typically, the length of a saltating particle trajectory is about 10 times the height. From 50 to 80 percent of total transport is by saltation.

Table 502–1 Crop tolerance to blowing soil

Tolerant T	Moderate tolerance 2 ton/a	Low tolerance 1 ton/a	Very low tolerance 0 to 0.5 ton/a
Barley	Alfalfa (mature)	Broccoli	Alfalfa seedlings
Buckwheat	Corn	Cabbage	Asparagus
Flax	Onions (>30 days)	Cotton	Cantaloupe
Grain Sorghum	Orchard crops	Cucumbers	Carrots
Millet	Soybeans	Garlic	Celery
Oats	Sunflowers	Green/snap beans	Eggplant
Rye	Sweet corn	Lima beans	Flowers
Wheat		Peanuts	Kiwi fruit
		Peas	Lettuce
		Potatoes	Muskmelons
		Sweet potatoes	Onion seedlings (<30 days)
		Tobacco	Peppers
			Spinach
			Squash
			Strawberries
			Sugar beets
			Table beets
			Tomatoes
			Watermelons

Surface creep—Sand-sized particles/aggregates are set in motion by the impact of saltating particles. Under high winds, the whole soil surface appears to be creeping slowly forward as particles are pushed and rolled by the saltation flow. Surface creep may account for 7 to 25 percent of total transport (Chepil 1945 and Lyles 1980).

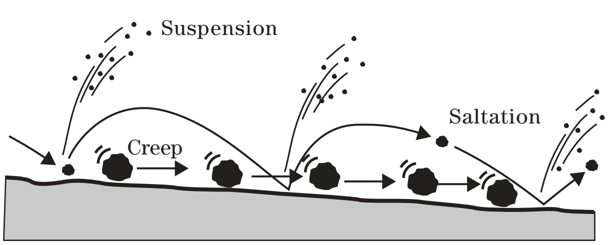
Suspension—The finer particles, less than 0.1 millimeter in diameter, are dislodged from an eroding area by saltation and remain in the air mass for an extended period. Some suspension-sized particles or aggregates are present in the soil, but many are created by abrasion of larger aggregates during erosion. From 20 percent to more than 60 percent of an eroding soil may be carried in suspension, depending on soil texture. As a general rule, suspension increases downwind, and on long fields can easily exceed the amount of soil moved in saltation and creep.

Saltation and creep particles are deposited in vegetated strips, ditches, or other areas sheltered from the wind, as long as these areas have the capacity to hold the sediment. Particles in suspension, however, may be carried a great distance.

The rate of increase in soil flow along the wind direction varies directly with erodibility of field surfaces. The increase in erosion downwind (avalanching) is associated with the following processes:

- the increased concentration of saltating particles downwind increases the frequency of impacts and the degree of breakdown of clods and crusts
- the accumulation of erodible particles and breakdown of clods tends to produce a smoother (and more erodible) surface

Figure 502–1 The wind erosion process



The distance required for soil flow to reach a maximum for a given soil is the same for any erosive wind. The more erodible the soil surface, the shorter the distance in which maximum flow is reached. Any factor that influences the erodibility of the surface influences the increase in soil flow.

502.12 Principles of wind erosion control

Five principles of wind erosion control have been identified (Lyles and Swanson 1976; Woodruff et al. 1972; and Woodruff and Siddoway 1965). These are:

- Establish and maintain adequate vegetation or other land cover.
- Reduce unsheltered distance along wind erosion direction.
- Produce and maintain stable clods or aggregates on the land surface.
- Roughen the land with ridge and/or random roughness.
- Reshape the land to reduce erosion on knolls where converging windflow causes increased velocity and shear stress.

The cardinal rule of wind erosion control is to strive to keep the land covered with vegetation or crop residue at all times (Chepil 1956). This leads to several principles that should be paramount as alternative controls are considered:

- Return all land unsuited to cultivation to permanent cover.
- Maintain maximum possible cover on the surface during wind erosion periods.
- Maintain stable field borders or boundaries at all times.
- Keep all residue standing as long as possible (standing residue is at least 3 time more effective at controlling wind erosion than flat residue

502.13 Tolerances in wind erosion control

In both planning and inventory activities, NRCS compares estimated erosion to soil loss tolerance (T). T is expressed as the average annual soil erosion rate (tons/acre/year) that can occur in a field with little or no long-term degradation of the soil resource, thus permitting crop productivity to be sustained for an indefinite period.

Soil loss tolerances for a named soil are recorded in the soil survey database in National Soil Information System (NASIS). WEPS can use the .mdb soil database from field office NRCS server or go directly to the National Soil Survey site for the data needed to make a soil loss estimate.

The normal planning objective is to reduce soil loss by wind or water to T or lower. In situations where treatment for both wind and water erosion is needed, soil loss estimates using the WEPS and RUSLE2 are not added together to compare to T, but are solved separately to find a treatment system that will adequately address both the wind and water erosion. Additional impacts of wind erosion that should be considered are damage to crops (crop tolerance) and the potential off-site damages, such as air and water pollution and the deposition of soil particles.

(a) Crop tolerance to blowing soil

Crop tolerance to soil blowing is an important consideration in wind erosion control. Wind or blowing soil, or both, can have an adverse effect on growing crops. Most crops are more susceptible to abrasion or other wind damage at certain growth stages than at others. Damage can result from desiccation, abrasion, and twisting of plants by the wind.

Crop tolerance can be defined as the maximum wind erosion that a growing crop can tolerate, from crop emergence to field stabilization, without an economic loss to crop stand, crop yield, or crop quality.

Many common crops have been categorized based on their tolerance to blowing soil. These categories of some typical crops are listed in table 502–1. Crops may tolerate greater amounts of blowing soil than shown in table 502–1, but yield and quality will be adversely affected.

(b) The effects of wind erosion on water quality

Some of the adverse effects of wind erosion on water quality include:

- Deposition of phosphours (P) into surface water
- Increased Biochemical Oxygen Demand (BOD) in surface water
- Reduced stream conveyance capacity because of deposited sediment in streams and drainage canals

Local water quality guidelines under Total Maximum Daily Loads (TDML) for nutrients may require that wind erosion losses be less than the soil loss tolerance (T) in order to achieve local phosphorus (P) or other pollutant reduction goals.

Subpart 502C Estimating Wind Erosion

502.20 How, why, and by whom wind erosion is estimated

NRCS estimates erosion rates to:

- help land users plan and apply conservation management systems
- inventory natural resources
- evaluate the effectiveness of conservation programs and conservation treatment applied to the land

Wind erosion is difficult to measure. Wind moves across the land in a turbulent, erratic fashion. Soil may blow into, within, and out of a field in several directions in a single storm. The direction, velocity, duration, and variability of the wind all affect the erosion that occurs from a wind storm. Much of the soil that erodes from a field bounces or creeps along near the surface; however, some of the soil blown from a field may be high above the ground in a dust cloud by the time it reaches the edge of a field (Chepil 1963).

502.21 Development of wind erosion prediction technology

Drought and wind erosion during the l9th century caused wind erosion to be recognized as an important geologic phenomenon. By the late 1930s, systematic and scientific research into wind erosion was being pioneered in California, South Dakota, Texas, and in Canada and England. This research produced information on the mechanics of soil transport by wind, the influence of cultural treatment on rates of movement, and the influence of windbreaks on wind flow patterns. The publication, The Physics of Blown Sand and Desert Dunes (Bagnold 1941), is considered a classic by wind erosion researchers.

In 1947, USDA began the Wind Erosion Research Program at Manhattan, Kansas, in cooperation with Kansas State University. That program was started under the leadership of Austin W. Zingg, who was soon joined by W.S. Chepil, a pioneer in wind erosion research in Canada. The research project's primary purposes were to study the mechanics of wind erosion, delineate major influences on that erosion, and devise and develop methods to control it.

By 1954, Chepil and his coworkers began to publish results of their research in the form of wind erosion prediction equations (Chepil 1954; Chepil 1957; Chepil et al. 1955; Woodruff and Chepil 1956).

In 1959, Chepil released an equation:

$$E = IRK \int BWD$$

where:

- E = quantity of erosion
- I = soil cloddiness
- R = residue
- K = roughness
- f = soil abradability
- B = wind barrier
- W = width of field
- D = wind direction

Wind velocity at geographic locations was not addressed in this equation (Chepil 1959).

In 1962, Chepil's group released the equation:

$$E = \int (ACKLV)$$

where:

- E = estimated average annual soil loss in tons per acre per year
- f = indicates relationships that are not straight-line mathematical calculations
- A = percentage of soil fractions greater than 0.84 millimeter;
- K = soil surface roughness factor
- C = climatic factor
- L = the unsheltered distance
- V = the vegetative cover factor

A C-factor map for the western half of the United States was also published in 1962 (Chepil et al. 1962).

In 1963, the form of WEQ was released as
E =f(IKCLV) (Chepil 1963).

where:

E	=	estimated average annual soil loss in tons per acre per year
f	=	indicates relationships that are not straight-line mathematical calculations
I	=	soil erodibility index
K	=	soil surface roughness factor
C	=	climatic factor
L	=	the unsheltered distance
V	=	the vegetative cover factor

The Wind Erosion Prediction System (WEPS) is a process-based, daily time-step model that simulates weather, field conditions, and erosion. The WEPS project was initiated in 1985 to overcome the shortfalls of WEQ. Leon Lyles, ARS, Manhattan, Kansas began the WEPS project, and Larry J. Hagen, ARS, lead the project from 1988 to 1994. Ed L. Skidmore, ARS, completed WEPS and made an official hand-off to NRCS in 2005.

WEPS uses climate generators for Cligen and Windgen to simulate 30 year records for wind, temperature and precipitation. A highly modified version of the Erosion Productivity Impact Calculator (EPIC) model is used to grow crops in the model. Soil information comes from the NRCS Soil Survey Geographic (SSURGO) Databases. User inputs are needed for the region (field) shape, size, and orientation; location is added from drop-downs; and management is added using a management editor. WEPS uses a Java-based interface to drive seven sub-models (hydrology, management, soil, crop, decomposition, erosion, and weather).

In 2010 WEQ was replaced by the WEPS for use by NRCS. See part 502D for the description and use of WEPS.

502.22 Data to support the previous WEQ for program purposes

Since 1963 the WEQ technology has been used by NRCS to assist farmer assess, plan, and implement wind erosion control systems on their farms. WEQ has also been used to determine Highly Erodible Land (HEL) land based on wind erosion and plan conservation systems to keep producers in HEL compliance. NRCS at the national, state, and field office levels will need to archive the procedures and WEQ data to continue to support the HEL determinations for wind erosion and to support current producer HEL plans based on the WEQ technology.

Data to support WEQ shall be archived when WEPS is implemented in the Field Office in 2010. The Climate (C) factors and soil erodibility (I) factors will be used to make Highly Erodible land determinations when land is sod busted or put into crop production.

Any existing localized values that were in use at the time WEPS was introduced shall be maintain and marked as archived.

502.23 Wind Erosion Prediction System

Wind Erosion Prediction System (WEPS) is the current technology used by NRCS to assess, plan, and implement wind erosion control systems on cropland and on other land (disturbed areas) where the inputs and data can be adequately defined. WEPS currently is not adapted to rangeland and woodland type land uses.

The WEPS is a process-based, daily time-step, wind erosion simulation model. It represents the latest in wind erosion prediction technology and is designed to provide wind erosion soil loss estimates from cultivated, agricultural fields.

The NRCS version of WEPS consists of the computer implementation of the WEPS science model with a graphical user interface designed to provide easy to use methods of entering inputs to the model and obtaining output reports. WEPS was developed by the Wind Erosion Research Unit (WERU) of the United States Department of Agriculture, Agricultural Research Service in Manhattan, KS. WEPS greatly expands the type of information about the soil loss.

WEPS uses many of the parameters that WEQ uses. Unsheltered distance (L) is now the Region with the shape, length, width, area, and orientation described. Random Roughness is calculated daily and has a similar influence as it did in WEQ. Oriented Roughness or ridge roughness is applied with each tillage operation and is degraded over time. Standing and flat residue is accounted for in several age pools. Green growing crops accumulate mass on a daily basis. Erodible Fractions related to the I factor for WEQ are calculated on a daily basis and displayed in the detailed report section of WEPS.

502.24 Using WEPS estimates with RUSLE2 calculations

The WEPS provides an estimate of average annual wind erosion and saltation, creep, and suspension erosion from all four sides of a field. RUSLE2 provide an estimate of average annual sheet and rill erosion from the slope length (L) entered into the model. Although both wind and water erosion estimates are in tons per acre per year, they are not additive unless the two equations represent identical flow paths across identical areas.

Subpart 502D Using WEPS

502.30 Using WEPS

WEPS has a very good user's manual located on the Web at: *http://www.weru.ksu.edu/weps/download/WEPSUsersManualDec07.pdf* Most of the information needed to run WEPS is contained in the manual. It will be updated periodically so users will need to check for the latest version. The following information is in addition to the material in the user's manual.

On the same Web site mentioned above there are training exercises. These exercises are designed to teach the use of the WEPS model on many of the common farming systems. New users should take the time to run these to become familiar with the model.

National crop management zone (CMZ) management files are stored on the same Web site. These can be downloaded and placed in the C:\Documents and Settings\All Users\Application Data\USDA\WEPS\Databases\nrcs\man subdirectory. They will then show up on the pull-down list inside WEPS.

Small changes in the management system can have significant changes in the soil loss output. It is recommended that until a user knows how the model works that they not assume that a change will not change the erosion rate. Make the run before a conclusion is made. With WEPS, areas around the Great Lakes and the Coastal Plains in the east may now predict some wind erosion where the WEQ did not predict erosion.

(a) Selection the location to run WEPS

Background—WEPS has a box, Location, in the right upper part of the main interface to identify where the model will run (fig. 502–2).

States with predetermined polygon maps (HI, AK, WA, OR, CA, AZ, NV, ID, UT, WY, parts of MT, parts of CO, parts of NM, and parts of TX) will use the Map Viewer button to select the approximate location to run the model. These states have developed Windgen and Cligen maps to designate the appropriate climate data station to be used in the map locations.

The remaining states will use the Cligen station closes to the latitude and longitude (decimal degrees) location and the Windgen station will be a weighted average of the three closest stations. WEPS uses this approach for Windgen because the climate stations are far apart, have sometimes very different data, fewer mountain ranges, and sharp changes in soil loss if a single station were used. This method produces a more gradual change moving from one station to another.

Selection process—To deal with this, within NRCS, States have the option and requirement to use the model in one of two ways.

- Option 1: NRCS Mode (with county centroids). This will give the user the option to select the county. The latitude and longitude boxes will only be changed by selecting the county. The map viewer will not be used to select the location of the Windgen file.
- Option 2: NRCS Mode (with sub-county zones). This mode allows the user to select the location by using the map viewer and double clicking to change the location to any location within a county. This will select a sub-county polygon with a predetermined Windgen station location for that zone. The State will need to do a great deal of testing to be sure the variability of the WEPS runs are within reasonable limits when moving from zone to zone within a given county. A GIS shape map will need to be developed for the State and counties. The state wind erosion specialist and GIS specialist should work together to make the needed shape file. The NTSCs will help if the states chooses this option.

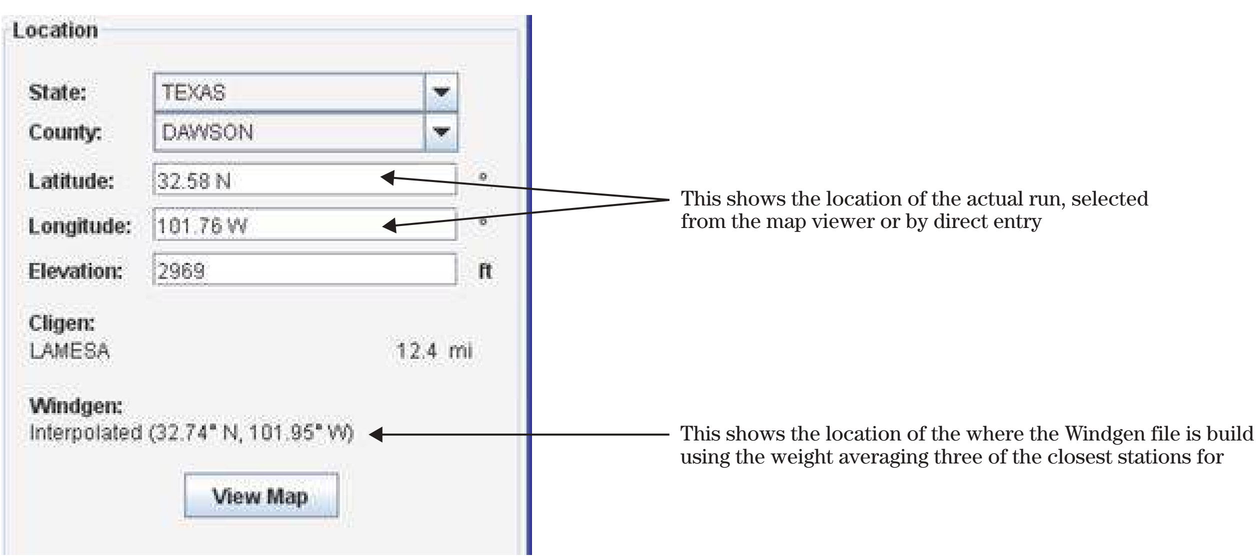
  Note that the western States (listed) with Windgen and the Cligen maps will use the Option 2 and select the location on the map viewer. The preselected station for each location will be used. The weight averaging will not be used in those States.

Those States using option 2 should set one location in the center of a group of fields. It is recommended that fields beyond 5 miles of the center be given a new latitude and longitude location. The distance from the center should be set by state policy.

(b) Generic soils list

Background—There is about 5 percent of the land in the United State without a soil survey. Some of the land is cropland with a wind erosion potential. There also is a need to provide a way to run WEPS on disturbed lands. A set of generic soils has been developed for use with WEPS.

Figure 502–2 Screen shot of location box in WEPS program



Method—The first set of 12 soils was selected from the centroid points of the standard USDA textural triangle. The centroid set the sand, silt, and clay percentages for the files. Bulk density was set using, BD = (1 – pore space) × 2.65. In the equation, percent pore space has to be expressed as a decimal. Eight important additional subclasses of sandy soil were added to the major group of 12 to make a total of 20 generic soils.

The fine sand, very coarse sand, coarse sand, medium sand, fine sand, and very fine sand were added to each of the soils as five-way split to start with. Then the sand values were hand adjusted to fit the rules in the National Soil Survey Handbook. Classification was checked using *http://soils.usda.gov/technical/aids/investigations/texture/* to see if they fit the textural classifications rules.

Soil depth was set to 1,500 mm or 60 inches and a 1 percent slope is assumed. Organic Matter was set to 1.5 percent as a mid range for arid and semi-arid soil where wind erosion is most common. No surface rock was assumed. Users can add the rock surface percentage on the main interface. T was set to 5 tons per acre as a deep soil is assumed. Table 502–2 shows the values used to make the WEPS generic (.ifc) records.

Table 502–2 Generic Soils List for WEPS

Tex abr	Tex. Name	Sand Tt (%)	Sand (percent fraction of Tt sand) V coarse	Coarse	Med	Fine	V fine	Silt (%)	Clay (%)	BD (g/cm)
SiC	Silty clay	7	1	2	2	1	1	48	45	1.22
CL	Clay loam	33	6	6	7	7	7	34	33	1.32
SiCL	Silty clay loam	11	2	2	2	2	3	56	33	1.28
C	Clay	18	3	3	4	4	4	17	65	1.21
SC	Sandy clay	53	10	10	11	11	11	7	40	1.33
L	Loam	41	8	8	8	8	9	41	18	1.43
SiL	Silt loam	21	4	4	5	4	4	66	13	1.44
SL	Sandy loam	65	11	11	11	16	16	24	11	1.55
CosSL	Coarse sandy loam	63	15	30	6	6	6	27	10	1.55
FSL	Fine sandy loam	63	5	6	6	31	15	27	10	1.55
SCL	Sandy clay loam	63	11	11	11	15	15	27	10	1.41
VFSL	Very fine sandy loam	63	2	3	3	18	37	27	10	1.55
Si	Silt	7	1	1	2	2	1	88	5	1.48
LFS	Loamy fine sand	83	7	7	7	55	7	12	5	1.67
LCosS	Loamy coarse sand	83	16	16	17	17	17	12	5	1.64
FS	Fine sand	93	7	7	8	60	11	4	3	1.67
LS	Loamy sand	83	10	10	10	23	30	12	5	1.64
S	Sand	93	20	20	20	15	18	4	3	1.67
LVFS	Loamy very fine sand	83	5	5	5	8	60	12	5	1.64
VFS	Very fine sand	93	3	4	4	22	60	4	3	1.67

Note: Sand and clay values were established using the USDA NRCS Textural Triangle. Sand textures were normalized to match the rules listed the USDA National Soil Survey Manual. They were checked by entering the listed values on the Web Soil Texture Calculator tool (*http://soils.usda.gov/technical/aids/investigations/texture/*).

Use of the Generic Soils—The generic soils can be use in at least three ways.

- NRCS has not completed a soil survey in an area where WEPS need to be run on cropland. In that case a field visits must be made to determine the texture of the soil(s) in the simulation area (field). It is advised that planner must be able to hand texture soil or take a person that can to the field. Once the planner has determined the critical dominant texture, a corresponding WEPS generic soil .ifc file can be selected from the NRCS Generic Soils subfolder.
- The soil has be removed or altered from the original soil mapped. These are likely to be construction sites; mine reclaim sites; or land-fill sites. Sometimes there will be lab data that will indicate the soil texture. In that case use the texture from the lab to select the corresponding WEPS file as stated.
- On fields that have a long history of wind erosion, a planner will find that the texture of the field is different than the soil map indicates. This has been documented in Texas and Idaho on fine sandy loams that are now loamy sand or loamy fine sand. Over the years the fine material on the surface has left the field by suspension. In these cases a planner can ask for a soil scientist to determine a more correct soil within the county survey or select a generic soil after making a field texture determination.

(c) Guidance using CMZ Templates

Crop Management Zone (CMZ) templates are available from the ARS Website in Manhattan, Kansas (*http://www.weru.ksu.edu/nrcs/wepsnrcs.html*). Click on the download button on the left side of the screen and navigate to the /WEPS database files/WEPS_Management_templates (CMZ files). In that directory any of the 75 CMZs can be downloaded and placed in the C:\Documents and Settings\All Users\Application Data\USDA\WEPS\Databases\nrcs\man folder of the computer. Do not unzip the folders.

The user must be careful using the management files from the CMZ folders. Some of the files that were converted from RUSLE2 have 2 years listed when they are a 1 year crop. In some cases the 0 year and year 1 were converted as 2 years in WEPS. Fall tillage was converted as a different year. All files must be opened and the operations and years checked for correctness of the dates.

Irrigation must be added by the user. There are no national management files with irrigation operation included. The user must open the management and add the appropriated irrigation operation to the file.

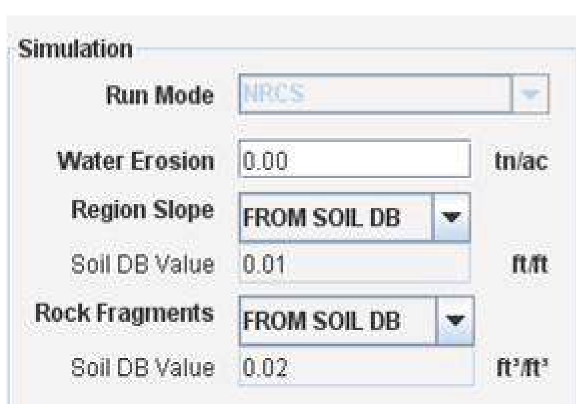
Once a CMZ file is corrected and the calibrated to a location it is highly recommended that a local record of the file be stored in the C:\Documents and Settings\All Users\Application Data\USDA\WEPS\Databases\nrcs\man\local subdirectory. This will reduce the time needed to recalibrate the next time the management is used.

(d) Soils with rock on the surface

WEPS estimates the surface rock from the soils data. Percent vertical surface rock in the first layer is converted to horizontal surface rock expressed as a percentage. Figure 502–3 has the Soil DB Value shown. The 0.02 indicates that the soils record has 2 percent rock on the surface.

Surface rock reduces the soil loss from wind greatly. It is critical for the user to evaluate whether there is surface rock present or not. The model will use the default (the soil survey data) unless the user clicks the pull down and changes it to override rock fragments.

Figure 502–3 Rock fragments pull-down and the 2% Soil DB Value for rock



(e) Muck soils

Histosols (muck or high organic soils) require special treatment when used in WEPS. WEPS 1.1.16 does not estimate Muck soils correctly. About 25 percent of the Histosols mapped by NRCS in the United States have the needed soil data WEPS. Much of the texture data in those records is populated with conceptual or estimated data not well-suited for use in WEPS. Wind erosion can be a serious problem on these high organic sites in Minnesota, Wisconsin, Michigan, North Carolina, and Florida. Representatives made up of ARS, NRCS, and university personal in 2008 met to review and discuss alternatives that might better reflect wind erosion on organic soils.

Short term
WEQ used an I factor of 134 tons per acre for Sapric Histosols. A group of I 134 mineral soils with a textural range of LFS, VFSL, LS, LCOS were evaluated to find the range of soil loss. A soil with the average soil loss of the group was selected to establish the sand, silt, and clay fractions to use in the generic organic soil file. By selecting the mid range soil texture WEPS would simulate a similar soil used in WEQ. The additional data needed for the organic soil file record comes from NRCS National Soils Lab in Lincoln, Nebraska.

WEPS has coding to assist users to select the generic organic soil file when Histosol is in the order name of the record. Any soil that has predominately Sapric organic material in the tillage layer is required to use the organic soils file in WEPS. Users should check to be sure that all “muck” soils are using the generic organic soil file listed in the NRCS Generic Soils list in WEPS.

WEPS is coded to use the first mineral layer on soils that have smaller amounts of organic material. Soils that have a thin organic surface layer such as Histic or Histic integrated will use the first mineral layer in the calculation. If the organic layer depth is greater than 4 inches, the model should use the organic soils file listed in WEPS. User should check to be sure the correct soil file is loaded.

Long term
ARS in Lubbock, Texas, and Manhattan, Kansas, have initiated efforts to better characterize wind erosion on organic soils. Plans include taking actual measurements in the field with a portable wind tunnel in Florida and Michigan. There is a plan to study soil from Florida and Michigan in the soils lab at ARS Manhattan, Kansas. It is anticipated that in 3 to 5 years, an improved method of estimating soil loss on organic soil will be available.

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Part 503 Crop Production

Contents

Figures

Tables

Part 503 Crop Production

Subpart 503A Crop rotation

503.00 Definition

A crop rotation is a sequence of different crops grown in a recurrent sequence over a given number of years. In some rotations a crop may occupy the land two years in succession. Crop rotations can vary in one or more of the following ways (Beck 1990):

- plant family–grass vs. broadleaf
- life cycle–annual vs. biennial vs. perennial
- season of growth–winter annual vs. spring/summer annual
- rooting depth–shallow vs. moderate vs. deep
- residue production–light vs. heavy
- residue type–fragile vs. non-fragile
- water use efficiency–high vs. low

To realize the greatest benefits, a crop rotation should not have the same annual crop grown 2 years in succession and should alternate plant families. This minimizes the potential for build-up and carryover of insect and disease populations, and maintains some degree of diversity in the cropping system.

503.01 Benefits of crop rotations

Properly designed crop rotations provide many benefits, and give producers more management options for their cropping systems. Conservation planners, when working with producers to develop a conservation management system, should emphasize the importance of maintaining the planned sequence of crops in the rotation. The benefits that accrue from the rotation, such as erosion reduction and pest management, depend on the crops being grown in the designated order. Crop rotations can help address the following resource concerns:

- *Pest management*—Rotations can reduce the incidence and severity of weeds, insects, and diseases in a cropping system. When a different crop is grown each year, a different host crop is present that is usually not compatible with pest problems that may have carried over from the previous year. Because of this, the levels of any given pest are kept at levels that make them easier to manage. A crop rotation allows the use of different management strategies for pest problems. Herbicides and insecticides with differing modes of action can be used, reducing the possibility that some species will become resistant to chemical control. Different crops each year may allow tillage to be used to control pests, further reducing the need for chemical controls (Sprague and Triplett 1986).
- *Erosion control*—Cropping systems that consist of continuous row crops and excessive tillage have a higher potential for wind or water erosion than rotations that include closely-spaced row crops or perennial crops. Different crops have different growth and development periods so that one crop may provide protection from erosive forces during a period of the year that another may not. Closely-spaced row crops, such as small grains or narrow-row soybeans, or perennial crops provide more canopy and surface cover than wide-row crops and reduce the potential for erosion.
- *Surface residue*—Surface residue is one of the most effective erosion reduction measures available. High residue-producing crops following low residue-producing crops help maintain higher levels of crop residue on the soil surface. Residue management practices, such as mulch tillage or no-till, can help maximize the amount of crop residue on the soil surface during critical erosion periods.
- *Soil quality*—Cropping sequences that include hay or pasture crops produce greater soil aggregate stability than systems that have continuous grain crops. In systems that have all grain crops, greater aggregate stability occurs with crops that produce higher amounts of residue. For example, rotations that alternate sorghum with soybeans result in greater organic carbon levels in the soil than with continuous soybeans (Unger 1994).
- *Nutrient management*—Crop rotations that have forage legumes or legume cover crops preceding grain crops can reduce the need for nitrogen (N) fertilizer for the grain crop.

Average corn yields of 160 bushels per acre have been obtained with corn following alfalfa (Triplett et al. 1979). Leguminous cover crops can provide an estimated 60 to 70 pounds of N per acre (Hargrove 1986). Small grain crops following legumes can scavenge the nitrogen fixed by the legume, reducing the potential for N losses by leaching.

- *Water management*—Dryland cropping systems can take advantage of stored soil moisture by alternating shallow and deep-rooted crops. For example, many areas in the Great Plains alternate winter wheat, a shallow-rooted crop, with safflower, a deep-rooted crop.
- *Livestock feed production*—For livestock operations, crop rotations that include hay and pasture can provide a major portion, and in some cases, all of the livestock forage and feed. Additional information on planning crop rotations for livestock operations is in the National Range and Pasture Handbook, chapter 5, section 2.

Subpart 503B Tillage systems

503.10 Introduction

The tillage system is an integral part of the cropping management system for a farm. The type, number, and timing of tillage operations have a profound effect on soil, water and air quality. Tillage systems vary widely depending on the crops, climate, and soils. The impacts of tillage on crop residue vary greatly depending on implements used, implement adjustments and the number of tillage trips. NRCS planners should be familiar with the tillage systems in their area, and how the application of these systems affects the resources.

503.11 Conservation tillage

Conservation tillage as defined by the Conservation Technology Information Center is any tillage and planting system with 30 percent or more residue cover remaining on the soil surface after planting to reduce soil erosion by water. Where soil erosion by wind is the primary concern, at least 1,000 pounds per acre of flat small grain residue equivalent are left on the soil surface during the critical wind erosion period.

(a) Residue management practices

Residue management practices that typically meet the conservation tillage definition include:

- *No-till, direct seed, and strip-till*—No-till, direct seed, and strip till systems manage the amount, orientation, and distribution of crop and other plant residues on the soil surface year-round, while growing crops in narrow slots, or tilled or residue-free strips in soil previously untilled by full-width inversion implements. The soil is left undisturbed from harvest to planting except for nutrient injection. Seeds are placed in a narrow seedbed or slot made by coulter(s), row cleaners, disk openers, in-row chisels, or rototillers where no more than one third of the row width is disturbed. Weeds are controlled primarily with herbicides. Row cultivation for emergency weed control should utilize undercutting implements that minimize residue burial.

- *Ridge-till*—Managing the amount, orientation, and distribution of crop and other plant residues on the soil surface year-round, while growing crops on pre-formed ridges alternated with furrows protected by crop residue. The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is done in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is done with herbicides or cultivation or both. Ridges are rebuilt during row cultivation.
- *Mulch-till*—Managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round, while growing crops where the entire field surface is tilled prior to planting. Tillage tools such as chisels, field cultivators, disks, sweeps, or blades are used. Weed control is done with herbicides or cultivation, or both.

(b) Crop residue management

Despite considerable acceptance of these definitions there is still some confusion as to the meaning of conservation tillage. Crop residue management is defined as: Any tillage and planting system that uses no-till, ridge-till, mulch-till, or other systems designed to retain all or a portion of the previous crop's residue on the soil surface. The amount required depends on other conservation practices applied to the field and the farmer's objectives.

Tillage systems, whether a conservation tillage system or some other system that retains little, if any, residue is an important part of a crop production system. Crop response to various tillage systems is variable and the variability if often difficult to explain because so many aspects of crop production are influenced by tillage. In addition, weather variability is an additional factor which influences crop production from one year to the next. Items to consider in designing a conservation tillage system include the following:

- *Soil temperature*—Crop residue insulates the soil surface from the sun's energy. This may be a plus at planting time or may delay planting and/or lead to poorer germination. If this is a concern, the use of planter attachments to remove residue from the row area will improve the situation. Later in the growing season crop residue on the soil surface may lower the soil temperature, resulting in increased crop growth and yield.
- *Allelopathy*—This refers to toxic effects on a crop because of decaying residue from the same crop or closely related crop. Crop rotation can eliminate this problem. The use of planter attachments to remove the residue from the row area may reduce the problem. Allelopathic effects can also be beneficial by reducing competition from some weeds.
- *Moisture*—When crop residue is on the soil surface, evaporation is reduced and water infiltration is increased. Although this may be a disadvantage at planting time in some areas, the extra soil moisture may increase yields if a dry period is encountered later in the growing season. No-till systems often have more water than conventional systems available for transpiration later in the growing season, resulting in increased yields.
- *Organic matter*—Soil organic matter tends to stabilize at a certain level for a specific tillage and cropping system. Each tillage pass aerates the soil, resulting in the oxidation of decaying residues and organic matter. Crop residue left on the soil surface in no-till or ridge-till systems decomposes slower, resulting in increased organic matter levels in the upper few inches.
- *Soil density*—All tillage systems have some effect on soil density. Systems that disturb the plow layer by inversion tillage or mixing and stirring temporarily decrease soil density. However, after the soil is loosened by tillage, the density gradually increases due to wetting and drying, wheel traffic, and secondary tillage operations. By harvest the soil density has returned to almost the same density as before tillage operations started. Cropping management systems that use several tillage operations can create a compacted layer at the bottom of the plow layer. If the compaction is excessive, then drainage is impeded, plant root growth is restricted, there is reduced soil aeration, herbicide injury may increase, and nutrient uptake may be restricted.

No-till systems have a higher soil density at planting time than other systems because the plow layer is not disturbed to form a seedbed. This higher density seldom has any effect on germination, emergence, and subsequent crop growth. Many times the crop will benefit from this because these soils retain more available moisture.

- *Stand establishment*—Regardless of tillage system uniform planting depth, good seed to soil contact, and proper seed coverage is needed to obtain a good stand. Coulter and/or row cleaners may be needed to ensure a good stand in a no-till system. In addition, extra weight and heavy-duty down-pressure springs may be needed for the planter or drill to penetrate undisturbed soil, especially under less than ideal moisture conditions.
- *Fertilizer placement*—Starter fertilizer (nitrogen and phosphorus) is generally recommended to help overcome the effects of lower soil temperatures at planting time. If fertility levels (P, K, and pH) are at maintenance levels before switching to a conservation tillage system, fertility should not be a problem. In a no-till system surface application of phosphorus and lime will result in stratification of these nutrients, but this has not shown to affect crop yield. It is generally recommended that nitrogen be knifed into the soil in a no-till system, or a nitrogen stabilizer be used. Surface-applied nitrogen may volatilize and be lost if a rain does not move the nitrogen into the soil profile shortly after application.
- *Weed control*—Controlling weeds is essential for profitable production systems. With less tillage, herbicides and crop rotations become more important in obtaining adequate weed control. Weed identification, herbicide selection, application rate, and timing are important. A burn-down may be needed in no-till and ridge-till systems. A change in weed species can be expected in no-till and ridge-till systems. Perennials may become more evident but usually can be controlled with good management. The combination of post-applied herbicides and bioengineered crops has made weed control much easier, even in a no-till system.
- *Insect management*—Regardless of tillage system, effective insect management guidelines, and tactics are available. Different tillage systems may affect potential insect pressure, but management addresses this.
- *Disease control*—Residue on the soil surface offers the potential for increased disease problems. However, there are numerous strategies to overcome this problem. Crop rotation or the selection of disease-resistant hybrids may nullify this potential problem.
- *Crop yields*—Weather has more affect on crop yields than does the tillage system used. Crop yields generally are better when a crop rotation is utilized, especially in no-till system.
- *Production costs*—All of the related costs associated with various tillage systems must be analyzed to evaluate the profitability.
- *Machinery and labor costs*—Total cost for machinery and labor per acre usually decrease as the amount of tillage is reduced. If the size of the power units can be decreased (no-till system) then the savings can be even more dramatic. No-till equipment (planters, drills, nutrient injection equipment) may be more expensive than that needed for conventional equipment; however, less equipment is required. No-till producers have been able to farm more acres than conventional tillage producers without additional labor because of the increased efficiency.

Subpart 503C Nutrient management

503.20 General

Nutrient management is defined as managing the rate, timing, form, and method of nutrient application to ensure adequate soil fertility for plant production and to minimize the potential for environmental degradation, particularly air, soil, and water quality impairment. Nutrient management is the implementation of management techniques that permit efficient crop production while protecting natural resource quality. Nutrients are considered any element or compound that are essential for plant growth, particularly the elements nitrogen (N), phosphorus (P), and potassium (K). Nutrient sources can be any material, such as fertilizers, animal manures, biosolids, and irrigation water that contain essential plant nutrients.

Natural Resources Conservation Service's role in nutrient management

United States Department of Agriculture (USDA) Natural Resources Conservation Service's (NRCS) role in nutrient management includes the following activities:

- evaluating environmental risk associated with nutrient recommendations for plant production
- developing appropriate mitigation alternatives to minimize environmental risks related to the management of nutrients
- assisting clients to develop and implement an integrated nutrient management component of their overall conservation plan

The NRCS does not develop individual field recommendations for application of nutrients, but relies on the State land-grant university to make nutrient recommendations for the rate of nutrients to be applied to individual fields. Neither does the NRCS dictate any material testing (soil, plant, manures, fertilizers, or water) procedures other than what is acceptable to the land-grant university.

Nutrient management plans

Nutrient management plans are documents of record of how nutrients will be managed for plant production. These plans are prepared in collaboration with the producer and/or landowner and are designed to help the producer with implementation and maintenance activities associated with the plan. Plans are developed in compliance with all applicable Federal, Tribal, State, and local regulations. Nutrient management plans may stand alone or be an element of a more comprehensive conservation plan such as a Comprehensive Nutrient Management Plan (CNMP). Nutrient management plans are developed in accordance with technical requirements of the NRCS Field Office Technical Guide (FOTG) and policy requirements of the General Manual, Title 190, Part 402, Nutrient Management; General Manual, Title 190, Part 405, Comprehensive Nutrient Management Plans; and guidance found in this document (NAM Subpart 503C). A nutrient management specialist is a person who provides technical assistance for nutrient management and has the appropriate certification.

Nutrient management plans will contain the following components:

- aerial site photograph(s) or site map(s), and a soil survey map of the site
- location of designated sensitive areas or resources and the associated nutrient management restriction
- current and/or planned plant production sequence or crop rotation
- results of soil, plant, water, manure and/or organic by-product sample analyses
- results of plant tissue analyses, when used for nutrient management
- realistic yield goals for the crops complete nutrient budget for N, P, and K for the crop rotation or sequence
- listing and quantification of all nutrient sources
- field specific nutrient application rates, timing, form, and method of application and incorporation
- guidance for implementation, operation, maintenance, and recordkeeping

A CNMP is a conservation plan that is unique to animal feeding operations. A CNMP is a grouping of conservation practices and management activities which, when combined into a resource management system, will help to ensure that both production and natural resource conservation goals are achieved. It incorporates practices to fully use animal manure and other organic by-products (any organic material applied to the land as a nutrient source) as a beneficial resource. A CNMP is designed to address identified site-specific natural resource concerns CNMPs shall be planned in accordance with the procedures identified in the USDA NRCS, General Manual, Title 190, Part 405 and technical criteria contained in the Field Office Technical Guide (FOTG) and State-developed guidance will also serve as essential references for development of a CNMP. CNMPs are developed by certified CNMP planners and specialists.

503.21 Nutrients in the agricultural production systems

Agricultural sources of water pollution

Despite the enormous progress that has been achieved in reducing water pollution, almost 40 percent of United States waters that have been assessed have not met water quality standards (Zygmunt, 2000). According to the State water quality agency data submitted to the United States Environmental Protection Agency (U.S. EPA), about 15,000 water bodies are impaired from siltation, nutrients, bacteria and other pathogens, oxygen-depleting constituents, trace elements, pesticides, and other organic chemicals. Many of these pollutants do not come from a single point such as a sewage outfall or an industrial discharge pipe and are thus termed nonpoint source pollution.

Nutrients, particularly N and P, are the major pollutants in lakes and estuaries and the second leading source of pollution in rivers (U.S. EPA 1998). Life within rivers, streams, lakes, and bays could not exist without nutrients; however, an excess of nutrients (eutrophication) may cause ecological problems and can harm aquatic life.

Effect of agricultural nonpoint source pollution on water quality

Excess nitrogen and phosphorous can cause excessive growth of algae, a type of phytoplankton, whose eventual death and decomposition reduces the dissolved oxygen (DO) concentration in the water. Low DO reduces respiration, growth, and reproduction of aquatic organisms and can result in the death of fish and other aquatic organisms.

Another adverse effect associated with excessive nutrient concentrations is the appearance of the toxic microorganism Pfiesteria in 1997, which caused both death of fish and adverse health effects in commercial and recreational fishermen. Foul tastes and odors often occur in drinking water populated by excessive algal blooms in surface water.

Excessive phytoplankton growth also reduces water clarity, which reduces light transmission available for the growth of submerged aquatic vegetation (SAV). Submerged aquatic vegetation serves as an important habitat for fish, crabs, and other species of economic and environmental importance.

Phosphorus is generally the limiting nutrient for phytoplankton growth in the saltwater during all seasons except summer. During the summer, however, nitrogen is the limiting nutrient. Since most phytoplankton growth occurs during the summer months, nitrogen control strategies become important.

Agricultural impacts, such as sedimentation, eutrophication, and general water quality degradation, due to presence of inorganic or organic constituents and pathogens in the water and sediments also occur. Phosphorus is usually the limiting nutrient freshwater bodies. Other agricultural impacts may include contamination of groundwater, which is a source of drinking water for many rural communities, resulting from migration of pesticides, nitrates, and pathogens.

Eutrophication standards vary among major types of water bodies such as rivers, lakes, reservoirs, estuaries, and coastal systems. For example, critical concentrations of dissolved P recommended or established for lakes (0.01–0.05 mg/L) and streams (0.10 mg/L) can differ by an order of magnitude (Sharpley et al. 1996). Critical concentrations have been suggested for total N (2.2 mg/L) and P (0.15 mg/L) in rivers, but these values are well above the average total dissolved nutrient concentrations expected for unpolluted major rivers (~0.375 mg N/L and ~0.025 mg P/L), respectively (Meybeck 1982). The nitrate nitrogen groundwater standard of 10 mg/L established to protect human health has been demonstrated to be too low; however, such a concentration may be too high as an ecological standard (L'Hirondel 2005).

Fate and transport of nutrients

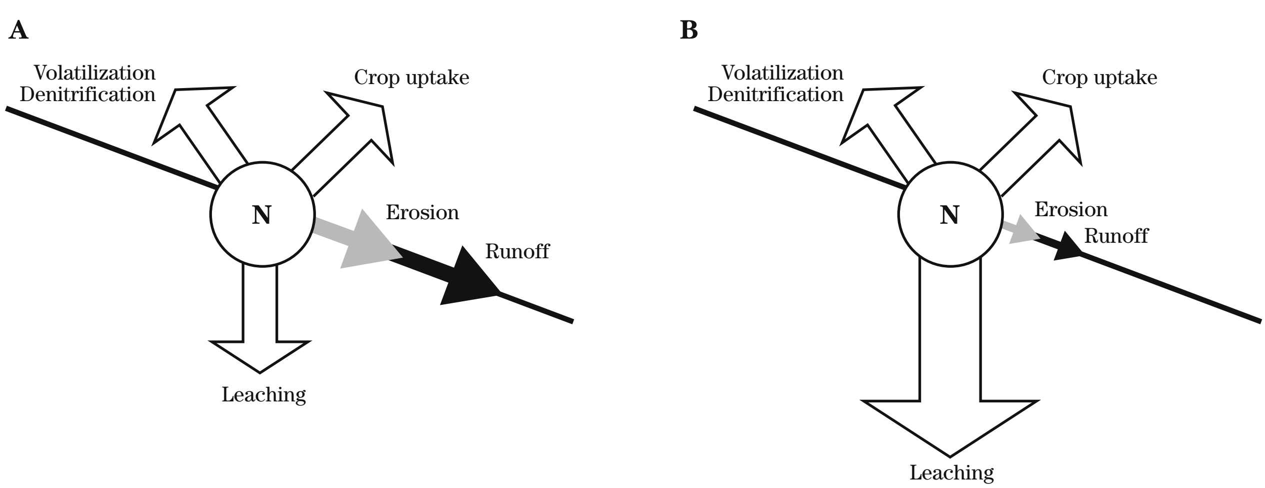
Nitrogen

Nitrogen, an essential element for plant growth and animal nutrition, is the nutrient taken up in the largest amount by crops. Nitrate (NO_3^-) is the major inorganic form of nitrogen in most soils. This anion is not attracted by the predominately negatively charged soil colloids and is, therefore, quite mobile and moves freely with soil water. Nitrogen application to soils beyond that required for plant uptake and maintenance of the soil microbial biomass will generally result in NO_3^- leaching and possible high NO_3^- levels in groundwater. Elevated concentrations of NO_3^- in drinking water may lead to methemoglobinemia in infants, the formation of carcinogenic nitrosamines in the human stomach, and hypertension. A national survey of drinking water wells (U.S. EPA 1990) found that NO_3^- was the most common contaminant, with 52 percent of the 94,600 community water systems tested containing detectable concentrations and 1.2 percent of those water sources exceeding the drinking water standard of 10 mg NO_3^-N per liter (10 ppm). Localized contamination has been measured beneath cropped, well-drained soils that received excessive applications of manure and commercial fertilizer (Spalding and Exner 1993).

While leaching losses are generally considered the major environmental threat from N, runoff losses are also possible. The potential of each system to contribute nitrogen to surface waters will depend upon its transport (i.e., erosion and runoff) capability and the surface soil nitrogen concentration (fig. 503–1). Nitrogen is lost to surface water as NO_3^- from recently applied inorganic fertilizers or in particulate organically-bound forms. Movement of excessive amounts of nitrogen to surface waters can result in a number of undesirable effects, such as eutrophication, associated algal blooms, and subsequent oxygen depletion.

Managing nitrogen to minimize NO_3^- losses is difficult because of the many possible loss pathways. For example, increased water infiltration may increase leaching of nitrate if practices to reduce runoff and erosion, such as no-till, are adopted (fig. 503–2). Similarly, incorporating manure to reduce nitrogen volatilization losses increases the risk of nitrogen loss through runoff, erosion, and leaching. Consequently, one of the primary emphases of nutrient management is minimizing the potential source of nitrogen in the system because any excess nitrogen will likely be lost to the environment in some manner.

Figure 503–1 General fate of N (A) and how adopting processes to reduce erosion and runoff increases nitrogen leaching losses (B)



Phosphorus

Phosphorus is another element required by plants and animals whose accumulation in water bodies may result in nutrient pollution. Increased public and regulatory concern over the use and application of phosphorous to agricultural lands is due to the eutrophication that can result from increased phosphorous loadings to surface waters (Daniel et al. 1998). Algal and aquatic weed growth in most inland surface water systems is P-limited, and elevated P levels result in algal blooms, oxygen depletion, and occasional problems with drinking water taste and odor.

Phosphorus is referred to as immobile in soil because it is strongly adsorbed by and/or precipitated as highly insoluble soil mineral phases. However, when a soil becomes saturated with P, desorption of soluble P can be accelerated, with a consequent increase in dissolved inorganic P in runoff. Thus, if the level of residual soil P is allowed to build up by repeated applications of P in excess of crop needs, a soil can become saturated with P and a potential for soluble P losses in surface runoff will increase significantly.

Much of the P that is applied to soils in fertilizer, manure, and biosolids is retained in the near-surface layer in various inorganic precipitates and in adsorbed forms that prevent it from leaching.

The risk of groundwater contamination by P in well-managed crop production systems is usually not high, although leaching can be a significant loss pathway for P in coarse-textured (sandy) soils with shallow water tables. Runoff and erosion losses to surface waters are the major water quality risks from P.

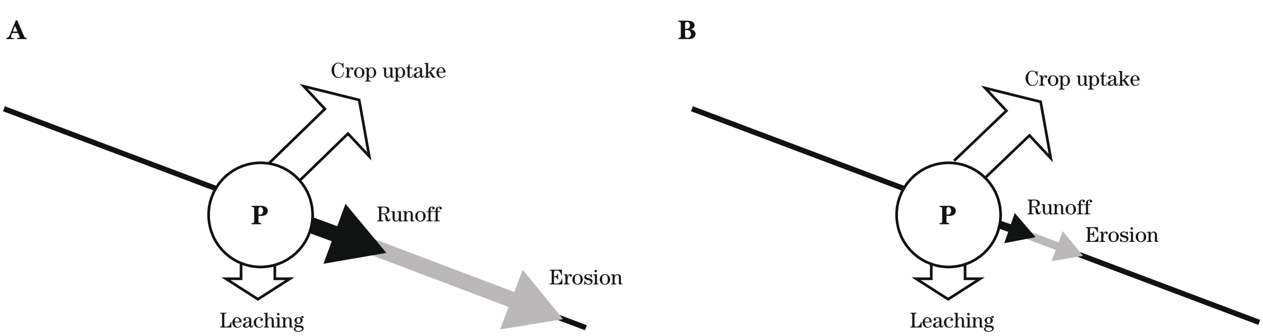
Because P is strongly adsorbed by soil solids, P runoff from permanently vegetated areas such as perennial sods or forests is minimal, and largely occurs as traces of orthophosphate (PO_4^{-3}) ions in solution. In areas where erosion risk increases, such as where annual crops are grown using conventional tillage, the total P loss increases greatly as the P is moved in solid particulate form with the eroding soil. Although water-soluble P is immediately available for biological uptake, sediment-bound or particulate P forms (bioavailable particulate P) are released over longer periods. The overall impact of a given production system on P runoff to local surface waters will, therefore, be primarily dependent upon relative rates of sediment loss and the P levels in these eroding soil surfaces.

Nutrient loss from organic wastes

Many crop production systems receive various organic wastes as fertilizer amendments. Organic amendments, such as manure, municipal wastewater sewage sludge (biosolids), municipal solid waste compost, and other miscellaneous agricultural, municipal, and industrial by-products, all have the potential to improve soil properties while increasing organic matter levels. Organic amendments are particularly effective at improving the productivity of marginal or degraded lands.

The major water quality concerns associated with the land application of organic by-products are the direct runoff or erosion of the organic material and any mobile constituents (such as N, P, or pathogens) into surface waters and the migration of NO_3 and pathogens to groundwater. Application rates for these materials are generally based on the estimated amount

Figure 503–2 General fate of P (A) and how adopting processes to reduce erosion and runoff increases nitrogen leaching losses (B)



of plant available nitrogen in the by-product, but P can be the limiting nutrient for application to soils whose P adsorption capacity is becoming saturated. Phosphorus runoff may occur in soils that have routinely received heavy annual applications of animal manure because the maximum P retention capability of such soils is being approached or exceeded.

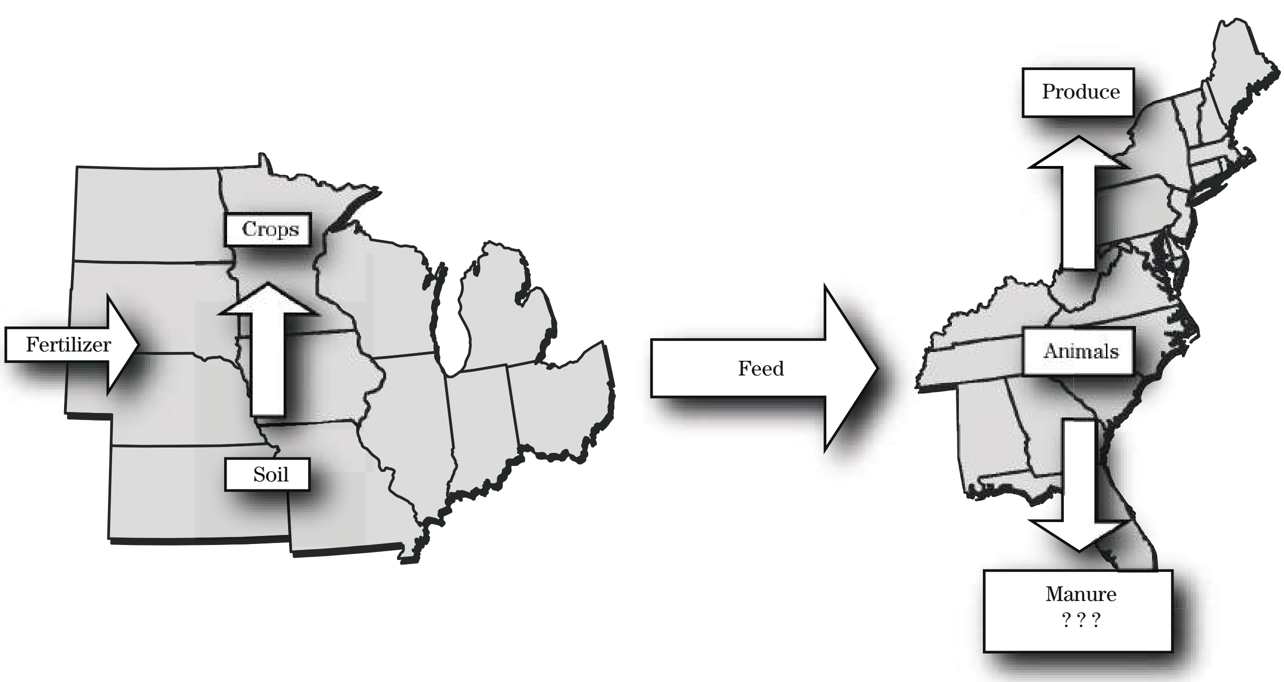
Nutrient cycles and management on different types of farms

Introduction: why nutrient losses are a problem
A common misconception is that farmers, in general, are mismanaging nutrients on their farms. While there is usually room for improved management, the nutrient pollution problems from agriculture primarily result from the way modern agriculture has evolved.

Prior to World War II, most farms included both animals and crops. Nutrient use on those farms was interdependent because manure nutrients were used to produce crops which were fed to animals that generated manure. Fertilizer nutrients became more economical after the war, which resulted in the separation of crop and animal agriculture. With the loss of the on-farm relationship between feed crops and animals came a significant increase in animal agriculture in some areas that was supported by concentrated crop agriculture in other areas, often far away. Currently, nutrients from imported feed often accumulate to very high levels on the farms where the animals are located because of manure applications on those farms (fig. 503–3).

While farmers collectively have been making sound economic management decisions, the unexpected consequence of these decisions has resulted in the increased potential for nutrient pollution in the areas where nutrients are accumulating. Significant long-term strategic changes in the structure of animal agriculture, rather than simple management changes, will be required to develop solutions to the problems inherent in this system. The following sections describe nutrient cycles and management on different farm types. Understanding these cycles can increase the adoption of strategies to enhance nutrient use efficiency and reduce potential environmental impacts.

Figure 503–3 Nutrient flows in modern animal agriculture



Cash crop farm

Nutrients come to a modern cash crop farm in fertilizers and other materials applied directly to the fields (fig. 503–4). Crops harvested from the fields remove a fraction of the applied nutrients, which leave the farm when the crops are sold. On a cash crop farm, there is a direct connection between the flow of nutrients and the agronomic or economic performance of the farm.

Traditional economic and agronomic incentives can be effective in guiding nutrient use on cash crop farms to optimize both crop production and environmental protection. Improper management can result in significant nutrient losses other than those removed in crops and negative economic consequences for the farmer. The cost of practices that reduce nutrient losses on a cash crop farm can at least be partially offset by decreased costs in purchased fertilizer. The nutrient balance on a well-managed farm is usually very close to zero (table 503–1).

Crop and livestock farm

On farms with livestock (e.g., a dairy), a large proportion of the plant nutrients from crops produced as feed for the animals are traditionally returned to the farm fields in manure (fig. 503–5). This pattern of nutrient use and cycling varies significantly from a modern cash crop farm. The plant nutrients in the feed inputs can offset the nutrients removed from the farm as sold animal products.

Off-farm feed inputs enable crop and livestock farms to have more animals on fewer acres. On modern crop-livestock farms, the manure produced by the animals is often not spread on the fields where the crops were produced. 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. Accounting for all sources of plant nutrients being applied to fields is an important management practice for protecting the environment from negative impacts caused by the over-application of nutrients to crop fields.

Neither crop production nor fertilizer use is directly connected to the output of such farms because farms with this structure primarily sell animal products. Farm performance depends more on the animal husbandry skills of the farmer than successful crop production. The economic viability of the farm is not as sensitive to the decisions about plant nutrient use in the fields as it is on the cash crop farm. The dairy farm given as an example in table 503–2 demonstrates the nutrient excess that can occur as imported feed becomes significant.

Intensive animal production 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 (fig. 503–6).

Although intensive poultry and swine farms may produce crops for off-farm sale, the land areas involved can be quite limited because management is focused

Figure 503–4 Nutrient cycles on cash crop farms

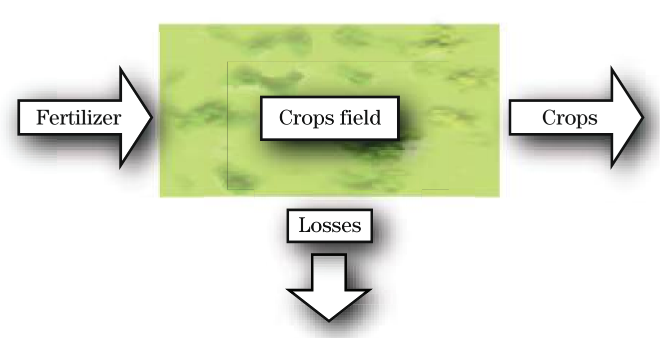


Table 503–1 Example of nutrient balance (P_2O_5) on a cash-crop farm in Pennsylvania

Input	P_2O_5/a/yr lb
Fertilizer	36
Output:	
Crop removal	32
Balance	+4

on animal production. The cash crop farm and the intensive livestock farm are connected by the flow of feed, but nutrients typically do not cycle back to their original locations. This will usually result in an excess of nutrients on the farm where the animals are located and a high potential for environmental problems there.

For example the poultry layer farm illustrated in table 503–3 has an excess of 2,350 pounds P pentoxide (P_2O_5) per acre per year. The field-based economic and agronomic incentives that can be effective in motivating farmers to manage nutrients on a cash crop farm (and that will also minimize potential environmental impacts) are not as critical on the intensive livestock production-oriented farm. It is unlikely that environmental quality can be protected on poultry and swine farms solely by recycling nutrients for crop production because of the small land area of the farm. Successful management of nutrients to protect the environment will depend on transportation of manure nutrients from the farm.

Note: Animal concentration areas: 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 out of buildings. The result is that the areas around farmyard facilities can become sources of nutrient losses from the farm. Animal concentration areas are such locations where the animals gather and deposit manure nutrients in quantities that exceed removal in growing vegetation. These areas often have little or no vegetation and may be located in environmentally sensitive areas, such as stream bottomland. These areas require special attention in nutrient management plans and usually require Best Management Practices (BMP) to protect water quality.

Figure 503–5 Nutrient cycles on a modern crop and livestock farm

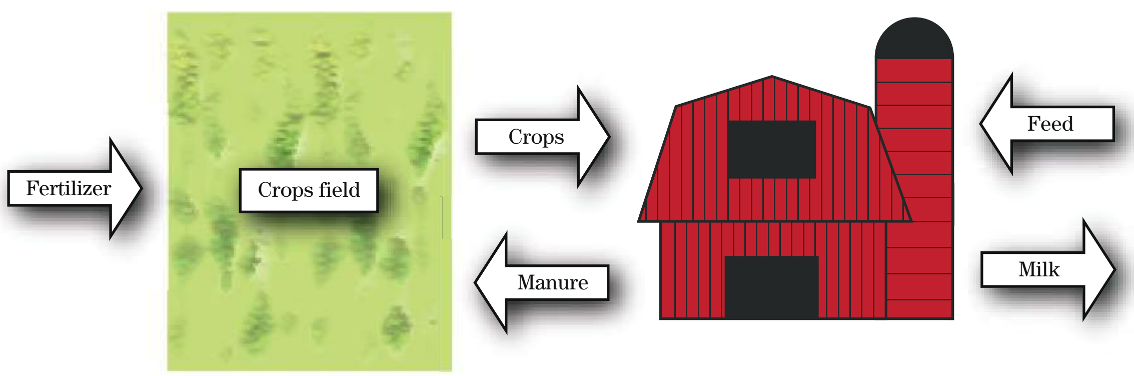


Table 503–2 Example of nutrient balance on a dairy farm in Pennsylvania

Inputs	lb P_2O_5/a/yr
Fertilizer	22
Feed	60
Output:	
Milk	24
Balance	+58

Table 503–3 Example of nutrient balance on a poultry layer farm in Pennsylvania

Inputs:	lb P_2O_5/a/yr
Fertilizer	0
Feed	3380
Output:	
Eggs	1030
Balance	+2350

Nutrient management planning

Purpose of nutrient management

Nutrient management is the implementation of practices that permit efficient crop production while protecting water quality from nutrient pollution. A nutrient management plan is a site-specific plan whose recommendations permit efficient nutrient use by crops and minimize nutrient losses to the environment (primarily water and air). Some amount of nutrient loss will occur even when the best nutrient management practices are employed, but these losses should be lower than would occur without nutrient management.

The nutrient management process

Nutrient management should be planned as a multistep, constantly evolving process. The key components of the process are: assessment, management option selection, planning, implementation, and recordkeeping (fig. 503–7).

Nutrient management assessment I: nutrient status and balance

A thorough assessment of the nutrient status of the farm and the potential for environmental impacts from nutrients should be conducted. Key criteria should include:

- farm management goals and constraints
- available farm resources (land, equipment, and financial resources) Karst lands (landscapes underlain by limestone bedrock or other highly soluble carbonate-bearing parent materials)
- potential critical problem areas on the farm (sensitive water bodies, neighbor concerns, existing problems such as barnyards, severe erosion, manure storage)
- nutrient balance

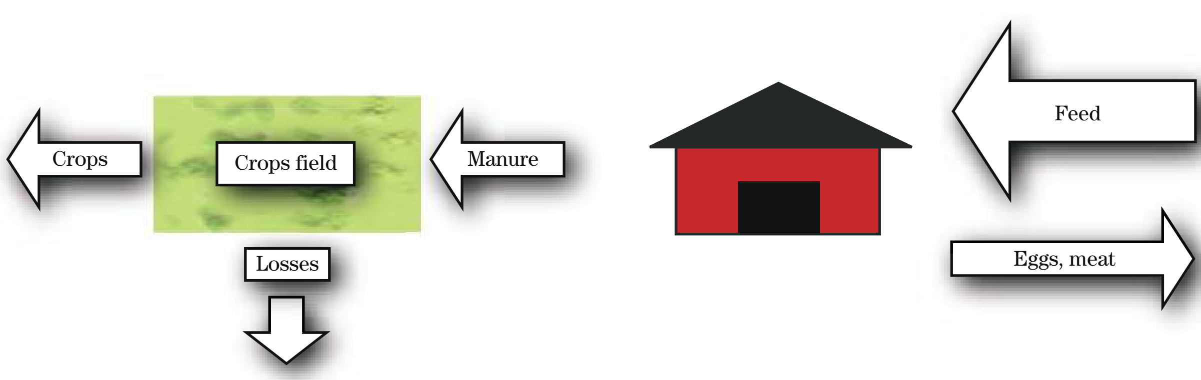
Nutrient balance can be estimated from easily determinable farm characteristics. Table 503–4 provides some simple criteria that can be used to assess farm nutrient balance. These are estimates only, and actual nutrient balance will vary depending on specific farm characteristics

Nutrient management assessment II: sites which may have accelerated nutrient loss

The potential for plant nutrients (particularly nitrogen and P) to migrate to surface water and groundwater is largely dependent upon soil and site conditions. Any combination of soil and site conditions that will lead to either rapid rainfall runoff 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 recognizing and delineating these sites for development of specific management practices to avoid the anticipated effects.

These soil/landscape features and properties are particularly vulnerable to the loss of nutrients from agricultural practices.

Figure 503–6 Intensive animal production farm with limited crop production



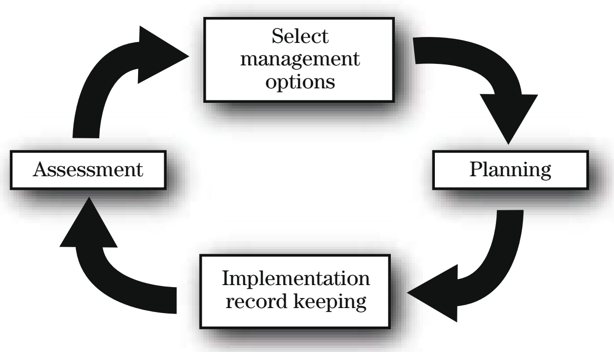
Soils with high leaching potentials

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 high risk for nutrient loss to groundwater and associated surface waters. If accurate soil survey information is available, the leaching index for a given soil can be obtained by following the procedures outlined in the USDA NRCS Field Office Technical Guide (available at http://www.nrcs.usda.gov/technical/efotg/).

Such soils should not receive nutrient applications during times of the year when nutrients are least likely to be assimilated by crops (i.e., late fall, winter). Nutrient management practices in fields containing significant areas of these soils should include such practices as split application of nitrogen on crops and the use of winter cover crops to scavenge residual soil N.

Figure 503–7 The nutrient management process



Sinkholes are formed by the long-term dissolution of carbonates underlying the surface, which eventually leaves a cavity that collapses over time.

Sinkholes may 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, in order to reduce runoff.

Shallow soils over fractured bedrock

Soils that are shallow (less than 41 in) to fractured bedrock are environmentally sensitive and should be managed like soils with a high leaching index. Although many of these soils do not have high leaching potential, once the soil water percolates to the fractured rock, the water and any dissolved nutrients can move rapidly to groundwater.

Table 503–4 On-farm criteria that can be used to estimate nitrogen [1/] balance

Criteria	Farm is deficient in N	Farm has balanced N	Farm has excess N
Feed source(percent off farm feed)	On farm (<50 percent)	Combination (50–80 percent)	Off-farm (>80 percent)
Animal density (AU/A) [2/]	Low (<1.25 AU/A)	Medium (1.25–2.25 AU/A)	High (>2.25 AU/A)
Pollution potential [3/]	Low	Medium	High

1 To estimate phosphorus balance, these numbers can be cut in half
2 AU = animal unit = 1000 lb live weight; A = acres available for manure application
3 Assuming good management

Lists of shallow soils in each State can be obtained from the NRCS and by reviewing county soil survey reports. Nutrient management practices in fields containing significant areas of these soils should include such practices as split application of nitrogen on crops and the use of winter cover crops to scavenge residual soil N.

Tile-drained lands
Artificially drained fields should be treated as environmentally sensitive because of 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. These soils should be treated like coarse-textured soils with high water tables. Nutrient management practices in fields containing significant areas of tile-drained soils should include split application of nitrogen on crops and the use of winter cover crops to scavenge residual soil N.

Irrigated lands
Fields receiving irrigation, because of the increased water input, 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.

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 percent are prone to runoff losses of surface-applied N and P. Significant amounts of sediment can be lost if a heavy rainfall event occurs following tillage to move these surface-applied nutrients below the flow of runoff. Applications of manure or biosolids may be limited to P soil test needs or crop uptake estimates, unless injection is used, if these organic byproducts are applied to such slopes. Soil conservation measures should be practiced on highly erodible lands.

Flood plains and other lands near surface waters
Runoff and leaching from agricultural lands that are close to surface waters can have a direct impact on surface water quality. If channelized flow develops, surface flow of runoff water from these areas has little chance to be filtered before discharge into adjacent waters. Subsurface flow in groundwater can also directly seep into the adjacent surface water body. If water containing NO_3^- flows into a wetland, however, significant amounts of nitrogen can be denitrified and lost to the atmosphere, with a subsequent reduction in the nitrogen levels that reach the adjacent surface waters.

Using manure or biosolids on flood plains is not a recommended practice. If manure or biosolids must be applied to a flood plain, incorporation or injection application methods should be used to minimize losses if flooding occurs.

The list of environmentally sensitive sites given is not all-inclusive but does include some of the more common agricultural landscape types. 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.

Selecting management options
After the nutrient management assessment of the farm, appropriate management options can then be selected for inclusion in the nutrient management plan. Each farm will have unique qualities, resources, and problems that must be addressed in the nutrient management plan.

Management options that maximize nutrient use efficiency by the crops and reduce the need to purchase nutrients would be emphasized on a farm that is nutrient deficient. On a farm with excess nutrients, practices that maximize safe use and off-farm distribution of nutrients would be emphasized. For example, spreading manure onto alfalfa would not be a recommended practice on a farm with a deficit of nitrogen because this would be an inefficient use of the manure nitrogen; however, spreading manure on alfalfa may be recommended to safely use the manure on a farm with excess nitrogen.

Table 503–5 summarizes important considerations in selecting appropriate management options depending on the assessment outcome. The economics of improved nutrient management are not always positive. In fact, on farms that have excessive nutrients, improving the nutrient management usually results in a negative economic return. This is a common misunderstanding by people who think that improved nutrient management will always give a positive economic return. Farmers would likely have already adopted the practices if the economics were positive.

Nutrient management planning involves integrating the management options based on the assessment into a comprehensive tactical and operational plan. The nutrient management planning process (table 503–6) is dependent upon the synthesis of information and data on the soils, cropping systems, nutrient amendments, management practices, and climate; therefore, care should be taken to ensure that the information used to develop the nutrient management plan is current and accurate.

Nutrient management plans must be tailored to specific soils and crop production systems. While each State in our region may have differing approaches to this process, the steps in table 503–6 will generally be essential.

Implementation

The nutrient management plan will not protect the environment unless it is implemented. Thus, it is essential to work with the farmer to assure that the plan is practical.

Keeping records

Keeping records is often required by law, but recordkeeping is a critical process regardless of any legal requirement. The record provides accountability to the public and is the foundation for an assessment that will start the next nutrient management planning cycle. In the end, nutrient management planning should be a continuous process of assessing the implementation successes and failures, selecting new management options as appropriate, revising the plan, and implementing this revised plan. With time, the implementation should more closely match the plan.

Recordkeeping should be part of the plan to facilitate the process. For example, it is easy for the farmer to acknowledge that a component of the plan was completed as planned, or to note that something was done differently, if space for records is included in the operational summary of the plan that the farmer will follow.

Table 503–7 is an excerpt from a nutrient management plan manure application summary which includes the records of what was done. In this example, manure to be applied for corn should be incorporated within 4 to 7 days after application, but the record shows that it was not incorporated. If this continues to be a common occurrence, incorporation may be omitted in future plans.

Table 503–5 Selecting management options depending on nutrient balance from the nutrient balance assessment

Option	Nutrient balance assessment deficient in nutrients	Balanced nutrients	Excess nutrients
Management emphasis	Maximize nutrient use efficiency utilization	Maximize safe nutrient utilization and move excess nutrients off farm	
Land available for spreading	Adequate	Adequate but limited	Inadequate for manure
Economics	Positive	Neutral	Negative

Table 503–6 Nutrient planning steps

Step 1 Obtain accurate soil information for each field or management unit by analyzing representative soil samples from each management unit. This may require a new farm soil map or a revision of existing USDA NRCS mapping coverage.

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

Step 3 Identify the total plant nutrient needs to achieve the expected yield potential. Usually this is based on the soil test recommendation.

Step 4 Estimate the nutrient contribution that can be expected from residual effects or carryover from previous fertilizer, manure, or biosolids applications. Include credit for nitrogen supplied to a row crop following a previous legume.

Step 5 Determine if any nutrients will be applied regardless of the manure application. Examples here might be starter fertilizers or fertilizers used as pesticide carriers.

Step 6 Calculate the rate of manure, composts or biosolids that would match or balance the net crop nutrient requirements.

Net Nutrient Requirement =
Total nutrient needs – residuals from manure and legumes – irrigation water credits – fertilizer to be applied regardless of manure

Usually this rate is calculated based on the net nitrogen or phosphorus requirement. If the rate is based on nitrogen, the availability of the manure nitrogen to crops must be considered in the calculation. The potential environmental risk from phosphorus applied at the nitrogen-based rate should be evaluated with the use of a tool such as the Phosphorus Index if the rate is based on nitrogen. The calculated rate is often adjusted to make it more practical for the farmer. The practical rate should not exceed the calculated balanced rate.

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

Step 8 Recommend appropriate management practices (e.g., tillage, irrigation, cropping system, buffer zones) to enhance the protection of surface water and groundwater.

Step 9 Identify and plan treatment for sensitive areas whose characteristics may increase the risk of nutrient loss.

Table 503–7 Nutrient management plan manure application

Field	Acre	Crop	Fertilizer	Actual	Type	Rate	Time	Method	Actual
1	10	Corn	10–20–10 Starter	Done 4/29	Dairy	5000 gal/a	Spring	Surface incorporate within 4–7 days	Done 4/10 Not incorporated
2	10	Hay	0–50–150	Applied 150 lb 0–0–60/a plus manure				Applied 3000 gal. dairy manure after first cutting 6/7	
3	10	Corn Starter	10–20–10	Done 5/2	Dairy 5000 gal/a		Spring	Surface incorporate within 4–7 days	Done 4/17 Not incorporated

503.22 Basic soil fertility

Plant nutrition

What is an essential element? An essential mineral element is one that is required for normal plant growth and reproduction. With the exception of carbon (C) and oxygen (O), which are supplied from the atmosphere, the essential elements are obtained from the soil. The amount of each element required by the plant varies; however, all essential elements are equally important in terms of plant physiological processes and plant growth.

The exact number of elements that should be considered essential to plant growth is a matter of some debate. For example, cobalt, which is required for nitrogen fixation in legumes, is not considered to be an essential element by some researchers. Table 503–8 lists 18 elements that are considered essential by many scientists. Other elements that are sometimes listed as essential are sodium (Na), silicon (Si), and vanadium (V).

Table 503–8 Eighteen essential elements for plant growth, and the chemical forms most commonly taken up by plants

Element	Symbol	Form Absorbed by Plants
Carbon	C	CO_2
Hydrogen	H	H^+, OH^-, H_2O
Oxygen	O	O_2
Nitrogen	N	NH_4^+, NO_3^-
Phosphorus	P	HPO_4^{2-}, $H_2PO_4^-$
Potassium	K	K^+
Calcium	Ca	Ca^{2+}
Magnesium	Mg	Mg^{2+}
Sulfur	S	SO_4^{2-}
Iron	Fe	Fe_2^+, Fe_3^+
Manganese	Mn	Mn^{2+}, Mn^{4+}
Boron	B	H_3BO_3, BO_3^-, $B_4O_7^{2-}$
Zinc	Zn	Zn^{2+}
Copper	Cu	Cu^{2+}
Molybdenum	Mo	MoO_4^{2-}
Chlorine	Cl	Cl–
Cobalt	Co	Co^{2+}
Nickel	Ni	Ni^{2+}

Categories of essential elements

Essential elements can be grouped into four categories based on their origin or the relative amount a plant needs in order to develop properly (table 503–9). See table 503–10 for functions of essential elements.

Non-mineral essential elements are derived from the air and water. Primary essential elements are most often applied in commercial fertilizers or in manures. Secondary elements are normally applied as soil amendments or are components of fertilizers that carry primary nutrients. Non-mineral, primary and secondary elements are also referred to as macronutrients since they are required in relatively large amounts by plants.

Micronutrients are required in very small, or trace, amounts by plants. Although micronutrients are required by plants in very small quantities, they are equally essential to plant growth.

Nutrient deficiency symptoms

Caution regarding visual diagnosis

Visual diagnosis of plant deficiencies can be very risky. There may be more than one deficiency symptom expressed, which can make diagnosis difficult. Both soil and tissue samples should be collected, analyzed, and interpreted before any recommendations are made concerning application of fertilizer (tables 503–11 and 503–12).

Nutrient uptake by crops refer to your State supplements, including 590 specifications, Manure Management Planner, or approved nutrient management software.

Element uptake is the amount of nine different elements taken up by selected crops is shown in tables 503–13 through 503–15.

Table 503–9 Essential elements, their relative uptake, and sources where they are obtained by plants

	Macronutrients		Micronutrients
Non-Mineral	Primary	Secondary	
Mostly from air and water	Mostly from soils	Mostly from soils	Mostly from soils
Carbon	Nitrogen	Calcium	Iron
Hydrogen	Phosphorus	Magnesium	Manganese
Oxygen	Potassium	Sulfur	Boron
			Zinc
			Copper
			Molybdenum
			Chlorine
			Cobalt
			Nickel

Table 503–10 Functions of essential elements in plants

Essential element	Function in plant
Carbon, hydrogen, and oxygen	• Directly involved in photosynthesis, which accounts for most of plant growth: $6CO_2 + 12\,H_2O \longrightarrow 6O_2 + 6\,(CH_2O) + 6\,H_2O$
Nitrogen	• Found in chlorophyll, nucleic acids, and amino acids • Component of protein and enzymes, which control almost all biological processes
Phosphorus	• Typically concentrated in the seeds of many plants as phytin • Important for plant development including: — development of a healthy root system — normal seed development — uniform crop maturation — photosynthesis, respiration, cell division, and other processes • Essential component of Adenosine Triphosphate (ATP), which is directly responsible for energy transfer reactions in the plant Essential component of DNA and RNA, and phospholipids, which play critical roles in cell membranes
Potassium	• Found in ionic form in the cell, rather than incorporated in structure of organic compounds • Responsible for: — regulation of water usage in plants — disease resistance — stem strength • Involved in: — photosynthesis — drought tolerance — improved winter-hardiness — protein synthesis • Linked to improvement of overall crop quality, including handling and storage quality

Table 503–10 Functions of essential elements in plants—continued

Essential element	Function in plant
Calcium	• Essential for cell elongation and division • Specifically required for: — root and leaf development — function and cell membranes — formation of cell wall compounds • Involved in the activation of several plant enzymes
Magnesium	• Primary component of chlorophyll and is therefore actively involved in photosynthesis • Structural component of ribosomes, which are required for protein synthesis • Involved in phosphate metabolism, respiration, and the activation of several enzyme systems
Sulfur	• Required for the synthesis of the sulfur-containing amino acids cystine, cysteine, and methionine, which are essential for protein formation • Involved with: — development of enzymes and vitamins — promotion of nodulation for nitrogen fixation by legumes — seed production chlorophyll formation — formation of several organic compounds that give characteristic odors to garlic, mustard, and onion
Boron	• Essential for: — germination of pollen grains and growth of pollen tubes — seed and cell wall formation — development and growth of new cells in meristematic tissue • Forms sugar/borate complexes associated with the translocation of sugars, starches, N, and P • Important in protein synthesis
Copper	• Necessary for chlorophyll formation • Catalyzes several enzymes
Iron	• Serves as a catalyst in chlorophyll synthesis — development of enzymes and vitamins — promotion of nodulation for nitrogen fixation by legumes — seed production chlorophyll formation — formation of several organic compounds that give characteristic odors to garlic, mustard, and onion
Boron	• Essential for: — germination of pollen grains and growth of pollen tubes — seed and cell wall formation — development and growth of new cells in meristematic tissue • Forms sugar/borate complexes associated with the translocation of sugars, starches, N, and P • Important in protein synthesis
Copper	• Necessary for chlorophyll formation • Catalyzes several enzymes
Iron	• Serves as a catalyst in chlorophyll synthesis • Involved in many oxidation-reduction reactions during respiration and photosynthesis
Manganese	• Functions primarily as a part of the enzyme systems in plants • Serves as a catalyst in chlorophyll synthesis along with iron • Activates several important metabolic reactions (enzymes) • Plays a direct role in photosynthesis
Zinc	• Aids in the synthesis of plant growth compounds and enzyme systems • Essential for promoting certain metabolic/enzymatic reactions • Necessary for the production of chlorophyll, carbohydrates, and growth hormones
Molybdenum	• Required for the synthesis and activity of nitrate reductase; the enzyme system that reduces NO_3^- to NH_4^+ in the plant • Essential in the process of symbiotic nitrogen fixation by Rhizobia bacteria in legume root nodules
Chlorine	• Involved in: — energy reactions in the plant — breakdown of water — regulation of stomata guard cells — maintenance of turgor and rate of water loss — plant response to moisture stress and resistance to some diseases • Activates several enzyme systems • Serves as a counter ion in the transport of several cations in the plant
Cobalt	• Essential in the process of symbiotic nitrogen fixation by Rhizobia bacteria in legume root nodules • Has not been proven to be essential for the growth of all higher plants
Nickel	• Component of the urease enzyme • Essential for plants supplied with urea and for those in which ureides are important in nitrogen metabolism

Table 503–11 Terminology used to describe deficiency symptoms

Term	Definition
Chlorosis	Yellowing or lighter shade of green
Necrosis	Browning or dying of plant tissue
Interveinal	Between the leaf veins
Meristem	The growing point of a plant
Internode	Distance of the stem between the leaves
Mobile	A mobile element is one that is able to translocate, or move, from one part of the plant to another depending on its need. Mobile elements generally move from older (lower) plant parts to the plant's site of most active growth (meristem)

Table 503–12 Mobility and specific deficiency symptoms

Essential element	Mobility	Deficiency symptoms and occurrence
Nitrogen	Mobile within plants: lower leaves	• Stunted, slow growing, chlorotic plants show chlorosis first • Reduced yield • Plants more susceptible to weather stress and disease • Some crops may mature earlier
Phosphorus	Mobile within plants: lower leaves	• Over-all stunted plant and a poorly developed root system show deficiency first • Can cause purple or reddish color associated with the accumulation of sugars • Difficult to detect in field
Potassium	Mobile within plants: lower leaves	• Commonly causes scorching or firing along leaf margins show deficiency first • Deficient plants grow slowly, have poorly-developed root systems, weak stalks; lodging is common • Seed and fruit are small and shriveled • Plants possess low resistance to disease • Deficiencies most common on acid sandy soils and soils that have received large applications of Ca and/or Mg
Calcium	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first	• Poor root growth: Ca deficient roots often turn black and rot • Failure of terminal buds of shoots and apical tips of roots to develop, causing plant growth to cease • Most often occurs on very acid soils where Ca levels are low • Other deficiency effects such as high acidity usually limit growth before Ca deficiency apparent
Magnesium	Mobile within plants: lower leaves	• Leaves show a yellowish, bronze or reddish color while leaf show deficiency first veins remain green
Sulfur	Somewhat mobile within plants but upper leaves tend to show deficiency first	• Chlorosis of the longer leaves • If deficiency is severe, entire plant can be chlorotic and stunted • Symptoms resemble those of nitrogen deficiency; can lead to incorrect diagnoses

Soil properties that influence nutrient availability

Influence of cation exchange capacity and base saturation on fertilizer management

A soil's cation exchange capacity (CEC) should be considered when determining the appropriate rates and timing of nutrient applications in a fertilizer program. In general, smaller amounts of fertilizer, applied more often, are needed in low CEC soils to prevent leaching losses, while larger amounts may be applied less frequently in high CEC soils. For example, it may not be wise to apply K on very sandy soils with low CEC in the fall to serve the next spring's crops, especially in areas where fall and winter rainfall is high. In comparison, on clayey soils with high CEC, adequate K can be applied in the fall for one or more future crops.

In the past, the concept of base saturation was used to develop fertilizer programs. This school of thought held that certain nutrient ratios, or balances, are needed for optimum crop nutrition. Most crops grow best at a base saturation of 80 percent or more; however, research has shown that saturation ranges for specific cations (K^+, Mg^{2+}, and Ca^{2+}) have little or no utility in the majority of agricultural soils. Under field conditions, relative amounts 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.

Ion mobility in soils

Anions (negatively charged ions) usually leach more readily than cations because they are not attracted to the predominantly negative charge of soil colloids. For example, NO_3^-, due to its negative charge and relatively large ionic radius, is not readily retained in the soil and is easily lost from soils by leaching.

An exception to this behavior is P anions (HPO_4^{2-}, $H_2PO_4^-$). These anionic forms do not easily leach through the soil profile because of their specific complexing reactions with soil components. Surface applications of inorganic and organic sources of P without incorporation will result in the accumulation of P near the soil surface. Estimates of vertical P movement in most agricultural soils are on the order of 0.5 to 1 inch per year with an average rainfall of 36 inches, with greater movement in coarse-textured than fine-textured soils. Since P can accumulate near the soil surface, losses of P from agricultural systems are associated with a combination of residual soil P levels and soil erosion.

Effect of pH on nutrient availability

Many soil elements change form as a result of chemical reactions in the soil. Plants may or may not be able to use elements in some of these forms. Because pH influences the soil concentration and, thus, the availability of plant nutrients, it is responsible for the solubility of many nutrient elements. Figure 503–8 illustrates the relationship between soil pH and the relative plant availability of nutrients.

- *K, Ca, and Mg*—These nutrients are most available in soils with pH levels greater than 6.0. They are generally not as available for plant uptake in acid soils since they may have been partially leached out of the soil profile.
- *P*—Phosphorus solubility and plant availability are controlled by complex soil chemical reactions, which are often pH-dependent. Plant availability of P is generally greatest in the pH

Figure 503–8 Relationship between soil pH and nutrient availability

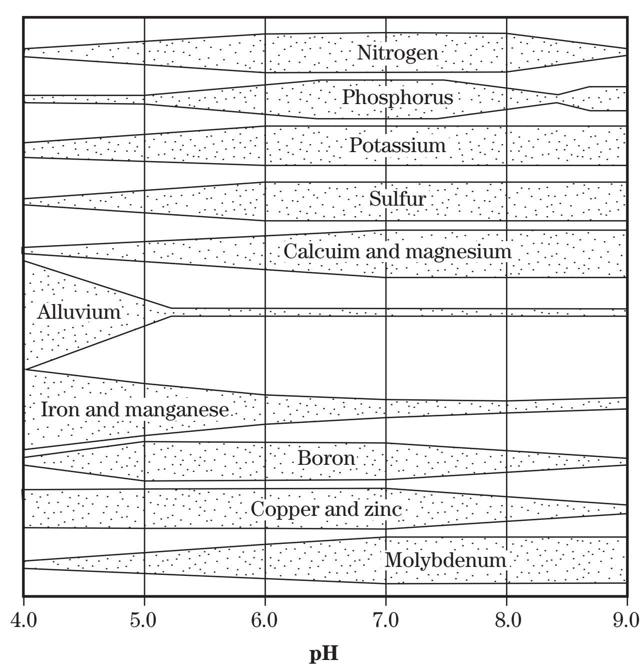


Table 503–12 Mobility and specific deficiency symptoms—continued

Essential element	Mobility	Deficiency symptoms and occurrence
Boron	Not mobile within plants: upper leaves and the growing point show symptoms first	• Reduced leaf size and deformation of new leaves • Interveinal chlorosis if deficiency is severe deficiency • May cause distorted branches and stems • Related to flower and or fruit abortion, poor grain fill, and stunted growth • May occur on very acid, sandy-textured soils or alkaline soils.
Copper	Not mobile within plants: upper	• Reduced leaf size leaves and the growing point show • Uniformly pale yellow leaves deficiency symptoms first • Leaves may lack turgor and may develop a bluish-green cast, become chlorotic and curl • Flower production fails to take place • Organic soils are most likely to be Cu deficient
Iron	Not mobile within plants: upper leaves show deficiency symptoms first	• Interveinal chlorosis that progresses over the entire leaf • With severe deficiencies, leaves turn entirely white • Factors contributing to Fe deficiency include imbalance with other metals, excessive soil phosphorus levels, high soil pH, wet, and cold soils
Manganese	Not mobile within plants: upper leaves show deficiency symptoms first	• Interveinal chlorosis • Appearance of brownish-black specks • Occurs most often on high organic matter soils and soils with neutral to alkaline pH with low native Mn content
Zinc	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first	• Shortened internodes between new leaves • Death of meristematic tissue • Deformed new leaves • Interveinal chlorosis • Occurs most often on alkaline (high pH) soils or soils with high available phosphorus levels
Molybdenum	Not mobile within plants: upper leaves show deficiency symptoms first	• Interveinal chlorosis • Wilting • Marginal necrosis of upper leaves • Occurs principally on very acid soils, since Mo becomes less available with low pH
Chlorine	Mobile within plant, but deficiency usually appear on the upper leaves first	• Chlorosis in upper leaves symptoms • Overall wilting of the plants • Deficiencies may occur in well drained soils under high rainfall conditions
Cobalt	Used by symbiotic N-fixing bacteria in root nodules of legumes and other plants	• Causes nitrogen deficiency: chlorotic leaves and stunted plants • Occurs in areas with soils deficient in native Colorado
Nickel	Mobile within plants	• Symptoms and occurrence are not well documented but may include chlorosis and necrosis in young leaves and failure to produce viable seeds

Note: Information given above on nutrient mobility and deficiency symptoms is condensed. For more information, or for information on deficiency symptoms for a specific crop, see Bennett 1993; Horst 1995; Jones 1998; PPI 2003; or your State's Cooperative Extension Service publications.

Table 503–13 Nutrient removal by selected hay crops

Crop	Yield (tons)	N	P	K	Ca	Mg	S	Cu	Mn	Zn
					---------------------pounds per acre ---------------------					
Alfalfa	6	350	40	300	160	40	44	0.10	0.64	0.62
Bluegrass	2	60	12	55	16	7	5	0.02	0.30	0.08
Coastal Bermuda-grass	8	400	45	310	48	32	32	0.02	0.64	0.48
Fescue	3.5	135	18	160	—	13	20	—	—	—
Orchard Grass	6	300	50	320	—	25	35	—	—	—
Red Clover	2.5	100	13	90	69	17	7	0.04	0.54	0.36
Soybean	2	90	12	40	40	18	10	0.04	0.46	0.15
Timothy	4	150	24	190	18	6	5	0.03	0.31	0.20

Table 503–14 Nutrient removal by selected field crops

Crop	Yield	N	P	K	Ca	Mg	S	Cu	Mn	Zn
					---------------------pounds per acre ---------------------					
Barley (grain)	60 bu	65	14	24	2	6	8	0.04	0.03	0.08
Barley (straw)	2 tons	30	10	80	8	2	4	0.01	0.32	0.05
Corn (grain)	200 bu	150	40	40	6	18	15	0.08	0.10	0.18
Corn (stover)	6 tons	110	12	160	16	36	16	0.05	1.50	0.30
Cotton(seed+lint)	1.3 tons	63	25	31	4	7	5	0.18	0.33	0.96
Cotton (stalk+leaf)	1.5 tons	57	16	72	56	16	15	0.05	0.06	0.75
Oats (grain)	80 bu	60	10	15	2	4	6	0.03	0.12	0.05
Oats (straw)	2 tons	35	8	90	8	12	9	0.03	—	0.29
Peanuts (nuts)	2 tons	140	22	35	6	5	10	0.04	0.30	0.25
Peanuts (vines)	2.5 tons	100	17	150	88	20	11	0.12	0.15	—
Rye (grain)	30 bu	35	10	10	2	3	7	0.02	0.22	0.03
Rye (straw)	1.5 tons	15	8	25	8	2	3	0.01	0.14	0.07
Soybean (grain)	50 bu	188	41	74	19	10	23	0.05	0.06	0.05
Soybean (stover)	3 tons	89	16	74	30	9	12	—	—	—
Wheat (grain)	60 bu	70	20	25	2	10	4	0.04	0.10	0.16
Wheat (straw)	2.5 tons	45	5	65	8	12	15	0.01	0.16	0.05
Tobacco (burley)	2 tons	145	14	150	—	18	24	—	—	—

range of 5.5 to 6.8. When soil pH falls below 5.8, P reacts with Fe and Al to produce insoluble Fe and Al phosphates that are not readily available for plant uptake. At high pH values, P reacts with Ca to form Ca phosphates that are relatively insoluble and have low availability to plants.

- *Micronutrients*—In general, most micronutrients are more available in acid than alkaline soils. As pH increases, micronutrient availability decreases, and the potential for deficiencies increase. An exception to this trend is Mo, which becomes less available as soil pH decreases. In addition, B becomes less available when the pH is <5.0 and again when the pH exceeds 7.0.
- *Al, Fe, and Mn toxicity*—At pH values less than 5.0, Al, Fe, and Mn may be soluble in sufficient quantities to be toxic to the growth of some plants. Aluminum toxicity limits plant growth in most strongly acid soils. Aluminum begins to solubilize from silicate clays and Al hydroxides below a pH of approximately 5.3, which increases the activity of exchangeable Al^{3+}. High concentrations of exchangeable Al are toxic and detrimental to plant root development.
- *Soil organisms*—Soil organisms grow best in near-neutral soil. In general, acid soil inhibits the growth of most organisms, including many bacteria and earthworms. Thus, acid soil slows many important activities carried on by soil microbes, including nitrogen fixation, nitrification, and organic matter decay. Rhizobia bacteria, for instance, thrive at near-neutral pH and are sensitive to solubulized Al.

Acid soils and liming

Acidification is a natural process that occurs continuously in soils. It is caused by the following factors:

- The breakdown of organic matter can cause acidification of the soil as amino acids are converted into acetic acid, hydrogen gas, dinitrogen gas, and carbon dioxide by the reaction:

  $$2C_3H_7NO_3 + O_2 \rightarrow 2HC_2H_3O_2 + 3H_2 + N_2 + 2CO_2$$

  The movement of acidic water from rainfall through soils slowly leaches basic essential elements such as Ca, Mg, and K below the plant root zone and increases the concentration of exchangeable soil Al. Soluble Al^{3+} reacts with water to form this equation, which makes the soil acid.
- Soil erosion removes exchangeable cations adsorbed to clay particles.
- Hydrogen is released into the soil by plant root systems as a result of respiration and ion uptake processes during plant growth.

Table 503–15 Nutrient removal by selected fruit and vegetable crops

Crop	Yield	N	P	K	Ca	Mg	S	Cu	Mn	Zn
				---------------------pounds per acre ---------------------						
Apples	500 bu	30	10	45	8	5	10	0.03	0.03	0.03
Cabbage	20 tons	130	35	130	20	8	44	0.04	0.10	0.08
Peaches	600 bu	35	20	65	4	8	2	-¬	-¬	0.01
Potato (sweet)	300 bu	40	18	96	4	4	6	0.02	0.06	0.03
Potato (white)	15 tons	90	48	158	5	7	7	0.06	0.14	0.08
Snap Bean	4 tons	138	33	163	—	17	—	—	—	—
Spinach	5 tons	50	15	30	12	5	4	0.02	0.10	0.10
Tomatoes (fruit)	20 tons	120	40	160	7	11	14	0.07	0.13	0.16

- Nitrogen fertilization speeds up the rate at which acidity develops, primarily through the acidity generated by nitrification:

$$2NH_4^+ + 4O_2 \rightarrow 2H_2O + 4H^+ + 2NO_3$$

- The harvesting of crops removes basic cations.

Effect of pH/liming on crop yields
Liming is a critical management practice for maintaining soil pH at optimal levels for growth of plants. Over-liming can induce micronutrient deficiencies by increasing pH above the optimum range.

Most crops grow well in the pH range 5.8 to 6.5. Legumes generally grow better in soils limed to pH values of 6.2 to 6.8. Plants such as blueberries, mountain laurel, and rhododendron grow best in strongly acid (pH < 5.2) soils. Most crops will grow well on organic soils (>20 percent organic matter), even if the pH is in the range of 5.0 to 5.5, because much of the acidity such soils is derived from non-toxic organic matter functional groups rather than toxic Al.

Benefits of liming

- Liming reduces the solubility and potential toxicity of Al and Mn.
- Liming supplies the essential elements Ca and/or Mg. Both are generally low in very acid soils.
- Liming increases the availability of several essential nutrients.
- Liming stimulates microbial activity (i.e., nitrification) in the soil.
- Liming improves symbiotic nitrogen fixation by legumes.
- Liming improves the physical conditions of the soil.

Maintaining a proper soil pH helps to improve the efficiency of some herbicides.

Determining lime requirements
Soil pH is an excellent indicator of soil acidity; however, it does not indicate how much total acidity is present, and cannot be used to determine a soil's lime requirement when used alone.

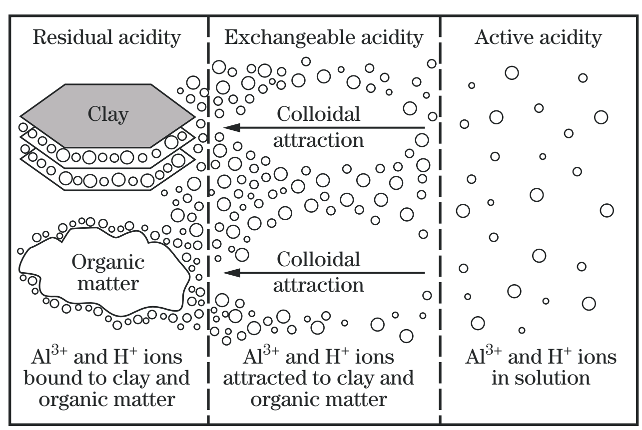
The lime requirement for a soil is the amount of agricultural limestone needed to achieve a desired pH National range for the cropping system used. Soil pH determines only active acidity (the amount of H+ in the soil solution at that particular time), while the lime requirement determines the amount of exchangeable, or reserve acidity, held by soil clay and organic matter (fig. 503–9).

Most laboratories use soil pH in combination with buffered solutions to extract and measure the amount of reserve acidity, or buffering capacity (chapter 3) in a soil. The measured amount of exchangeable/reserve acidity is then used to determine the proper amount of lime needed to bring about the desired increase in soil pH. The rate of agricultural limestone applied to any agricultural field should be based on soil test recommendations.

Selecting a liming material
Factors to consider in selecting a liming material include:

- *Calcium carbonate equivalence (CCE)*—CCE is a measure of the liming capability of a material relative to pure calcium carbonate expressed as a percentage. A liming material with a CCE of 50 has 50 percent of the liming capability of calcium carbonate.
- *Length of time between application of lime and planting of crop*—The choice between a slower acting and a quick-acting liming material is often determined by the time between application of lime and crop planting.

Figure 503–9 Relationship between residual, exchangeable, and active acidity in soils



- *Crop value*—The value of the crop, especially those crops that are acid-sensitive or have a critical pH requirement, should be considered in determining what lime source to use. It may be desirable to use pulverized, hydrated ($Ca(OH)_2$), or burned (CaO) lime, which will neutralize soil acidity quickly, when growing an acid-sensitive crop in strongly acid soils. Although the cost per acre will be greater, improved crop performance should result in higher net income. Aglime has its maximum effect in a period of 1 to 3 years, while suspension lime, burned lime, and hydrated lime have their maximum effect in 3 to 6 months.
- *Need for magnesium*—Calcitic lime should be used in soils with high magnesium levels, while dolomitic limes should be used on soils low in magnesium. Use soil test data to determine which type of lime to use

Frequency of lime applications

Intensive cropping systems result in more frequent need for liming as Ca and Mg are depleted with crop removal and soil becomes acidified due to higher ammonium-N applications. A soil test every 2 or 3 years will reveal whether or not lime is needed. Sandy soils generally require less lime at any one application than silt loam or clay soils to decrease soil acidity by a given amount. Sandy soils, however, usually need to be limed more frequently because their buffering capacity is low.

Applying lime

Lime moves slowly in soil from the point of application, and lime particles dissolve more slowly as acidity is reduced. In conventionally tilled systems, lime should be mixed to tillage depth in order to effectively neutralize soil acidity in the primary root zone. On moderately acid soils (pH 5.2–5.7), a single application of lime made either before or after tillage will usually give good results. For strongly acid soils (pH 5.0 and lower) that have very high lime requirements, it may be desirable to apply half of the lime before tillage and the remaining half after tillage. For large areas that have high lime requirements (3–4 tons/acre), it may be best to apply half of the required lime in a first year application and the remainder in the second year. Agricultural limestone can be applied anytime between the harvest of a crop and the planting of the next. Lime is usually broadcast on the soil surface before tillage operations and incorporated into the soil. In conservation tillage systems and on pastures and hay fields, surface applications can be made whenever soil conditions allow spreaders to enter the fields. Research with no-tillage corn and forages has shown that surface applied lime has been effective in reducing soil acidity in the surface two to four inches of soil

Nitrogen

The nitrogen cycle

Nitrogen is subject to more transformations than any other essential element. These cumulative gains, losses, and changes are collectively termed the nitrogen cycle (fig. 503–10). The ultimate source of nitrogen is N_2 gas, which comprises approximately 78 percent of the earth's atmosphere. Inert N_2 gas, however, is unavailable to plants and must be transformed by biological or industrial processes into forms which are plant-available. As a result, modern agriculture is heavily dependent on commercial nitrogen fertilizer. Some of the more important components of the nitrogen cycle are described next.

Nitrogen fixation

Nitrogen fixation is the process whereby inert N_2 gas in the atmosphere is transformed into forms that are plant-available, including NH_4^+ or NO_3^-. Fixation can take place by biological or by non-biological processes.

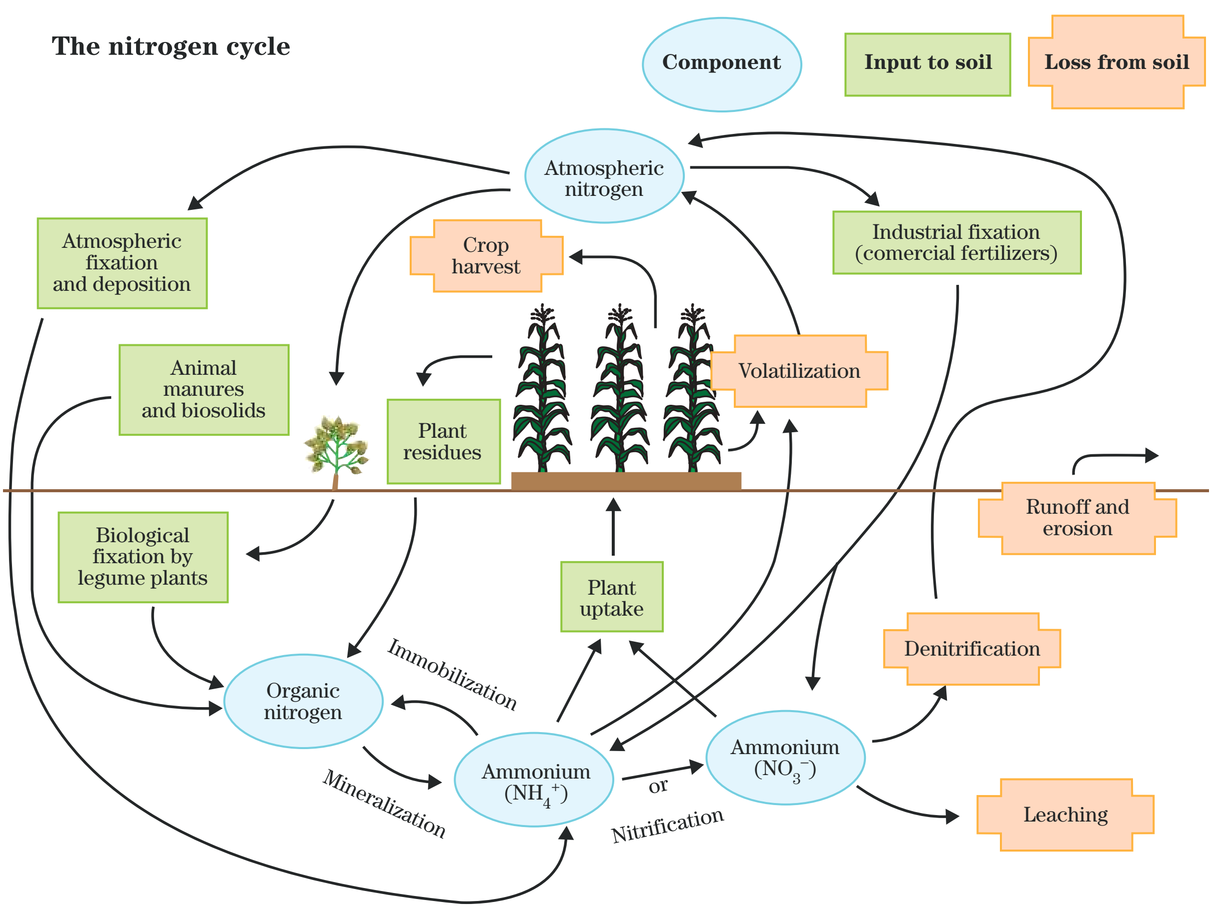
- Biological nitrogen fixation processes include:
  — *Symbiotic nitrogen fixation*—This process is mediated by bacteria with the ability to convert atmospheric N_2 to plant-available nitrogen while growing in association with a host plant. Symbiotic Rhizobium bacteria fix N_2 in nodules present on the roots of legumes. Through this relationship, the bacteria make N_2 from the atmosphere available to the legume as it is excreted from the nodules into the soil. In the Mid-Atlantic region, the quantity of nitrogen fixed by most leguminous crops is probably less than 150 pounds per acre per year.
  — *Non-symbiotic nitrogen fixation*—This is a N_2 fixation process that is performed by free-living bacteria and blue-green algae in the soil. The amount of N_2 fixed by these organisms is much lower than that fixed by symbiotic N_2 fixation.

- Non-biological nitrogen fixation processes include:
  — *Atmospheric additions*—Small amounts of nitrogen in the order of 5 to 15 pounds per acre per year can be added to the soil in the form of rain or snowfall. This includes nitrogen that has been fixed by the electrical discharge of lightning in the atmosphere and industrial pollution.
  — *Synthetic or industrial processes of nitrogen fixation*—The industrial fixation of nitrogen is the most important source of nitrogen as a plant nutrient. The production of nitrogen by industrial processes is based on the Haber-Bosch process where hydrogen (H_2) and N_2 gases react to form NH_3:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Hydrogen gas for this process is obtained from natural gas and N_2 comes directly from the atmosphere. The NH_3 produced can be used directly as a fertilizer (anhydrous NH_3) or as the raw material for other nitrogen fertilizer products, including ammonium phosphates, urea, and ammonium nitrate.

Figure 503–10 The nitrogen cycle (modified from the International Plant Institute Web site at www.ppi-ppic.org)



Residual nitrogen from legume cover crops

Nitrogen contained in the residues from a previous legume crop is an important source of nitrogen and should be considered when developing an nitrogen fertilization program. The amounts of residual nitrogen left in the soil from previous legume crops are summarized in table 503–16 for the Mid-Atlantic region. State supplements should be utilized for legume credits. Accounting for residual nitrogen from legumes can reduce both nitrogen fertilizer costs and the risk of NO_3^- losses by leaching.

Forms of soil nitrogen

Soil nitrogen occurs in both inorganic and organic forms. Most of the total nitrogen in surface soils is present as organic nitrogen (fig. 503–11).

- Inorganic forms of soil nitrogen include:
  — ammonium (NH_4^+)
  — nitrite (NO_2^-)
  — nitrate (NO_3^-)
  — nitrous oxide (N_2O gas)
  — nitric oxide (NO gas)
  — elemental nitrogen (N_2 gas)
  NH_4^+, NO_2^-, and NO_3^- are the most important plant nutrient forms of nitrogen and usually comprise 2 to 5 percent of total soil N.

Table 503–16 Example residual nitrogen credits provided by legumes, by Mid-Atlantic State sources: Pennsylvania: Pennsylvania Agronomy Guide, 2005–2006, 2005; Maryland: Maryland Nutrient Management Manual, 2005; Delaware: Sims and Gartley, 1996; Virginia/West Virginia: Virginia Division of Conservation and Recreation, 2005

		-------------------------State-------------------------			
Legume	**Criteria**	**Pennsylvania**	**Maryland**	**Delaware**	**Virginia/West Virginia**
		------------ nitrogen credit, lb/acre -----------			
Alfalfa	First year after legume	—	100–150 [2/]	90	—
	> 50 percent stand	80–120 [1/]	—	—	90
	25–49 percent stand	60–80 [1/]	—	—	70
Red clover and trefoil	First year after legume		40	60	
	> 50 percent stand	60–90 [1/]	—	—	80 [2/]
	25-49 percent stand	50–60 [1/]	—	—	60 [2/]
	< 25 percent stand	40	—	—	40 [2/]
Ladino clover		—	60	—	—
Crimson clover		—	50–100 [3/]	—	—
Hairy vetch		—	75–150	—	50–100
Austrian winter peas		—	75–150	—	—
Lespedeza		—	20	—	—
Peanuts		—	—	—	45
Soybeans	First year after grain	1 lb N/bu soybeans	15–20 [4/]	0.5 lb/bu soybeans	0.5 lb/bu of soybeans or 20 lb if yield is unknown

1 Actual rate depends on soil productivity group
2 Depends on stand; if stand is good (> 4 plants/ft^2), credit 150 lb; if stand is fair (1.5 to 4 plants/ft^2), credit 125 lb; if stand is poor (< 1.5 plants/ft^2), credit 100 lb
3 Depends on planting date (and biomass production), kill date, and subsequent tillage
4 A minimum of 15 lb and may be as much as 1 lb per bushel of soybeans, up to a maximum of 40 lb

- Organic soil nitrogen occurs in the form of amino acids, amino sugars, and other complex nitrogen compounds.

N mineralization (fig. 503–11) is the conversion of organic nitrogen to NH_4^+. This is an important process in the nitrogen cycle since it results in the liberation of plant-available inorganic nitrogen forms.

N immobilization is the conversion of inorganic plant available nitrogen (NH_4^+ or NO_3^-) by soil microorganisms to organic nitrogen forms (amino acids and proteins). This conversion is the reverse of mineralization, and these immobilized forms of nitrogen are not readily available for plant uptake.

Carbon to nitrogen ratios (C:N)
Immobilization and mineralization are ongoing processes in the soil and are generally in balance with one another. This balance can be disrupted by the incorporation of organic residues that have high carbon to nitrogen ratios (C:N).

The ratio of percent C to percent N, or the C:N ratio, defines the relative quantities of these elements in residues and living tissues. Whether nitrogen is mineralized or immobilized depends on the C:N ratio of the organic matter being decomposed by soil microorganisms:

- Wide C:N ratios of > 30:1—Immobilization of soil nitrogen will be favored. Residues with wide C:N ratios include hay, straw pine needles, cornstalks, dry leaves, and sawdust.
- C:N ratios of 20:1 to 30:1—Immobilization and mineralization will be nearly equal.
- Narrow C:N ratios of < 20:1—Favor rapid mineralization of N. Residues with narrow C:N ratios include alfalfa, clover, manures, biosolids, and immature grasses.

The decomposition of a crop residue with a high C:N ratio is illustrated in figure 503–12. Shortly after incorporation, high C:N ratio residues are attacked and used as an energy source by soil microorganisms. As these organisms decompose the material, there is competition for the limited supply of available nitrogen since the residue does not provide adequate nitrogen to form proteins in the decaying organisms. During this process, available soil nitrogen is decreased and the C in the residues is liberated as CO_2 gas. As decomposition proceeds, the residue's C:N ratio narrows and the energy supply is nearly exhausted. At this point, some of the microbial populations will die and the mineralization of nitrogen in these decaying organisms will result in the liberation of plant-available N. The timing of this process will depend on such factors as soil temperature, soil moisture, soil chemical

Figure 503–11 Forms of soil nitrogen

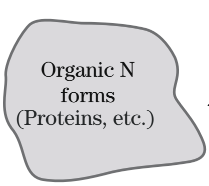
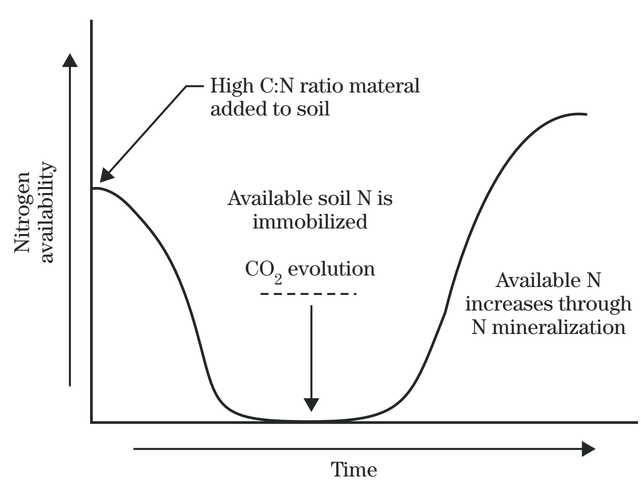


Figure 503–12 Nitrogen immobilization and mineralization after material with a high C:N ratio is added to soil



properties, fertility status, and the amount of residues added. The process can be accelerated by applying nitrogen fertilizer sources at the time of application of the residue.

Nitrification

Nitrification is the biological oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) in the soil. Sources of NH_4 for this process included both commercial fertilizers and the mineralization of organic residues. Nitrification is a two-step process where NH_4^+ is converted first to NO_2^- and then to NO_3^- by two autotrophic bacteria in the soil (Nitrosomonas and Nitrobacter). These bacteria get energy from the oxidation of nitrogen and C from CO_2.

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

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} NO_3^-$$

Nitrification is important because:

- Nitrate is readily available for uptake and use by crops and microbes.
- Nitrate is highly mobile and subject to leaching losses. NO_3^- leaching is generally a major nitrogen loss mechanism from agricultural fields in humid climates and under irrigation. Potential losses are greater in deep sandy soils as compared to fine textured soils. Nitrogen losses can be minimized through proper nitrogen management, including the proper rate and timing of nitrogen fertilizer applications.
- Nitrate-nitrogen (NO_3^-N) can be lost through denitrification, the process where NO_3^- is reduced to gaseous nitrous oxide (N_2O) or elemental nitrogen (N_2) and lost to the atmosphere.
- During nitrification, $2H^+$ ions are produced for every NH_4^+ ion that is oxidized. These H^+ cations will accumulate and significantly reduce soil pH; thus, any ammonium-containing fertilizer will ultimately decrease soil pH due to nitrification. This acidity can be managed through a well-planned liming program.

Note: The proper way to express NO_3^- concentrations is as NO_3^-N or as elemental N. Use the following conversions, which are based on molecular weight:

To convert NO_3^-N to NO_3^-: $NO_3^-N \times 4.4 = NO_3^-$

To convert NO_3^- to NO_3^-N: $NO_3^- \times 0.23 = NO_3^-N$

Phosphorus

The phosphorus cycle

Soil P originates primarily from the weathering of soil minerals such as apatite and from P additions in the form of fertilizers, plant residues, agricultural wastes, or biosolids (fig. 503–13). Orthophosphate ions (HPO_4^{-2} and $H_2PO_4^-$) are produced when apatite breaks down, organic residues are decomposed, or fertilizer P sources dissolve. These forms of P are taken up by plant roots and are present at very low concentrations in the soil solution.

Many soils contain large amounts of P (800–1600 lb P/a), but most of that P is unavailable to plants. The type of P-bearing minerals that form in soil is highly dependent on soil pH. Soluble P, regardless of the source, reacts very strongly with Fe and Al to form insoluble Fe and Al phosphates in acid soils and with calcium to form insoluble calcium phosphates in alkaline soils. Phosphorus in these insoluble forms is not readily available for plant growth and is said to be fixed.

Phosphorus availability and mobility

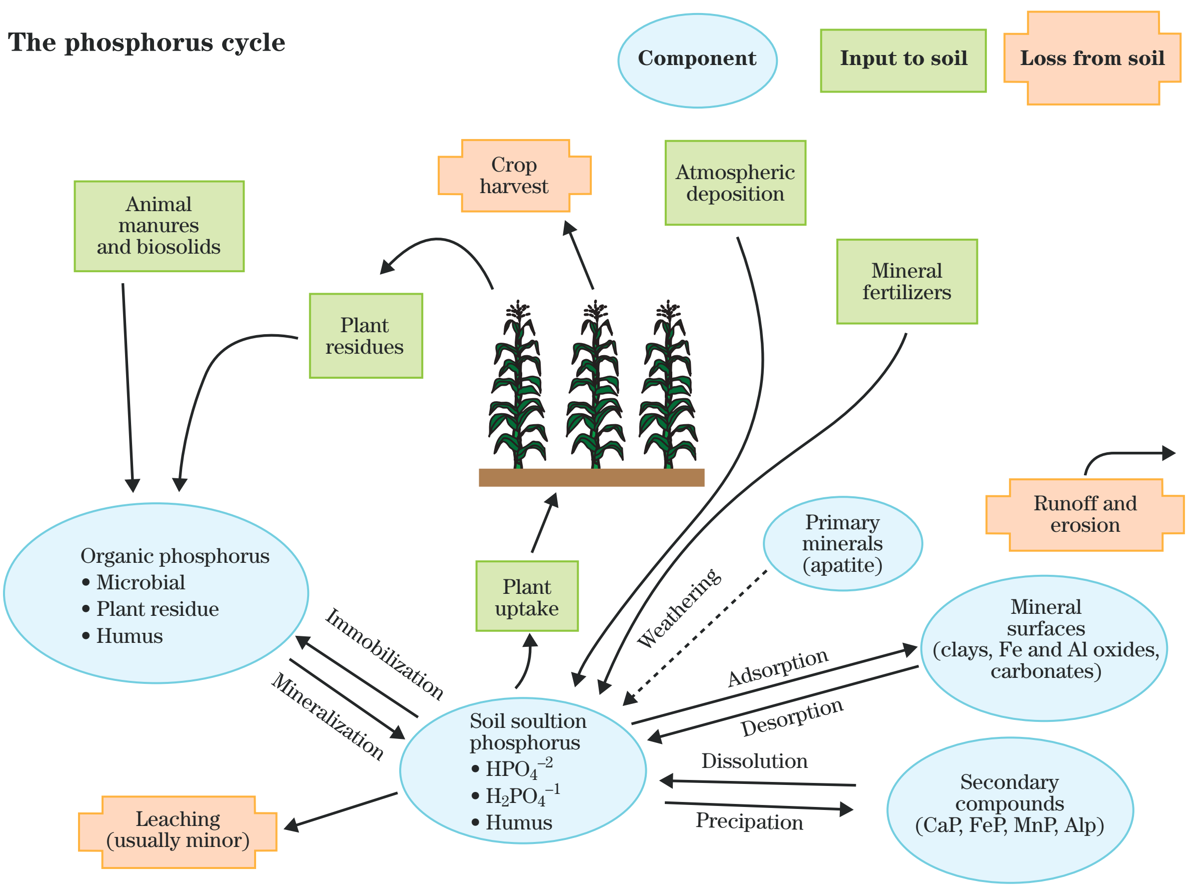
Phosphorus is a primary nutrient and plant roots take up P in the forms of HPO_4^{-2} and $H_2PO_4^-$. The predominant ionic form of P present in the soil solution is pH dependent. In soils with pH values greater than 7.2, the HPO_4^{-2} form is predominant, while in soils with a pH between 5.0 and 7.2, the $H2PO_4^-$ form predominates.

Phosphorus has limited mobility in most soils because P reacts strongly with many elements, compounds, and the surfaces of clay minerals. The release of soil P to plant roots and its potential movement to surface waters is controlled by several chemical and biological processes (fig. 503–13). Phosphorus is released to the soil solution as P-bearing minerals dissolve, as P bound to the surface of soil minerals is uncoupled or desorbed, and as soil organic matter decomposes or mineralizes (fig. 503–14). Most of the P added as fertilizer and organic sources is rapidly bound by soil minerals in chemical forms that are not subject to rapid release; thus, soil solution P concentrations are typically very low. Soluble P in the soil solution of most agricultural soils ranges from <0.01 to 1 parts per million; thus, an entire acre-furrow slice of soil generally contains less than 0.4 pounds of P in solution at any one time. As illustrated, supplying adequate P to a plant depends on the soil's ability to replenish the soil solution throughout a growing season.

Phosphorus availability and mobility is influenced by several factors:

- *Effect of soil pH*—In acid soils, P precipitates as relatively insoluble Fe and Al phosphate minerals. In neutral and calcareous soils, P precipitates as relatively insoluble calcium phosphate minerals. As illustrated in figures 503–14 and 503–15. Phosphorus content of the soil solution, soil P, is most available in the pH range of 5.5 to 6.8, which is where soluble Al and Fe are low.
- *Movement of soil P to plant roots*—Phosphorus moves from soil solids to plant roots through the process of diffusion. Diffusion is a slow and short-range process with distances as small as 0.25 inches. This limited movement has important implications since soil P located more than 0.25 inches from a plant root will never reach the root surface. Dry soils reduce the diffusion of P to roots; therefore, plants take up P best in moist soils.

Figure 503–13 The phosphorus cycle (modified from the International Plant Nutrition Institute Web site at *www.ppi-ppic.org*)



- *Fertilizer P recovery*—A crop uses only 10 to 30 percent of the P fertilizer applied during the first year following application. The rest goes into reserve and may be used by later crops. Many growers have built up large reserves of soil P.
- Timing and placement of P fertilizer—Although most agricultural soils are naturally low in available P, many years of intensive P fertilization, the application of organic P sources, or both, has resulted in many soils that now test high in available P. On these soils, broadcast P applications are not very efficient. Low rates of P in starter fertilizers placed with or near the seed are potentially beneficial on high-P soils when the crop is stressed by cold conditions. 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 crop growth.

Phosphorus transport to surface waters
Transport of soil P occurs primarily via surface flow (runoff and erosion). Although leaching and subsurface lateral flow should also be considered in soils with high degrees of P saturation and artificial drainage systems. Water flowing across the soil surface can dissolve and transport soluble P, or erode and transport particulate P, out of a field. Virtually all soluble P transported by surface runoff is biologically available, but particulate P that enters streams and other surface waters must undergo solubilization before becoming available for aquatic plants. Thus, both soluble and sediment bound P are potential pollutants of surface waters and both can contribute to excessive growth of aquatic organisms, which can have detrimental environmental impacts.

Soils have a finite capacity to bind P. When a soil becomes saturated with P, desorption of soluble P can be accelerated, with a consequent increase in dissolved inorganic P in runoff. Thus, if the level of residual soil P is allowed to build up by repeated applications of P in excess of crop needs, a soil can become saturated with P and the potential for soluble P losses in surface runoff will increase significantly. Recent research shows that the potential loss of soluble P will increase with increasing levels of soil test P. Very high levels of soil test P can result from over-application of manure, biosolids, or commercial phosphate fertilizer. Soils with these high soil test P levels will require several years of continuous cropping without P additions to effectively reduce these high P levels.

Figure 503–14 Phosphorus content of the soil solution

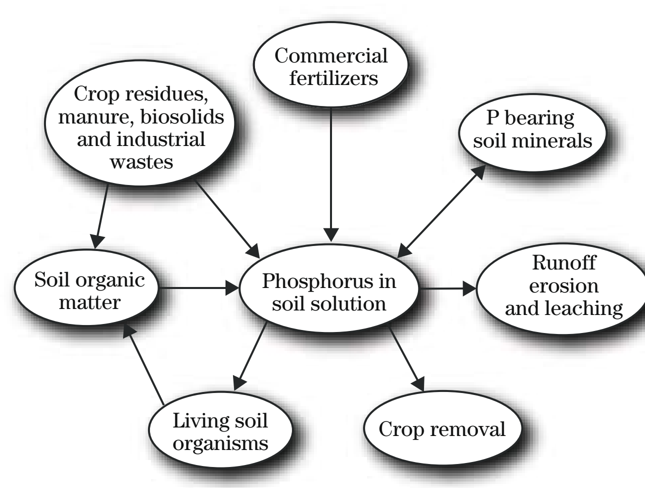
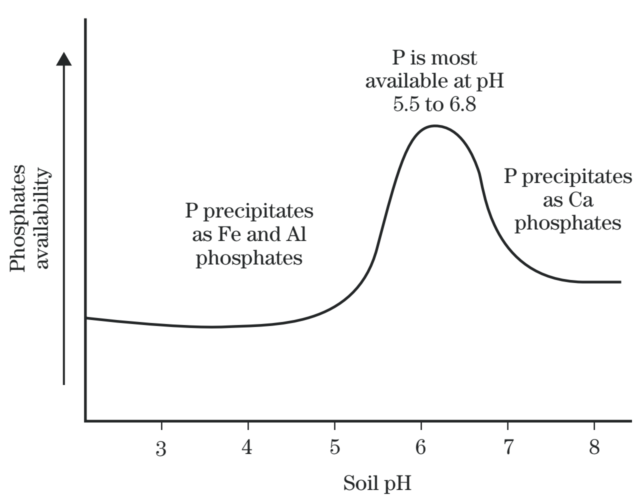


Figure 503–15 Effect of pH on P availability to plants



Potassium

The K cycle

Potassium (K) is the third primary plant nutrient and is absorbed by plants in larger amounts than any other nutrient except N. Plants take up K as the monovalent cation K+. Potassium is present in relatively large quantities in most soils, but only a small percentage of the total soil K is readily available for plant uptake.

In the soil, weathering releases K from a number of common minerals including feldspars and micas. The released K^+ can be taken up easily by plant roots, adsorbed by the cation exchange complex of clay and organic matter, or fixed in the internal structure of certain 2:1 clay minerals. Potassium that is fixed by these clay minerals is very slowly available to the plant. The various forms of K in the soil are illustrated in figure 503–16.

Potassium availability and mobility

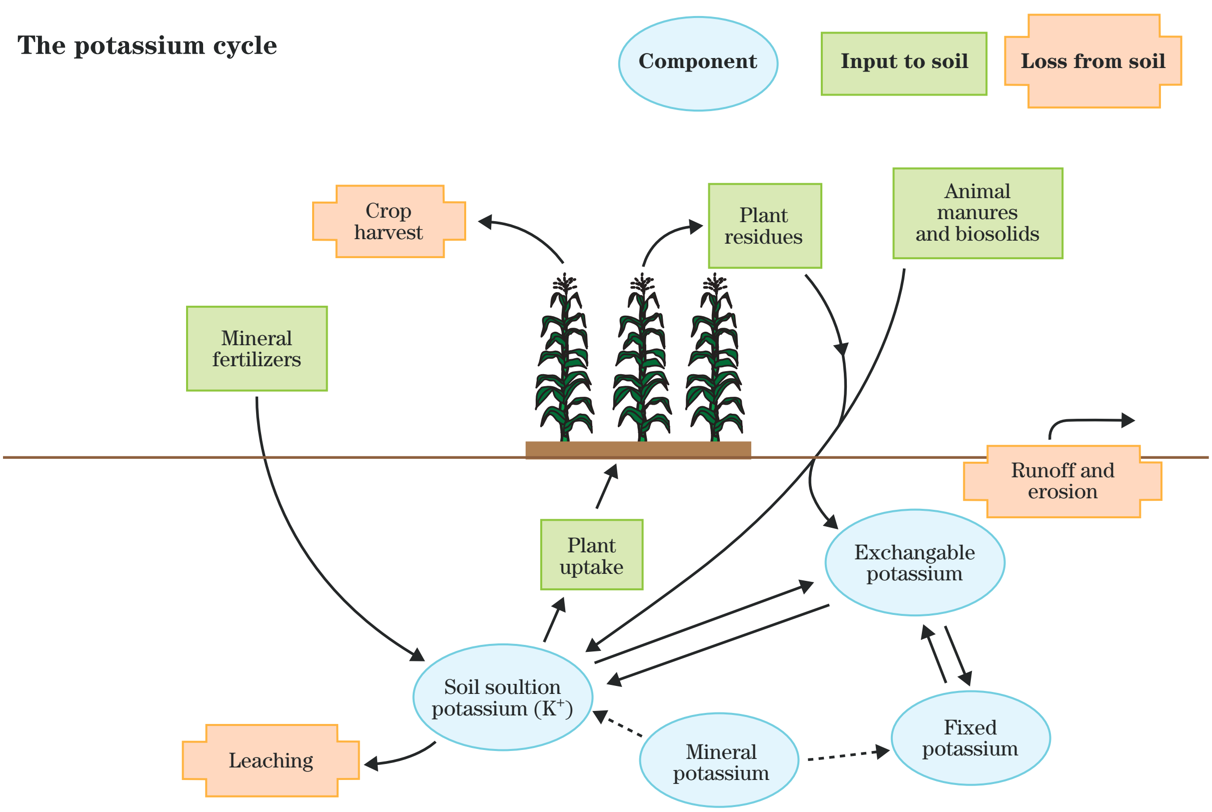
- Plant-available K—Although mineral K accounts for 90 to 98 percent of the total soil K, readily and slowly available K represent only 1 to 10 percent of the total soil K. Plant available K (K that can be readily absorbed by plant roots) includes the portion of the soil K that is soluble in the soil solution and exchangeable K held on the exchange complex.

Exchangeable K—that portion of soil K which is in equilibrium with K in the soil solution:

Exchangeable K ↔ Solution K

- K is continuously made available for plant uptake through the cation exchange process. There can be a continuous, but slow, transfer of K from soil minerals to exchangeable and slowly available forms as K are removed from the soil solution by crop uptake and leaching.

Figure 503–16 The K cycle (modified from the International Plant Nutrition Institute Web site at *www.ppi-ppic.org*)



- Effect of K fertilization on soil K forms—Potassium applied as fertilizer can have various fates in the soil:
  - potassium cations can be attracted to the cation exchange complex where it is held in an exchangeable form and readily available for plant uptake
  - some of the K^+ ions will remain in the soil solution
  - exchangeable and soluble K may be absorbed by plants
  - in some soils, some K may be fixed by the clay fraction
  - applied K may leach from sandy soils during periods of heavy rainfall
- *Movement of K in the soil*—Potassium moves more readily in soil than P, but less readily than N. Since K is held by cation exchange, it is less mobile in fine-textured soils and most readily leached from sandy soils. Most plant uptake of soil K occurs by diffusion.

Timing and placement of K fertilizer

Potassium fertilizers are completely water-soluble and have a high salt index; thus, they can decrease seed germination and plant survival when placed too close to seed or transplants. The risk of fertilizer injury is most severe on sandy soils, under dry conditions, and with high rates of fertilization. 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 applications when the rate of application is low or soil levels of K are low.

A convenient and usually effective method of applying K fertilizers is by broadcasting and mixing with the soil before planting. Fertilizer injury is minimized by this method but, on sandy soils, some K may be lost by leaching.

Split application of K fertilizer on long-season crops such as alfalfa or grass crops that are harvested several times during the growing season is often recommended. Luxury consumption is a term used to describe the tendency of plants to take up K far in excess of their needs if sufficiently large quantities of available K are present in the soil. The excess K absorbed does not increase crop yields to any extent. Split application of K can minimize luxury consumption and provide adequate available K during the latter part of the growing season.

Secondary plant nutrients

Introduction

Secondary macronutrients, which include calcium (Ca), magnesium (Mg), and sulfur (S), are required in relatively large amounts for good crop growth. These nutrients are usually applied as soil amendments or applied along with materials which contain primary nutrients. Many crops contain as much or more S and Mg as P, but in some plants Ca requirements are greater than those for P. Secondary nutrients are as important to plant nutrition as major nutrients since deficiencies of secondary nutrients can depress plant growth as much as major plant nutrient deficiencies.

Calcium and magnesium

- *Behavior of Ca and Mg in the soil*—Calcium and Mg have similar chemical properties and thus behave very similarly in the soil. Both of these elements are cations (Ca^{2+}, Mg^{2+}), and both cations have the same amount of positive charge and a similar ionic radius. The mobility of both Ca and Mg is relatively low, especially compared to anions or to other cations such as Na and K; thus, losses of these cations via leaching are relatively low.
- *Soil Ca*—Total Ca content of soils can range from 0.1 percent in highly weathered tropical soils to 30 percent in calcareous soils. Calcium is part of the structure of several minerals and most soil Ca comes from the weathering of common minerals, which include dolomite, calcite, apatite, and calcium feldspars. Calcium is present in the soil solution and since it is a divalent cation, its behavior is governed by cation exchange as are the other cations. Exchangeable Ca is held on the negatively charged surfaces of clay and organic matter. Calcium is the dominant cation on the cation exchange complex in soils with moderate pH levels. Normally, it occupies 70 to 90 percent of cation exchange sites above pH 6.0.
- *Soil Mg*—Total soil Mg content can range from 0.1 percent in coarse, humid-region soils to 4 percent in soils formed from high-Mg minerals. Magnesium occurs naturally in soils from the

weathering of rocks with Mg-containing minerals such as biotite, hornblende, dolomite, and chlorite. Magnesium is found in the soil solution and, since it is a divalent cation (Mg^{2+}), its behavior is governed by cation exchange. Magnesium is held less tightly than Ca by cation exchange sites, so it is more easily leached; thus, soils usually contain less Mg than Ca. In the Mid-Atlantic region, Mg deficiencies occur most often on acid and coarse-textured soils.

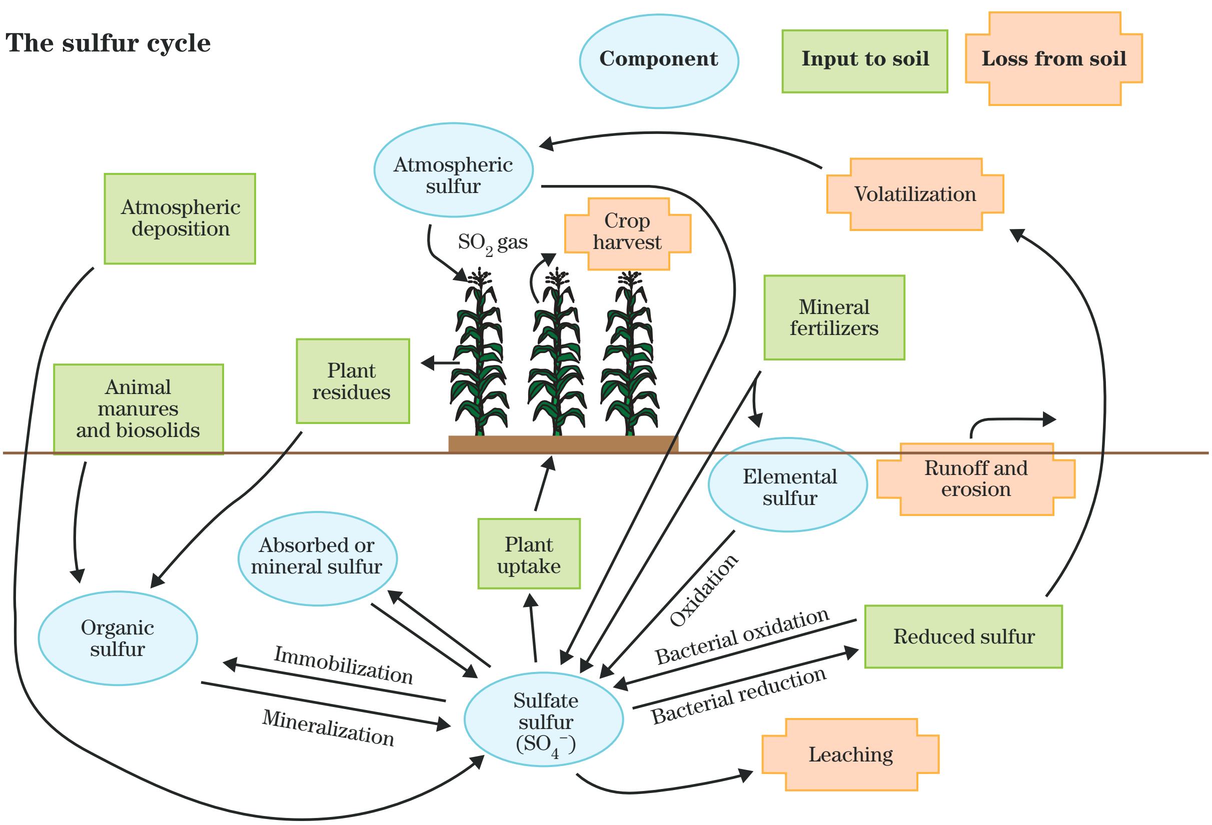
Sulfur

- *Forms of sulfur and the sulfur cycle*—Most crops need less sulfur (S) relative to the other macronutrients. The S cycle for the soil-plantatmosphere system is very similar to nitrogen and is illustrated in figure 503–17. Soil S is present in both inorganic and organic forms.

Most of the sulfur in soils comes from the weathering of sulfate minerals such as gypsum; however, approximately 90 percent of the total sulfur in the surface layers of non-calcareous soils is immobilized in organic matter. Inorganic S is generally present in the sulfate (SO_4^{2-}) form, which is the form of sulfur absorbed by plant roots. Both soluble SO_4^{2-} in the soil solution and adsorbed SO_4^{2-} represent readily plant available S. Elemental S is a good source of sulfur, but it must first undergo biological oxidation to SO_4^{2-}, driven by Thiobacillus thiooxidans bacteria, before it can be assimilated by plants. This oxidation can contribute to soil acidity by producing sulfuric acid through the reaction:

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4$$

Figure 503–17 The S cycle (modified from the International Plant Nutrition Institute Web site at *www.ppi-ppic.org*)



- *Sulfur-containing fertilizers and soil acidity*—Several fertilizer materials contain the SO_4^{2-} form of S including gypsum ($CaSO_4$), potassium sulfate (K_2SO_4), magnesium sulfate ($MgSO_4$), and potassium magnesium sulfate (K-Mag, or Sul-Po-Mag). These fertilizer sources are neutral salts and will have little or no effect on soil pH. In contrast, there are other SO_4^{2-} containing compounds including ammonium sulfate ($(NH_4)_2SO_4$), aluminum sulfate ($(Al_2SO_4)_3$) and iron sulfate ($FeSO_4$) that contribute greatly to soil acidity. The SO_4^{2-} in these materials is not the source of acidity. Ammonium sulfate has a strong acidic reaction primarily because of the nitrification of NH_4^+, and Al and Fe sulfates are very acidic due to the hydrolysis of Al^{3+} and Fe^{3+}.
- Movement of sulfur—Sulfate, a divalent anion (SO_4^{2-}) is not strongly adsorbed and can be readily leached from most soils. In highly-weathered, naturally acidic soils, SO_4^{2-} often accumulates in subsurface soil horizons, where positively charged colloids attract the negatively charged SO_4^{2-} ion. Residual soil SO_4^{2-} resulting from long-term applications of S containing fertilizers can meet the S requirements of crops for years after applications have ceased.
- *Crop responses to sulfur*—Sulfur deficiencies are becoming more common in some areas since both S supplied by pollution and fertilizer-derived S have been reduced in recent years. Acid rain supplies some sulfur due to the emission of SO^2 during the burning of fossil fuels, but lowered emissions have reduced the amount of S supplied to soil in rainfall. Commercial fertilizers previously contained significant amounts of S (i.e. normal superphosphate). With the adoption of high analysis fertilizers such as urea, triple superphosphate, and ammonium phosphates, which contain little or no S, application of this important plant nutrient has been reduced.

Micronutrients

Introduction

Eight of the essential elements for plant growth are called micronutrients or trace elements: B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn. Cobalt (Co) has not been proven to be essential for higher plant growth, but nodulating bacteria need Co for fixing atmospheric nitrogen in legumes.

Micronutrients are not needed in large quantities, but they are as important to plant nutrition and development as the primary and secondary nutrients. A deficiency of any one of the micronutrients in the soil can limit plant growth, even when all other essential nutrients are present in adequate amounts.

Determining micronutrient needs

The need for micronutrients has been known for many years, but their wide use in fertilizers has not always been a common practice. Increased emphasis on micronutrient fertility has resulted from a number of factors, including:

- *Crop yields*—Increasing per-acre crop yields remove increasing amounts of micronutrients. As greater quantities of micronutrients are removed from the soil, some soils cannot release adequate amounts of micronutrients to meet today's high-yield crop demands.
- *Fertilizer technology*—Today's production processes for high-analysis fertilizers remove 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. A micronutrient deficiency, if suspected, can be identified through soil tests, plant analysis, 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.

Forms in the soil

Micronutrients can exist in several different forms in soil:

- within structures of primary and secondary minerals
- adsorbed to mineral and organic matter surfaces
- incorporated in organic matter and microorganisms
- in the soil solution

Many micronutrients combine with organic molecules in the soil to form complex molecules called chelates. A chelate is a metal atom surrounded by a large organic molecule.

Micronutrient soil-plant relationships

Plant roots absorb soluble forms of micronutrients from the soil solution. Soils vary in micronutrient content, and they usually contain lower amounts of micronutrients than primary and secondary nutrients. Total soil content of a micronutrient does not indicate the amount available for plant growth during a single growing season although it does indicate relative abundance and potential supplying power. Availability decreases as pH increases for all micronutrients except Mo and Cl. Specific soil-plant relationships for B, Cu, Fe, Mn, Mo, Zn, and Cl are described in the next sections.

Boron

- *Soil boron*—Boron exists in minerals, adsorbed on the surfaces of clay and oxides, combined in soil organic matter, and in the soil solution. Organic matter is the most important potentially plant-available soil source of B.
  - — Factors affecting plant-available B: *Soil moisture and weather*—Boron deficiency is often associated with dry or cold weather, which slows organic matter decomposition. Symptoms may disappear as soon as the surface soil receives rainfall or soil temperatures increase and root growth continues, but yield potential is often reduced.
- *Soil pH*—Plant availability of B is maximum between pH 5.0 and 7.0. Boron availability decreases with increasing soil pH; thus, B uptake is reduced at high pH.
- *Soil texture*—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 in areas of high rainfall.
- *Crop needs and potential toxicity*—Crops vary widely in their need for and tolerance to B; however, B should be applied judiciously because the difference between deficient and toxic amounts is narrower than for any other essential nutrient. This is especially important in a rotation involving crops with different sensitivities to B.
- *Rates of boron fertilization*—Recommended rates of B fertilization depend on such factors as soil test levels, plant tissue concentrations, plant species, cultural practices (including crop rotation), weather conditions, soil organic matter, and the method of application. Depending on the crop and method of application, recommended rates of application generally range from 0.5 to 3 pounds per acre.

Copper

- *Soil copper*—In mineral soils, Cu concentrations in the soil solution are controlled primarily by soil pH and the amount of Cu adsorbed on clay and soil organic matter. A majority of the soluble Cu_2^+ in surface soils is complexed with organic matter, and Cu is more strongly bound to soil organic matter than any of the other micronutrients.
- *Copper deficiencies*—Organic soils are most likely to be deficient in Cu. Such soils usually contain plenty of Cu, but hold it so tightly that only small amounts are available to the crop. Sandy soils with low organic matter content may also become deficient in Cu because of leaching losses. Heavy, clay-type soils are least likely to be Cu deficient. The concentrations of Fe, Mn, and Al in soil affect the availability of Cu for plant growth, regardless of soil type.
- *Copper toxicity*—Like most other micronutrients, large quantities of Cu can be toxic to plants. Excessive amounts of Cu depress Fe activity and may cause Fe deficiency symptoms to appear in plants. Such toxicities are not common.

Iron

- *Soil iron*—Iron is the fourth most abundant element, with total Fe ranging from 0.7 to 55 percent. Solubility of Fe is very low and is highly pH-dependent. Iron solubility decreases with increasing soil pH. Iron can react with organic compounds to form chelates or Fe-organic complexes.
- *Iron deficiencies*—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
- — a combination of high pH, high lime, wet, cold soils, and high bicarbonate levels

- *Plant genetic differences*—Plant species can differ significantly in their ability to take up Fe. Iron-efficient varieties should be selected where Fe deficiencies are likely to occur. Roots of Fe-efficient plants can improve Iron availability and uptake by secretion of H, organic acids and organic chelating compounds low soil organic matter levels

Reducing 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

- *Soil manganese*—Availability of Mn to plants is determined by the equilibrium among solution, exchangeable, organic, and mineral forms of soil Mn. Chemical reactions affecting Mn solubility include oxidation-reduction and complexation with soil organic matter. Redox or oxidation-reduction reactions depend on soil moisture, aeration and microbial activity.

- *Manganese deficiencies*—Manganese solubility decreases with increasing soil pH:

  - — Manganese deficiencies occur most often on high organic matter soils and on those soils with neutral-to-alkaline pH that are naturally low in Mn.
  - — Manganese deficiencies may result from an antagonism with other nutrients such as Ca, Mg, and Fe.
  - — Soil moisture also affects Mn availability. Excess moisture in organic soils 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.
  - — Several plant species have shown differences in sensitivity to Mn deficiencies.

Molybdenum

- *Soil molybdenum*—Molybdenum is found in soil minerals, as exchangeable Mo on the surfaces of Fe/Al oxides, and bound soil organic matter. Adsorbed and soluble Mo is an anion (MoO_4^-).

- *Molybdenum deficiencies*—Molybdenum becomes more available as soil pH increases

  - — Deficiencies are more likely to occur on acid soils. Since Mo becomes more available with increasing pH, liming will correct a deficiency if the soil contains enough of the nutrient.
  - — Sandy soils are deficient more often than finer-textured soils.
  - — Soils high in Fe/Al oxides tend to be low in available Mo because Mo is strongly adsorbed to the surfaces of Fe/Al oxides.
  - — Heavy P applications increase Mo uptake by plants, while heavy S applications decrease Mo uptake.
  - — Crops vary in their sensitivity to low Mo and Mo-efficient/Mo-inefficient varieties have been identified for some plants species.

Zinc

- *Soil zinc*—The various forms of soil Zn include soil minerals, organic matter, adsorbed Zn on the surfaces of organic matter and clay, and dissolved Zn in the soil solution. Zinc released from soil minerals during weathering can be adsorbed onto the CEC, incorporated into soil organic matter, or react with organic compounds to form soluble complexes. Organically complexed or chelated, Zn is important for the movement of Zn to plant roots. Soils can contain from a few to several hundred pounds of Zn per acre. Fine-textured soils usually contain more Zn than sandy soils.

- *Factors affecting plant-available Zn*—The total Zn content of a soil does not indicate how much Zn is available. The following factors determine its availability:

  - — Zinc becomes less available as soil pH increases. Coarse-textured soils limed above pH 6.0 are particularly prone to develop Zn deficiency. Soluble Zn concentrations in the soil can decrease three-fold for every pH unit increase between 5.0 and 7.0.

— Zinc deficiency may occur in some plant species on soils with very high P availability and marginal Zn concentrations due to Zn-P antagonisms. Soil pH further complicates Zn-P interactions.
— Zinc forms stable complexes with soil organic matter. A significant portion of soil 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 due to slow root growth. Plants sometimes appear to outgrow this deficiency, but yield potential may have already been reduced.
— Zinc availability is affected by the presence of certain soil fungi, called mycorrhizae, 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.
— Susceptibility to Zn deficiency is both species and variety dependent. For example, corn, beans, and fruit trees have a high sensitivity to Zn deficiency.

Chlorine

- *Soil chlorine*—In soils, chlorine is found in the form of chloride (Cl–), a soluble anion which is contained in negligible amounts in the mineral, adsorbed and organic soil fractions. Chloride has a high mobility in soils, which enables it to undergo extensive leaching when rainfall or irrigation exceeds evapotranspiration.

- *Chloride fertilization*—About 60 pounds per acre of Cl– per surface 2 feet of soil seems to be adequate for top yields of small grains. This amount can be provided by fertilizer or the soil. The most practical source is potassium chloride (KCl), or muriate of potash, which contains about 47 percent Cl. Preplant, at seeding, and top-dressed applications have all been effective. Higher rates should be applied preplant or by topdressing. Since Cl– is highly mobile in the soil, it should be managed accordingly.

Saline and sodic soils

In saline soils, the salinity does not affect the physical properties of soil, but it is harmful because elevated soluble salts in the soil solution reduce the availability of soil water to plants. As soils dry out due to evapotranspiration, the soil water becomes more saline and less available to plants. Saline soils normally have a pH value below 8.5 and have good physical properties. The electrical conductivity (EC) of the soils is generally greater than 4.0 dS/m and the exchangeable sodium percentage (ESP) less than 15. Reclamation of these soils can be accomplished by leaching with high-quality irrigation water. Chemical amendments are usually not needed. Successful reclamation requires adequate drainage, irrigation water management, and use of the correct amount of water. States should follow their leaching index.

Sodic soils have an exchangeable sodium percentage that is high enough to cause a deleterious change in soil flocculation (i.e. a deterioration in soil aggregation). In extreme cases, sodium ions disperse the mineral colloids, which then form a tight soil structure. This structure slows the infiltration/percolation of water. Irrigation waters containing high amounts of sodium salts versus calcium and/or magnesium salts can create a build-up of exchangeable sodium in the soil. Sodic soils have an EC less than 4.0 dS/m and an ESP greater than 15. Sodic soils normally have a pH greater than 8.5. At very high pH values (>8.5), plant-available P and boron actually increase due to the influence of soluble sodium. On non-calcareous soils, gypsum or other soluble calcium salts must be applied. Another approach sometimes used is to apply elemental S with a liming material, thereby forming gypsum in the soil. On calcareous soils, treatment may be with acidifying materials that dissolve native calcium, with gypsum, or with a combination of both. Soluble calcium replaces sodium on the clay surface and improves physical properties that allows sodium and excess salts to be leached. Organic materials such as crop residues, manure, and compost may be helpful in providing more soil porosity and better physical condition for leaching.

Saline-sodic soils contain large amounts of soluble salts and a high percentage of exchangeable sodium. These soils have an EC above 4.0 dS/m and an ESP greater than 15. They are similar to saline soils in appearance and character except that the soluble salts are leached out by artifical drainage. After leaching the soluble salts, the soils become sodic and degrade in quality (i.e., develop poor soil structure). Thus, they require an amendment before commencing leaching. Such amendments are elemental sulfur, sulfuric acid, aluminum sulfate, and ferric and ferrous sulfate. Good drainage and leaching are required to remove the sodium. States should follow their leaching index and land grant university recommendations for the most effective and economical amendments.

An additional reference available for diagnosing and managing saline and sodic soils Waskom et al. 2006 (*http://www.ext.colostate.edu/pubs/crops/00521.html*).

503.23 Sources and forms of nutrients

Commercial fertilizers

Introduction

Plants require optimal amounts of available nutrients for normal growth. These nutrients can come from several sources, including soil organic matter, native soil minerals, organic materials that are added to the soil (e.g., animal manures), air (e.g., legumes), and commercial fertilizers. When a soil is not capable of supplying enough nutrients to meet crop/plant requirements, commercial fertilizers can be added to supply the needed nutrients. There are numerous types of fertilizers that can be used to supply primary, secondary, or micronutrients. This chapter will provide an overview of the key issues related to commercial fertilizers.

Before using any fertilizers, it is important to understand how to read a fertilizer label. All fertilizers are labeled as percent N, percent P_2O_5, and percent K_2O. For example, a fertilizer labeled as a 15–5–10 means that the product contains 15 percent N, 5 percent P_2O_5, and 10 percent K_2O by weight.

Nitrogen fertilizers

Introduction

Inorganic nitrogen fertilizers are produced by fixing nitrogen from the atmosphere. Natural gas is used as the energy source and is a major component of the cost of nitrogen fertilizers. The following section lists the primary nitrogen materials used by the fertilizer industry and describes some of the key characteristics of each product.

Urea [$CO(NH_2)_2$]:

- Fertilizer grade: 46–0–0
- Soluble, readily available source of N
- Dry fertilizer product
- Produced by reacting ammonia (NH_3) with carbon dioxide under pressure at an elevated temperature
- Contains the highest percentage of nitrogen of all dry fertilizers
- Applying too much near germinating seeds can kill seedlings due to NH_3 release
- Rapid hydrolysis to ammonium carbonate can cause significant nitrogen losses as NH_3 gas through volatilization when urea is applied to the surface of soil and is not incorporated

  $$CO\left(NH_2\right)_2 + H_20 \Rightarrow 2\left(NH_3\right)\left(gas\right) + CO_2$$

- Incorporation or injection into the soil is important to avoid volatilization losses as NH_3 gas
- Rainfall or irrigation (0.5 inches or more) will prevent NH_3 volatilization

Ammonium nitrate (NH_4NO_3):

- Fertilizer grade: 34–0–0
- Soluble, readily available source of N
- Dry fertilizer product
- 50 percent of the nitrogen is present as ammonium (NH_4^+)
- 50 percent of the nitrogen is present as nitrate (NO_3^-), which is the form susceptible to leaching and denitrification losses
- NH_3 volatilization is **not** an issue unless applied to high pH soils (i.e., >7.5)

- Strong oxidizer that can react violently with other incompatible materials
- Should be stored properly to prevent risk of explosion
- Natural affinity to absorb moisture limits bulk storage during summer

Ammonium sulfate [$(NH_4)_2SO_4$]:
- Fertilizer grade: 21–0–0–24S
- Contains 24 percent sulfur
- Soluble, readily available source of nitrogen and S
- 21–0–0 is dry fertilizer product
- NH_3 volatilization is not an issue unless applied to high pH soils (i.e., >7.5)
- Also marketed in a liquid form as 8–0–0–9S
- Density of 8–0–0–9 is 10.14 pounds per gallon at 60 °F; salting out temperature is 15 °F

Non-pressure nitrogen solutions:
- Fertilizer grade: ranges from 28–0–0 to 32–0–0
- Soluble, readily available source of N
- Liquid fertilizer product that does not require pressure for storage
- Usually referred to as urea and ammonium nitrate (UAN)
- Works well as herbicide carrier
- Prepared by dissolving urea and ammonium nitrate in water
- NH_3 volatilization is an issue for the urea portion of this fertilizer
- Density and salting out:
  - — Density of 28–0–0 is 10.65 pounds per gallon at 60 °F; salting out temperature is 1 °F
  - — Density of 30–0–0 is 10.84 pounds per gallon at 60 °F; salting out temperature is 14 °F
  - — Density of 32–0–0 is 11.06 pounds per gallon at 0 °F; salting out temperature is 28 °F

Aqua ammonia (NH_4OH):
- Fertilizer grade: 20–0–0 (most common)
- Density of 20–0–0 is 7.60 pounds per gallon at 60 °F
- Produced by dissolving NH_3 gas in water
- Liquid product that must be kept under pressure to prevent free NH_3 losses
- Must be injected into the soil to prevent NH3 losses

Anhydrous ammonia (NH_3):
- Fertilizer grade: 82–0–0
- Fertilizer with the highest analysis of N
- Stored as a liquid under pressure
- Injected into soil as a gas
- Density of 82–0–0 is 5.15 pounds per gallon at 60 °F
- Losses during application can occur if not applied properly. Losses are more prevalent when soils are too dry or too wet during application
- Use extreme caution during handling. Accidents can cause severe burning of skin, lungs, and eyes

Ammonium thiosulfate [$(NH_4)_2S_2O_3$]:
- Fertilizer grade: 12–0–0–26S
- Density of 12–0–0–26S is 11.1 pounds per gallon at 60 °F; salting out temperature is 23 °F
- Readily available source of nitrogen and S
- Liquid fertilizer that does not require pressure for storage
- Can inhibit germination if placed too close to germinating seeds

Sulfur-coated urea
- Nitrogen content usually ranges from 30 to 40 percent
- Slow release form of N
- Urea fertilizer granule is coated with elemental S
- N release is dependent on breakdown of S coating

Urea-formaldehydes (ureaforms and methylene ureas):

- Nitrogen content usually about 35 to 40 percent
- Slow release form of N
- Products are a mixture of urea and formaldehyde
- N release is primarily driven by microbial decomposition
- Environmental conditions influence nitrogen release by impacting microbial activity
- Urea forms usually contain more than 60 percent of N as insoluble, because they contain relatively long chained molecules, while methylene ureas usually contain 25 to 60 percent of N as insoluble, and contain relatively medium-chained-length molecules

Isobutylidene diurea IBDU

- Nitrogen content usually at least 30 percent
- Slow release form of N
- Products are a mixture of urea and isobutyraldehyde
- Nitrogen release is primarily driven by hydrolysis, which is accelerated by low soil pH and high temperatures

Polymer-coated urea:

- Nitrogen content varies with the product
- Slow release form of N
- Release rate of nitrogen depends on the product and is influenced mainly by temperature controlled breakdown of the polymer coating
- Release rate of nitrogen is more precise than most slow-release products
- Often more expensive than other forms of N

Phosphorus fertilizers

Introduction

The basic ingredient for producing P fertilizers is rock phosphate. Most rock phosphate comes from the mineral apatite, a calcium phosphate mineral that is mined out of the ground. The primary areas in the United States where rock phosphate is mined are in Florida, North Carolina, and several western States.

Most conventional P fertilizers are made by reacting rock phosphate with sulfuric acid to produce phosphoric acid. The phosphoric acid is then further processed to create many of the more common P fertilizers. The following section lists common P fertilizers and describes some of the key characteristics of each product.

Diammonium phosphate [$(NH_4)_2HPO_4$]:

- Fertilizer grade: 18–46–0
- Soluble, readily available source of P and N
- Dry fertilizer product
- Initial soil reaction can produce free NH3, which can cause seedling injury if too much fertilizer is placed near the seed
- Acid-forming fertilizer

Monoammonium phosphate ($NH_4H_2PO_4$):

- Fertilizer grade: 11–52–0
- Soluble, readily available source of P and N
- Dry fertilizer product
- Acid-forming fertilizer

Ammonium polyphosphate (NH_4PO_3):

- Fertilizer grade: 10–34–0 or 11–37–0
- Soluble, readily available source of P and N
- Liquid fertilizer product
- Popular source for starter fertilizers
- Good fertilizer source for mixing and applying with micronutrients
- Density of 10–34–0 is 11.65 pounds per gallon at 60 °F
- Density of 11–37–0 is 11.9 pounds per gallon at 60 °F

Concentrated superphosphate [$Ca(H_2PO_4)_2 \cdot H_2O$]:

- Fertilizer grade: 0–46–0
- Soluble, readily available source of P
- Dry fertilizer product
- Also called triple or treble superphosphate

Potassium chloride (KCl):

- Most abundantly used form of potassium fertilizer
- Contains 60 to 63 percent K2O
- Often referred to as Muriate of Potash
- Water soluble source of K

Potassium sulfate (K_2SO_4):

- Contains 50 to 53 percent K_2O, 18 percent S, and no more than 2.5 percent Cl
- Major use is for chloride sensitive crops

Potassium-magnesium sulfate (K_2SO_4•2MgSO$_4$):

- Contains about 22 percent K_2O, 11 percent Mg, 22 percent S, and no more than 2.5 percent Cl
- Along with the K, this product is a good source of Mg and S
- Often referred to as Sul-Po-Mag or K-Mag
- Water soluble source of nutrients

Potassium nitrate (KNO_3):

- Contains about 44 percent K_2O and 13 percent N
- All nitrogen is in the nitrate (NO_3^-) form

Sulfur, calcium, and magnesium fertilizers

Sulfur fertilizers

Sulfur is sometimes applied when other fertilizer sources are applied. For example, when ammonium sulfate is applied to supply N, plant-available S is also applied. Sulfur is taken up by plants as the sulfate ion (SO_4^{2-}), so most fertilizers that are applied in the sulfate form will be immediately available for root uptake by plants. Gypsum ($CaSO_4$) is less water soluble than the other sulfate fertilizers, but it can be an effective and efficient source of S, as well as Ca.

Sulfur that is applied in a form other than sulfate, such as elemental S, must be oxidized by S-oxidizing bacteria in the soil before the S can be taken up by plants. The oxidation of elemental S to sulfate creates acidity, so elemental S can be used as an amendment to reduce soil pH. Elemental S is quite insoluble, so it will take several weeks to reduce soil pH. Factors that will influence the rate of oxidation of elemental S include: temperature, moisture, aeration, and particle size of the fertilizer granules.

Common types of S, Ca, and Mg fertilizers are shown in table 503–17.

Calcium fertilizers

Calcium is a nutrient that is present in soils in relatively large amounts. Most soils that are deficient in Ca are acidic, so a good liming program will usually provide adequate Ca to meet most plant needs. Gypsum ($CaSO_4$) can be a good source of Ca in the unusual situation that Ca is needed but lime is not needed to increase soil pH.

Magnesium fertilizers

The most common fertilizer source of Mg is dolomitic limestone. When a soil test shows that lime is needed to raise the soil pH and soil Mg concentrations are low to marginal, apply dolomitic limestone to raise soil pH and add Mg to the soil. Limestone has a low solubility and breaks down slowly in soils; therefore, if a quick response to Mg is needed, a more soluble source of Mg fertilizer should be considered (e.g., Epsom salts).

Micronutrient fertilizers

Using micronutrient fertilizers

There are many different fertilizers that are marketed as micronutrients. Usually, micronutrients are mixed with fertilizers containing N, P, and/or K. Because there are so many brands of micronutrients, it is important to read the label to determine the source of the micronutrient in the fertilizer.

The three primary classes of micronutrient sources are:

- inorganic
- synthetic chelates
- natural organic complexes

Because micronutrients are needed in such small amounts, the best method to correct a micronutrient deficiency is usually by application of the micronutrient through foliar fertilization. It is important to remember that there is a strong relationship between micronutrient availability and soil pH; therefore, micronutrient availability can be maximized by keeping the soil pH in the correct range.

Some common types of micronutrient fertilizers are shown in table 503–18.

Table 503–17 Sulfur, Ca, and Mg fertilizer materials

Element	Name of material	Chemical composition	Percent of element	CCE*
S	Elemental sulfur	S	100.0	none
S	Ammonium bisulfate	NH_4HSO_4	17.0	none
S	Ammonium polysulfide	$(NH_4)_2S_x$	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	$(NH_4)_2S_2O_3 \bullet 5H_2O$	26.0	none
S	Gypsum	$CaSO_4$	18.6	none
S	K-Mag	$K_2SO_4 \bullet 2MgSO_4$	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	—	29.0	50–70
Mg	Dolomitic limestone	$CaMg(CO_3)_2$	3–12	95–108
Mg	Epsom salts	$MgSO_4 \bullet 7H_2O$	9.6	none
Mg	Kiserite	$MgSO_4 \bullet H_2O$	18.3	none
Mg	K-Mag	$K_2SO_4 \bullet 2MgSO_4$	11.0	none
Mg	Magnesium nitrate	$Mg(NO_3)_2$	19.0	none
Mg	Magnesia	MgO	55–60	none
Mg	Basic slag	—	3	none

* CCE (calcium carbonate equivalent) = Relative neutralizing value, assuming pure calcium carbonate at 100 percent.

Applying fertilizers

Solubility of fertilizers: liquid vs. dry

It is sometimes assumed that nutrients will be more available to plants if fertilizer is applied in a liquid form than if it is applied in a dry form. Research has shown, however, that there is generally no measurable difference in crop/plant response between a dry and a liquid fertilizer, as long as the two fertilizers are supplying the same amount of soluble nutrient.

For example, research has shown ammonium nitrate or urea (both dry fertilizers) will provide the same crop response as urea ammonium nitrate (UAN) solutions as long as the products are compared at the same rate of N. This should not be surprising considering the amount of water that is present in soils. The surface 4 inches of a silt loam soil at field capacity will normally contain more than 30,000 gallons of water. Therefore, if a dry fertilizer that is nearly 100 percent water soluble is applied to this soil, the nutrients in the fertilizer will quickly be dissolved in this very large amount of water.

A more important issue to consider when comparing fertilizer products is the **water solubility** of the product. If two products are being compared and one product has much greater water solubility than the other product, it would be expected that the product with the greater water solubility would provide a more rapid crop/plant response. Most common N, P, and K products are usually 90 to 100 percent water soluble, so little difference in response would be expected among these products, regardless of whether the products are in a liquid or dry form.

When evaluating micronutrient fertilizers, the solubility of products should be evaluated carefully because there can be a great deal of variation in the solubility of micronutrient fertilizers. If a fertilizer with low water solubility is applied to a soil, it may take several months, or even years, for the nutrient to dissolve and become available to plants.

When making decisions on the best fertilizer material to apply, the following questions should be considered:

- What is the solubility of the product?
- Based on the available equipment, does a dry or liquid product best fit the operation?

Table 503–18 Micronutrient fertilizer materials

Element	Name of material	Percent element in material
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

- What products are available from local fertilizer dealers?
- What is the cost of those materials that are available?

Fertilizer placement and application methods
There are many methods that can be used for applying fertilizers. Understand the relative merits of each before deciding the most cost effective and efficient method for application is important. For some nutrients and situations, multiple methods can be equally effective when applying fertilizers.

- One common method of application is broadcast applications, which simply means that the fertilizer (either dry or liquid) is spread uniformly over the surface of the soil. This method of application is generally preferred for plants that are actively growing over most (or all) of the soil surface, such as turfgrasses, pastures, alfalfa, clovers, winter wheat, and winter barley. For certain situations where nutrients (e.g., P) can be fixed or tied-up by soils, broadcast applications can be an inefficient method of application because there is much greater soil to fertilizer contact resulting in more fixation or tie-up of the nutrient.
- Band application is another common method of applying fertilizers. Using this method, fertilizer is applied in a concentrated band either on the soil surface or below the soil surface. One common band application method is banding starter fertilizer near the seed to supply available nutrients as the seed germinates and the plant begins to grow. For row crops, banding is generally the most efficient method for applying micronutrient fertilizers.
- Banding has been shown to be the most efficient method of applying P to row crops on soils that are low or deficient in P. On soils with low available P, it has been shown that only 50 percent as much band-applied fertilizer is required to get the same crop response as fertilizer applied broadcast. If P is simply being applied to maintain soil test levels and a direct crop response is not expected, little difference should be expected between broadcast or banded applications.
- Another common form of banding is the application of sidedress nitrogen on corn where UAN fertilizers are applied in a band that is either injected into the soil or dribbled on the soil surface, or where anhydrous NH_3 is injected. Any time that anhydrous NH_3 is applied as a fertilizer it must be injected into the soil to prevent loss of the gaseous NH_3. The UAN fertilizers are banded when sidedressed because UAN will cause severe burning of the plant leaves if applied directly to the leaves, and because broadcast applications of urea fertilizer have a greater risk of loss through NH_3 volatilization than banded applications.
- Foliar application of fertilizers is an efficient method of micronutrient application. If a visual micronutrient deficiency is observed, micronutrient fertilizers should be foliar applied as soon as possible. Typically, the greater the degree of the deficiency, the less likely it is that the deficiency can be completely corrected with foliar fertilization. If a micronutrient deficiency occurs nearly every year in the same location, it may be cost-effective to either apply a band application of micronutrient at planting or apply a preventative foliar application of fertilizer before deficiency symptoms appear. Research has shown that foliar applications of macronutrients are generally not cost effective because plants' requirements for macronutrients are greater than the amount that can be taken up through the plant leaves.
- Fertigation is the application of fertilizers by injecting fertilizer into irrigation water. The most common use of fertigation is in applying nitrogen to crops that require significant quantities of nitrogen (e.g., corn). It is also possible to apply micronutrient fertilizers through fertigation. Applying nitrogen fertilizers through fertigation can be one of the most efficient methods of nitrogen application because this method applies a small amount of nitrogen to an actively growing crop. Because the crop is actively growing and because relatively small amounts of nitrogen are applied (i.e., 20 to 30 lb N/a), the loss potential of nitrogen through leaching or denitrification is minimized. Efficient application of fertilizers through fertigation, however, assumes that the irrigation system is uniformly

applying water and is not applying water at rates greater than needed by the growing crop.

Timing of application

Understanding crop nutrient-use patterns and nutrient/soil interactions are important for optimizing fertilizer timing. If soils are low in P or K and have a tendency to fix these nutrients, it is important to apply these nutrients as close to planting as possible to minimize fixation. If fixation is of no concern, timing of application for P and K is generally not that important.

Timing of application can be critical for optimal efficiency of nitrogen fertilizers. Soils that are prone to leaching (i.e., coarse-textured sandy soils) or denitrification should receive applications of nitrogen just prior to rapid nitrogen uptake by the plant for optimal efficiency. For example, corn usually begins rapid uptake of nitrogen when it is 12 to 18 inches tall. Applying nitrogen as closely as possible to the time of rapid uptake will minimize the risk of nitrogen loss to the environment and maximize nutrient-use efficiency by the corn crop.

Calculating fertilizer rates

- Calculating how much N, P, or K is in a particular fertilizer:

  A fertilizer label identifies the percent by weight of N, P_2O_5, and K_2O in the fertilizer.
  - — 60 pounds of a 21–5–7 fertilizer would contain 13.2 pounds of N (60 ×0.21), 3 pounds of P_2O_5 (60 ×0.05), and 4.2 pounds of K_2O (4.2 ×0.07).

- Calculating how much fertilizer to apply for a specific amount of nutrient:

  The basic formula for calculating how much fertilizer to apply to a given area for a specific amount of nutrient is the following:

$$\text{Amount of fertilizer} = \frac{\text{Amount of nutrient needed}}{\text{Percent nutrient in the fertilizer}}$$

  - — How much 34–0–0 is needed to apply 30 pounds of N? 88 pounds (30 ÷ 0.34) of 34–0–0
  - — If 15–8–10 was used to apply 45 pounds of N, how much P_2O_5 and K_2O would be applied with this application? 300 pounds (45 ÷ 0.15) of 15–8–10 to apply 45 pounds of N Therefore, a 300 pound application of 15–8–10 would supply 24 pounds of P_2O_5 (300 × 0.08) and 30 pounds of K_2O (300 × 0.10).

- Calculating rates of liquid fertilizers:

  When doing fertilizer calculations with liquid fertilizers, the calculations are similar but the density of the liquid fertilizer must be known before doing any calculations.

  - — Example: If a jug contains 2 gallons of a 9–18–6 liquid fertilizer that weighs 11.1 pounds per gallon, how much N, P_2O_5, and K_2O would be in this jug of fertilizer? First, calculate how much fertilizer is present in the 2 gallons. There would be 22.2 pounds of fertilizer (11.1 lb/gal × 2 gal). So, there would be 2 pounds of nitrogen (22.2 × 0.09), 4 pounds of P_2O_5 (22.2 × 0.18), and 1.3 pounds of K_2O (22.2 ×0.06) in this 2 gallon container of fertilizer.

- Calculating the amount of fertilizer needed for a specific area of land:

  - — *Pounds per acre:*
    For example, how much urea (46–0–0) is needed to apply 135 pounds of nitrogen to 30 acres of land (1 acre = 43,560 ft^2)?

    Begin by calculating how much urea is needed to provide 135 pounds of nitrogen per acre. This would be 293.5 pounds (135 ÷ 0.46). So, the total urea needed for 30 acres would be 8,804 pounds (293.5 × 30) or 4.4 tons (there are 2,000 pounds in a ton).

  - — *Pounds per 1000 square feet:*
    For turfgrasses or horticultural crops, fertilizer is often applied in pounds of nutrient per 1000 square feet. For example, how much ammonium sulfate (21–0–0) is needed to supply 1 pound of N per 1000 square feet to a lawn that is 7,500 square feet?

    It would take 4.76 pounds of ammonium sulfate to supply 1 pound of (1 ÷ 0.46). Therefore, it would take 35.7 pounds ((7,500 ÷ 1000) ×4.76) of ammonium sulfate for this lawn.

- Calculating fertilizer costs

  Bulk fertilizer is often sold by the ton; therefore, it is important to know how to convert the cost per ton to the cost per unit of a specific nutrient so that price comparisons can be made between various fertilizer choices.

  — *Example 1:*
  Urea (46–0–0) is currently selling for $340 per ton, ammonium sulfate (21–0–0) is selling for $240 per ton, and UAN (30–0–0) is selling for $204 per ton. What is the price of each of these fertilizers when priced per unit of N?

  There are 920 pounds (2000 × 0.46) of nitrogen in a ton of urea, 420 pounds (2000 × 0.21) of nitrogen in a ton of ammonium sulfate, and 600 pounds (2000 × 0.3) of nitrogen in a ton of this UAN. This means that the cost per pound of nitrogen is $0.37 for urea ($340 ÷ 920), $0.57 for ammonium sulfate ($240 ÷ 420), and $0.34 for UAN ($204 ÷ 600).

  — *Example 2:*
  Diammonium phosphate (18–46–0) is currently selling for $280 per ton. What is the cost per pound of nitrogen and per pound of P_2O_5?

  A ton of 18–46–0 contains 360 pounds of nitrogen (2000 × 0.18) and 920 pounds of P_2O_5 (2000 ×0.46); therefore, the cost per pound of nitrogen is $0.78 ($280 ÷ 360), while the cost per pound of P_2O_5 is $0.30 ($280 ÷ 920). This example demonstrates that if nitrogen is the only nutrient needed, diammonium phosphate would be an expensive fertilizer choice. However, if P and nitrogen are both needed by the crop, then diammonium phosphate would be an excellent fertilizer choice because the P and some of the nitrogen required by the crop would be supplied by the same fertilizer. Diammonium phosphate is typically used to meet the P need rather than the nitrogen need of a crop. The nitrogen supplied by diammonium phosphate application is then deducted from the crop's nitrogen requirement.

  — *Example 3:*
  If liquid ammonium sulfate (8–0–0–9) is selling for $90 per ton and UAN (30–0–0) is selling for $204 per ton, what is the cost per gallon of each of these products knowing that 8–0–0–9 weighs 10.14 pounds per gallon and 30–0–0 weighs 10.84 pounds per gallon?

  One ton of 8–0–0–9 would consist of 197.2 gallons (2000 ÷ 10.14), while a ton of 30–0–0 would consist of 184.5 gallons (2000 ÷ 10.84); so, one gallon of 8–0–0–9 ($90 ÷ 197.2) would cost $0.46 and one gallon of 30–0–0 would cost $1.11 ($204 ÷ 184.5). The cost per pound of nitrogen for each of these products would be $0.57 [0.46 ÷ (10.14 lb/gal × 0.08)] for the 8–0–0–9 and $0.34 [$1.11 ÷ (10.84 lb/gal × 0.3)] for the 30–0–0.

Liming materials

Introduction

Maintaining soil pH in the proper range is important to the optimal growth of plants. If soil pH drops below about 5.5, Al begins to become soluble in soils. The amount of soluble Al increases dramatically as the soil pH continues to drop. Many plants do not grow well when large amounts of Al are present in the soil solution, so lime must be added to these soils to prevent soil pH from getting too low. An understanding of liming materials is important when deciding the type of lime to use.

Limestone is a naturally occurring mineral resulting from the deposition and compression of the skeletal remains of marine organisms (e.g., coral, shellfish, etc.), and it contains high amounts of calcium and magnesium carbonates. Because limestone is a naturally occurring mineral, there are varying degrees of purity and chemical composition. Pure calcium carbonate ($CaCO_3$) has been assigned an arbitrary index of 100 to define its neutralizing value. All liming materials are then compared to pure $CaCO_3$ and rated on their neutralizing ability relative to pure $CaCO_3$. This rating, referred to as the calcium carbonate equivalency (CCE), is assigned to all liming materials. 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.

The property that distinguishes lime from other calcium or magnesium bearing materials is that lime contains calcium and/or magnesium in forms that, 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 calcium and magnesium can be used for liming purposes. For example, calcium and magnesium sulfates and chlorides will supply calcium and magnesium, but will not reduce soil acidity.

The carbonates, oxides, and hydroxides of calcium and magnesium are only sparingly soluble in water. These materials require soil acidity in order to react, and the reaction is fairly slow due to their low solubility. Burned lime and hydrated lime are highly reactive and react quickly with soil acidity. To obtain the greatest benefit from these materials, especially at higher rates of application, they should be thoroughly mixed with the soil by disking and/or plowing.

Calcitic and dolomitic lime

Calcitic and dolomitic limes are made by grinding or crushing mined limestone rock to a certain fineness. The degree of fineness must be specified when sold. In order to be useful as an agricultural liming material, crushed limestone must react with soil acids within 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. Dolomitic lime contains both magnesium and calcium, whereas calcitic lime contains mainly calcium. The CCE of these limes is similar (table 503–17).

Acid soils that are deficient in magnesium should be treated with dolomitic limestone. Calcitic lime should be used on acid soils where the ratio of soil test calcium to magnesium is less than 1.4. Either dolomitic or calcitic lime may be used in all other situations.

Calcium oxide or burned lime

Calcium oxide, or burned lime, is made by roasting crushed limestone in an oven or furnace. This process changes the chemical form of Ca 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 but usually ranges from 150 to 175. No other liming material has such a high neutralization value. Approximately 1,140 pounds of burned lime with a CCE of 175 is equivalent to 2,000 pounds of calcitic lime with a CCE of 100.

Burned lime is usually 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 is somewhat difficult to mix with the soil. Thorough mixing at the time of application is necessary due to a tendency for burned lime to absorb moisture, resulting in the formation of lime granules or aggregates.

Hydrated lime

Hydrated lime is calcium hydroxide but is usually called slaked or builders' lime. This type of lime is made by reacting burned lime with water and drying the resulting calcium hydroxide. Hydrated lime is similar to burned lime in that it is powdery, reacts quickly, and is unpleasant to handle. The CCE ranges from 110 to 135 depending on the purity of the burned lime.

Marl

Marls are found in beds, mixed with earthen materials, in the form of calcium carbonate. These calcium 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 the CCE, which usually ranges from 70 to 90, and the cost of processing into usable material. Marls are usually low in magnesium, and their reaction within the soil is similar to calcitic lime.

Slags

Slag is a by-product of the steel industry and consists primarily of calcium silicate minerals. Slags can make a good liming material, but most slags have a lower CCE than calcitic lime, requiring the use of a higher rate.

One important note about slags is that they can sometimes contain significant quantities of heavy metals. Thus, it is important to know the composition of the slag before using the material as a soil amendment.

Ground oyster shells

Oyster shells and other sea shells are composed primarily of calcium carbonate. These materials can work well as liming materials. As with any lime, the fineness of the material and the CCE will determine the appropriate rate to apply to a soil for proper pH adjustment.

Particle size of liming materials
Fineness, or mesh size, of applied lime is the main factor that influences the rate of reaction. All of the lime applied does not need to react with the soil immediately to be of maximum value. The coarser mesh sizes dissolve over a longer period of time and in so doing, tend to maintain soil pH.

A certain amount of lime should be sufficiently fine (pass an 80-mesh sieve) to react rapidly with the soil acidity. Part of the lime should be sufficiently fine (about 40 to 60 mesh) to react within one to two years, and the remainder of the lime should be large enough (about 20 mesh) to react 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 that is pulverized to 100 mesh, or finer, will react 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 have a much finer mesh than the ground limestone 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.

503.24 Animal manure

Introduction

Manure is an important agricultural by-product and may be a potentially valuable source of nutrients containing N, P, and K. Depending upon the type of manure and the characteristics of the animal feeding operation, it may also contain other essential nutrients such as calcium (Ca), sulfur (S), boron (B), magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn). Although animal manure has historically been applied to agricultural land in areas where animals are produced, its nutrient content has often been discounted or ignored in nutrient management.

Manure is an unavoidable by-product of animal production. Manure can be a valuable source of nutrients for crop production when properly managed; however, improper management of manure can result in environmental degradation, damage to crops, and conflicts with neighbors and the public because of odors, pests, or other nuisances.

Proper management of manure must consider all aspects of the operation, including how and where manure is generated, how it is stored, and how it is ultimately used. Although there are various alternative uses for manure (e.g., biogas generation), this chapter will address the issues of manure production, storage, and land application for managing manure as a nutrient source for crops.

Manure production and composition

Quantity of manure produced
The quantity (volume or mass) of manure produced and its nutrient content are the most critical factors that govern its use as a nutrient source. The quantity of manure produced varies considerably among species because of differences in animal diets and metabolism and within species due primarily to differences in management (e.g. bedding, feed source). Estimates of dry and semi-solid manure production by species have been summarized by Tetra Tech, Inc. (table 503–19).

Variation in manure NPK content among species
Animals are relatively inefficient in their utilization of N, P, and K from feed, with more than 50 percent commonly passing through to the feces. These nutrients may end up in the manure and, in the case of N, be lost to the atmosphere. In addition to variability in feed conversion efficiency, the amount and type of bedding (if any) will also influence the nutrient content of the material.

As might be expected, the quantity of nutrients in the manure varies considerably by species (table 503–20). For example, broiler litter may contain four to five times as much N, and ten times as much P, as horse manure.

See table 503–21 Poultry litter moisture and nutrient values from 2,054 samples in Arkansas (Van Devender et al., 2004) for poultry litter nutrient levels by moisture content.

Improving the digestibility of P

Deviations from the nutrient content values listed above may occur for a number of reasons. One of the most important reasons is diet manipulation. Cereal grains (such as corn and soybeans) are major feed ingredients in poultry and swine diets (National Research Council, 1994). Approximately two-thirds of the P in these grains is in the form phytic acid, or phytate, that is poorly-digested by non-ruminants. This results in inefficient use of most of the grain-P, which subsequently passes through the animal in the manure. Because of this poor utilization, non-ruminant diets commonly are supplemented with more digestible forms of P, such as calcium phosphate (Angel et al., 2001).

One technique to increase the digestibility of P in feed grains is to add phytase to the feed. Phytase is an enzyme that helps the birds utilize more of the indigestible P, which reduces the need for supplemental P. Research has shown reductions in P excretions of 25 to 50 percent when phytase is added to poultry or swine diets and supplemental P (e.g., calcium phosphate) is reduced (Maguire et al. 2005; Nahm 2002). Hansen et al. (2005) found that the recent adoption of phytase has lowered the P content of poultry litter in Delaware by 30 to 40 percent compared to traditional values.

Table 503–19 Annual manure production estimates for various species (Tetra Tech, Inc., 2004)

Species	Animals per AU [a/]	Annual manure production per AU
	— 1000 lb —	— tons —
Beef cattle	1.00	11.50
Dairy cattle	0.74	15.24
Swine (breeders)	2.67	6.11
Swine (other)	9.09	14.69
Hens (laying)	250.00	11.45
Pullets (over 3 months)	250.00	8.32
Pullets (under 3 months)	455.00	8.32
Broilers	455.00	14.97
Turkey (slaughter)	67.00	8.18

a AU = animal unit

Table 503–20 Nutrient content of various types of manure

Manure type	Nitrogen (total)	Phosphorus (P_2O_5)	Potassium (K_2O)
	-------------------lb/ton -----------------		
Broiler litter [b/]	59	63	40
Turkey (fresh) [a/]	27	25	12
Layer [a/]	35	42	28
Horse [b/]	9	6	11
	----------------lb/1000 gal ---------------		
Swine [b/]	40	37	23
Dairy [b/]	28	19	25

a Zublena et al. 1990
b Bandel 1990

Other nutrients in manure

Manure is usually managed to provide the three major plant nutrients (N, P, and K). However, varying amounts of other essential elements, including Ca, S, B, Mg, Mn, Cu, Mo, Fe, Na, and Zn, enhance the value of manure as a balanced nutrient source. Tables 503–22 and 503–23 contain typical concentrations of secondary and micro-nutrients of various poultry and swine manures, respectively.

Manure sampling and testing

It is important to realize that actual manure nutrient content can be dramatically different from typical values. Testing of manure from specific operations is critical to accurately assess nutrient concentrations for the purpose of calculating manure application rates to supply crop nutrient needs.

Table 503–21 Poultry litter moisture and nutrient values from 2,054 samples in Arkansas (Van Devender et al. 2004)

	Moisture content	Nitrogen (total)	Phosphorus (P_2O_5)	Potassium (K_2O)
	------ percent-----		------------lb/ton -----------	
Minimum	2	22	18	23
Maximum	47	98	96	80
Mean	23	60	58	52

Table 503–22 Typical content of secondary and micronutrients in poultry manures (Zublena et al. 1990)

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	0.5	0.27	0.05	<0.01	0.32	0.04
Highrise stored	86.0	6.0	8.8	5.0	1.8	0.52	0.05	<0.01	0.37	0.04
Broiler litter										
Broiler house	41.0	8.0	15.0	13.0	1.3	0.67	0.05	<0.01	0.63	0.45
Roaster house	43.0	8.5	14.0	13.0	1.6	0.74	0.05	<0.01	0.68	0.51
Breeder house	94.0	6.8	8.5	8.6	1.3	0.57	0.04	<0.01	0.52	0.21
Stockpiled	54.0	8.0	12.0	6.2	1.5	0.59	0.04	<0.01	0.55	0.27
Turkey litter										
Brooder house	28.0	5.7	7.6	5.9	1.4	0.52	0.05	<0.01	0.46	0.36
Grower house	42.0	7.0	10.0	8.4	1.3	0.65	0.05	<0.01	0.64	0.51
Stockpiled	42.0	6.8	9.5	6.4	1.5	0.62	0.05	<0.01	0.56	0.34
					lb/1000 gal					
Layer										
Liquid slurry	35.0	6.8	8.2	5.3	2.9	0.42	0.01	0.02	0.43	0.08
Lagoon sludge	71.0	7.2	12.0	1.2	2.2	2.3	0.08	0.01	0.80	0.14
					lb/acre-inch					
Layer										
Lagoon liquid	25.0	7.4	52.0	51.0	2.0	0.24	0.4	0.02	0.70	0.19

Table 503–23 Typical content of secondary and micronutrients in swine manures (Zublena et al. 1990)

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	0.04	0.07	<0.01	0.12	0.03
Paved lot scraped	12.0	2.3	2.2	1.6	1.03	0.19	0.02	<0.01	0.35	0.15
					lb/1000 gallons					
Liquid slurry	8.6	2.9	4.7	3.7	0.7	0.15	0.07	<0.01	0.39	0.11
Lagoon sludge	15.8	4.5	8.3	2.9	1.8	0.28	0.02	0.01	0.67	0.23
					lb/acre-inch					
Lagoon liquid	25.5	8.3	10.0	57.7	2.4	0.34	0.18	<0.01	1.50	0.30

A manure sample must be collected for laboratory analysis in order to determine the exact nutrient content. Proper collection of this sample is critical to ensure that it accurately represents the manure to be used.

Detailed sampling and handling procedures

In practice, it is difficult to obtain a truly representative sample because of the inherent variability in manure within a stockpile, a lagoon, or other storage facility. The following guidelines (adapted from Hermanson 1996) will help to assure the best sample possible:

- Semi-solid lot manure:
  - Scraped directly from lot into spreader:
    – Collect about 2 pounds of manure using nonmetallic collectors from different locations within a loaded spreader.
  - From storage:
    – Collect manure using nonmetallic collectors from under the surface crust while avoiding bedding materials.
- Liquid manure slurry:
  - From under-slotted-floor pit:
    – Extend a half-inc nonmetallic conduit open on both ends into manure to pit floor.
    – Seal upper end of conduit by placing a thumb over open end to trap manure, remove and empty slurry into plastic bucket or nonmetallic container.
    – Take subsamples totaling at least 1 quart from 5 or more locations.
  - From exterior storage basin or tank:
    – Ensure that manure has been well mixed with a liquid manure chopper-agitator pump or propeller agitator.
    – Take subsamples from 5 pit locations from agitator pump or from manure spreader, and place in a plastic bucket.
- Lagoon liquid:
  - Recycled liquid:
    – Collect recycled lagoon liquid from inflow pipe to flush tanks in a nonmetallic sample container.
  - From lagoon:
    – Place a small bottle (1/2 pint or less) on end of 10- to 15-foot pole.
    – Extend bottle 10 to 15 foot from bank edge.
    – Brush away floating scum or debris.
    – Submerge bottle within 1 foot of liquid surface.
    – Empty into a plastic bucket, repeat 5 times around lagoon, and mix.
- Broiler or turkey litter:
  - House litter:
    – Visually inspect litter for areas of varying quality (e.g., areas around feeders and waterers), and estimate percent of floor surface in each area.
    – Take 5 litter subsamples at representative locations representative of overall litter characteristics.
    – At each location, collect litter from a 6- by 6-inch area to earth floor and place in a plastic bucket.
    – Mix the 5 subsamples in the bucket transfer to a nonmetallic sample container, such as a 1-gallon freezer bag, and seal.
  - From stockpile:
    – Collect subsamples from 5 locations at least 18 inches into pile.
    – Mix, transfer 2 to 3 pounds to nonmetallic sample container, and seal.

Manure samples should be either refrigerated or sent immediately to the testing laboratory. Glass containers should never be used because pressure from developing gases may fracture the glass.

Manure storage and handling

Nutrient loss

The nutrient content of manure, particularly nitrogen, can change during storage; therefore, sampling and analysis should be performed as close to the time of application as possible. Changes in nutrient content can occur due to dilution (e.g., rainwater entering a liquid storage system), settling (e.g., phosphorus precipitation and accumulation in lagoon sludge), or gaseous loss (e.g., nitrogen volatilization).

Some typical storage-related losses of nitrogen, P, and K for various manure systems are presented in table 503–24. The losses were calculated by subtracting the nutrient contents after storage from “as-excreted” values so they include both storage and handling losses. Handling losses likely account for a consistent, but small, amount of nutrient loss.

Except for lagoons, losses of P and K during storage are relatively low and are likely due more to handling than actual storage. Large losses occur in lagoon systems as solids settle from the slurry to the bottom of the lagoon. By contrast, nitrogen losses during storage can range from 15 percent to as much as 90 percent. Note that the ranges can be fairly broad and actual losses may exceed the tabulated ranges due to differences in management, weather, and mitigation strategies.

Estimating nutrient loss during storage

Nutrient losses during storage are commonly estimated with the use of a standard loss factor for each type of storage (table 503–25). Such calculations can be helpful for planning purposes, but it is best to test the manure before using it to supply plant-available nutrients. Enter total manure nutrients produced (from table 503–20) in columns 2, 5, and 8 and multiply by the relevant factor for the storage or management system.

Note: Determining the storage needs of the various types of operations is beyond the scope of this manual; however, there are some general factors that should be considered in essentially any situation where manure is stored before being applied to land. These considerations include the characteristics of the land (i.e., slope, vegetation, soil type, proximity to water) and the type of manure to be used (i.e. liquid, semi-solid, or solid).

Information regarding siting and sizing of storage facilities can be found in the NRCS Field Office Technical Guide available in electronic form for individual States at: http://www.nrcs.usda.gov/technical/efotg/.

Land application of manure

Introduction

Most manure generated by agricultural operations is applied to soils as a nutrient source for crop production. Manure has also been found to improve certain soil properties, including soil structure, water-holding capacity, and populations of beneficial organisms.

It is critical both from crop production and environmental perspectives that the application rates provide adequate nutrient levels while avoiding the application

Table 503–24 Typical manure losses during handling and storage (Fulhage and Pfost 2002)

Manure system	Nitrogen	Phosphorus (P_2O_5)	Potassium (K_2O)
	------------------percent lost-----------------		
Solid			
Daily scrape and haul	20–35	5–15	5–15
Manure pack	20–40	10–20	10–20
Poultry, deep pit or litter	25–50	5–15	5–15
Solids on open lot			
Scrape once/year	40–55	20–40	30–50
Daily scrape and haul	20–35	10–20	15–25
Separated solids, 90 days storage	30	10–20	10–20
Liquid (slurry)			
Anaerobic pit	15–30	5–20	5–20
Aboveground storage	10–30	5–15	5–15
Manure basin or runoff pond, 120–180 days storage	20–40	5–50	5–50
Liquid-lagoon	70–85	50–80	30–80
Lagoon, 365 days	90	50–80	30–80

of excess nutrients that can leave the field via runoff or leaching. Over application of manure has been linked to environmental problems, including eutrophication.

Manure is usually managed to provide the three major plant nutrients: N, P, and K. The goal of proper manure management for crop production is to apply the manure using appropriate methods and rates to maximize the amount of land-applied nutrients that are taken up by plants.

Availability of manure nutrients to plants

The plant-availability of the P and K in manure is commonly assumed to be similar to the availability of these nutrients in commercial fertilizer because most of the P and K in land-applied manure are present in inorganic forms. Determining the availability of P and K is a relatively simple matter of determining the P and K content of the manure. By contrast, determining the availability of nitrogen in manure is more complicated.

Forms of nitrogen in manure

Nitrogen in manures is found in two forms: organic and inorganic (fig. 503–18). Organic nitrogen is the fraction in dead plant and animal material and is found primarily in amine groups ($–NH_2$) and uric acid. Inorganic manure nitrogen can be either ammonium (NH_4^+) or nitrate (NO_3^-). The most common form of inorganic nitrogen in manure is ammonium, which is specified in most laboratory analyses.

Estimating nitrogen mineralization rate

The inorganic fraction, which can comprise 20 to 65 percent of the total quantity of nitrogen in manure (table 503–26), is considered immediately available to plants. The organic fraction must first be converted to inorganic N: a process termed mineralization. The rate at which the organic nitrogen is mineralized is highly variable and influenced by factors such as temperature, moisture, and C:N ratio of the manure. Despite this variability in mineralization rate, researchers have adopted some general mineralization factors that are

Table 503–25 Estimating annual nutrient availability after losses from open lot, storage or lagoon[a/]

Manure storage/treatment system	Nitrogen			Phosphorus (P_2O_5)			Potassium (K_2O)		
	N produced	Factor [b/]	Available N	P produced	Factor [b/]	Available P	K produced	Factor [b]	Available K
Example: poultry manure on sawdust; per ton (from table 503–21)	60	× 0.50	30	58	× 1.0	58	52	× 1.0	52
Open lot or feedlot		× 0.50			× 0.95			× 0.70	
Storage (slurry manure, bottom loaded storage)		× 0.85			× 1.0			× 1.0	
Storage (liquid manure, top loaded storage)		× 0.70			× 1.0			× 1.0	
Storage (pit beneath slatted floor)		× 0.75			× 1.0			× 1.0	
Poultry manure in pit beneath slatted floor		× 0.85			× 1.0			× 1.0	
Poultry manure on shavings or sawdust held in house		× 0.50			× 1.0			× 1.0	
1-cell anaerobic treatment lagoon		× 0.20			× 0.35			× 0.65	
Multi-cell anaerobic treatment lagoon		× 0.10			× 0.35			× 0.65	

a Source: University of Nebraska
b Multiplication factor: the portion of nutrients retained in the manure or effluent

commonly employed to estimate nitrogen availability for various types of manure during the season following the application (table 503–27). These factors represent the percentages of the organic fraction that are expected to become available to plants during the first year after application of manure.

Sources of volatilizable N

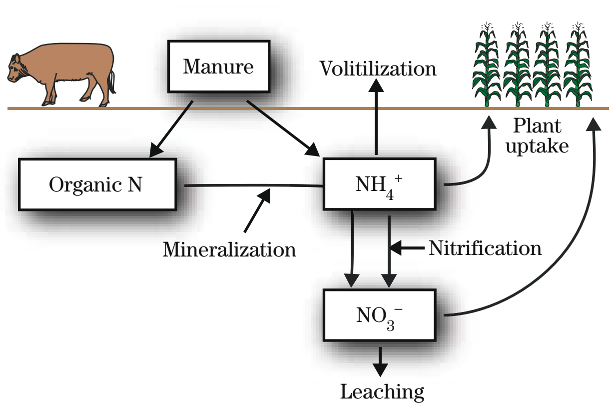
Volatilization is the loss of nitrogen as ammonia gas (NH_3). There are two major pathways for this loss in agriculture: conversion of ammonium-N (NH_4^+–N) to NH_3 and the conversion of urea ($CO(NH_2)^2$) to NH_3. Urea is a nitrogen-containing compound that is readily converted to ammonia upon catalysis by the ubiquitous enzyme urease via the following reaction:

$$CO(NH_2)_2 + H_2O + \text{urease} \rightarrow 2NH_3 + CO_2$$

Effect of soil pH on nitrogen volatilization

The most important factor influencing nitrogen volatilization of reduced inorganic nitrogen (i.e., ammonium and ammonia) in manure is pH (fig. 503–19). Nearly all of these nitrogen forms are present as ammonium at pH levels typically encountered in soils (i.e., <6.5). The percentage of ammonia increases and volatilization losses are more likely to occur as pH rises. This equilibrium is typically shifted toward am-monia in freshly excreted manures, which have higher pH values than soil.

Figure 503–18 Partial nitrogen cycle showing the forms and transformations of nitrogen in manure



Effect of incorporation on nitrogen volatilization

The best way to minimize nitrogen volatilization losses from applications of manure is incorporation. Table 503–28 shows the volatilization factors that can be used to predict losses of ammonia under three different application scenarios. This factor should be multiplied by the manure ammonium/ammonia content to predict plant-available N.

Calculating plant-available nitrogen

The amount of nitrogen available to crops during the first year following application of manure is referred to as plant-available nitrogen (PAN). PAN is the total

Table 503–26 Average percentage of forms of nitrogen in different types of manure in Virginia (Virginia Department of Conservation and Recreation 1993)

Manure type	Organic N	Inorganic nitrogen (NH_4^+)
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

Table 503–27 Fraction of organic nitrogen mineralized from various manure types and application scenarios in the year of application (Virginia Department of Conservation and Recreation 2005)

Manure type	Spring or early fall applied [a] grass	Winter topdress or spring grass residual [b]	Perennial
	---------- N mineralization factor ---------		
Dairy or beef	0.35	0.20/0.15	0.35
Swine	0.50	0.25/0.25	0.50
Poultry	0.60	0.30/0.30	0.60

a Factors for manure applied in spring for summer annual crops or in early fall for small grain crops

b Factors for manure applied in early winter/available in spring of the inorganic nitrogen (primarily ammonium, or NH_4^+–N) and the percentage of the organic nitrogen that will mineralize during the growing season.

Step 1: Determine the amount of organic and inorganic nitrogen in your manure. Most manure analyses do not provide this information directly. Instead, they give the total amount of N, usually as total Kjeldahl nitrogen (TKN), and the inorganic N (NH_4^+–N) present (as pounds of nutrient per ton or per 1,000 gallons) in the sample. To determine the organic fraction, simply subtract the NH_4^+–N value from the TKN value:

TKN–NH_4^+–N = Organic N

Step 2: Estimate the amount of organic nitrogen that will mineralize during the first year. This is calculated by multiplying your value for organic nitrogen by a mineralization factor. Table 503–27 can be used to obtain a mineralization factor that matches a particular manure type. Take the organic N value (from step 1) times the mineralization factor (from table 503–27) and that equals the organic N available in year 1 (lb/ton or lb/1000 gal).

Organic N × Mineralization factor = Organic N Available First Year

Step 3: Estimate the amount of NH_4^+–N that will be available following land application. This can be estimated using the volatilization factors from table 503–10.

NH_4^+–N ×volatilization factor = available NH_4^+–N (lb/ton or lb/1000 gal)

To calculate PAN, simply add the organic nitrogen available the first year (from step 2) to the available ammonium-nitrogen (NH_4^+–N) available (from step 3).

Step 4: Available NH_4^+–N + organic available year 1 = PAN (lb/ton or lb/1,000 gallons)

Equipment calibration

The information in the preceding sections will be useless if the manure is not applied uniformly and at a known rate. Proper calibration of manure application equipment is a critical part of manure and nutrient management.

Figure 503–19 The NH_3/NH_4^+ (ammonia to ammonium) ratio as a function of pH (adapted from Gay and Knowlton 2005)

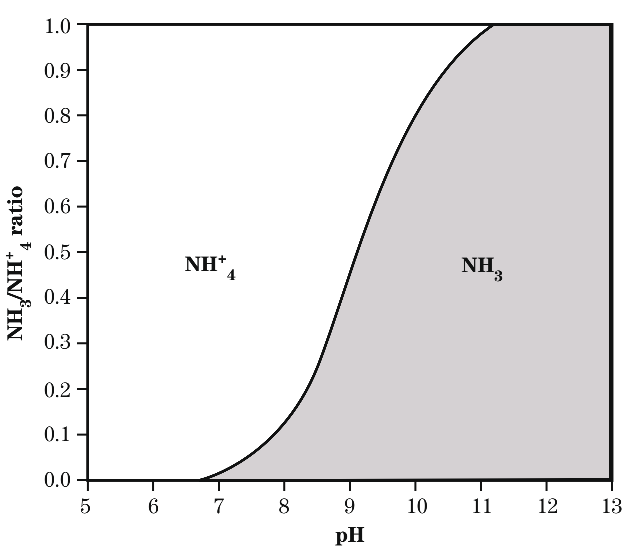


Table 503–28 Manure ammonium-N availability factors for Virginia (Virginia Department of Conservation and Recreation 2005)

Application method	Semi-solid manure	Liquid slurry	Lagoon liquid	Dry litter
	---------- N availability factor ------			
Injection	—	0.95	0.95	—
Broadcast with immediate incor poration	0.75	0.75	0.90	0.90
Incorporated after 2 days	0.65	0.65	0.80	0.80
Incorporated after 4 days	0.40	0.40	0.60	0.65
Incorporated after 7 days or never incorpo¬ rated	0.25	0.25	0.45	0.50
Irrigation without incorporation	—	0.20	0.50	—

Regardless of the design of the equipment or type of manure, manure application equipment can be calibrated in one of three basic ways (Koelsch 1995):

- *The tarp method*—Place a tarp flat on the field, spread manure on the tarp, weigh the manure, and calculate the application rate.
- *The swath and distance method*—Determine the swath width and distance traveled to empty the spreader and calculate the rate based on area covered and the weight of the load.
- *The loads-per-field method*—Simply count the number of loads of manure applied and divide by the numbers of acres.

Note: For each of the calibration methods, it is critical that all of the controllable variables (i.e., equipment speed, gate settings, type and consistency of manure) remain constant.

Calibrating with the tarp method

The tarp method consists of placing a tarp (or plastic sheet) on the ground and using the manure spreader to spread the manure on the tarp. The collected manure is weighed, and the application rate is determined from the weight of the manure collected and the area of the plastic sheet or tarp used. This measurement should be repeated at least three times and the results averaged to ensure a consistent application rate.

Table 503–29 provides conversion factors to easily calculate the application rate based on the quantity of manure collected and some common tarp sizes. Alternately, the rate can be calculated by simply dividing the number of pounds of manure collected by the area (in square feet) of the tarp. The result will be the pounds of manure per square foot. This number can be multiplied by 21.78 to give the tons per acre.

Example: You have an 8 by 8 foot tarp and collect 8.8 pounds of manure on the tarp. The calculation would be:

$$\frac{8.8\text{ lb}}{64\text{ ft}^2}\left(8\text{ ft}\quad 8\text{ ft} = 64\text{ ft}^2\right) = 0.1375\text{ lb/ft}^2$$

$$0.1375\text{ lb/ft}^2\quad 21.78 = 3\text{ tons/acre applied}$$

Calibrating with the swath and distance method

Calculations for determining application rate for the swath and distance method are similar to those used for the tarp method above. First, determine the weight of a load of manure either by direct measurement (i.e., weighing) or by converting from volume measurement. Many applicators are rated by bushel or cubic foot capacity. Second, determine the width of the application swath and the distance required to apply the load. From this point, the calculations are identical to those used in the previous method.

Example: You have a spreader that holds 7000 pounds of manure (3.5 tons). Your application width is 35 feet and the equipment travels 1200 feet along a field to empty the load. The calculation would be:

$$\frac{7000\text{ lb}}{42{,}000\text{ ft}^2}\left(35\text{ ft}\quad 1200\text{ ft} = 42{,}000\text{ ft}^2\right) = 0.1667\text{ lb/ft}^2$$

$$0.1667\text{ lb/ft}^2\quad 21.78 = 3.63\text{ tons/acre applied}$$

Calibrating with the loads-per-field method

The loads-per-field method is the easiest to calculate. The major drawback of this method is that it is an after the fact calculation so that the applicator does not have the opportunity to make adjustments in the application rate for the particular field. This method may best be used as a method of monitoring application rates during the clean-out of a storage facility, using the first two methods described to actually calibrate the spreader before the full scale application of manure begins.

Table 503–29 Application rate in tons per acre (T/A) for four common tarp sizes (Mancl 1996)

Pounds (lb) of waste collected	---------Tarp dimensions-----------			
	6 × 6 ft	**8 × 8 ft**	**10 × 10 ft**	**10 × 12 ft**
	-----------Application rate (T/A) ---------			
1	0.61	0.34	0.22	0.18
3	1.82	1.02	0.65	0.54
4	2.42	1.36	0.87	0.73
5	3.03	1.70	1.09	0.91
10	6.05	3.40	2.18	1.82
15	9.08	5.10	3.27	2.72
20	12.10	6.81	4.36	3.63

First, determine the weight in tons of a load of manure. Second, determine the size of the field in acres. It is then a simple matter of counting the number of loads applied to the field, multiplying that number by the weight in tons of a single load, and then dividing that number by the acreage of the field.

Example: A spreader holds 7000 pounds of manure (3.5 tons). The field is 55 acres and 35 loads are applied to the field. The calculation would be:

$$\text{35 loads} \quad \text{3.5 tons/load} = \text{122.5 tons}$$

$$\frac{\text{122.5 tons}}{\text{55 acres}} = \text{2.23 tons/acre applied}$$

Manure nutrient content

Significant differences usually exist in the nutrient content of manure as excreted from the animal and that which remains when the manure is applied to the land. This is particularly true of nitrogen. Further changes may occur in the nitrogen content after it is applied to the land depending upon the method of application. Manure that is broadcast on the surface and never incorporated will contain less nitrogen than manure which is injected or broadcast and then incorporated within 24 hours of application because of nitrogen volatilization losses

A source of manure nutrient content information frequently used by NRCS is chapter 4 of the NRCS Agricultural Waste Management Field Handbook (AWMFH), Agricultural Waste Characteristics. The AWMFH includes more detailed information about the nutrient content of different types of animal manure managed under different handling and treatment systems (ASAE 2005).

Nitrogen

Nitrogen, because of its chemical nature, is more difficult to manage in manure than are the other nutrients. Manure contains two forms of N, the unstable organic form and the stable organic form (fig. 503–20). Both forms of organic nitrogen must be decomposed by microorganisms before they are available to plants. The resulting inorganic forms are available to the crop as ammonium (NH_4^+) and nitrate (NO_3^-).

The unstable organic nitrogen in the urine of dairy and swine manure is in the form of urea, and may account for 50 to 60 percent of the total N. In poultry manure it is in the form of uric acid, and may account for 70 percent of the total N. Urea in manure is no different than urea in commercial fertilizer.

Urea or uric acid mineralizes rapidly to ammonium nitrogen (NH_4^+) and then converts very rapidly to ammonia (NH_3) as the pH increases and the manure dries. Ammonia nitrogen is very volatile, so increased exposure on the barn floor in storage or on the soil surface after spreading increases nitrogen loss. The total nitrogen loss through volatilization from a combination of handling, storage, and field application may be as high as 80 to 90 percent of the nitrogen contained in the manure when excreted. Figure 503–21 shows how quickly ammonia can be lost after surface application of manure.

Nitrogen contained in the feces is more stable and more slowly released than nitrogen from urine. Mineralization from the organic form to a plant-available form occurs in two phases. The first phase includes the less resistant organic N, which mineralizes during the first year after application. The second phase includes the more resistant residual organic N, which mineralizes very slowly in subsequent years. Repeated annual applications to the same field will result in the creation of a slow-release manure nitrogen source.

Nitrogen availability from manure is influenced by the relationship between the amount of N which is immediately available (ammonium N, NH_4^+) and that which is available over time (the unstable and stable organic forms). In determining the immediate plant availability of N in manures, the relative amount of NH_4^+ in comparison to the slowly available organic nitrogen must be considered. The common means of reporting manure N content by testing labs is the NH_4^+ nitrogen and total nitrogen (TN) or total Kjeldahl nitrogen (TKN). The organic N in manures can be determined by subtracting NH_4^+ nitrogen from TN or TKN. The ratio of organic N to total N varies by the type of manure. On average, swine manure contains a much higher percentage of NH_4^+ nitrogen relative to organic N than does beef or dairy manure.

The amount of organic N in solid manure that mineralizes into NH_4^+ is largely determined by the C:N ratio of the manure. Greater amounts of nitrogen are mineralized at lower C:N ratios. The rate of mineralization is determined by both C:N ratio and physical

Figure 503–20 Forms and degree of nitrogen availability in manure (Chesapeake Bay Region Nutrient Management Training Manual)

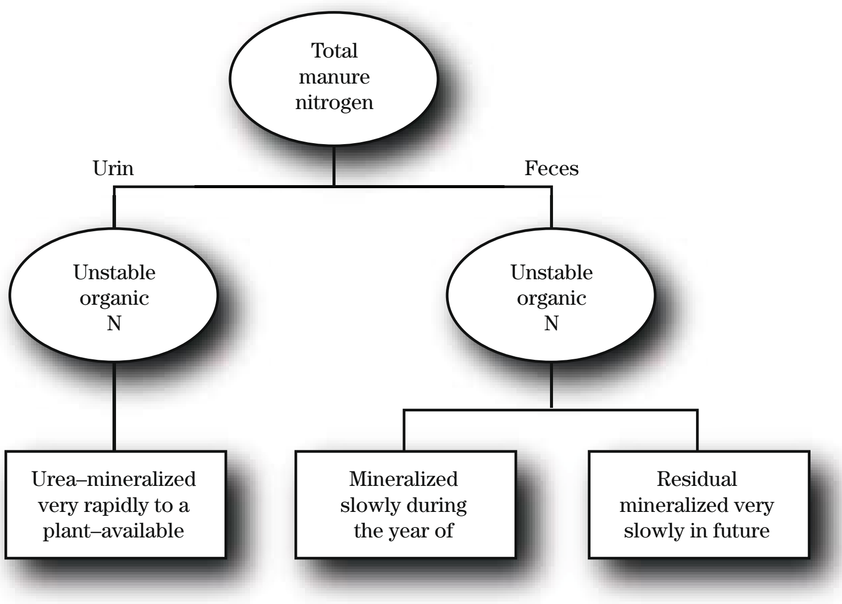
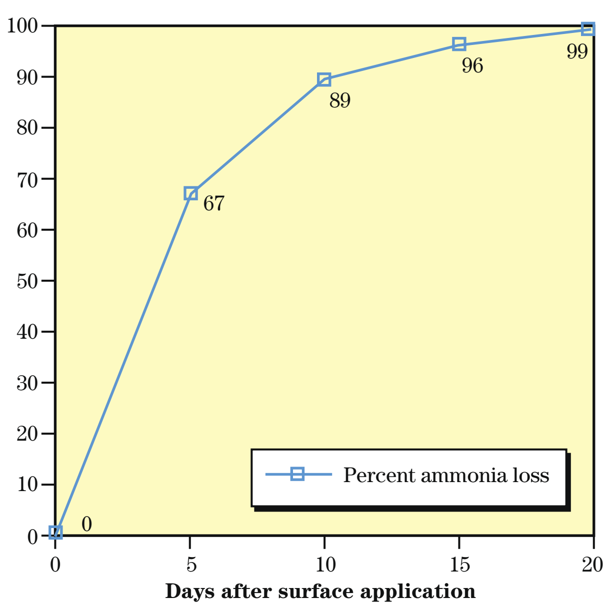


Figure 503–21 Typical ammonia loss after surface application of dairy manure (Klausner and Bouldin 1983)



effects, such as temperature and moisture. In poultry manure, the C:N ratio is approximately 7:1 or less, resulting in rapid mineralization. For dairy manures, the C:N ratio is approximately 13:1, resulting in slower mineralization. Swine manure is intermediate in mineralization rate.

Phosphorus and potassium

Manure is an excellent source of both P and K. When manure is applied over a long period of time, these nutrients will accumulate in the soil.

Phosphorus in manure is contained primarily in organic forms. It becomes available to plants when the organic matter is broken down. For nutrient planning purposes, nearly all the P in manures should be considered plant-available.

Potassium in manure is present primarily in the urine as inorganic K. It is available for plant uptake during the year it is applied.

Pathogens and heavy metals

Manures may also contain pathogens and other potentially harmfully material. The excreta from warm-blooded animals have countless microorganisms, including bacteria, viruses, parasites, and fungi. Some of the organisms are pathogenic (disease causing), and many of the diseases carried by animals are transmittable to humans, and vice versa. Table 503–30 lists some of the common diseases and parasites transmittable to humans from animal manure.

One indicator organism used widely to check for the presence of pathogens is a family of bacteria known as the coliforms. The total group of coliforms is associated with both the feces of warm-blooded animals and with soils.

However, the fecal coliform group associated with manure represents a part of the total coliforms and is easily differentiated from the total coliforms during testing. A positive test for fecal coliform bacteria is a clear indication that pollution from warm-blooded animals exists. A high count indicates a greater probability that pathogenic organisms will be present. The most commonly recognized fecal coliform is *Escherichia coli* (E. coli) which helps maintain normal intestinal function; not to be confused with the pathogenic strains.

Many entities use fecal coliform bacteria as an indicator of pollution from warm-blooded animals, including humans. The test for fecal coliforms is relatively simple and inexpensive compared to testing for specific pathogens. To test water for specific pathogens, such as salmonella, a number of samples of the suspect water must be collected to ensure that any pathogenic organisms in the water are actually captured.

The alternative to this impractical approach is to use an indicator organism that simply indicates when pollution from the manure of warm-blooded animals is present, thus providing a way to estimate the potential for the presence of pathogenic organisms. The indicator organism must have the following characteristics:

- It must exist in large numbers in the source (animals, humans) in far greater numbers than the pathogens associated with the source.
- The die-off or re-growth rate of the indicator organism in the environment should be approximately the same as most pathogens.
- The indicator should be found only in association with the source of manure; its presence, therefore, would be a definite indicator that pollution from that type of source is present.

In recent years several manure-related organisms have received much attention. These include *Cryptosporidium*, *Giardia*, and *Escherichia coli 0157:H7*. *Cryptosporidium parvum* (*C. parvum*) is a protozoal parasite that is shed by humans, cattle, sheep, swine, and horses, but not by poultry. *C. parvum* is also shed by wildlife such as deer and raccoons, and rabbits. The infectious stage of *C. parvum* is in the egg form (oocyst), and it is very environmentally-resistant. The most common source of *C. parvum* is from livestock under six months of age, however, the movement of the oocyst from the manure to the water is not well understood if the manure is deposited on dry land.

The ingestion of *Giardia duodenalis* can lead to an intestinal disorder often called Beaver Fever. *Giardia* is often associated with wildlife such as beaver and bear, humans, and pets. *Giardia* is present in the manure of livestock such as pigs, cattle, and sheep, but

Table 503–30 Diseases and organisms transmittable to humans by animals

Disease	Responsible organism	Disease	Responsible organism
Bacterial		Viral	
Salmonella	*Salmonella* sp.	New Castle	Virus
Leptospirosis	*Leptospiral pomona*	Hog Cholera	Virus
Anthrax	*Bacillus anthracis*	Foot and Mouth	Virus
Tuberculosis	*Mycobacterium tuberculosis*	Psittacosis	Virus
	Mycobacterium avium		
Johnes disease	*Mycobacterium paratuberculosis*	Fungal	
		Coccidioidomycosis	*Coccidioides immitus*
		Histoplasm capsulatum	
Brucellosis	*Brucella abortus* *Brucella melitensis* *Brucella suis* *Histoplasmosis*	Ringworm	Various microsporum and trichophyton
Listerosis	*Listeria monocytogenes*	Protozoal	
Tetanus	*Clostridium tetani*	Coccidiosis	*Eimeria* sp.
Tularemia	*Pasturella tularensis*	Balantidiasis	*Balatidium coli*
Erysipelas	*Erysipelothrix rhusiopathiae*	Toxoplasmosis	*Toxoplasma* sp.
Colibacilosis	*E. coli* (some serotypes)		
Coliform mastitis-metritis	*E. coli* (some serotypes)	Parasitic	
		Ascariasis	*Ascaris lumbricoides*
Rickettsial		Sarcocystiasis	*Sarcocystis* sp.
Q fever	*Coxiella burneti*		

Source: NRCS AWMFH, chapter 3

no conclusive evidence exists that the organism from livestock can infect humans.

While most *E. coli* strains are harmless and live in the intestines of healthy humans and animals, *E. coli 0157:H7* has proved to be a particularly deadly bacterium that can cause severe diarrhea and dehydration, and has been found in the manure of a small percentage of cattle and calves. The *0157:H7* strain produces a powerful toxin that can lead to renal failure and other devastating reactions. The most common form of infection from *0157:H7* is through eating foods or drinking liquids contaminated with the bacteria, although the contamination in the food or drink may result from contact with manure containing the strain.

Pfiesteria piscicida is a toxic dinoflagellate which has been associated with fish lesions, fish kills, and detrimental effects to humans have been identified in coastal waters from Delaware to North Carolina. While not directly linked to manure or the livestock or poultry industry, the organism is most commonly a problem in waters rich with nutrients. Most dinoflagellate are plant-like and receive their energy through photosynthesis, while some, like *Pfiesteria* are more animal-like and obtain some, if not all their energy from consuming other organisms. Human health impacts are thought to result from *Pfiesteria*-related toxins being released into the water column.

Copper (Cu) and zinc (Zn), although essential plant nutrients, may be harmful in excess quantities. Both of these elements are regulated under Federal law applicable to the land application of sewage sludge. Copper and zinc are fed as supplements in the diets of some animals, particularly in the diets of swine and poultry. When sewage sludge, animal manures, or other organic by-products are applied to the land and are known to contain copper or zinc, the potential for them to contribute to animal or plant health problems should be considered in the plan for land application.

503.25 Other organic sources

Any organic material may be a potential source of nutrients, depending upon the characteristics of the waste. Chapter 4, Agricultural Waste Characteristics, of the NRCS AWMFH includes information about the nutrient content of residential and municipal wastes, and that of the waste resulting from various types of food processing.

As with animal manures, other organic by-products applied as a source of nutrients may contain other less desirable and potentially harmful material. Prior to using any such material, both its nutrient content and content of other material should be determined.

Digested sewage sludge

What are biosolids and how are they different from sewage sludge?
Biosolids are solid, semi-solid, or liquid materials resulting from treatment of domestic sewage that have been sufficiently processed to permit these materials to be land-applied safely. The term was introduced by the wastewater treatment industry in the early 1990s and has been recently adopted by the U.S. EPA to distinguish high quality, treated sewage sludge from raw sewage sludge and from sewage sludge containing large amounts of pollutants.

Table 503–31 provides a description of various wastewater and biosolids treatment processes and methods and their effects on land application practices.

Benefits of land application of biosolids
Biosolids can be considered as a waste or as a beneficial soil amendment. As an alternative to disposal by landfilling or incineration, land application recycles soil-enhancing constituents such as plant nutrients and organic matter. The main fertilizer benefits are through the supply of N, P, and lime (where lime-stabilized biosolids are applied). Biosolids also ensure against un-foreseen nutrient shortages by supplying essential plant nutrients (e.g., sulfur (S), manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), molybdenum (Mo), and boron (B)) that are seldom purchased by farmers because crop responses to their application are unpredictable.

Characterizing biosolids
The suitability of a particular biosolid for land application can be determined by biological, chemical, and physical analyses. Biosolids' composition depends on wastewater constituents and treatment processes. The resulting properties will determine application method and rate and the degree of regulatory control

required. Several of the more important properties of biosolids are:

- *Total solids* include suspended and dissolved solids and are usually expressed as the concentration present in biosolids. The content of total solids depends on the type of wastewater process and biosolids' treatment prior to land application. Typical solids contents of various biosolids' processes are: liquid (2–12%), dewatered (12–30%), and dried or composted (50%).
- *Volatile solids* provide an estimate of the readily decomposable organic matter in biosolids and are usually expressed as a percentage of total solids. Volatile solids content is an important determinant of potential odor problems at land application sites. A number of treatment processes, including anaerobic digestion, aerobic digestion, alkaline stabilization, and composting, can be used to reduce volatile solids content and thus, the potential for odor.

Table 503–31 Description of various wastewater and biosolids treatment processes and methods and their effects on land application practices (Adapted from U.S. EPA 1984)

Process/method	Process definition	Effect on biosolids	Effect on land application process
		Wastewater treatment process	
Thickening	Low force separation of water and solids by gravity, flotation, or centrifugation	Increase solids content by removing water	Lowers transportation costs.
		Stabilization methods	
Digestion (anaerobic and/or aerobic)	Biological stabilization through conversion of organic matter to carbon dioxide, water, and methane	Reduces biological oxygen demand, pathogen density, and attractiveness of the material to vectors (disease-spreading organisms)	Reduces the quantity of biosolids.
Alkaline stabilization	Stabilization through the addition of alkaline materials (e.g., lime, kiln dust).	Raises pH. Temporarily decreases biological activity. Reduces pathogen density and attractiveness of the material to vectors.	High pH immobilizes metals as long as pH levels are maintained.
Heat Drying	Drying of biosolids by increasing temperature of solids during wastewater treatment.	Destroys pathogens, eliminates most of water.	Greatly reduces sludge volume.
		Chemical and physical processes that enhance the handling of stabilized biosolids	
Conditioning	Processes that cause biosolids to coagulate to aid in the separation of water.	Improves sludge dewatering characteristics. May increase dry solids mass and improve stabilization.	The ease of spreading may be reduced by treating biosolids with polymers.
Dewatering	High force separation of water and solids. Methods include vacuum filters, centrifuges, filter and belt presses, etc.	Increase solids concentration to 15 to 45 %. Lowers N and K concentrations. Improves ease of handling.	Reduces land requirements and lowers transportation costs.
		Advanced stabilization method	
Composting	Aerobic, thermophilic, biological stabilization in a windrow, aerated static pile, or vessel.	Lowers biological activity, destroys most pathogens, and degrades sludge to humus-like material.	Excellent soil conditioning properties. Contains less plant available nitrogen than other biosolids.

- *pH and Calcium Carbonate Equivalent (CCE)* are measures of the degree of acidity or alkalinity of a substance. The pH of biosolids is often raised with alkaline materials to reduce pathogen content and attraction of disease-spreading organisms (vectors). High pH (greater than 11) kills virtually all pathogens and reduces the solubility, biological availability, and mobility of most metals. Lime also increases the gaseous loss (volatilization) of the ammonia (NH^3) form of N, thus reducing the N-fertilizer value of biosolids. CCE is the relative liming efficiency of the biosolids expressed as a percentage of calcium carbonate (calcitic limestone) liming capability.

- *Nutrients* are elements required for plant growth that provide biosolids with most of their economic value. These include N, P, K, calcium (Ca), magnesium (Mg), sodium (Na), S, B, Cu, Fe, Mn, Mo, and Zn. Concentrations in biosolids can vary significantly (table 503–32), so the actual material being considered for land application should be analyzed.

- *Trace elements* are found in low concentrations in biosolids. The trace elements of interest in biosolids are those commonly referred to as heavy metals. Some of these trace elements (e.g., Cu, Mo, and Zn) are nutrients needed for plant growth in low concentrations, but all of these elements can be toxic to humans, animals, or plants at high concentrations. Possible hazards associated with an accumulation of trace elements in the soil include their potential to cause phytotoxicity (i.e., injury to plants) or to increase the concentration of potentially hazardous substances in the food chain. Federal and State regulations have established standards for nine trace elements: arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn).

- *Organic chemicals* are complex compounds that include fabricated chemicals from industrial wastes, household products, and pesticides. Many of these compounds are toxic or carcinogenic to organisms exposed to critical concentrations over certain periods of time, but most are found at such low concentrations in biosolids that the U.S. EPA concluded they do not pose significant human health or environmental threats. Although no organic pollutants are included in the current Federal biosolids regulations, further assessment of several specific organic compounds is being conducted as has been recommended by the National Research Council (2002).

- *Pathogens* are disease-causing microorganisms that include bacteria, viruses, protozoa, and parasitic worms. Pathogens can present a public health hazard if they are transferred to food crops grown on land to which biosolids are applied; contained in runoff to surface waters from land application sites; or transported away from the site by vectors such as insects, rodents, and birds. For this reason, Federal and State regulations specify pathogen and vector attraction reduction requirements that must be met by biosolids applied to land.

Typical nutrient levels in biosolids

There have been very few comprehensive surveys of nutrient levels in biosolids during the past 25 years. One such recent study conducted by Stehouwer et al. (2000) demonstrated that the macronutrient (N, P, and K) concentration of biosolids has changed very little from the late 1970s to the mid 1990s. The data in table 503–32 represent the means and variability of more than 240 samples collected and analyzed from 12 pub-licly owned treatment works (POTWs) in Pennsylvania between 1993 and 1997. The POTWs each provided a minimum of 20 analytical records between 1993 and 1997. The 12 POTWs generated

Table 503–32 Means and variability of nutrient concentrations [a/] in biosolids collected and analyzed in Pennsylvania between 1993 and 1997 (Stehouwer et al. 2000)

Nutrient	Total N [b/]	NH_4–N	Organic N	Total P	Total K
	-----------	-----------	%	-----------	-----------
Mean	4.74	0.57	4.13	2.27	0.31
Variability c	1.08	0.30	1.03	0.89	0.27

a Concentrations are on a dried solids basis
b Determined as total Kjeldahl nitrogen

between 110 and 60,500 tons of biosolids per year and employed either aerobic digestion (3 facilities), anaerobic digestion (4 facilities), or alkaline addition (5 facilities).

Federal regulations

Introduction

Land application of biosolids involves some risks, which are addressed through Federal and State regulatory programs. Pollutants and pathogens are added to soil with organic matter and nutrients. Human and animal health, soil quality, plant growth, and water quality could be adversely affected if land application is not conducted in an agronomically and environmentally sound manner. In addition, N and P in biosolids, as in any fertilizer source, can contaminate groundwater and surface water if the material is overapplied or improperly applied. There are risks and benefits to each method of biosolids disposal and use.

The Part 503 Rule

As required by the Clean Water Act Amendments of 1987, the U.S. EPA developed the regulation, The Standards for the Use or Disposal of Sewage Sludge (Title 40 of the Code of Federal Regulations [CFR], Part 503). This is commonly known as the Part 503 Rule. The Part 503 Rule establishes minimum requirements when biosolids are applied to land to condition the soil or fertilize crops or other vegetation grown in the soil. The Clean Water Act required that this regulation protect public health and the environment from any reasonably anticipated adverse effects of pollutants and pathogens in biosolids.

Federal regulations require that State regulations be at least as stringent as the Part 503 Rule. The underlying premise of both the Federal and State regulations is that biosolids should be used in a manner that limits its risks to human health and the environment. The regulations prohibit land application of low-quality sewage sludge and encourage the application of biosolids that are of sufficient quality that they will not adversely affect human health or the environment. Determination of biosolids quality is based on trace element (pollutant) concentrations and pathogen and vector attraction reduction.

Pollutants and concentration limits

The Part 503 Rule prohibits land application of sewage sludge whose pollutant concentrations exceed certain limits (table 503–33) for nine trace elements: As, Cd, Cu, Pb, Hg, Mo, Ni, Se, and Zn, Such materials should not be applied to land and are not considered biosolids.

- Ceiling concentration limits (CCL) are the maximum concentrations of the nine trace elements allowed in biosolids to be land applied. Sewage sludge exceeding the ceiling concentration limit for even one of the regulated pollutants is not classified as biosolids and, hence, cannot be land applied.
- Pollutant concentration limits (PCL) are the most stringent pollutant limits included in Part 503 for land application. Biosolids meeting pollutant concentration limits are subject to fewer requirements than biosolids meeting ceiling concentration limits. Results of the U.S. EPA's 1990 National Sewage Sludge Survey (NSSS) (U.S. EPA, 1990) demonstrated that the mean concentrations of the nine regulated pollutants are considerably lower than the most stringent Part 503 pollutant limits.
- The cumulative pollutant loading rate (CPLR) is the total amount of a pollutant that can be applied to a site in its lifetime by all bulk biosolids applications meeting ceiling concentration limits. No additional biosolids meeting ceiling concentration limits can be applied to a site after the maximum cumulative pollutant loading rate is reached at that site for any one of the nine regulated trace elements. Only biosolids that meet the more stringent pollutant concentration limits may be applied to a site once a cumulative pollutant loading rate is reached at that site.

In 1987, the U.S. EPA established pretreatment specifications (40 CFR Part 403) that require industries to limit the concentrations of certain pollutants, including trace elements and organic chemicals, in wastewater discharged to a treatment facility. An improvement in the quality of biosolids over the years has largely been due to pretreatment and pollution prevention programs (Shimp et al. 1994).

Part 503 does not regulate organic chemicals in biosolids because the chemicals of potential concern have been banned or restricted for use in the United States; are no longer manufactured in the United

States; are present at low concentrations based on data from the U.S. EPA's 1990 NSSS (U.S. EPA 1990); or because the limit for an organic pollutant identified in the Part 503 risk assessment is not expected to be exceeded in biosolids that are land applied (U.S. EPA 1992a). The National Research Council concluded, in their review of the science upon which the Part 503 Rule was based, that additional testing of certain organic compounds should be conducted (National Research Council 2002). These included poly-brominated diphenyl ethers, nonylphenols, pharmaceuticals, and other potential carcinogenic and endocrine-pathway disrupting personal care products. Restrictions will be imposed for agricultural use if testing of these organic compounds verifies that biosolids contain levels that could cause harm.

Individual States may impose additional regulations that are at least as stringent as the federal regulations.

Pathogen reduction categories
Federal and state regulations require the reduction of potential pathogens and vector attraction properties. Biosolids intended for land application are normally treated by chemical or biological processes that greatly reduce the number of pathogens and odor potential in sewage sludge. Two levels of pathogen reduction, Class A and Class B, are specified in the regulations:

- The goal of Class A requirements is to reduce the pathogens (including *Salmonella* sp., bacteria, enteric viruses, and viable helminth ova) to Class A biosolids can be land applied without any pathogen-related site restrictions. Processes to further reduce pathogens (PFRP) treatment, such as those involving high temperature, high pH with alkaline addition, drying, and composting, or their equivalent are most commonly used to demonstrate that biosolids

Table 503–33 Regulatory limits (adapted from U.S. EPA 1995) and mean concentrations measured in biosolids from the National Sewage Sludge Survey (U.S. EPA 1990) and a survey of 12 Pennsylvania POTWs between 1993 and 1997 (Stehouwer et al. 2000)

Pollutant	CCL [a,b] ppm [f]	PCL [a,c] ppm	CPLR [a,d] lb/A	Mean [a,g] ppm	Mean [a,h] ppm
Arsenic (As)	75	41	36	10	5
Cadmium	85	39	35	7	3
Copper	4300	1500	1340	741	476
Lead	840	300	270	134	82
Mercury	57	17	16	5	2
Molybdenum	75	e/	e/	9	13
Nickel	420	420	375	43	23
Selenium	100	100	89	5	4
Zinc	7500	2800	2500	1202	693

a Dry weight basis
b Ceiling concentration limits (CCL) = maximum concentration permitted for land application
c Pollutant concentration limits (PCL) = maximum concentration for biosolids whose trace element pollutant additions do not require tracking (calculation of CPLR)
d Cumulative pollutant loading rate (CPLR) = total amount of pollutant that can be applied to a site in its lifetime by all bulk biosolids applications meeting CCL
e The February 25, 1994, Part 503 Rule amendment deleted the molybdenum PCL for sewage sludge applied to agricultural land but retained the molybedenum CCL
f Part per million
g Data from U.S. EPA, 1990
h Data from Stehouwer et al. 2000

meet Class A requirements. Biosolids that meet the Part 503 PCLs, Class A pathogen reduction, and a vector attraction reduction option that reduces organic matter are classified as exceptional quality or EQ biosolids.

- The goal of Class B requirements is to ensure that pathogens have been reduced to levels that are unlikely to cause a threat to public health and the environment under specified use conditions. Processes to significantly reduce pathogens (PSRP), such as digestion, drying, heating, and high pH, or their equivalent are most commonly used to demonstrate that biosolids meet Class B requirements. Because Class B biosolids contain some pathogens, certain site restrictions are required. These are imposed to minimize the potential for human and animal contact with the biosolids until environmental factors (temperature, moisture, light, microbial competition) reduce the pathogens to below detectable levels. The site restriction require ments in combination with Class B treatment is expected to provide a level of protection equivalent to Class A treatment. All biosolids that are land applied must, as a minimum, meet Class B pathogen reduction standards.

Vector attraction reduction
The objective of vector attraction reduction is to prevent disease vectors such as rodents, birds, and insects from transporting pathogens away from the land application site. There are ten options available to demonstrate that land-applied biosolids meet vector attraction reduction requirements. These options fall into either of the following two general approaches: reducing the attractiveness of the biosolids to vectors with specified organic matter decomposition processes (e.g., digestion, alkaline addition) and preventing vectors from coming into contact with the biosolids (e.g., biosolids injection or incorporation below the soil surface within specified time periods).

N, P, and lime application rate
Federal regulations specify that biosolids may only be applied to agricultural land at or less than the rate required to supply the nitrogen need of the crops to be grown. This agronomic rate is designed to provide the amount of nitrogen needed by the food crop, feed crop, fiber crop, or vegetation grown on the land; and to minimize the amount of nitrogen in the biosolids that passes below the root zone of the crop or vegetation grown on the land to the groundwater [40 CFR 503.11 (b)]. Agronomic rate may also be based on crop P needs if it is determined that excessive soil P poses a threat to water quality.

Although not technically a nutrient, lime may also be used as a basis for agronomic biosolids application rate. Biosolids rate may be limited by the CCE when the application of alkaline-stabilized biosolids on an nitrogen or P basis may raise soil pH to a level that can induce a trace element deficiency. By signing the land application agreement with a biosolids contractor, the farmer is obligated to make every reasonable attempt to produce a crop on sites receiving biosolids that matches the agronomic rate applied.

Site suitability
Federal, State, and local regulations, ordinances or guidelines place limits on land application based on site physical characteristics that influence land application management practices. These include topography; soil permeability, infiltration, and drainage patterns; depth to groundwater; and proximity to surface water.

Potentially unsuitable areas for biosolids application include:

- areas bordered by ponds, lakes, rivers, and streams without appropriate buffer zones
- wetlands and marshes
- steep areas with sharp relief
- undesirable geology (karst, fractured bedrock) if not covered by a sufficiently thick layer of soil
- undesirable soil conditions (rocky, shallow)
- areas of historical or archeological significance
- other environmentally sensitive areas, such as floodplains

Managing biosolids for agricultural use

Selecting suitable crops for fertilization with biosolids
Crops such as corn, soybean, small grains, and forages have high nitrogen assimilative capacities. When these crops are grown on land used for biosolids

recycling, the amount of land required when biosolids are applied on an nitrogen basis can be reduced. Crops grown for their flowering parts, such as cotton, may produce undesirable amounts of vegetative growth if they continue to accumulate nitrogen late in the season, so slow release nitrogen sources such as biosolids may not be desirable fertilizer sources for such crops. Biosolids can, however, be used without concern on other crops in rotation with cotton. The tobacco industry, however, has expressly forbidden the use of biosolids for fertilizing tobacco because the crop readily accumulates heavy metals such as Cd.

Biosolids can be applied to vegetable crops, but green leafy vegetables accumulate higher concentrations of metals than do the grain of agronomic crops. Some scientists have cautioned against using biosolids on vegetable crops because they provide a direct pathway of potentially harmful trace elements from the soil to humans, while others (Chaney 1994) have demonstrated that certain soil and plant barriers exist that prevent trace elements in biosolids of current quality from posing such risks. Regardless of one's interpretation of the trace element bioavailability evidence, grain and forage crops are better choices for biosolids application than vegetables due to other issues (for example, the time required by regulation between Class B biosolids application and permitted harvesting of crops that can be consumed by humans).

Determining biosolids application rates
Biosolids supply some of all of the essential plant nutrients and soil property-enhancing organic matter. Land application rates, however, are primarily based on the abilities of biosolids to supply N, P, and (in the case of alkaline stabilized materials) lime.

The general approach for determining biosolids application rates on agricultural land is summarized in the following steps:

Step 1 Determine nutrient needs for crop yield expected for the soil on which the crop will be grown, and soil test nutrient and pH levels to account for residual nutrient availability.

Step 2 Calculate biosolids agronomic rates based on either:

- crop nitrogen needs (normally)
- soil test P levels (if excess P is a problem)
- soil lime requirement (when lime-supplying biosolids are used and will raise soil pH above the desirable range if they are applied on an nitrogen basis)

Step 3 Calculate supplemental fertilizer needs by subtracting the amount of plant-available N, P, and K supplied by biosolids from the crop's N, P, and K needs.

Determining nutrient needs
Fertilizer recommendations are based on the nutrient-supplying capability of the soil and the additional nutrients needed by crops to achieve their potential yield. Soil testing is required prior to the application of biosolids to determine the suitability of soil pH and the availability of P and K. Soil testing can disclose whether limestone, P or K is required for optimum crop productivity. Nitrogen application rates are based on crop N needs for expected yields for a specific soil.

Determining agronomic rates
Biosolids are normally applied at rates to provide the N needed or that which can be assimilated by the crop. This is known as the agronomic N rate. Fertilizer N is not normally applied to legumes, which can obtain nitrogen from the atmosphere; however, nitrogen assimilative capacity is used to establish agronomic N rates for legumes because they will use biosolids-furnished soil nitrogen. The relative concentrations of nutrients in biosolids are rarely present in the proportions required by the target crop; thus, supplemental fertilization (for example, with K) may be needed to promote optimum vegetative growth and yield.

Biosolids should be applied at rates that supply no more than the agronomic N rate for the specific crop and soil type.

Why is the application rate for biosolids usually based on crop nitrogen needs?
Nitrogen is required by crops in greater amounts than any other nutrient; thus, the crop's requirement for most other nutrients is normally met when the agronomic N rate is applied. Biosolids rate is further limited to nitrogen supplying capacity because N (as nitrate) is the nutrient most likely to be lost to sur-

face and groundwater if applied at greater than agronomic rates.

The following cautions regarding the determination of agronomic N rates should be considered:

- The amount of plant-available N can be underestimated or overestimated because the N composition of biosolids that is used to establish the average N concentration can vary significantly during the period of time that samples are collected and analyzed to establish the agronomic N rate.
- The equations used to calculate plant-available N are not site or source specific, and the actual amounts of plant-available N may vary from the target rates.
- These problems occur with other types of organic wastes, such as manures and yard waste composts, and are not unique to biosolids.

What is PAN, and how is it determined?

Only a portion of the total N present in biosolids is available for plant uptake. This plant available nitrogen (PAN) is the actual amount of N in the biosolids that is available to crops during a specified period. Equations for calculating PAN are relatively straightforward, but selecting precise site and source specific availability coefficients and reasonable input values is more challenging. Site-specific data, when available, should always be used in preference to book values.

Determining availability of ammonium in biosolids

Nitrogen in biosolids may occur in the ammonium (NH_4^+) or nitrate (NO_3^-) forms that are found in commercial inorganic fertilizers, or in organically-bound forms that are found in materials such as manures and composts. The amount of N that will be available to plants varies for each N form. Nitrate is readily plant-available but is not found in high concentrations in most biosolids. Ammonium is also available to plants, but it can be lost to the atmosphere (via volatilization) as ammonia (NH_3) gas when biosolids are applied to land without prompt incorporation into the soil. The available (non-volatilizable) fraction of NH_4^+–N may be estimated based on the time of incorporation after application. Examples of N availability coefficients from the non-volatized fraction of NH_3 used in Virginia are presented in table 503–34.

Determining availability of organic nitrogen in biosolids

Organic N must be broken down to NH_4^+ (via mineralization) and NO_3^- (via nitrification) by soil microorganisms before this form of N is available for plants to use. Organic N can thus be considered to be a slow release form of nitrogen. The amount of PAN from organic N is estimated by using factors established by research, such as those presented in table 503–35. Biosolids organic N mineralization factors recommended by Gilmour et al. (2000, 2003) for annual (K_{min}) and growing season (E_{min}) periods in the Mid-Atlantic States under dryland and irrigated conditions. E_{min} is the effective mineralization factor for the growing season portion of the year. Nitrogen use efficiency for this period was determined to be 71 percent. The largest portion of organic N in biosolids is converted to plant available N during the first year after application to the soil.

For example, if the values in table 503–35 are applied to Virginia, the percentages of organic N that will become available for non-irrigated corn uptake (E_{min}) upon mineralization of land-applied biosolids that have been treated via aerobic or anaerobic digestion, alkaline addition or heating are:

- 30 percent during the first year after application
- 10 percent of the remaining organic N during each of the second and third years
- 5 percent of the remaining organic N during the fourth year

The values in tables 503–34 and 503–35 may not be the most appropriate for all biosolids applied to any soil, but such book values are normally used when site specific data are not available. The amounts of available ammonium (NH_4^+) plus the available portion of the organic N are used to calculate the rate of biosolids needed to supply a given amount of plant available N. Equations for calculating PAN are relatively straightforward, but selecting precise site and source specific availability coefficients is an imprecise exercise. Site-specific data should be used if it is available.

Will agronomic nitrogen rates of biosolids meet all crop nutrient needs?

Agronomic nitrogen rates of biosolids do not necessarily meet all crop nutrient requirements. For ex-

Table 503–34 Examples of estimated plant available percentage of ammonia from biosolids (adapted from Virginia Biosolids Use Regulations—table 12; Virginia Department of Health 1997)

	Management practice	Biosolids with pH lower than 10	Biosolids with pH higher than 10
		------- available percent NH_3 ------	
Injection below surface	100	100	
Surface application with:			
• incorporation within 24 hours	85	75	
• incorporation within 1–7 days	70	50	
• incorporation after 7 days	50	25	

Table 503–35 Examples of estimated plant available percentage of ammonia from biosolids

	---------- Non-irrigated --------------------				Irrigated -----------			
State	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 1**	**Year 2**	**Year 3**	**Year 4**
				------------------------------------ K_{min} ----------------------------------				
PA	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
DE	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
MD	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
WV	0.42	0.14	0.14	0.07	0.42	0.21	0.14	0.07
VA	0.42	0.14	0.14	0.07	0.50	0.21	0.14	0.07
				------------------------------------ E_{min} ------------------------------------				
PA	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
DE	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
MD	0.30	0.10	0.10	0.05	0.30	0.15	0.10	0.05
VA	0.30	0.10	0.10	0.05	0.35	0.15	0.10	0.05
WV	0.30	0.10	0.10	0.05	0.30	0.15	0.10	

ample, K is often recommended for agronomic crops grown in Virginia soils, but the nutrient is present in low concentrations in biosolids. Supplemental K fertilization based on soil testing may be required for optimum plant growth where biosolids are applied.

What problems can be caused by applying biosolids at agronomic nitrogen rates?

Biosolids normally supply similar amounts of plant available N and P, but crops require one-fifth to a half as much P as N. If P in a certain biosolid is largely contained in forms that are readily soluble/plant available, then applying the biosolids at rates to supply the nitrogen needs of crops will eventually supply more P than necessary. Many soils contain very high concentrations of P due to long-term manure application or repeated fertilization with commercial P fertilizer. Long-term application of N-based biosolids rates can increase the potential for P contamination of surface water where soil P concentrations are already high. To alleviate the potential of P runoff or leaching in such cases, it may be advisable to apply the biosolids at rates to meet the P needs of the crop. The need to apply biosolids on a P basis can be verified with the use of a site-specific assessment tool, such as the P Index, which incorporates P transport risk in addition to soil P quantity factors. Applying biosolids on a P basis would likely require a farmer to purchase fertilizer N to meet the crop needs.

How are plant availabilities of P and K from biosolids determined?

The U.S. EPA (1995) estimated that 50 percent of the total P and 100 percent of the total K applied in biosolids would be available for plant uptake in the year of application. A Mid-Atlantic regional water quality workgroup has established that the availability of P in biosolids varies widely (i.e., <20% to >80%) according to the composition of P-binding constituents (esp., Al, Fe, and Ca) and the treatment processes to which the wastewater solids are subjected. Such variability in biosolids P solubility is employed in specialized P application rate recommendations tools, such as the P Site Index .

The quantities of available P and K applied to soil with the biosolids may be credited against fertilizer recommendations in the year of application. Any P and K in excess of plant needs will contribute to soil fertility levels that can regularly be monitored via soil testing and taken into account when determining fertilizer recommendations in succeeding years.

Using soil pH and CCE as the basis for determining biosolids rate

Soil pH influences the availability and toxicity of naturally occurring metals and metals applied to soil in biosolids. Most crops grow well at pH levels between 5.8 and 6.5. Based on previous U.S. EPA guidance, some States require that soils treated with biosolids be maintained at a pH of 6.5 or higher to reduce metal uptake by crops. Federal regulations do not require a minimum soil pH because pH was factored into the Part 503 risk assessment on which the regulation was based (U.S. EPA, 1992b). It is advisable to maintain the pH of agricultural soils where biosolids have been applied in the optimum range for crop growth (i.e., 5.8 to 6.5) to avoid phytotoxicity.

The CCE of the alkaline-stabilized biosolids may be used to determine application rates. The pH of coarse-textured (i.e., sandy) soils can rise rapidly when limed. Deficiencies of manganese in wheat and soybean and zinc in corn have sometimes been caused by excessive liming (pH > 6.8) of coarse-textured, Coastal Plain soils. Application of lime-stabilized biosolids at agronomic nitrogen rates to such soils that already have high pH values can induce such deficiencies. Crop yield reductions may result if the deficiency is not corrected, and the nitrogen not utilized by the crop can potentially leach into groundwater; thus, alkaline-stabilized biosolids should not be applied at rates that raise the soil pH in Coastal Plain soils above 6.5 and in all other soils above 6.8.

Magnesium deficiencies have been reported in row crops where repeated applications of calcitic (high Ca, low Mg) limestone has reduced soil Mg concentrations. Such soils can be identified by soil testing and should not receive further additions of calcium only liming materials, including Ca-based, lime-stabilized biosolids.

Calculating nutrient-based biosolids application rates

Calculating annual agronomic nitrogen rate

Step 1 Determine N recommendation for the crop based on the expected yield level for the soil. Use State or private soil testing laboratory fertilizer nutrient recommendations or similar tool (e.g., VALUES).

Step 2 Subtract anticipated N credits (i.e., other sources of N) from the recommended N rate, such as:

- Residual nitrogen from a previous legume crop.
- N that has already been applied or will be applied for the crop by fertilizer, manure, or other sources that will be readily available to plants.
- Residual nitrogen remaining from application of previous by-product (e.g., manure, biosolids).

Step 3 Calculate the adjusted biosolids N rate by subtracting N available from existing and planned sources from total N requirement of crop.

Step 4 Calculate the PAN/dry ton of biosolids for the first year of application using:

$$\text{PAN} = \text{NO}_3 - \text{N} + \text{K}_{\text{vol}}\left(\text{NH}_{4^+} - \text{N}\right) + \text{K}_{\text{min}}\left(\text{Org} - \text{N}\right)$$

where:

PAN	=	lb plant-available N/dry ton biosolids
NO_3–N	=	lb nitrate N/dry ton biosolids
K_{vol}	=	volatilization factor, or plant-available fraction of NH_4–N (table 10.4)
NH_4–N	=	lb ammonium N/dry ton biosolids
K_{min}	=	mineralization factor, or plant-available fraction of Org-N (table 10.5)
Org-N	=	lb organic N/dry ton biosolids (estimated by subtraction NH_4–N from total Kjeldahl N)

Step 5 Calculate the amount of biosolids required to supply the crop nitrogen needs using:

$$\text{Dry tons biosolids required/acre} = \frac{\text{adjusted biosolids N rate (lb/acre)}}{\text{PAN/dry ton biosolids}}$$

Then divide the tons of dry biosolids by the percent solids to convert to wet weight of biosolids required.

Calculating annual agronomic P rate

Applying biosolids to meet the P, rather than the N, needs of the crop is a conservative approach for determining annual biosolid application rates. A scientifically sound approach, which accounts for both P availability and P transport, is the use of a tool such as the P Index. Supplemental N fertilization will be needed to optimize crop yields (except for N-fixing legumes) if biosolids application rates are based on a crop's P needs.

Calculating agronomic lime requirement

Application rates for lime-stabilized or lime-conditioned biosolids may be computed by determining the biosolids' CCE. The CCE provides a direct comparison of the liming value of the biosolids with calcium carbonate limestone, which is the basis for soil testing liming requirements. Biosolids conditioned or stabilized with lime may have a CCE between 10 and 50 percent on a dry weight basis. The agronomic lime rate for a biosolid can be determined by using:

$$\text{Dry tons biosolids per acre} = \frac{\text{tons of CCE required/acre}}{\text{biosolids CCE/100}}$$

Example: Determining N, P, and lime agronomic rates for a specific situation

A lime-stabilized biosolid has a pH greater than 10, a CCE of 40 percent, a NO_3–N concentration of 1,000 parts per million (0.1%), an NH_4–N concentration of 2,000 parts per million (0.2 percent), a TKN concentration of 27,000 parts per million (2.7%), and a total P concentration of 21,000 parts per million (2.1%), all on a dry weight basis (% dry solids is 17.6%). Corn for grain is to be grown on a Kempsville sandy loam soil that has a pH of 6.2, high K, Ca, and Mg soil test ratings, and a very high P soil test rating. The biosolids will be surface-applied and disked into the soil within 24 hours. How can the agronomic rate of the biosolid be determined?

Determining N, P, and lime-based agronomic rates

Step 1 Determine N recommendation for the crop based on the expected yield level for the soil.

The estimated yield potential of corn grown on a Kempsville soil according to one method (VALUES) is 120 bushels per acre (Simpson et al. 1993), which should require about 132 pounds N per acre (assumption: 1.1 lb N per bushel of corn).

Step 2 Calculate the N-based agronomic rate by:

- Calculating the components of PAN in the biosolid:
  NO_3–N = 1,000 ppm x 0.002 = 2 lb/ton
  NH_4–N = 2,000 ppm x 0.002 = 4 lb/ton
  TKN = 27,000 ppm x 0.002 = 54 lb/ton
  Org–N = 54–(2 + 4) = 48 lb/ton
- Calculating PAN:
  PAN = 2 + 0 75 (4 lb/ton)+ 0 3. (48 lb/ton)
  = 2 + 3 + 14 4
  = 19.4 lb/ton
- Dividing the adjusted fertilizer N rate (132 lb N/dry ton) by the PAN/dry ton biosolid (19.4 lb N/dry ton) to obtain the agronomic N rate (6.8 dry tons/acre).

Step 3 Calculate the P-based agronomic rate using your State's P Site Index.

Step 4 Calculate the lime-based agronomic rate:

The coarse-textured Kempsville soil requires 0.75 tons limestone per acre to raise the pH to 6.5 (Donohue and Heckendorn 1994). Determined the rate of lime-stabilized biosolids needed to provide 0.75 tons CCE/acre:

Lime-based biosolids rate = tons of CCE required/acre ÷biosolid's CCE/100 (0.75 tons CCE/acre) ÷ 40%/100 = 1.88 dry tons/acre.

Step 5 Compare the rates calculated in the first four steps:

The N- and lime-based agronomic rates for the example above are 6.8 and 1.9 dry tons/acre, respectively. Dividing each of these rates by the fraction of solids in the biosolids (0.176) gives the wet weights of biosolids that must be applied to meet N- (39 wet tons/acre) and lime-based (11 wet tons/acre) application rates.

No P (and, thus, no biosolids) would be recommended to meet plant P needs; however, a tool such as the P Index can be employed to calculate at what rate biosolids can be applied in an environmentally sound manner. Finally, the capability of equipment to spread very low rates and the economics of applying low rates may prevent biosolids from being applied at all.

Land application methods for biosolids

Introduction

The most appropriate application method for agricultural land depends on the physical characteristics of the biosolids and the soil, as well as the types of crops grown. Biosolids are generally land- applied using one of the following methods:

- sprayed or spread on the soil surface and left on the surface for pastures, range, and forest land
- incorporated into the soil after being surface-applied or injected directly below the surface for producing row crops or other vegetation

Both liquid and dewatered (or cake) biosolids may be applied to land with or without subsequent soil incorporation.

Applying liquid biosolids

Liquid biosolids can be applied by surface spreading or subsurface injection. Surface methods include spreading by tractor-drawn tank wagons, special applicator vehicles equipped with flotation tires, or irrigation systems. Surface application with incorporation is normally limited to soils with less than a 7 percent slope. Biosolids are commonly incorporated by plowing or disking after the liquid has been applied to the soil surface and allowed to partially dry, unless minimum or no-till systems are being used.

Spray irrigation systems generally should not be used to apply biosolids to forage or row crops during the growing season, although a light application to the stubble of a forage crop following a harvest is acceptable. The adherence of biosolids to plant vegetation can have a detrimental effect on crop yields by reducing photosynthesis and provides a more direct pathway for pollutant consumption by grazing animals. In addition, spray irrigation increases the potential for odor problems and reduces the aesthetics at the application site.

Liquid biosolids can also be injected below the soil surface using tractor-drawn tank wagons with injection shanks and tank trucks fitted with flotation tires and injection shanks. Both types of equipment minimize odor problems and reduce ammonia volatilization by immediate mixing of soil and biosolids. Injection can be used either before planting or after harvesting crops, but it is likely to be unacceptable for forages and sod production. Some injection shanks can damage the sod or forage stand and leave deep injection furrows in the field.

Subsurface injection will minimize runoff from all soils and can be used on slopes up to 15 percent. Injection should be made perpendicular to slopes to avoid having liquid biosolids run downhill along injection slits and pond at the bottom of the slopes. As with surface application, drier soil will be able to absorb more liquid, thereby minimizing downslope movement.

Applying dewatered biosolids

Dewatered biosolids can be applied to cropland by equipment similar to that used for applying limestone, animal manures or commercial fertilizer. Typically, dewatered biosolids will be surface-applied and incorporated by plowing or another form of tillage. Incorporation is not used when applying dewatered biosolids to forages. Biosolids application methods such as incorporation and injection can be used to meet Part 503 vector attraction reduction requirements.

Timing of biosolids application

The timing of biosolids application must be scheduled around the tillage, planting, and harvesting operations and will be influenced by crop, climate, and soil properties. Traffic on wet soils during or immediately following heavy rainfalls may cause compaction and leave ruts in the soil, making crop production difficult and reducing crop yields. Muddy soils also make vehicle operation difficult and can create public nuisances by carrying mud out of the field and onto roadways.

Applications should also be made when crops will soon be able to utilize the N contained in the biosolids. Failure to do so could result in potential nitrate contamination of groundwater due to leaching of this water-soluble form of nitrogen. It is advisable that biosolids applied to land between autumn and spring have a vegetative cover (i.e., permanent pasture, winter cover crop, winter annual grain crop) to reduce erosion of sediment-bound biosolids, runoff of N, P, and pathogens, and leaching of nitrate.

Split applications may be required for rates of liquid biosolids (depending on the solids content) in excess of 2 to 3 dry tons per acre. Split application involves more than one application, each at a relatively low rate, to attain a higher total rate when the soil cannot assimilate the volume of the higher rate at one time.

Biosolids storage

In-field storage of biosolids at or near the application site is often needed. Storage facilities are required to hold biosolids during periods of inclement weather, equipment breakdown, frozen or snow-covered ground, or when land is unavailable due to growth of a crop. Liquid biosolids can be stored in digesters, tanks, lagoons, or drying beds; and dewatered biosolids can be stockpiled. Recommended guidelines for such storage have been specified by the U.S. EPA (2000).

Disadvantages of land application

Large land areas may be needed for agricultural use of biosolids because application rates are relatively low. Transportation and application scheduling that is compatible with agricultural planting, harvesting, and possible adverse weather conditions require careful management.

Biosolids are typically delivered to the application site by tractor trailers containing approximately 20 tons. At a solids content of 15 to 25 percent, this is approximately 3 to 5 dry tons per trailer, or about the amount of biosolids that is normally spread onto one acre of land for crops such as corn, soybean or wheat. Therefore, there will be considerable truck volume over the course of several weeks for large sites of several hundred acres. Increased traffic on local roads, odors, and dust are potential impacts on the local community that should be addressed by notifying neighbors in public informational meetings or public hearings. Working out delivery schedules that are least likely to be disruptive will minimize the problems caused by biosolids transportation.

Biosolids, even when properly treated, will have odors. Under unfavorable weather conditions, the odors may be objectionable, even to rural communities accustomed to the use of animal manure. Odors may be reduced by stabilization process, application method, storage type, climatological conditions, and site selection, as described next.

- Stabilization reduces the biological activity and odor of biosolids. The products of aerobic digestion, heat treatment, and composting tend to result in the least objectionable odors. Anaerobic digestion has the potential to cause more odor than other treatment methods if not performed properly. Likewise, lime-stabilized biosolids, the most commonly used material in the State, may generate odors if not properly stabilized and managed.
- Application method affects the odor potential at the site. Immediate soil incorporation or direct soil injection will reduce the potential for odor problems.
- Biosolids storage can occur at the treatment plant, the site of application, or a temporary facility. Storage at the treatment plant (if isolated from the public) is the preferred method. Off-site storage requires proper site selection and management to minimize the potential for odor problems.
- Weather conditions (i.e., temperature, relative humidity, wind) will affect odor severity when biosolids are surface applied. Spreading in the morning when air is warming and rising will help dilute the odor in the immediate vicinity.
- The selection of the application site is important to the success of the operation. Ideally, the site should be located away from residential areas.

Objectionable odors will sometimes be present despite adequate stabilization processes and favorable weather conditions. Complaints can be expected if adjacent property owners are subjected to persistent odors. A well-managed system with the proper equipment and stabilized biosolids will substantially reduce the potential for unacceptable odors.

Plant residue

Plant residues which are left in the field following crop harvest are a potentially valuable source of nutrients for succeeding crops. Table 503–36 shows the N, P, and K content of the residues of some of the major crops.

As with any organic source of nutrients, nutrients from crop residue become available for plant use after the residue has decomposed. The rate of decomposition is influenced by moisture and temperature. Moderate or warm temperatures and moist conditions promote more rapid decomposition, while cool temperatures coupled with very wet or very dry conditions will result in slower decomposition. The C:N ratio of the residue affects the rate of decomposition. A lower C:N ratio results in faster decomposition, which makes the nutrients available more quickly. Soybean residue, with a C:N ratio of 25:1, will decompose much quicker than corn residue, which has a C:N ration of 60:1.

Adding residues with a high C:N ratio (greater than 30:1) can result in a short-term lowering of N levels in the soil. The microbial population increases rapidly in response to the addition of residue. Because the residue is low in N, the microorganisms use N from the soil, reducing the amount available for crops. Over time, as the amount of residue decreases some of the microbial population dies, releasing N back to the soil. This temporary decrease in N level can be overcome by adding additional nitrogen fertilizer with the high C:N material. A rule of thumb is to add 1 pound of N for every 100 pounds of residue returned to the soil.

Table 503–36 Nutrient content of selected crop residues (average concentration of nutrients)

Crop	Pounds of residue	Nitrogen	Phosphorus	Potassium
		(% of dry harvested biomass)		
Corn	9000	1.11	0.20	1.34
Barley	2000	0.75	0.11	1.25
Wheat	3000	0.67	0.07	0.97
Sorghum	6000	1.08	0.15	1.31
Rye	3000	0.50	0.12	0.69
Oats	4000	0.63	0.16	1.66
Soybeans	4000	2.25	0.22	1.04
Rice	5000	0.60	0.09	1.16
Flax	3500	1.24	0.11	1.75
Peanuts	4400	2.23	0.24	1.75

USDA-SCS 1975, 1992; Kilmer 1982; Morrison 1959; Sanchez 1976

Legumes

Legumes, through the symbiotic relationship they have with various soil organisms (primarily *Rhizobium* spp.), can be a valuable source of nitrogen for a succeeding crop. The soil organisms, which invade the root hairs and receive energy from the plant, fix nitrogen from the atmosphere that is later available for the growing legume crop and to succeeding crops.

The proper species of *Rhizobium* must be present in the soil or applied with the seed to ensure that fixation will occur at rates which supply the N requirements of the legume crop and make N available to succeeding crops. Table 503–37 gives the major legume groups and the *Rhizobium* bacteria required to inoculate the species in each group.

A significant amount of the total nitrogen requirements of the first crop succeeding the legume crop may be supplied by the legume the first year after it is destroyed. Table 503–38 shows two estimates of fixation by legumes. The low values reflect fixation during the first year of growth. The higher values reflect estimates of fixation for stands of legumes that have been in place two or more years. These values do not reflect the amount of nitrogen used by the legume itself, and are greater than values typically estimated as available to the first crop planted following the legume crop.

In many situations, legumes may be established as a cover crop, grown with the express purpose of producing nitrogen for a succeeding crop. The major factor limiting the use of legume cover crops and subsequent nitrogen availability is climate. Legumes raised as cover crops for the production of nitrogen must put on adequate fall growth and produce biomass in the spring before being destroyed so the subsequent crop may be established.

When developing nutrient budgets, follow Land Grant University guidelines to estimate the amount of nitrogen supplied by legumes to a following crop or crops.

Municipal solid waste

Municipal solid waste can include anything from shredded cardboard and newspapers to grass clippings and leaves. These materials vary widely in nutrient content (from 0.1% N up to 3.4% N), moisture

Table 503–37 Legume groups and associated rhizobia

Group	Rhizobium species	Legume
Alfalfa	*Rhizobium meliloti*	*Melilotus* (certain clovers), *Medicago* (alfalfa), *Trigonella* (fenugreek)
Clover	*Rhizobium trifolii*	*Trifolium* spp. (clovers)
Soybean	*Rhizobium. japonicum*	*Glycine max* (soybeans)
Lupine	*Rhizobium. lupine*	*Lupinus* (lupines), *Ornithopus* spp. (serradella)
Bean	*Rhizobium phaseoli*	Phaseolus vulgaris (dry bean), Phaseolus coccineus (runner bean)
Peas and vetch	*Rhizobium leguminosarum*	Pisum (peas), Vicia (vetch), Lathyrus (sweet pea), Lens spp. (lentil)
Cowpea miscellany	Various	*Vigna* (cowpea), *Lespedeza* (lespedeza), *Arachis* (pea¬nut), *Stylosanthes* (stylo), *Desmodium* (desmodium), *Cajanus* (pigeon pea),

Source: Brady, Nyle C. 1990. The Nature and Properties of Soils, 10th ed.

Table 503–38 Estimated nitrogen fixation rate (lb/acre/year)—selected legumes

Plant	Low	High	Plant	Low	High
Alfalfa	62	535	Lentils	147	170
Soybeans					
–Midwest	49	85	Peas	49	174
–South	62	196	Vetch	80	107
Clovers	89	178			

Sources: National Research Council (NRC) 1993; Evans and Farber 1977; Follett, et al. 1987; Meisinger and Randall 1991; Peterson and Russelle 1991; Schepers and Fox 1989; Schepers and Mosier 1991; Thurlow and Hiltbold 1985; Tisdale and Nelson, 1966 content and C:N ratio. Table 503–39 gives representative values of these characteristics for different types of materials.

The important characteristic is C:N ratio. Materials with a high C:N ratio, such as corrugated cardboard, take longer to decompose and require lots of energy by soil microorganisms to decompose them.

Food processing wastes

Food processing wastes can include peels, tops, trimmings, cull or damaged fruit and vegetables from packing houses and canneries, as well as filter press cakes from facilities that produce fruit or vegetable juice. These materials have a low nutrient content and a low C:N ratio. The primary value of these materials, as with the municipal solid waste materials, is in the organic matter they can add to the soil rather than their nutrient content.

503.26 Other sources of nutrients

Table 503–39 Characteristics of selected solid waste materials [1/]

Material	% nitrogen (dry weight)	C:N ratio	% moisture
Apple-processing sludge	2.8	7	59
Corrugated cardboard	0.10	560	8
Fruit wastes	1.4	40	80
Grass clippings	3.4	17	82
Leaves	0.9	54	38
Newsprint	0.06–0.14	398–852	3–8
Tree trimmings (shredded)	3.1	16	70
Sawdust	0.24	442	40
Vegetable Wastes	2.5–4	11–13	—
Wood (chips, shavings)	0.09	560–640	—

1 These are representative or typical values from a wide range of sources. Source: On-Farm Composting Handbook, NRAES, 1992.

Atmospheric deposition

In some locations, atmospheric deposition may need to be considered as a source of N and K. The effects of N and K from atmospheric deposition can be highly localized. Check with the nutrient management specialist with the land grant university to find out if additions from atmospheric deposition are already considered in their nutrient management recommendations.

Irrigation water

In production systems in which irrigation is used to supply some or most of the required moisture for the crop, the nutrient content of the irrigation water may be an important nutrient source, particularly of nitrogen.

Whether to consider the nutrient content of irrigation water as a source of nutrients must be decided during the development of a nutrient management plan. This decision can be based on the nutrient content of the water (determined by testing) and whether irrigation supplies a supplemental or major portion of the total moisture requirements for the crop.

503.27 Nutrient testing, analysis, and assessment

Soil testing

Components of a soil testing program

A soil testing program can be divided into four main components: sample collection, laboratory analysis, interpretation of results, and the recommendations for nutrient application. This chapter describes these four components. It is important to understand all these components to maximize the effectiveness of soil testing.

Two types of soil tests are run routinely. Soil tests for properties such as pH and CEC are direct measures or estimates of soil properties that affect the fertility of the soil. Other soil tests (for example, those for P, K, Ca, Mg, and micronutrients) use extractants to assess the amount of each nutrient that is related to the plant-availability of that nutrient.

Soil testing is also being used in environmental management to reduce non-point source pollution from agriculture. Use of P soil tests in the P Index is an example of this and is discussed in this chapter.

Soil sampling

Understanding soil variability

The largest source of error in soil testing usually results from not obtaining representative samples. Frequently, these sampling errors are due to the inherent variability of soils. This variability can be either natural or fabricated.

- Natural variability in nutrient levels is due to ongoing soil forming processes and is characterized by soil properties such as soil texture, mineralogy, depth, drainage, slope, aspect, and 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 will hold fewer cations such as calcium (Ca), magnesium (Mg), and K. Low N concentrations, due to denitrification, may be found in low lying, wet soils.
- Fabricated variability in nutrient levels is usually due to farming practices. The most obvious source of artificial 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 caused unintentionally by improper adjustment or operation of application equipment.

Tillage is a very important factor in artificial nutrient variation in the soil. The following sections describe how different tillage systems affect soil nutrient and pH content.

Nutrient variability under conventional tillage

The repeated mixing of the surface layer of soil by conventional tillage reduces the effects of artificial variation due to nutrient application.

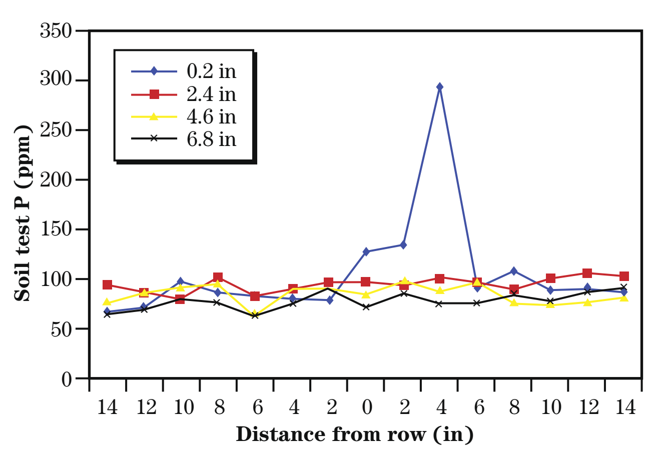
Conventional tillage can also increase the variability of soil test levels over time if tillage is not performed consistently. For example, the depth of plowing can alter soil nutrient concentrations. Occasionally, deep plowing may mix low fertility subsoil material with the plow layer and thus, lower the soil test levels for nutrients in this soil layer.

Cultural practices performed after tillage (e.g., banding a starter fertilizer), however, can result in variation for the rest of the growing season. The spike in figure 503–22 is an example of the effect of the starter fertilizer band from the previous year. This variability will persist until the fall or early spring and must be taken into account when soil testing is preformed for the next year's fertilizer recommendations. Consequently, for example, most labs recommend sampling in the middle of the row to avoid the effects of banded fertilizer from the previous year.

Nutrient variability under no-tillage and reduced tillage

In no-tillage and reduced tillage systems, there is increased emphasis on residue management, which results in even more soil nutrient variation. There is no mechanical mixing of the soil in no-tillage systems, so natural or artificial variation in soil nutrient levels tends to become amplified over time. Application of immobile nutrients such as P in fertilizer or manure will result in higher soil test nutrient levels near the surface and declining soil test levels with distance down through the plow layer (fig. 503–23). Nutrients and organic matter released from crop residues also accumulate at the soil surface.

Figure 503–22 Variation in P across the row and with depth in a long-term conventional till corn field



Variation in soil pH with depth often results from no-tillage systems. Nitrification of surface-applied fertilizer and manure nitrogen causes lower soil pH at the surface of no-till fields (fig. 503–24).

The effects of surface-applied limestone will be greatest at the surface of the soil because limestone is immobile in the soil. Thus, limestone application will usually result in a higher pH near to the soil surface. Figure 503–25 shows that when the lime is applied to the soil surface of a continuous no-till field, there is little pH effect below the surface 2 inches even after 7 years.

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. In a 10-acre field there are approximately 20 million pounds of soil in the plow layer. Out of this, a sample of a quarter pound is collected that will ideally represent 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.

The two main questions that must be considered when developing the sampling plan for a field are:

- How deep should the samples be taken?
- What pattern should be followed when selecting sampling locations?

Sampling depths
Depth is an important factor that must be considered in developing a sampling plan for a field. Traditionally, it has been recommended to sample the plow layer (6–8 inches) for P, K, Ca, Mg, micronutrients, pH, and lime testing.

Under conventional tillage, nutrients and pH in the plow layer of soil are most affected 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 usually will not affect fertilization recommendations because the plow layer is uniform throughout under conventional tillage.

Figure 503–23 Variation in P across the row and with depth in a corn field in long-term conservation tillage

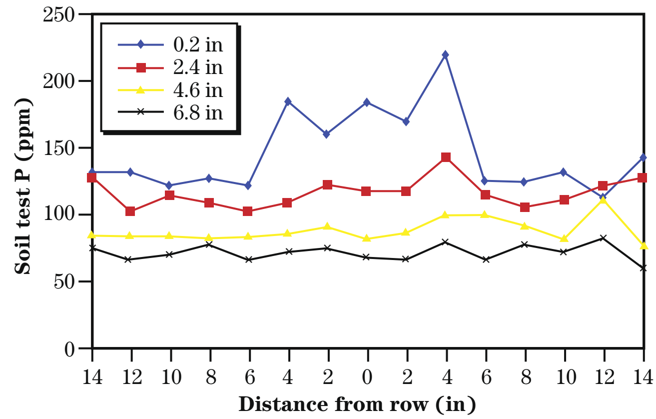


Figure 503–24 Variation in pH across the row and with depth in a long term no-till corn field

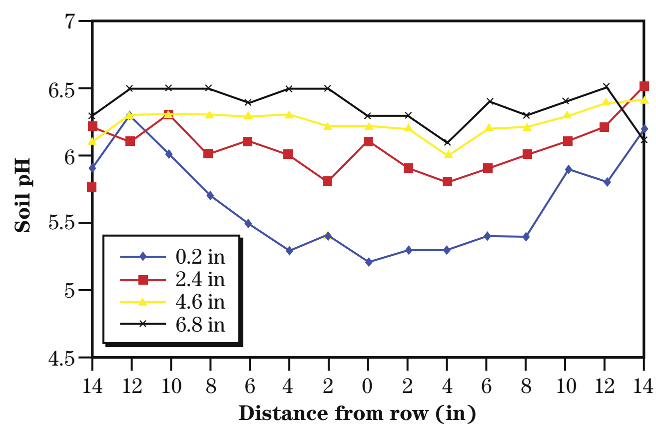
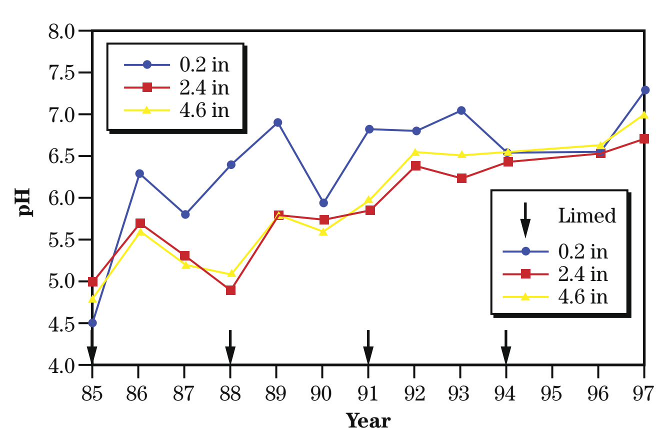


Figure 503–25 Soil pH vs. time for a no-till soil limed at 6000 lb/a every third year



In reduced and no-tillage systems, the correct sampling depth is less clearly defined, yet the depth sampled has a much greater impact on the soil test result than in conventional tillage systems because nutrients concentrate near the surface. Root systems and nutrient uptake zones are also concentrated near the surface in conservation tillage systems, so shallower sampling than 6 to 8 inches may be more appropriate. Some soil testing labs now recommend that minimum and no-till fields be sampled to plow depth, and that an additional shallower 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.

The recommended sampling depth for nitrogen is deeper than for other soil tests because of the greater mobility of nitrogen. The most common soil test for nitrogen in the humid region of the United States is the pre-sidedress soil nitrate test (PSNT) for corn. The recommended sampling depth for this test is 12 inches.

These are general guidelines for sampling depth, but because soil test interpretations and recommendations are based on a specific sampling procedure, it is critical that the exact instructions from the soil testing lab be followed.

Sampling patterns: random

There are two general patterns for sampling a field: random sampling and grid sampling (or systematic sampling).

The best approach for a uniform field is to collect a random composite sample by randomly selecting locations in the field from which to take soil cores, which are then thoroughly mixed and subsampled for lab analysis. The result is an average soil test level for the field. Usually, 15 to 20 cores are taken at random locations to make up the composite sample. In practice, the locations for taking cores are not usually chosen completely at random, but are selected by walking a zigzag pattern that covers the whole field and approximates a random sample and collecting a core at regular intervals (fig. 503–26).

Sampling patterns: grid sampling

A soil test value 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 because of natural or artificial variation caused by different soil types, topographic locations, previous management, old field layouts, and so forth. Thus, the soil test value resulting from a randomly collected composite sample may not actually exist anywhere in the field.

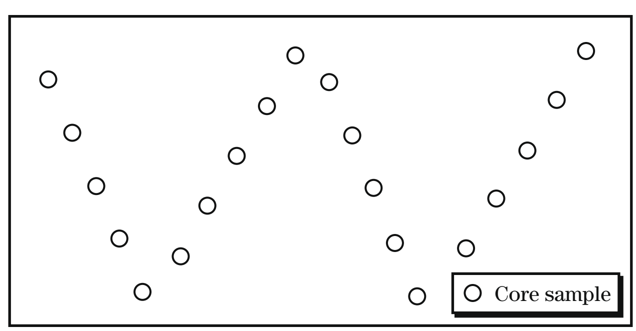
Ideally, the variability in a non-uniform field should be determined and mapped to permit the various areas of the field to be managed differently. The usefulness of characterizing the variability in a field will depend on the ability to change management based on this variability. A grid sampling (or systematic 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 2 acres or approximately 300 feet on a side. At each intersection of grid lines, 5 to 10 soil cores are taken within a 10 foot circle and composited to make up the sample for that point (fig. 503–27). This systematic sampling approach is best suited for large, regularly-shaped fields.

Soil fertility maps

Analysis of the composite samples from each of these grid points is used to make a soil fertility map showing the variation across the field. A simple example of such a map is shown in figure 503–28. This is a map of soil test levels based on the analyses of the samples taken from the grid layout.

Figure 503–26 Example of a random sampling pattern in a field



Notice the generally high levels along the northwest side of the field. The southeast end of the field has very low soil test levels with some medium and low areas in between. Ideally, nutrient application rates will be adjusted accordingly when fertilizer or manure is applied to this field.

Sampling on the basis of known or suspected variability

Small and irregularly shaped fields make grid sampling and variable management very difficult. One common compromise is to systematically sample on the basis of known or suspected variability in the field. Examples of known or suspected variability might include: historical manure or fertilizer spreading patterns, soil drainage, soil type, and slope. This type of sampling is illustrated in figure 503–29. 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 nutrient concentrations; a small area of wet soil that is not productive and has not received much manure; and a well-drained unmanured area.

Do not attempt to take a random composite sample that represents the whole field depicted in figure

Figure 503–28 Example of a soil fertility map

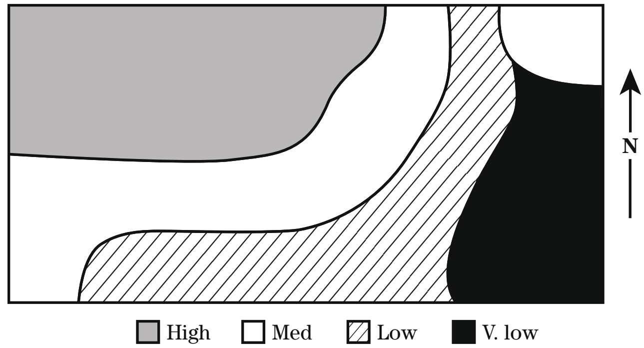


Figure 503–29 Example of systematically dividing a field for soil sampling on the basis of known or suspected variability

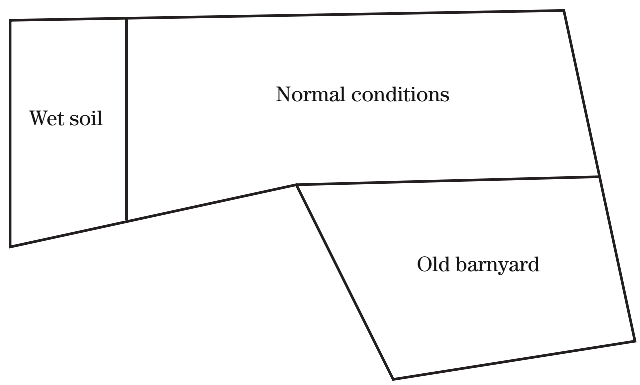
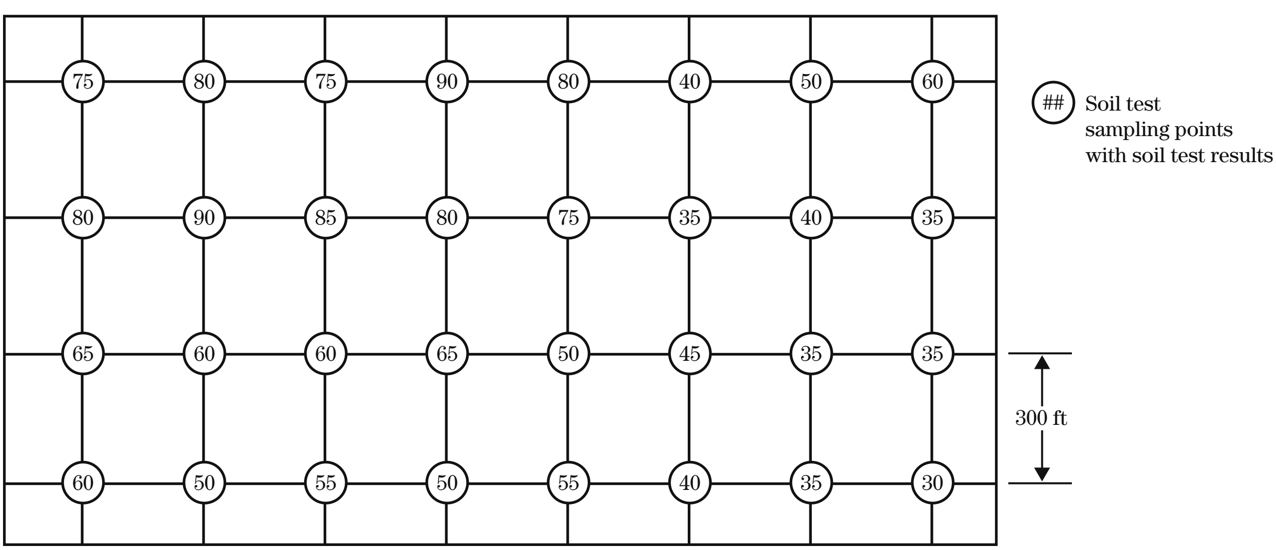


Figure 503–27 Example of a systematic or grid sampling pattern in a field



503–29. The result of the soil tests on that composite sample will be useless in most cases. If the field cannot be divided, sampled, and managed separately, it is probably best to sample the largest and/or most productive section of the field and ignore the odd areas. An individual composite sample should be taken and analyzed from each different area in the field.

Soil laboratory analysis

Understanding soil test extractants

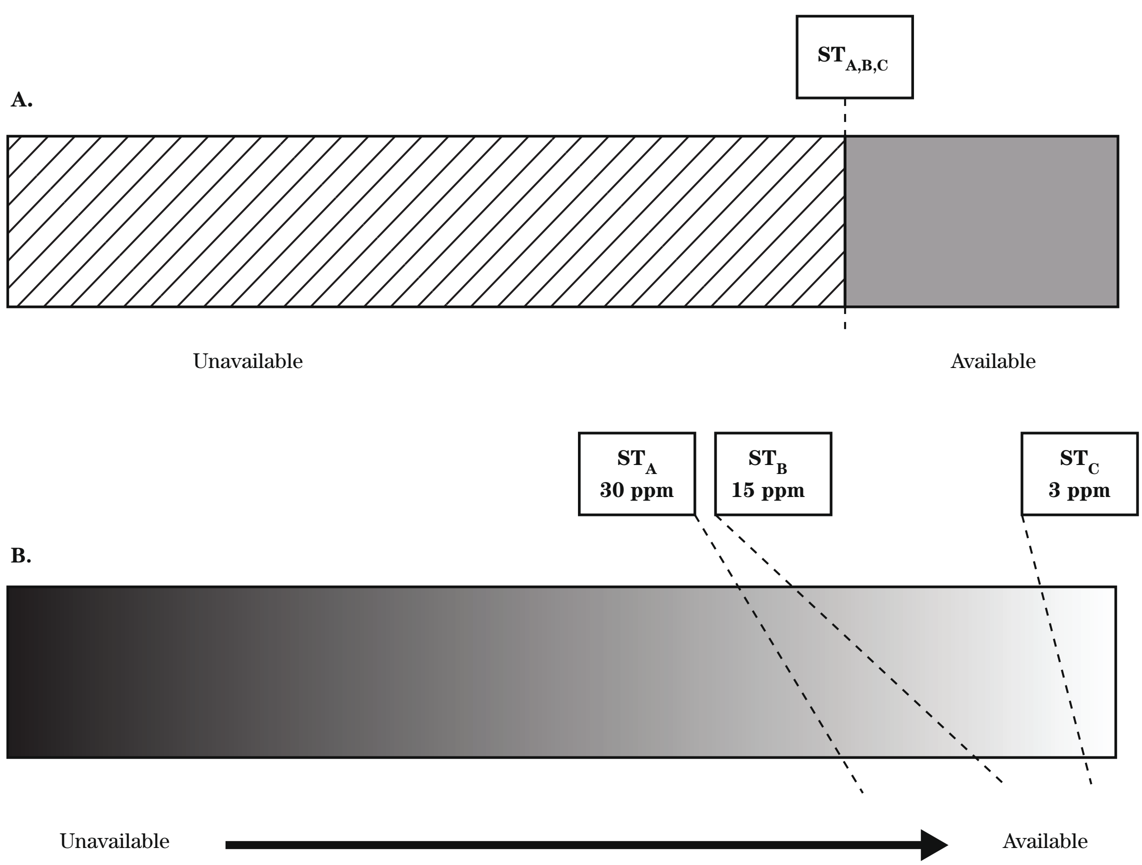
Laboratory analysis of a properly sampled soil provides the basis for assessing soil nutrient status. With few exceptions, such as the measurement of NO_3^-–N, most soil test extractants do not directly measure the total amount of available nutrients in the soil because there is usually not a clear cut distinction between available and unavailable nutrients.

Part A of figure 503–30 illustrates the commonly held misconception about available nutrients in the soil. The availability of nutrients ranges from completely insoluble (unavailable) to completely soluble (readily available). Availabislity is a relative term covering this available term. Soil tests generally extract a fraction of the nutrient from the soil that is correlated to the plant-available portion of that nutrient.

Different extraction methods can extract different amounts of nutrients and provide different soil test results. Research is conducted to determine which soil test extractant works best for predicting the ability of a soil to supply available nutrients for crop uptake under conditions where the test will be used.

An example of how three extractants might extract different fractions from the same soil, resulting in

Figure 503–30 Illustration of how different soil test extractants might extract different fractions of the nutrient in the soil



three differing soil test levels, is illustrated in part B of figure 503–30. All three of these extracted fractions may be correlated with plant availability, or one of these tests may perform better under certain conditions. It is important to use a test that has been verified to work under conditions similar to the ones in your area. A is the common incorrect view of nutrient availability and soil test extraction. B is nutrient availability as a continuum, showing how different soil tests ($ST_{A,B,C}$) extract different fractions of this continuum. (In this example, the numbers would be representative of ppm P by ST_A= Mehlich 3, ST_B=Bray P1, ST_C= Modified Morgan.)

Using soil test procedures recommended for your region

Generally, the soil test user need not be concerned with the details of the soil test methods. The most important consideration for the user is that the testing lab is using standard procedures that are recommended for the region where the samples were collected. If not, the results and/or interpretations may be misleading. Be careful if you consider sending samples to a lab in another part of the country. The lab may have an excellent reputation, but the procedures that they use may be totally inappropriate for soil conditions.

Know which analytical methods are used when comparing results from different labs and only compare results from laboratories that use the same methods. If test results from two different labs are being compared and both are 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 differ.

The most common analytical method used is the Mehlich 3 soil test. Other methods that have been used (and that are still used occasionally) in the region are the Mehlich 1, Bray P1, and 1N Ammonium Acetate. Each of these methods will extract a different amount of the nutrient but, if properly calibrated, they can all provide valid results for our region. Some States have developed conversions between the different methods. Use conversion factors with caution. It is always better to use the recommended test rather than using an alternative test and converting the results.

The units employed to express soil test results sometimes cause confusion. The most common system is based on an actual or assumed weight for the soil. Results in this system are usually presented as parts per million (ppm) or pounds per acre (lb/a). As a further complication, some labs present results as pure elements (P, K), while others use the fertilizer oxide form (P_2O_5, K_2O). Results for cations like Ca_2^+, Mg_2^+, and K^+ are sometimes presented as milliequivalents per 100 grams (meq/100g). All these units can be converted mathematically to each other. Some common conversion factors are given in table 503–40.

Soil test interpretation

The soil test-yield response relationship

The analytical results from a soil test 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 the conditions where the test might be used.

An example of the relationship between yield and soil test levels is illustrated in figure 503–31. The value presented as percent yield is the yield in the unfertilized soil divided by the yield in a soil where the nutrient is non-limiting. For example, 70 percent yield means that the crop yield with the unfertilized soil

Table 503–40 Common conversions for soil test units

ppm × 2* = lb/a	
lb/A ÷ 2* = ppm	
P × 2.3 = P_2O_5	P_2O_5 ÷ 2.3 = P
K × 1.2 = K_2O	K_2O ÷ 1.2 = K
NO_3^-–N × 4.4 =NO_3^-	NO_3^- ÷ 4.4 =NO_3–N
meq K/100g × 780 = lb	K/a meq K/100g × 390 = ppm K
meq Mg/100g × 240 = lb	Mg/a meq Mg/100g × 120 =ppm Mg
meq Ca/100g × 400 = lb	Ca/a meq Ca/100g × 200 = ppm Ca

* This factor only applies to furrow slice depth, approximately 7 inches, which is assumed to weigh 2,000,000 lb/a

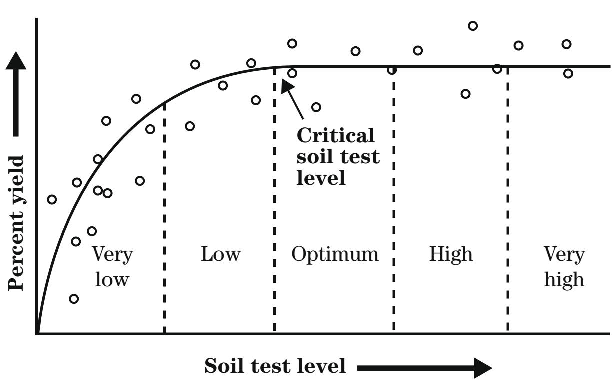
is 70 percent of the yield at optimum concentration of the nutrient. This soil test-yield response relationship shows that at low soil test levels yields are low relative to the optimum. As soil test levels increase, yield increases until that nutrient is no longer limiting and then the response curve levels off. This point where the relationship levels off is called the critical level and indicates the soil test level above which you would not expect a yield increase from adding more of the nutrient. Each point in the graph would be the relative yield for an individual field experiment.

Soil test critical levels will vary among soils, crops, climatic regions, and extractants. For example, the critical level for soil test P for the Mehlich 3 soil test is around 30 ppm for Mid-Atlantic soils. If the test is below 30 ppm we would expect a profitable increase if we add P. However, if the soil test is above 30 ppm, no yield response is expected. For soils in the Midwest, this critical level is closer to 20 ppm. Ideally, we would like to maintain the soil test level at the critical level for optimum economic production.

Soil testing interpretation categories

Use a laboratory where the soil test results have been calibrated for your region so that an accurate interpretation of values can be determined. Most soil test laboratories use the response curve from the calibrations to develop interpretation categories. The dotted lines and names in figure 503– 31 illustrate how the data might be used to develop soil test interpretation categories.

Figure 503–31 Example relationship between yield and soil test level



Defining the terms used for interpretation categories

The qualitative terms used for the interpretation categories are related to quantities of nutrients extracted but may have different absolute meanings depending on the laboratory using them. It is important to understand exactly what these terms mean for any laboratory that you use. For example, Pennsylvania once termed the category that is designated as optimum in figure 503–31 as medium, while Maryland termed that same category as high. Today that category is called optimum in both States, which has eliminated the previous confusion between State testing lab results. Soil test labs may report these interpretations in different ways. Some labs use words such as low, optimum, or high, while some use abbreviations such as L, O, or H. Often the results are presented in graphical form. An example of an interpretation in the form of a chart from the Penn State Soil Testing Program report is shown in figure 503–32.

Finally, 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 below 100 would indicate the fraction of nutrient 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, the lab should provide clear definitions of the terms used so that the user knows exactly what the results mean. For example, the Penn State Soil Testing for Agronomic Crops provides the definitions in table 503–41 on all soil test reports.

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Figure 503–32 Example of a bar chart for displaying the soil test interpretation on a soil test report (from Penn State Soil Testing for Agronomic Crops)

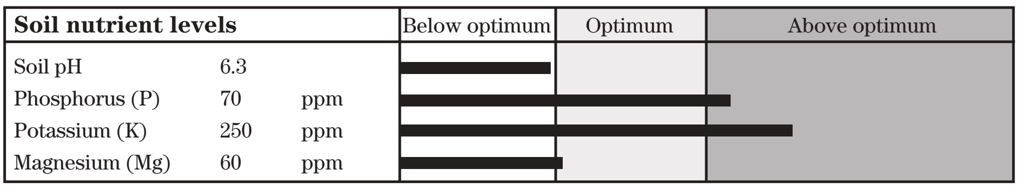


Table 503–41 Example of definitions for soil test interpretation categories (from the Penn State Soil Testing Program for Agronomic Crops)

Category	Definition and interpretation
Below optimum	• Indicates that the nutrient is probably deficient and that the deficiency will likely limit crop growth • High probability of a profitable return from correcting a low level. • Recommendations for a soil testing “below optimum” are designed to gradually build up the nutrient level to optimum and to maintain it at that level.
Optimum	• Indicates that the nutrient is probably adequate and will likely not limit crop growth in a typical growing season. • There is a low probability of a profitable return from increasing the soil test level above optimum. • Recommendations for a soil testing “optimum” are designed to offset crop removal in order to maintain the nutrient in the optimum range. • If you are soil testing on an annual basis, no maintenance fertilizer is needed when the soil tests in the optimum range.
Above optimum	• Indicates that the nutrient is more than adequate and will not limit crop growth. • Very low probability of a profitable return from applying additional nutrients to a soil testing “above optimum.” • No fertilizer is recommended on these soils. Too much of a plant nutrient may cause a nutrient imbalance in the soil and, as a result, in the plant, which may adversely affect plant growth and environmental quality.

Predicting potential environmental impact from nutrients

Soil test results are most commonly interpreted on the basis of the probability of an economic response to adding additional nutrients. Because of the concern about the potential impact of nutrients on the environment, soil tests are increasingly being considered in terms of predicting potential environmental impact from nutrients. However, it is not possible to directly use conventional soil test interpretations for crop response to make an environmental interpretation. If a soil test is above or below optimum for crop response to a particular nutrient, this tells us nothing about whether that level of the nutrient represents an environmental threat. Calibrations that relate soil test level to nutrient loss are required in order to determine this information.

An example of such a relationship between soil test and P loss is shown in figure 503–33. One challenge is that there is often not a clear critical level in this type of calibration data. A value judgment is usually needed, and the soil test level should be interpreted in the context of the characteristics of the soil and the site.

An instance of this approach is the PI. The PI provides a site vulnerability index for potential P loss based both on the soil test level and on other site characteristics such as soil erosion, irrigation erosion, runoff class, P fertilizer application rate, method of P fertilizer application, organic P (manure, sludge, compost) application rate, and organic P application method.

Soil test recommendations

Developing fertilizer recommendations

The final step in the soil testing process is making a recommendation. Soil test calibration studies similar to the one shown in figure 503–33 can provide the data on whether or not additional nutrients are needed. However, additional information is required in order to determine the appropriate amount to apply.

To determine how much of a nutrient is needed at a given soil test level, experiments with multiple rates of the nutrient are conducted on soils with a range of test levels. For example, in figure 503–34, rate experiments were conducted on soils with a soil test level of 5 and 15 ppm where 0, 40, 80, and 120 pounds per acre of the nutrient were applied at each site. At the end of the growing season, yield was plotted versus the fertilizer added for each experiment. From these results we can see that at a 5 ppm soil test, approximately 50 pounds of fertilizer were required for maximum yield. Conversely, at a soil test of 15

Figure 503–33 Example of soil test calibration for P based on environmental impact (adapted from Sharpley et al, 2001)

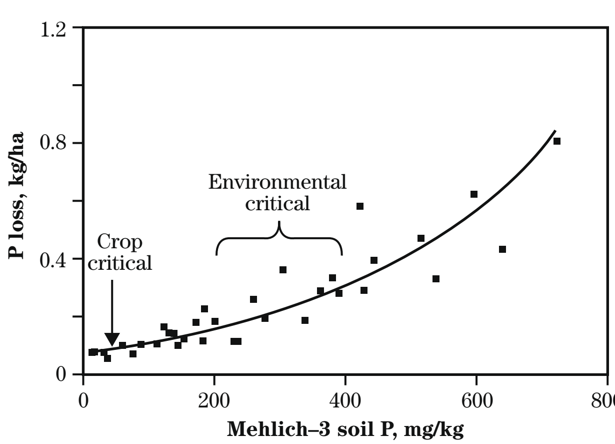
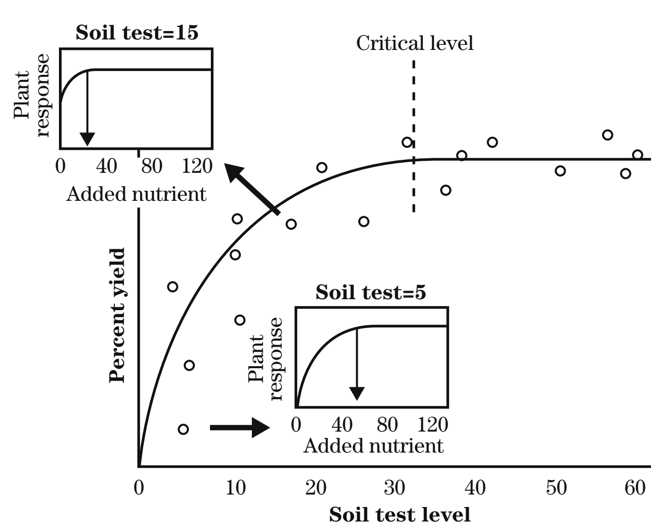


Figure 503–34 Illustration of how fertilizer recommendations are developed



ppm, only 20 pounds of fertilizer were required. This type of experiment is then repeated on many sites with different soil test levels below the critical level to develop the relationship between soil test level and nutrient requirement (fig. 503–35).

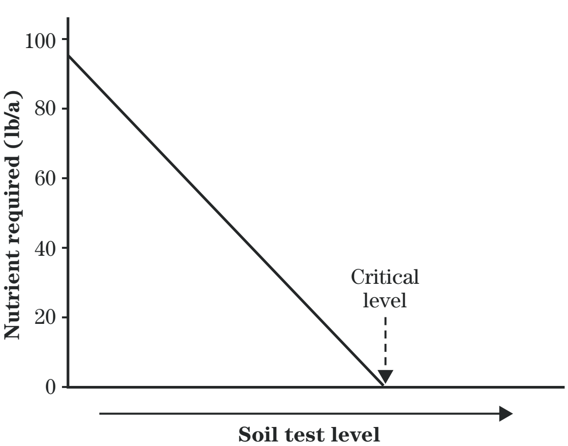
Fertilizing the soil versus fertilizing the crop
A factor that sometimes results in different recommendations is the philosophy of fertilization recommendations. Fertilizer recommendations are usually based on one of two general approaches: fertilizing the soil or fertilizing the crop.

Fertilizer recommendations based on fertilizing the soil are intended to:

- Build the soil test values to a level determined by field calibrations to be sufficient for optimum crop production (buildup)
- Maintain that optimum value over time by replacing nutrients removed by the crop

The fertilize the soil approach is most appropriate for longer-term management where a return from the investment in building soil test nutrient values into the optimum range will be achieved. Soil testing every 3 years is recommended with this approach.

Figure 503–35 Illustration of the relationship between soil test level and nutrient recommendations



Recommendations based on this approach differ in advocating how quickly nutrient levels in the soil should be built up. Some soil testing programs recommend that the soil be built up within the first year of application. This approach can lead to some large, economically questionable recommendations. Most labs follow a slower approach to buildup, either by dividing the estimated buildup requirement over a certain number of years, or by simply including a small, fixed, buildup component to the recommendations for soils with low levels of a particular nutrient.

The maintenance component of the fertilize the soil approach is based on the crop nutrient removal, which is estimated from the expected yield of the crop. Long-term average yields and standard crop removal levels for those yields will usually keep soil test levels within the optimum range. If the yield and crop removal estimates are in error, regular soil testing will allow for periodic corrections before soil nutrient levels become too high or too low.

Fertilizer recommendations using the fertilize the crop (or sufficiency level) approach are based on applying just enough nutrients to achieve optimum response of the crop at a given soil test level. It can be easily argued that this approach has a sounder agronomic and economic basis than the fertilize the soil approach. This approach is especially appropriate when short-term economics and short-term land tenure are critical management factors. Numerous public soil testing labs use this method, but it has not been as widely adopted as the fertilize the soil approach. Rigorous application of this method requires annual soil testing to determine the nutrient requirement for the current crop, and very few farmers will soil test annually.

Soil test recommendations are increasingly becoming a hybrid of these two strategies. The soil test goal for buildup in the fertilize the soil approach is often very close to the critical level for sufficiency in the fertilize the crop approach. It is often difficult to clearly distinguish whether the critical level is a sufficiency level for crop fertilization or an optimum level for soil fertilization because of the inherent variability in soil test calibration data and the high level of uncertainty in determining either the actual sufficiency level for a crop or the optimum value for a soil. This then becomes a question of philosophical perspective and, in some cases, simply semantics. Many labs that use the fertilize the crop approach to make recommendations also recognize the periodic nature of soil testing by farmers and include a maintenance component in their recommendations to account for the impact of crop removal on the soil test level between soil testings. In the long run, with periodic soil testing, either approach should result in similar annual recommendations.

Assessing soil acidity

Soil pH and lime requirement

Two soil tests are normally run to provide information to manage soil acidity:

- soil pH
- lime requirement (or buffer pH)

Results from these tests may be the most important parts of a soil assessment, since soil acidity affects many critical processes in the soil-plant system, such as root growth, nutrient solubility, microbial activity, pesticide activity, and others. It is also important that the soil pH be in the optimum range to assure maximum response from other inputs and management.

The soil pH provides a measure of the current acidity level in the soil. The optimum pH for most crops and soils is 6 to 7. The exact optimum varies with the crop and soil conditions. If a soil's pH is below optimum, it is not possible to determine how much limestone is required from the pH measurement alone. A lime requirement test is run to determine how much limestone will be needed to raise the pH into the optimum range.

Limestone recommendations are made as amount of neutralizing agent to apply, and are usually given as pounds of calcium carbonate equivalent (CCE) per acre. The major quality factors that determine the effectiveness of a limestone are CCE, fineness, and Mg content. Limestone recommendations either assume that a certain quality of limestone will be used or provide instructions for adjusting the recommended amount of limestone to account for the quality of the limestone to be used.

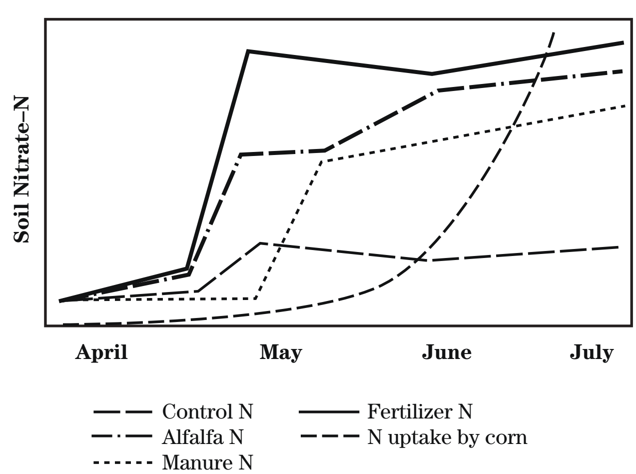
Assessing soil N levels

Introduction

Soil testing has been used effectively for years to de-termine the availability of P and K in agricultural soils and to determine fertilizer recommendations for these nutrients. Due to the complex behavior of nitrogen in the soil, however, 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 503–36, which illustrates the considerable increase in soil NO_3^-–N levels from early in the season to the time when the major demand for N by a corn crop occurs. In this example, if the early season soil NO_3^-–N levels were used to predict availability, all of the fields would have the same soil test level and thus, the same recommendation. However, later in the season when the crop takes up most of the nitrogen, nitrogen availability is very different among the fields. Thus, an at-planting NO_3^-–N test would have been misleading and, because of this, attempts to develop a reliable soil test for N as part of a traditional preseason soil testing program have not been successful. Since corn has the greatest need for N

Figure 503–36 Relative levels of nitrate–N versus corn N uptake soil in corn fields with different management systems (R.H. Fox, Penn State University, unpublished data)



several weeks after emergence, a successful soil test for N should reflect nitrogen availability at that time.

The pre-sidedress soil nitrate test

An 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. The PSNT involves taking 12-inch-deep soil samples just before sidedressing (after the spring wet period but before the period of major nitrogen demand by corn) and determining the amount of NO_3^-–N in this soil sample. At this point in the season, the NO_3^-–N level in the soil is the result of the integration of many factors that influence the soil N transformation from organic forms to NH_4^+ to NO_3^- and has been found to be related to the soil's nitrogen supplying capability over the growing season. The results of the test provide an index of N availability for corn production and are used to make sidedress N recommendations.

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. Data from field research experiments conducted in Pennsylvania, Maryland, and Delaware with the PSNT 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 1 in fig. 503–37).

The vertical line in figure 503–37 at 21 ppm soil NO_3^-–N is the critical level for the PSNT 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 the sites with soil NO_3^-–N levels above this critical level did not respond to added N.

In most States, the PSNT is primarily recommended for use on fields where there are significant organic N contributions such as a history of manure, biosolids applications, or forage legumes in rotation (these are represented by open circles in fig. 503–37). In the past, these fields have been the most difficult sites for which to determine a sound N recommendation. The PSNT is of limited value on most fields without organic N contributions (represented by squares in fig. 503–37), because these sites generally have low N levels where the standard recommendations are usually adequate.

The best use of the PSNT is to confirm the adequacy of N to meet the needs of a corn crop on sites 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.

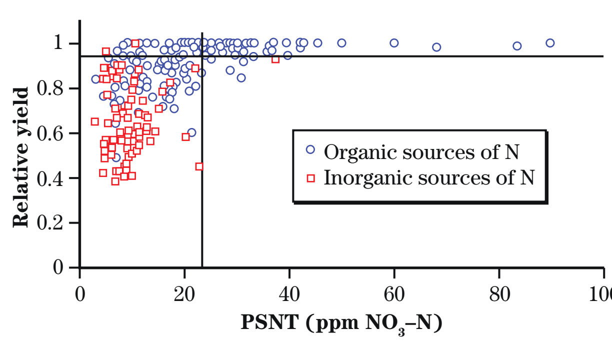
Be sure to follow the specific PSNT procedure for your State.

Test-based recommendations for N

Below the critical level, the PSNT can give some guidance for adjusting N recommendations. However, there is considerable scatter in the data below the critical level (fig. 503–37). It is generally agreed that no sidedress N should be recommended when the soil test value is above the critical level. When the test level is below the critical level, there are several general approaches to making recommendations:

- In the first approach, if the test value is below the critical level, the full rate of N is recommended.

Figure 503–37 Pre-sidedress Soil Nitrate Test calibration data from Pennsylvania, Maryland, and Delaware combined (Fox et al. 1992)



- A second approach is to fall back on traditional methods of adjusting N recommendations based on field history, manure applications, and previous legumes to make an adjusted recommendation when the test value is below the critical level.
- The third approach is to use the test value 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 value in combination with some of the traditional factors to come up with a recommendation.

Again, it is important to follow the recommendation procedure developed for your State.

Chlorophyll meter N test
An alternative to the PSNT soil test used in some States is the chlorophyll meter test. Instead of taking a soil sample, a chlorophyll meter (Minolta Spad Meter) is used to estimate the N status of the corn plants. The basic principle of this test is the same as the PSNT in that this is an in-season assessment of N status that can be used to estimate corn response to N and help improve sidedress N recommendations. Research in Pennsylvania has shown that the accuracy of the chlorophyll meter test is similar to the PSNT for predicting response to N (fig. 503–38).

This test has not been adopted in all States. Check with your local cooperative extension service to see if this test has been adopted in your State and for the specific procedures to be followed.

The chlorophyll meter readings are taken by placing the sensor of the chlorophyll meter on the fifth leaf of the plant about three-quarters of the way towards the outside of the leaf and midway between the edge and the midrib, when the corn is at the 6 leaf stage of growth. The meter will take the reading, display the results, and keep a running average of the results. Usually, readings are taken on 20 to 30 plants randomly selected across a field. After the readings are taken, the results can be averaged, and this average used to make a recommendation. The advantage of this procedure is that the results are instantaneous and there are no samples to process or analyze. The meter is relatively expensive (~$1,500) but, when compared to the labor and analysis costs for the PSNT, it can be very cost effective.

The chlorophyll meter measures the greenness of the corn leaf, which is correlated to the N status of the plant. One problem with this method is that other factors can affect the greenness of the plant, such as hybrid differences and weather. Several approaches have been developed to compensate for this problem.

Figure 503–38 Chlorophyll meter nitrogen test

The most common approach is to establish a small high N reference area early in the season in fields to be tested with the chlorophyll meter. When it is time to run the test (6 leaf stage), readings are taken in both the high N reference area and the rest of the field. Interpretations are made by comparing the results of these two readings. This method normalizes many of the non-N-related influences.

An alternative procedure for the high N reference area approach involves taking multiple readings in a field with time. In this procedure, readings are taken at the 6 leaf stage. Based on this reading, recommendations can be made for fields that test very high or very low. Fields that do not test very high or very low are then tested again in 4 to 7 days. This second reading is used to make recommendations for this second group of fields. This method seems to be more practical for consultants to use than the high N reference area method.

Late season stalk nitrate test

A final nitrogen testing procedure used in the Mid-Atlantic region is the Late Season Stalk Nitrate Test. The Late Season Corn Stalk Nitrate Test has been shown to be a reliable end of season indicator of crop N status. It provides a good assessment of whether the crop had the right amount of N, too much N, or not enough N. This information, combined with records of N management, can be very useful for making future management decisions. Testing a few representative fields will probably be adequate to provide a good assessment of your N program.

The stalk nitrate test is performed anytime between a quarter milkline, which is just before silage harvest, to about 3 weeks after black layer formation. To collect a sample, cut 8-inch-long sections of corn stalk (subsequently cut into two-inch-long segments) starting 6 inches above the ground. If possible, dry the samples immediately or send them to the lab as soon as possible after collection. If more than a day will pass between sampling and sending, refrigerate (do not freeze) the samples until you can send them to the lab. Keep the samples in paper (not plastic) bags. The results of the nitrate analysis on these samples will indicate if the crop had adequate, deficient, or excess N. This information can be used to adjust future nitrogen management.

Assessing soil P levels for environmental management

The critical source area approach

Soil testing for environmental protection is becoming more important. While it has been shown that soil test levels for P are related to P loss, many other factors also play important roles in determining P loss from a given field.

The most common approach to managing P in order to minimize environmental impact is the critical source area approach (fig. 503–39). This approach is based on integrating site specific information on sources of P (soil, fertilizer, manure) and on transport mechanisms (erosion, runoff, leaching, distance to water) to delineate areas on a landscape that have a high risk for P loss. These critical source areas are areas where a high source of P and a high potential for transport overlap. Once these areas are identified, management can be focused where it will have the greatest impact on protecting water quality.

This targeting provides maximum management flexibility for the whole farm because only a small proportion of most farms will be designated as critical source areas. For example, research in an agricultural watershed in Pennsylvania showed that 90 percent of the P that was getting into the water came from just 10 percent of the watershed. This 10 percent of the watershed was the critical source area. The other 90 percent of the watershed did not require special P management.

The Phosphorus Index

The Phosphorus Index (P Index) is a tool that can be used on a farm to estimate the relative risk of P loss based on site characteristics and management. A P Index value is established by evaluating source and transport factors to determine the risk of P loss to the environment (fig. 503–40). The P Index evaluations used by other states in the region are very similar (Coale 2005; Mullins et al. 2005; Sims and Leyten 2002).

If a site has a low P Index value, no specific management modifications beyond standard best management practices are required to address P. If the P Index is high, however, the amount of P that can be applied is limited, usually to the amount of P that will be removed by crops. If the P Index is very high, no P can be applied.

One of the strengths of the P Index is that it provides options for managing phosphorus to protect the environment. If the P Index is high, one option is to restrict phosphorus application, but an analysis of the P Index to determine what factors gave the high result may suggest other management practices that could protect the environment without restricting P applications. For example, if erosion is high, then adopting improved erosion control practices may reduce the risk of P loss and thus, allow P applications.

The P Index is important in the nutrient management planning process. Most nutrient management plans are based initially on balancing the crop nitrogen requirements with manure N. As the plan is developed these N- based rates and management must be evaluated with the P Index.

Based on the results of a PI risk assessment nutrient plans will have to be modified to address this risk of P loss either by restricting or eliminating P applications or by changing management to reduce the potential for P loss.

Plant analysis

Purpose of plant analysis
Plant analysis is the laboratory determination of elemental composition of a 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 and is most effective when used in conjunction with a regular soil testing program.

Elements analyzed
The number of elements measured will depend on the laboratory analyzing the samples. The most common elements analyzed in plant tissue samples are:

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)

Figure 503–39 Critical source areas are locations where a high source of P coincides with high potential for transport of the P

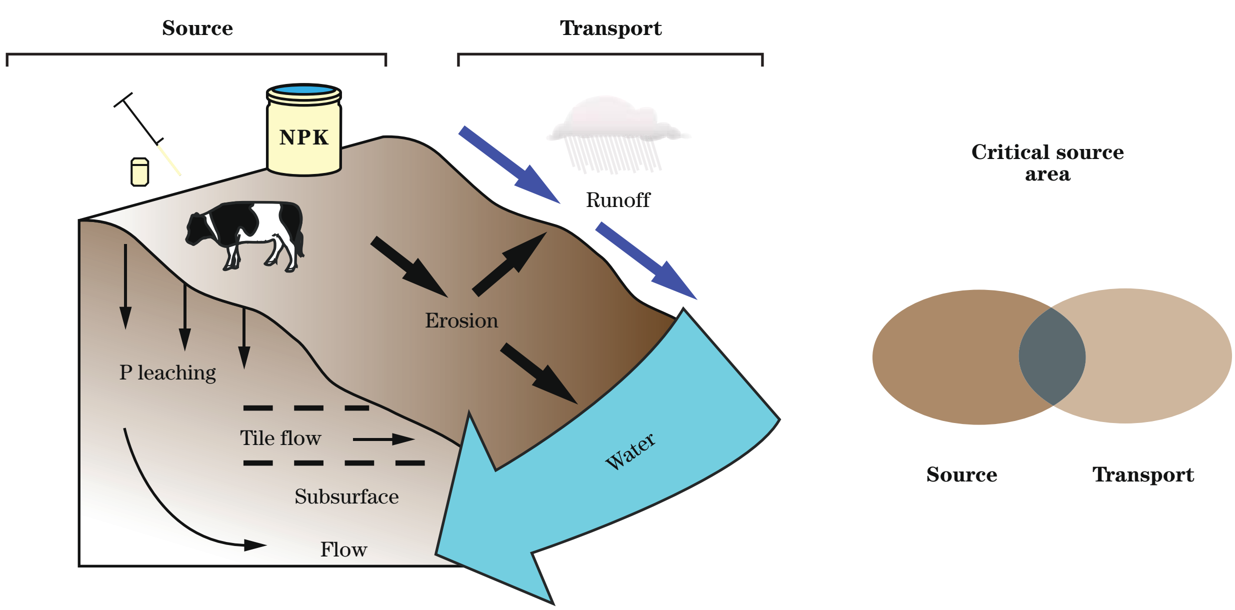


Figure 503–40 The Pennsylvania Phosphorus Index (Beegle et al. 2003)

PART A: Screening Tool

	CMU/Field ID
Is the CMU/field in a special protection watershed?	If the answer is yes to any of these questions, Part B must be used .
Is there a significant farm management change as defined by Act 38?	
Is the soil test Mehlich 3 P greater than 200 ppm P? (Enter soil test value in ppm P.)	
Is the contributing distance from this CMU/field to receiving water less than 150 feet?	

PART B: Source Factors

					CMU/Field ID
Soil Test	Mehlich 3 Soil Test P (ppm P)				
Soil Test Rating = 0.20* Mehlich 3 Soil Test P (ppm P)					
Fertilizer P Rate	Fertilizer P (lb P_2O_5/acre)				
Fertilizer Application Method	0.2 Placed or injected 2 inches or deeper (e.g., starter fertilizer)	0.4 Incorporated less than 1 week following application	0.6 Incorporated more than 1 week or not incorporated following application in April to October	0.8 Incorporated more than 1 week or not incorporated following application in November to March	1.0 Surface applied to frozen or snow-covered soil
Fertilizer Rating = Fertilizer Rate x Fertilizer Application Method					
Manure P Rate	Manure P (lb P_2O_5/acre)				
Manure Application Method	0.2 Placed or injected 2 inches or more deep	0.4 Incorporated less than 1 week following application	0.6 Incorporated more than 1 week or not incorporated following application in April to October	0.8 Incorporated more than 1 week or not incorporated following application in November to March	1.0 Surface applied to frozen or snow-covered soil
P Source Coefficient	Refer to: Test results for P Source Coefficient OR Book values from P Index Fact Sheet, Table 1				
Manure Rating = Manure Rate x Manure Application Method x P Source Coefficient					
Source Factor = Soil Test Rating + Fertilizer Rating + Manure Rating					

PART B: Transport Factors

					CMU/Field ID
Erosion	Soil Loss (ton/acre/yr)				
Runoff Potential	0 Drainage class is Excessively	2 Drainage class is Somewhat Excessively	4 Drainage class is Well/Moderately Well	6 Drainage class is Somewhat Poorly	8 Drainage class is Poor/Very Poorly
Subsurface Drainage	0 None		1 Random		2* Patterned
Contributing Distance	0 More than 500 feet	2 350 to 500 feet	4 200 to 349 feet	6 100 to 199 feet OR less than 100 feet with 35-foot buffer	9‡ less than 100 feet
Transport Sum = Erosion + Runoff Potential + Subsurface Drainage + Contributing Distance					
Modified Connectivity	0.85 50-foot Riparian Buffer Applies to distances less than 100 feet		1.0 Grassed Waterway or None		1.1 Direct Connection Applies to distances greater than 100 feet
Transport Sum x Modified Connectivity / 24					

P Index Value = 2 x Source x Transport

* OR rapid permeability soil near a stream
‡ "9" factor does not apply to fields with a 35-foot buffer receiving manure

- Calcium (Ca)
- Magnesium (Mg)
- Iron (Fe)
- Manganese (Mn)
- Boron (B)
- Copper (Cu)
- Zinc (Zn)
- Aluminum (Al)

Other elements 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)
- Selenium (Se)

Although some of these elements are not essential for plant growth, the results may be used to identify elemental toxicities.

Sampling plant tissue for elemental analysis

Sampling in different situations
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. The sampling procedure will vary depending on the situation.

- For routine monitoring of crop nutritional status, specific plant sampling instructions must be followed so that the results can be properly interpreted. The exact instructions for sampling will depend on the published values that will be used for interpretation.
- For diagnosing nutritional problems, sampling is usually guided by the plant symptoms. Two samples should be collected: one from plants showing the symptoms and one from nearby non-symptomatic plants growing under the same conditions as the symptomatic plant.

When and what to sample
Proper sampling for a particular crop requires that a specific plant part be taken, such as a particular leaf, group of leaves, or portion of the plant. Instructions will also include the number of individual parts to sample, as well as the number of plants. This procedure will ensure that a sufficient quantity of plant tissue is submitted for analysis and that the collected sample is statistically representative of the area sampled.

Plant nutrient concentrations vary with position within the plant. For mobile nutrients like N, P, and K, concentrations will usually be lower in the bottom of the plant as the plant approaches deficiency. For immobile nutrients, concentrations will be lowest in the new growth as the plant approaches deficiency. Follow the sampling instructions from the lab or person that will be interpreting the results of the analysis as closely as possible.

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, or seed are not usually suitable plant tissues for analysis because they do not reflect the general nutrient status of the whole plant.

For many plants, the recommended time to sample is just prior to the beginning of the reproductive stage. However, sampling earlier or even later than that may be recommended for specific plants or circumstances. Plant nutrient concentrations change throughout the life of the plant. For example, the P concentration in a healthy seedling corn plant is approximately twice the concentration found in the same plant at the reproductive stage. Thus, it is critical to follow the recommendations for time of sampling.

When sampling, do not include diseased or dead plant material in a sample. Do not sample plants or leaf tissue that has been damaged by insects, mechanically injured, or stressed extensively by cold, heat, or moisture deficiency/excess. Remove the roots from whole plant samples. Examine the roots. The presence of nematodes, insect damage, or disease damage could preclude the need to sample.

Multiple sampling for diagnosing nutritional problems

When a nutrient deficiency is suspected at a time other than a time recommended for routine sampling, collect two sets of samples: one from plants showing symptoms and one 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 grown under the same conditions. 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.

The best time to sample plants that are showing a suspected nutrient deficiency symptom is when, or shortly after, the visual symptoms appear. The best plant part to sample is the uppermost recently mature leaves. Be sure to take the same plant part in both samples. The plant showing the deficiency may be of different size, or at a different growth stage, than the non-affected plant, so it may be necessary to count leaves or nodes to ensure that the sample is collected from the same position on the both plants.

Interpreting plant analysis data

Introduction

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

Plant analysis data can be interpreted using several techniques, which include:

- critical levels or sufficiency ranges
- total nutrient accumulation
- nutrient use efficiencies

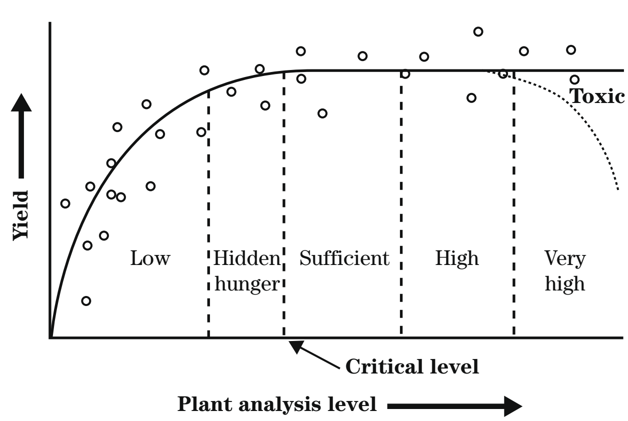
Critical levels and sufficiency ranges

The most common approach is to interpret plant analysis based on critical levels (also called critical values or standard values). This concept is the same as the critical level in soil testing. The critical level is determined by research plot calibration in the same way as for soil testing.

A critical level is that concentration below which deficiency occurs (fig. 503–41). A sufficiency range, which is similar to the optimum soil test range, is also designated. A plant analysis value in the sufficiency range indicates that the nutrient level is neither limiting nor too high. The effects of sampling time, variety, or hybrid, and environmental factors, such as soil moisture, temperature, and light quality and intensity may significantly affect the relationship between nutrient concentration and plant response. Thus, a defined sufficiency range may not apply to all situations or environments.

An additional category in tissue analysis is the hidden hunger category. This occurs where the plant is suffering from a deficiency of a nutrient that is causing reduced yield and/or quality but is not severe enough to cause clear deficiency symptoms. Plant analysis is very useful for finding hidden hunger in crops. In some situations, the levels of an element in a plant can be so high that they are toxic, so the interpretation may include a toxic category.

Figure 503–41 Relationship between plant response (yield) and plant analysis level



Using plant analysis data to determine timing of nutrient addition, and nutrient use efficiency
Plant analysis is useful in optimizing the timing and rates of nutrient addition. Information gained though plant analysis can be used to anticipate times when high plant nutrient concentrations must be maintained for rapid uptake and assimilation, or times when nutrients may be more vulnerable to loss. This approach identifies periods of intra-seasonal variation in plant nutrient accumulation which can be used to schedule efficient, sustainable, fertilizer applications.

Plant analysis data is used to determine relative nutrient use efficiency (NUE) for crop and soil management practices. If total dry matter and plant nutrient concentrations are measured, NUE values can be determined by dividing these values by the amount of fertilizer applied or the amount of nutrient available in the soil. These efficiency values may be used to determine the recovery of applied fertilizer and the uptake of residual nutrients.

Using plant analysis data with soil test results
Whenever possible, plant analyses should be interpreted in conjunction with a soil test from the same area to determine the actual cause of a deficiency.

For example, if the plant analysis is low in K and the soil test is low in K, the interpretation is simple. The soil is deficient in K and the addition of K is necessary to correct this deficiency. In this case, either test would have provided the information needed to make an appropriate management decision.

However, if the plant analysis is low in K, but the soil is optimum or high in K, the problem is due to the inability of the plant to take up soil K, rather than a deficiency in soil K. Thus, adding more K will not likely solve the problem. Possible causes may be restricted root growth from compaction or acidity, root diseases, or root injury from herbicides or fertilizer. Either a soil test or plant analysis alone would not provide this information.

503.28 Manure testing and analysis

It is essential that the nutrient content of animal manure is known when it is applied to the land. Whether this is determined by using book values or from laboratory analysis, an accurate estimate of manure nutrient content must be available if manure is to be utilized effectively in a nutrient management plan.

Manure sampling

When laboratory analysis is used to determine the manure nutrient content, effective sampling is critical. A poor sampling technique will likely result in laboratory results which may not accurately reflect the nutrient content of the manure.

Semi–solid lot manure may be sampled by digging under the crusted layer in several locations, or by using a probe. Mix about 5 pounds of manure in a bucket. Fill the sample bottle about half full. If manures will be supplemented with commercial fertilizer, it may be practical to collect samples from application equipment. Collect about 5 pounds of manure from at least 10 subsamples. When the results are returned, adjustments should be made in future nutrient applications to compensate for the nutrients already applied.

Liquid manure slurry samples should be taken from at least 6 locations in the storage pit or tank after agitation of the storage structure by pump or propeller, and mixed in a bucket. If this is not possible, at least 6 subsamples should be taken from the discharge pipe when the storage structure is emptied, and combined into a single sample. When the results of laboratory analysis arrive after the manure has been applied, any supplemental nutrient applications should be adjusted to reflect the nutrients supplied in the manure.

Lagoon liquid may be sampled directly from the lagoon.

- place a small bottle on the end of a 10-to 15-foot-long pole
- extend the bottle 10 to 15 feet away from the bank edge
- brush away any floating scum or debris
- submerge the bottle within 1 foot of the liquid surface; collect the subsample
- pour the subsample into a bucket

Repeat the procedure at least 5 times from different locations around the lagoon. Thoroughly mix the subsamples in the bucket and fill the sample container half full. From a multistage lagoon system, sample the cell from which liquid is applied to the field.

If lagoon effluent is recycled as flush water for production facilities, collect approximately half pint of the recycled lagoon liquid from the inflow pipe to the flush tanks.

Broiler or turkey litter sampled in–house should be collected as follows:

- 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 the areas.
- Collect approximately five subsamples of litter at locations proportionate to their percentage to the total floor surface. For example, if 20 percent of the litter is around feeders and waterers, collect one subsample from these areas and the other four subsamples from the remainder of the floor area.
- At each location, collect litter from a 6- by 6-inch area down to the earth floor and place in a bucket or container.
- After five subsamples have been collected, mix the contents of the bucket thoroughly, and fill the sample container half full.

Broiler or turkey litter sampled from stockpiled litter should be collected as follows:

- Collect subsamples from approximately 5 locations around the pile at least 18 inches into the pile.
- Thoroughly mix the subsamples, and fill the sample container half full.

In many cases, the phosphorus and potassium content of manures is expressed as pounds in elemental form (P and K). The P and K content of commercial fertilizer is usually expressed in pounds in oxide form (P_2O_5 and K_2O). When developing plans for nutrient management, a common set of units must be used when both commercial fertilizer and manure are sources of nutrients. Normally, it is most convenient to convert the amounts of P and K in manure, usually given in elemental form, to their equivalent quantities, expressed as P_2O_5 and K_2O. Table 503–42 gives the appropriate factors to use when converting elemental P and K to equivalent quantities expressed as P_2O_5 and K_2O. It also shows how to convert quantities of P and K in oxide form to equivalent quantities expressed as elemental form.

503.29 Nutrients and water quality

Introduction

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.

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 nitrogen in most soils. Nitrate, an anion, is not attracted by the negatively charged soil colloids and is, therefore quite mobile and moves freely with soil water. Nitrogen application to soils beyond that required for plant uptake and maintenance of the soil microbial biomass will generally

Table 503–42 Converting between elemental and oxide forms of phosphorus (P) and potassium (K)

Converting elemental to oxide form	Converting oxide to elemental form
Pounds P ×2.2915 = Pounds P2O5	Pounds P2O5 ×0.4364 = Pounds P
Pounds K ×1.2045 = Pounds K2O	Pounds K2O ×0.8302 = Pounds K

lead to NO_3^- leaching and long-term groundwater degradation.

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 soils 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.

Potassium (K) is the third primary plant nutrient. Potassium is required in approximately the same quantity as N. Fortunately, K tends to remain where fertilization puts it. Potassium usually moves only short distances by diffusion through water films surrounding water particles. High soil K levels speed up the rates of diffusion and dry conditions retard movement. At this time, K contamination of surface and groundwater is not considered a major environmental problem. However, technical nutrient application guidelines typically do not recommend, or may ban, applications of K in excess of crop removal.

Health effects of nitrogen

Nitrogen has been associated with a number of potentially adverse impacts on health and the environment (table 503–43). All are typically, but not always, caused by human manipulations of the nitrogen cycle.

Many of the health risks associated with high nitrate consumption are a consequence of the fact that nitrates (NO_3^-) can be reduced to nitrites (NO_2^-) in the intestine of ruminant animals and in human infants.

Nitrogen and human health

Researchers have used average food and water consumption information to calculate the average daily ingestion of NO_3^- and NO_2^- by persons living in the United States (table 503–44). Major sources of nitrate (NO_3^-) in the diet are vegetables and cured meats. The only recognized source of nitrite (NO_2^-) in the diet is cured meats. However, bacteria reduces nitrate to nitrite in the oral cavity and saliva transfers it to the stomach. Most of the ingested NO_3^- is from vegetables and most NO_2^- comes from saliva.

Table 503–43 Potential adverse environmental and health impacts of N

Impact	Causative agents
Human health	
Methemoglobinemia in infants	Excess nitrate (NO_3^-) and nitrite (NO_2^-) in water and food
Cancer	Nitrosamines from NO_2^-, secondary amines
Respiratory Illness	Peroxyacyl nitrates, alkyl nitrates, NO_3^- aerosols, NO_2^-, HNO_3 vapor in urban atmospheres
Animal health	
Environment	Excess NO_2^- in feed and water
Eutrophication	Inorganic and organic nitrogen in surface waters
Materials and ecosystem damage	HNO_3 aerosols in rainfall
Plant toxicity	High levels of NO_2^- in soils
Excessive plant growth	Excessive available N
Stratospheric ozone depletion	Nitrous oxide from nitrification, denitrification , stack emissions

Source: D.R. Keeney, Nitrogen management for maximum efficiency and minimum pollution

Nitrate in drinking water

In rural areas, where many households are dependent on wells as a primary source of potable water, nitrate is a common ground water contaminant. Excess nitrate consumption can cause methemoglobinemia (blue baby syndrome) in human infants. Human babies are particularly susceptible to nitrate poisoning because their digestive systems contain bacteria that convert nitrate (NO_3^-) to toxic nitrite (NO_2^-). Ingested nitrates are converted to nitrite that is rapidly absorbed into the blood where it oxidizes the iron (Fe) of hemoglobin forming methemoglobin which cannot transport oxygen. Untreated, the condition can be lethal when more than 50 percent of the blood hemoglobin is oxidized. After the age of 3 to 6 months, the acidity of babies' digestive systems increases resulting in an undesirable condition for the conversion of nitrite to nitrate.

The Federal standard for nitrate in drinking water is set at 10 parts per million (ppm) nitrate-N, primarily because of the potential effects of nitrate on the health of infants. Babies consume large quantities of water relative to their body weights. Older children and adults can drink water containing high nitrate levels without ill effects. Nitrate in drinking water starts affecting the health of the general populace at levels around 100 to 200 ppm nitrate-N. Undoubtedly, some consumed nitrates are converted into nitrites in the body and under certain conditions can combine with amines to form nitrosamines, which are well documented carcinogens.

Table 503–44 Calculated average daily intake of NO_3^-–N and NO_2^-–N by persons living in the United States (White 1975)

Source	NO_3^-–N		NO_2^-–N	
	mg/day	percent of total	mg/day	percent of total
Vegetables	19.1	86.0	0.06	1.8
Fruits, juices	0.2	1.4	0.00	0.0
Milk and products	<0.1	<0.4	0.00	0.0
Bread	0.4	1.8	<0.01	<0.3
Water	0.2	0.9	0.00	0.0
Cured meats	2.1	9.5	0.72	21.1
Saliva	—	—	2.62	76.8
Total	22.2	100	3.41	100

Source: Effect of nitrogen excess on quality of food and fiber

Respiratory illness

Airborne nitrogen compounds can affect human health directly and contribute to the formation of other air pollutants including smog and fine particles. Nitrogen oxides can cause lasting damage to the lungs and increase susceptibility to respiratory infections.

Ammonia emissions

Ammonia (NH_3) is a gas that is readily released from a variety of biological sources (human and animal wastes, soil, and commercial fertilizers), as well as industrial processes. The amount of ammonia released can be substantial and can directly, or indirectly impact human health. Ammonia plays a key role in the formation of fine particulate matter (< 2.5 mm in diameter or $PM_{2.5}$). Ammonia in the air quickly reacts with sulfur and nitrogen compounds to form fine particles of ammonium sulfate and ammonium nitrate. Health experts believe that $PM_{2.5}$ particles can be inhaled by humans causing serious respiratory health problems.

Suspended particulate matter has an indirect effect on human health and safety because it is associated with poor visibility (haze).

Nitrous oxides (NO_x)

Nitrogen dioxide (NO_2) gas is irritating to human lungs and aids in the formation of particulate matter and ozone. These airborne by-products of nitrogen emissions can cause premature mortality and chronic respiratory illness such as bronchitis or asthma, as well as aggravate existing respiratory illness.

Animal health

The effects of nitrate or nitrite toxicity in livestock are generally similar to those observed in humans. Typically, much higher doses are required to reach toxicity levels in mature animals. Cows, sheep, horses, baby chickens, and baby pigs have digestive systems that support bacteria that convert nitrate to nitrite, and they are likewise susceptible to methemoglobinemia. Currently, there is no regulatory drinking water standard for livestock. The USEPA has recommended that drinking water for livestock be no more than 100 ppm nitrate-N, although most species can tolerate higher levels.

503.30 Site vulnerability assessments

Many factors combine to make every field unique. These factors include the soil present on that site, the cropping sequence followed, climatic factors (temperature, precipitation, and length of growing season), and where that field is located in the landscape, relative to other fields, water bodies, or the drainage network. The interactions of all these factors determine, among other things, the potential for nutrient losses from the site. This subpart describes two tools that have been developed to help planners assess the potential for nutrient loss, and which can also be used to provide guidance on how to minimize those losses.

Vulnerability assessment for nitrogen loss

Nitrogen forms some of the most mobile compounds in the soil-water-plant system. Of particular concern are nitrates (NO_3–), which move readily with water through the soil, and can be easily carried downward to the aquifer or move laterally with subsurface flow and enter surface water bodies. There it can contribute to various water quality problems, including excess algae growth and accelerated eutrophication.

Leaching index

The leaching index (LI) is a simple tool for estimating the potential for percolation below the root zone for a particular site (soil, precipitation, and climate), and thus the potential for movement of soluble materials below the root zone. Refer to State guidance for information about the existence and use of the LI.

Vulnerability assessment for P loss

Phosphorus is generally the limiting nutrient in fresh water systems and any increase in P usually results in more aquatic vegetation. The movement of P in runoff from agricultural land to surface water can accelerate eutrophication. The net result of the eutrophic condition and excess plant growth in water is the depletion of oxygen in the water due to the heavy oxygen demand by microorganisms as they decompose the organic material. Little attention has been given to management strategies to minimize the non-point movement of P in the landscape because of the easier identification and control of point source inputs of P to surface waters and a lack of direct human health risks associated with eutrophication.

Phosphorus index

The phosphorus index (PI) was conceived as a field-based method for determining the relative potential for P movement from a site. Originally, the PI was developed as a simple matrix using a limited number of landform and management characteristics. The input into the matrix is designed to be from readily accessible field data. From the start the concept of the PI was as an assessment tool, not a process model. Planners should follow State-specific guidance when using PI tools

503.31 Managing nutrient losses

Managing nutrient losses is important both agronomically and environmentally. Agronomically, nutrient losses from a field represent a loss of a costly input to the system and have the potential to reduce yields. Environmentally, excess nutrients in surface or ground water contribute to a host of problems: accelerated eutrophication of lakes, excess growth of aquatic vegetation, fish kills, human and animal health concerns, and many others.

The ability to manage nutrient losses begins with an understanding of how and where in the system these losses occur. Three processes are involved in nutrient loss: availability, detachment, and transport.

Availability is the presence of a nutrient in amounts and forms that can be moved off-site. Availability is influenced by nutrient and soil chemistry, which determines the chemical charge the nutrient has, how tightly it may be adsorbed to the soil or whether it is in a form that is soluble in water. Detachment is the process that allows nutrients to become available for transport. Detachment may be wind picking up soil particles from the soil surface, nutrients dissolving in water, or raindrop impact loosening soil particles. Transport is the physical movement of the nutrient, in whatever form, from one place to another. For water quality purposes, the concern is nutrient movement beyond the edge of the field or below the root zone.

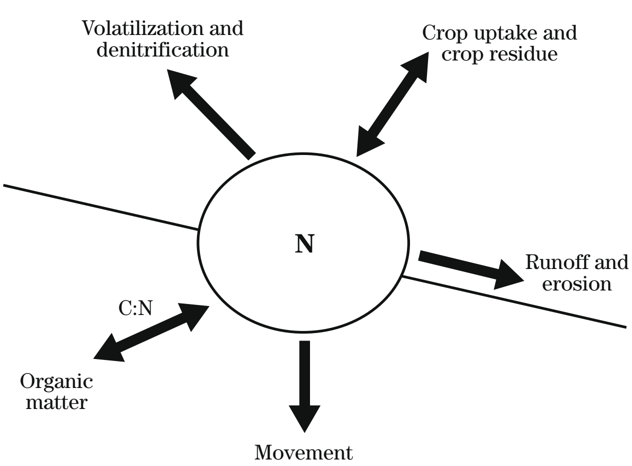
The next two sections will cover how these three processes affect nitrogen and P losses, and the management options that are available to prevent or minimize these losses.

Nitrogen availability, detachment, and transport

Nitrogen is the nutrient present in the greatest amount in the soil. A representative mineral soil contains 2500 to 3000 pounds per acre of nitrogen in the top 12 inches, with 95 to 97 percent of this in organic forms and 3 to 5 percent in inorganic forms. The nitrogen cycle, presented in a very simplified format in figure 503–42, illustrates these forms and the loss pathways of nitrogen in the soil system.

The oval in the center represents the total amount of available nitrogen in the soil at any given time. The arrows indicate movement into or out of this pool of available nitrogen (additions of nitrogen from fertilizer, manure or other sources are assumed but not shown). Arrows pointing in both directions indicate cycling between those subpools and the main pool of available N. The plant–available forms in the pool are nitrate (NO_3^-) and ammonium (NH_4^+). Regardless of the source, whether added directly in fertilizers or mineralized from organic materials in the soil, these forms of nitrogen are susceptible to detachment and transport if they are present in the soil when these processes occur.

Figure 503–42 Simple nitrogen cycle



NO_3^- is highly soluble in water and is not held on exchange sites in the soil. If water, whether from rainfall or over-irrigation, moves downward through the soil, it will carry any available NO_3^- with it. Once it moves below the root zone, the NO_3^- in the water is unavailable for crop uptake. It will continue moving downward as additional water leaches through the soil, eventually entering the aquifer. Depending on the hydrogeology of an area, the water may stay in the aquifer or it may move laterally until it enters a stream via subsurface flow or emerges as a spring and enters a surface water body. NO_3^- is also carried off the field in solution in surface runoff.

Some NH_4^+ moves in solution with water, but its primary loss pathway is attached to soil particles that are detached and transported by intense rainfall or over-irrigation and the resulting runoff. When these sediments enter surface water bodies, the NH_4^+ is available to aquatic vegetation.

Organic forms of N are also susceptible to loss in surface runoff. Manure solids that are surface applied, but not incorporated, can be carried off the field and into surface water bodies. Soil organic matter can be detached by raindrop impact and carried in surface runoff.

Denitrification is another loss pathway for nitrogen from the soil. In this process, NO_3^- in the soil is converted to N_2 gas by bacteria. The nitrogen gas then escapes to the atmosphere. This process usually occurs under anaerobic conditions, predominately in poorly-drained soils.

Reducing nitrogen losses

The key to reducing these nitrogen losses is to disrupt or minimize one or more of the three processes involved. Nitrogen availability can be reduced in many ways. The most obvious is to apply only the amount of nitrogen needed by the crop. A good nutrient budget can accomplish this. If there is any NO_3^- remaining in the soil after harvest, it is susceptible to being leached below the root zone before the next cropping season. Split applications of N minimize the amount of available N in the soil at any one time, and allow crops to use a greater percentage of applied nitrogen. Cover crops can be planted after harvest that will scavenge excess N in the soil, converting it to an organic form that is less susceptible to loss. Manure can be injected rather than surface applied, so that it won't be carried off the field in surface runoff.

Detachment can be reduced by any conservation practice that protects the soil surface from the forces of rainfall impact and surface runoff. Anything that intercepts rainfall, such as a standing crop with a full canopy or maintaining a high percentage of the surface covered with crop residue, during periods when erosive rains are likely to occur, will reduce particle detachment. Crop residue on the surface also slows over-land flow, reducing its potential to detach and carry soil particles or manure solids. Adding close-growing crops to the rotation, growing cover crops after crops that produce low amounts of residue or whose residue decomposes quickly, and adding perennial crops to the rotation all help increase residue cover or increase the time that the soil is protected by a crop canopy.

Denitrification can also be viewed as a form of detachment, because the NO_3^- in solution is converted to N_2 gas, a form that cannot be held in the soil. As noted above, denitrification occurs under anaerobic conditions primarily in poorly drained soils. Diverting excess surface water from low-lying areas and improving the drainage will reduce the time soils are saturated and thus reduce the potential for anaerobic conditions that promote denitrification.

Slowing or redirecting surface runoff reduces its potential to carry detached soil or manure solids off a field. Crop residue on the surface interferes with overland flow patterns, slowing it to the extent that much of the particulate matter is carries will be deposited contour farming, stripcropping, vegetative barriers and terraces all can shorten the length of overland flow paths, reducing the potential energy of overland flow and causing much of the suspended materials to drop out.

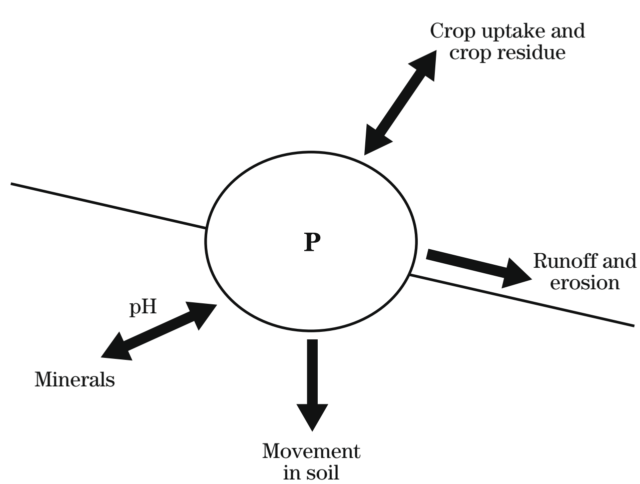
Managing P loss

The total amount of P in a representative native (undisturbed) mineral soil may be only 700 to 900 pounds per acre, with only 0.01 percent of that in available forms at any one time. A simplified version of the P cycle (fig. 503–43) illustrates these forms and the P loss pathways in a cropping system. The oval in the center represents the total amount of P available at any one time. The arrows indicate movement into or out of this pool of available P (additions of P from fertilizer, manure or other sources are assumed but not shown). Arrows pointing in both directions indicate cycling between those subpools and the main pool of available P.

Agricultural soils have more total P than native soils, but the ratio of unavailable P to available P is about the same as for undisturbed soils. Much of the P added as fertilizer is converted to unavailable forms or adsorbed tightly to clay or organic matter particles, making it unavailable to crops. On soils with highly reactive clays, it may take as much as 9 pounds of P per acre to increase the available P by one pound per acre.

Phosphorus is usually the limiting nutrient in freshwater systems. When excess P enters these systems, the eutrophication process is accelerated. As with nitrogen, three processes must occur before P becomes a water quality problem: availability, detachment and transport.

Figure 503–43 Simple P cycle



The availability of excess P in the soil is well documented. In 1989, a survey of State soil test laboratories across the country showed that in 18 States, 50 percent or more of soil samples analyzed tested high or excessive in P. Twelve of these 18 States had more than 60 percent or more of the samples test high or excessive. These high soil test P levels are primarily the result of using manure as the nutrient source, but basing manure application on the nitrogen requirement of the crop and ignoring the amount of P applied. By applying more P than is removed by the crop year after year, the soil test P level was gradually increased. Some soils build up quicker because they have fewer exchange sites (low O.M., low clay content) to tie up the applied P.

Another source of available P is when manure is surface applied and not incorporated. The manure solids are susceptible to detachment and transport during intense rainfall events.

Phosphorus detachment occurs during rainfall events that produce sheet and rill erosion, when soil particles are loosened by raindrop impact making them available for transport. On cultivated land, 80 to 90 percent of the P lost is attached to soil or organic matter particles, with the remainder in solution.

Just the opposite occurs on grassland or forests. Because these areas produce very little sediment, the majority of P lost is in solution. Because the P levels in the soil on these areas are usually much lower than on agricultural land, the total amount of P lost is much lower.

Transport of P occurs when sediment and other particulates with attached P are carried off the field in runoff from severe rainfall events or when irrigation water is applied at a rate greater than soil intake. There is also some P dissolved in the runoff water. When these sediments enter a water body, the dissolved P and some of the attached P becomes available to aquatic vegetation. Transport of P also occurs, although to a lesser extent, when water moves through the soil profile, carrying soluble P below the root zone and into a shallow water table. This water then moves laterally and comes to the surface in drainage ditches or small streams. This mode of transport predominates where the soils have a low capacity to fix P and the water table is close to the soil surface for much of the year.

Reducing phosphorus losses

As with nitrogen, disrupting one or more of the three processes involved in P loss will help reduce those losses. One way to reduce P availability is to apply only the amount of P required for the crop being grown. While this will not reduce soil test P levels, it will at least not increase the amount of available P in the soil.

Another method is to apply fertilizer P based on soil test results. In this situation, if soil test P is already high or excessive, no fertilizer P is applied. The crop has adequate P for the expected yield, and the P level in the soil is reduced by the amount of P that is taken off the field in the harvested crop. Doing this every year will gradually decrease the soil test P level. It is a slow process, though, because soil test P is well buffered. When the available P level is lowered, some of the P that was previously unavailable comes into the available pool, maintaining equilibrium among the various forms of P in the soil.

A third method of reducing P availability is to inject or incorporate fertilizers and manure. This gets the P into contact with the soil, where some of it is fixed in the soil so that it will not become dissolved in runoff water, or be washed off the field by heavy rainfall events.

Disrupting the detachment and transport processes results in the greatest reductions in P losses. This can be done with conservation practices that reduce sheet and rill erosion and slow runoff, since most of the P lost from agricultural land is attached to soil and organic matter particles. Crop residue management practices such as mulch tillage or no tillage, small grains or close-growing crops in the rotation, contour farming, stripcropping and terraces all help reduce erosion and sediment transport.

The PI for a field can tell the planner and producer where the greatest potential for P loss is. The site characteristics that contribute the most to the field rating value are the ones that need to be adjusted, if possible. If the soil erosion rate is high, plan and apply erosion control practices. If fertilizer or manure is being surface-applied but not incorporated, alternatives might be to inject them, or to incorporate them soon after application. If the proximity of a water body is causing the high field rating, alternative might be contour buffer strips, a filter strip at the edge of the field, or a terrace system or diversion to keep surface runoff out of the water body.

503.32 Developing and implementing nutrient management plans

Nutrient management is defined as managing the amount, source, placement, and timing (the 4 R's are right time, right place, right amount, and right source) of the application of nutrients and soil amendments. Producers, whether working with a conservation planner or on their own, need a basic set of information in order to successfully manage their nutrients while protecting the natural resources of the community.

Components of a nutrient management plan

The nutrient management component of a conservation plan must contain, in some form or manner, the information listed in the following nine elements.

Element 1—Site aerial photographs or maps, including a soil map
These maps are generally part of the over-all conservation plan. However, additional site information may be needed for the fields where nutrients will be applied. This information may include proximity to sensitive resource areas, areas with some type of restriction on nutrient applications, and soil interpretations for nutrient application.

Element 2—Location of nutrient management restrictions within or near sensitive areas or resources
If present, sensitive resource areas will be delin-eated on the maps. Any restrictions on nutrient application will also be delineated. This may include set backs required for application of animal manure or where reduced application rates must be used, soil conditions that require reduced application rates or restrictions on time of application, or areas with special resource concerns. The producer will remain aware of these areas and modify management accordingly.

Element 3—Soil, plant, water, and organic sample analysis results
Since nutrient management is based on crop needs and sources of nutrients, an analysis of these factors is essential to know the supplying power of the nutrients and the crop response. These are basic factors to determine the nutrient budget. Soil tests tell the producer the nutrient status of the soil. Plant tissue testing, done at various times during the growing season, can show if the plant is getting adequate nutrients. Testing irrigation water and any biosolids added to the field tell the producer the amount of nutrients supplied by these sources.

Element 4—Current or planned plant production, sequence or crop rotation
Nutrient application is based on crop requirements. The sequence of crops will determine nutrient needs as well as nutrients that may carry over from one crop to another.

Element 5—Realistic yield goals
The expected crop yield is the basis for determining the nutrient requirement for that particular yield level. Generally, the higher the yield expectation the higher the nutrient requirement to reach that yield. There are a number of methods available to calculate expected yield goals.

Element 6—Quantification of all important nutrient sources
Nutrient sources may include, but are not limited to, commercial fertilizer, animal manure and other organic by-products, irrigation water, atmospheric deposition, and legume credits. The estimates used to determine the amount of nutrient supplied is based on the soil, plant, water, and organic analysis mentioned in element 3.

Element 7—A nutrient budget for the complete plant production system
A nutrient budget determines the amount of nutrients available from all the sources and compares this to the amount of nutrients required to meet the realistic yield goal. If the total amount of nutrients from element 6 is not adequate to meet the crop requirement based on expected yield, additional nutrients must be provided. On the other hand, if nutrient supply

exceeds crop needs, management changes should be planned that either reduce the excess or that minimize the potential for nutrient losses from the site.

Element 8—Recommended rates, timing, and methods of application
These are the specifications given to the producer. The specifications are for individual fields or for groups of fields, depending on the soil and crop rotation. The specifications for rates are based on the nutrient requirement of the crop (usually taken from soil test recommendations or university publications). Timing is determined by crop growth stage and nutrient needs and by the climatic conditions that can affect the transformation and transport of nutrients. How the nutrient is applied is based on the form and consistency of the nutrient, soil conditions, and potential for movement and loss to the environment.

Element 9—Operation and maintenance
A number of items need to be reviewed on a regular basis. These include calibration of application equipment, maintaining a safe working environ-ment, review and update of plan elements, periodic soil, water, plant, and organic waste analysis, and monitoring of the resources. This element reminds the producer to continually keep the nutrient management component plan up to date.

Nutrient management considerations in conservation planning

The nutrient management component of a conservation plan must be compatible with other resource concerns addressed in the plan. For example, if manure is a nutrient source, the nutrient management component may require incorporation of the manure to minimize losses in surface runoff and to reduce odors. The tillage operations necessary to incorporate the manure could reduce the residue cover, causing higher sheet and rill erosion rates. Other practices will be needed as a part of the resource management system to keep sheet and rill erosion within tolerable limits.

Comprehensive nutrient management planning
A comprehensive nutrient management plan (CNMP) is a part of the conservation plan for an animal feeding operation, but it has more requirements than a regular nutrient management plan. The concept of a CNMP was developed because of an increase in the number of animal feeding operations (AFOs) where animals are kept and raised in confinement and confined animal feeding operations (CAFOs), AFOs with more than 1000 animal units in confinement in the United States.

A CNMP is a conservation plan for an AFO that:

- Must include:
  - — The production area, including the animal confinement, feed, and other raw materials storage areas, animal mortality facilities, and the manure handling containment or storage areas.
  - — The land treatment area, including any land under control of the AFO owner or operator, whether it is owned, rented, or leased, and to which manure or process wastewater is, or might be, applied for crop, hay, pasture production, or other uses.
- Meets NRCS Field Office Technical Guide (FOTG) Section III quality criteria for water quality (nutrients, organics, and sediments in surface and groundwater) and soil erosion (sheet and rill, wind, ephemeral gully, classic gully, and irrigation-induced natural resource concerns on the production area and land treatment area).
- Mitigates, if feasible, any excessive air emissions and/or negative impacts to air quality resource concerns that may result from practices identified in the CNMP or from existing on-farm areas/activities;
- Complies with Federal, State, Tribal, and local laws, regulations, and permit requirements; and
- Satisfies the owner/operator's production objectives.

The Producer Activity Document (PAD) is an abbreviated CNMP document for the producer's use that sum-marizes the day-to-day activities needed to implement the CNMP. The PAD provides a place for the producer to maintain records as part of a record-keeping system. A template for a PAD is available in the MMP software.

Minimum specific elements for a CNMP include:

- background and site information
- manure and wastewater handling and storage
- farmstead safety and security
- land treatment practices
- soil and risk assessment analyses
- Nutrient Management according to the criteria in the Nutrient Management Conservation Practice (Code 590)
- Feed Management (optional)
- Other utilization options (optional)
- recordkeeping
- references

Note: Feed management and other utilization options are not required elements of a CNMP. However, the feed management element and/or other utilization options should be included in the CNMP, if needed, to help manage the farm nutrient balance.

Note: Where air quality has been identified as a resource concern due to agricultural operations, an air quality element may be needed.

503.33 References

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Subpart 503D Integrated Pest Management

503.40 Introduction to integrated pest management in the conservation planning process

Integrated Pest Management (IPM) is incorporated into the Natural Resources Conservation Service (NRCS) conservation planning process to address all natural resource concerns related to pest management, including pesticide risks to humans and non-target plants and animals. This approach is well documented in NRCS Pest Management Policy: GM_190_404_A-D, Amendment 12, dated March 2009 (*http://directives.sc.egov.usda.gov/RollupViewer.aspx?hid=17015*). IPM is appropriate for all conservation planning with goals that can range from preventing contamination of pristine resources to remediating degraded resources.

503.41 NRCS roles in pest management

NRCS Pest Management Policy states that NRCS has four roles in pest management:

- Evaluate environmental risks associated with a client's probable pest suppression strategies.
- Provide technical assistance to clients to mitigate identified environmental risks.
- Assist clients to adopt IPM techniques that protect natural resources.
- Assist clients to:
  - — Inventory, assess, and suppress noxious and invasive weeds on non-cropland.
  - — Suppress weeds to ensure successful implementation and/or maintenance of permanent vegetative conservation practices (e.g., buffer type practices).

Roles 1, 2 and 3 are addressed in the conservation planning process with the application of Integrated Pest Management (IPM) (Code 595) and other conservation practices. Even though NRCS does not provide technical assistance for managing pests on cropland, NRCS can work closely with Extension and producers and their crop consultants to integrate IPM into the conservation planning process to prevent and/or mitigate pest management environmental risks. IPM techniques such as preventing a pest population from developing, avoiding a pest population, monitoring a pest population to determine when suppression is needed, partially substituting for risky suppression techniques, and utilizing application techniques that minimize pesticide loss or exposure can all be combined into an IPM system that is designed to manage environmental risks as well as pests..

Integrated Pest Management (IPM) (Code 595) is designed to support the adoption of a comprehensive IPM system that incorporates a site-specific combination of pest **P**revention, **A**voidance, **M**onitoring, and **S**uppression (PAMS) strategies.

The two primary goals of the IPM standard are to prevent environmental risks if possible and to mitigate environmental risks that cannot be prevented.

A comprehensive IPM system prevents and avoids *pests* as much as possible to reduce the need for *pest suppression*, including the use of hazardous pesticides.

A comprehensive IPM system also includes carefully monitoring pest populations and only utilizing suppression techniques when the economic benefit is greater than the cost. These economic pest thresholds must be developed for each pest in each cropping system based on the biology of the crop, pest, and natural enemies of the pest. The economic threshold is then dynamically adjusted based on the cost of the pest suppression technique and the projected value of the crop.

A comprehensive IPM system also includes carefully managing the use of different pest suppression techniques to delay the onset of pest resistance to each suppression technique. Utilizing a combination of different techniques including pesticides with different modes of action is critical to maintaining the efficacy of each suppression technique.

And finally, a comprehensive IPM system must also mitigate environmental risks that cannot be prevented by utilizing appropriate IPM techniques that minimize risks to non-target species in the field and reduce off-site movement of hazardous pesticides. A key component of many IPM systems is partial substitution to reduce the use of hazardous suppression techniques.

In some cropping systems a comprehensive IPM system will not be feasible because appropriate IPM technology has not been developed. Integrated Pest Management (IPM) (Code 595) can be used to support the application of individual IPM techniques if they appropriately prevent or mitigate site-specific pest suppression risks to natural resources and/or humans. Note that identified risks can also be addressed with other conservation practices such as Residue Management, Irrigation Water Management, or a Filter Strip, or a system of conservation practices that includes 595._

Role 4 in NRCS Pest Management Policy is addressed in the conservation planning process with the application of Brush/Shrub Control (Code 314) and Herbaceous Weed Control (Code 315) on non-cropland to address natural resource concerns related to the plant pests themselves, including invasive, noxious, and prohibited plants. Integrated Pest Management (IPM) (Code 595) should be used to prevent and/or mitigate pest management environmental risks associated with the application of 314 and 315.

503.42 NRCS pesticide risk analysis in the conservation planning process

The United States Environmental Protection Agency (EPA) regulates pesticides under two major Federal statutes: the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA), both amended by the Food Quality Protection Act (FQPA) of 1996.

Under FIFRA, pesticides intended for use in the United States must be registered (licensed) by EPA before they may be sold or distributed in commerce. EPA registers a pesticide if scientific data provided by the applicant shows that, when used according to labeling directions, it will not cause “unreasonable adverse effects on the environment.” FIFRA defines “unreasonable adverse effects on the environment” as “…any unreasonable risk to man or the environment, taking into account the economic, social and environmental costs and benefits of the use of any pesticide…”

Under FFDCA, EPA is responsible for setting tolerances (maximum permissible residue levels) for any pesticide used on human food or animal feed.

With the passage of the FQPA in 1996, both major pesticide statutes were amended. FQPA mandated a single, health-based standard for setting tolerances for pesticides in foods; provided special protections for infants and children; expedited approval of safer pesticides; and required periodic re-evaluation of pesticide registrations. FQPA also limited the consideration of benefits when setting tolerances. FQPA did not address the consideration of ecological risk.

The EPA pesticide registration process, including any pesticide label use restrictions, is based on a comprehensive *pesticide risk assessment* for typical conditions under which the pesticide will be used. This risk assessment is designed to address many different risks to many different species that might be impacted by a given pesticide use, but it does not include how these risks can vary substantially across the landscape based on site-specific conditions. Even when a pesticide is applied according to pesticide label instructions, site-specific conditions, and extreme weather events may cause a pesticide use to pose significant risks to nearby water resources that are sensitive to pesticide contamination.

NRCS utilizes the Windows Pesticide Screening Tool (WIN-PST) for water quality pesticide risk analysis in the conservation planning process. The *risk analysis* done with WIN-PST for drinking water and aquatic habitat is not as comprehensive as the *risk assessment* that supports the EPA pesticide registration process, but it is sufficient to guide the site-specific application of prevention/mitigation techniques to address identified natural resource concerns. NRCS uses WIN-PST to identify sensitive soil/pesticide combinations and what type of mitigation will help protect site-specific natural resources based on pesticide loss pathways.

503.43 WIN-PST applied in the conservation planning process

(a) WIN-PST analysis parameters

WIN-PST is the NRCS supported technical tool that is used to evaluate relative pesticide leaching, solution runoff, and adsorbed runoff risks to water quality. WIN-PST analysis is based on:

- Soil properties
- Pesticide physical properties
- Pesticide toxicity data

(b) WIN-PST outputs

The major components of the NRCS non-point source water quality pesticide risk analysis are:

- The potential for pesticide loss in:
  — water that leaches below the root zone
  — water that runs off the edge of the field
  — sediment that leaves the field in run off
- Chronic (long term) pesticide toxicity to human drinking water and aquatic habitat
- Combination of pesticide loss potential with pesticide toxicity to provide site-specific ratings for pesticide hazards in leaching, solution runoff, and sediment adsorbed runoff

The final ratings are called WIN-PST Soil/Pesticide Interaction Hazard Ratings. The term hazard is used even though these ratings include both pesticide toxicity and a partial exposure analysis based on field conditions. It is the responsibility of the planner to put these hazard ratings into proper context by using their professional judgment to assess the potential for pesticide movement below the bottom of the root zone or beyond the edge of the field to identified ground or surface water resources, as well as the potential for contamination to impact those resources based on watershed and water body characteristics. This entire process is considered a risk analysis, so the term hazard is used in the final WIN-PST ratings to remind users that they must put these partial risk ratings into the proper context to fully analyze risk to human drinking water and aquatic habitat.

WIN-PST provides ratings for 5 different categories of resource concerns:

- human hazard leaching for leaching risk to drinking water
- fish hazard leaching for leaching risk to aquatic habitat (lateral flow to streams)
- human hazard solution for solution runoff risk to drinking water
- fish hazard solution for solution runoff risk to aquatic habitat
- fish hazard adsorbed for adsorbed runoff risk to aquatic habitat including benthic organisms

Note: there is no WIN-PST rating for Human Hazard Adsorbed since human exposure to sediment is minimal.

The final WIN-PST soil/pesticide interaction hazard ratings are very low, low, intermediate, and high or extra high.

To fully analyze the risk of a pesticide to a human drinking water supply or aquatic habitat, the user must consider the impact of flow path characteristics between the field and the water body of concern (through the vadose zone to groundwater or overland flow to surface water); watershed characteristics; and water body characteristics.

On the higher end of the overall risk spectrum, the flow path from the field to the water body will be short and direct with little opportunity for pesticide degradation or assimilation; the watershed will have significant pesticide loading potential from numerous fields that are managed in a similar fashion as the field being analyzed; and the water body will be sensitive to pesticide contamination due to limited flushing and dilution.

On the lower end of the overall risk spectrum, the flow path to the water body will be long and arduous with lots of opportunity for pesticide degradation and assimilation; the watershed will have only a few fields that are managed in a similar fashion so there will only be limited loading potential for the pesticide in question; and the water body will not be very sensitive to pesticide contamination due to substantial flushing and dilution.

If the overall risk is low, the conservation planner may not identify a water quality concern related to the use of pesticides, so no mitigation may be needed. If the overall risk is high, a suite of conservation practices may be needed to provide sufficient mitigation to meet eFOTG quality criteria. Appropriate mitigation is determined by the final WIN-PST hazard ratings for applicable pesticide loss pathways to identified water resource concerns.

(c) Conduct a WIN-PST analysis

Choose all the major soil types that cover 10% or more of the field or planning area

Choose all the pesticides that the client is planning to use (Note that each pesticide can be chosen by product name, EPA registration number, or active ingredient name, but the final ratings are specific to each active ingredient)

Analyze the results for each soil/pesticide interaction

Select the highest hazard soil/pesticide combination for the identified natural resource concern(s) and plan appropriate mitigation

In table 503–45, there is a solution runoff concern to aquatic habitat. Pesticides X and Y are planned for a field that contains Soils A, B and C.

In this example, the high rating for the combination of soil C with pesticide Y would be selected to plan an appropriate level of mitigation to protect the aquatic habitat. Note that the same process is used for all loss pathways to all natural resource concerns to determine total mitigation requirements, however, many mitigation techniques apply to more than one loss pathway.

Table 503–45 Example WIN-PST Output

Soil/pesticide combination	WIN-PST fish hazard solution rating
Soil a—pesticide X (20% of the area)	Very low
Soil b—pesticide X (50% of the area)	Low
Soil c—pesticide X (25% of the area)	Intermediate
Soil a—pesticide Y (20% of the area)	Low
Soil b—pesticide Y (50% of the area)	Intermediate
Soil c—pesticide Y (25% of the area)	High

503.44 Applying the integrated pest management (Code 595) standard

If a conservation planner identifies natural resource concerns related to pest management activities, practice 595 may be applied to address those concerns. Degraded resources are an obvious concern, but many different pesticides are used in crop production and each has the potential to have different impacts on different natural resources, so the practice 595 standard will also be used on many cropland acres to prevent future resource degradation.

If a pesticide related water resource concern is identified, the 595 standard requires a specific level of mitigation based on WIN-PST results.

For identified water quality concerns related to pesticide leaching, solution runoff and adsorbed runoff, WIN-PST must be used to evaluate potential hazards to humans and/or fish as appropriate, for each pesticide to be used. The minimum level of mitigation required for each resource concern is based on the final WIN-PST soil/pesticide interaction hazard ratings, table 503–46.

Note that the IPM standard can be applied to document that only low or very low risk pesticides for the identified natural resource concern(s) will be utilized as well as what IPM techniques will required to prevent or mitigate risks for intermediate, high, and extra high risk pesticides.

(a) Mitigation—environmental check point

Mitigation requirements can be met with IPM techniques and/or conservation practices.

See table 503–47 for mitigation index values for IPM techniques and table 503–48 for mitigation index values for conservation practices. The index values from table 503–47 can be added to the index values from table 503–48 to calculate the total index score for the planned conservation system.

For example, if fish hazard solution is identified as a pathway of concern for an identified surface water resource and WIN-PST reports an intermediate rating, IPM techniques from table 503–47 or conservation practices from table 503–48 that address solution runoff must be applied so that the sum of the index values from either table in the solution runoff column for the selected IPM mitigation techniques and conservation practices will be 20 or more. Similarly, a high rating would require a sum of 40 or more, and an extra high rating would require a sum of 60 or more. This will be the case for all natural resource concerns and all applicable pesticide loss pathways identified by the conservation planner with the aid of WIN-PST.

As an alternative to mitigation, the conservation planner can work with extension personnel, published extension recommendations, the producer, or their crop consultant to see if there are lower risk alternatives that still meet the producer's objectives. A producer can choose to use pesticides that have risk if they also apply appropriate mitigation, or they can choose low or very low risk pesticides that need no mitigation. Pesticide choice is the producer's decision, but all planned pesticides must be documented to apply the 595 standard.

Pesticide drift has been identified as an important pesticide loss pathway that can have impacts on humans as well as non-target plants and animals. Nearby pollinator and beneficial insect habitat may be especially sensitive to pesticide spray drift.

Pesticide drift can also be a major pesticide loss pathway to surface water in some cases. Appropriate mitigation for drift may be required in addition to mitigation for leaching, solution and adsorbed pesticide loss pathways in order to adequately protect a surface water resource.

Table 503–46 Mitigation index scores needed based on hazard rating

WIN-PST identified final hazard rating	Minimum mitigation index score level needed
Low or very low	None needed
Intermediate	20
High	40
Extra high	60 or more

Spray droplet size as determined by nozzle configuration and pressure plays an important role in pesticide spray drift. Predicting drift is difficult because it is also influenced by rapidly changing site-specific factors including wind speed, relative humidity, temperature and the presence of temperature inversions.

If the conservation planner identifies a natural resource concern related to pesticide spray drift, the minimum level of mitigation required is a drift index score of 20. The index values from table 503–47 can be added to the index values from table 503–48 to calculate the total index score for the planned conservation system.

Pesticide volatilization has been identified as a contributor to air quality concerns through volatile organic compound (VOC) emissions that are a key precursor to ground-level ozone. The state of California has local air shed rules and regulations in place for non-attainment areas, and other States may follow.

Pesticide-related VOC emissions are influenced by the vapor pressure of the active ingredient and the way the pesticide product is formulated. Emulisifiable concentrates have higher VOC emissions than other formulations. If the conservation planner identifies a VOC-related natural resource concern, one or more of the following VOC mitigation techniques must be applied:

- Use lower VOC emitting pesticide formulations—specifically minimizing the use of emulsifiable concentrates when other formulations are available.
- Use precision pesticide application or smart sprayer technology to reduce VOC emissions. Appropriate technologies include:
  - — near-infrared-based weed sensing systems
  - — map/GPS-based variable rate application
  - — Sonar-based vegetation sensors
  - — computer controlled spray nozzles
  - — hoods and shields to direct applications

— wicks

— backpacks

— remote sensing, GIS, or other spatial information system

— steam desiccation systems

— fumigant delivery with precision application

— fumigant delivery with drip irrigation

— fumigant soil retention using precision water application;

- Use impermeable tarps to cover fumigated areas
- Shift dates of fumigant application to outside the May to October timeframe to move VOC emissions out of the non-attainment period
- Use solarization (e.g. irrigate and tarp during summer fallow to kill pests without fumigation
- Use biofumigants or other soil treatments (e.g. thiosulfate) instead of pesticides
- Fallow fields for several years before replanting an orchard crop or inoculate young trees (e.g. with yeast) to reduce fumigant use;

Pesticide Direct Contact can affect pollinators and other beneficial species while pesticides are being applied and later when pollinators and other beneficial species reenter the treated area. This direct exposure to pesticides in the application area can occur even when spray drift is minimized.

For more information, see How to Reduce Bee Poisoning from Pesticides available at: *http://extension.oregonstate.edu/catalog/pdf/pnw/pnw591.pdf*

If the conservation planner identifies a pesticide direct contact concern to pollinators and other beneficial species, choose two or more of the following mitigation techniques:

- Time pesticide applications when pollinators are least active (e.g. at night or when temperatures are low.). Note that dewy nights may cause an insecticide to remain wet on the foliage and be more toxic to bees the following morning.
- Time pesticide applications when crops are not in bloom and keep fields weed free to discourage pollinators from venturing into the crop.
- Use pesticides that are less toxic to pollinators and beneficial species. Note: all pesticide recommendations must come from Extension or an appropriately certified crop consultant.
- Use selective insecticides that target a narrow range of insects (e.g. *Bacillus thuringiensis (Bt)* for moth caterpillars) to reduce harm to beneficial insects like bees.
- Use liquid formulations instead of dusts and fine powders that may become trapped in the pollen collecting hairs of bees and consequently fed to developing larvae.
- Use alternatives to insecticides such as pheromones for mating disruption and kaolin clay barriers for fruit crops.

Cultural and mechanical pest management techniques can also cause natural resource degradation. For example, burning for weed control can cause air pollution concerns and tillage for weed control can cause soil erosion. All natural resource concerns from all forms of pest management should be evaluated and treated to eFOTG planning criteria levels.

503.45 Developing an IPM plan

IPM elements and guidelines from extension or the Land Grant University should be utilized where available. A national listing is available at: *http://www.ipmcenters.org/ipmelements/index.cfm*. The goal is to develop an efficient IPM system that uses prevention, avoidance, monitoring, and then finally judicious suppression only when a pest population exceeds an economic threshold. IPM helps assure that environmental risks are avoided or mitigated.

The best way to develop a good IPM system is to consider economics, efficacy, and environmental risk in a single decision-making process.

Traditionally, IPM plans used to focus on economics and efficacy (including resistance management). Environmental risk reduction was an indirect benefit of an efficient IPM system.

With the advent of the National IPM Roadmap in 2004, environmental risk reduction became a core principle of IPM and is now just as important as economics and efficacy. The National IPM Roadmap can be viewed at: http://www.ipmcenters.org/Docs/IPMRoadMap.pdf.

Developing an IPM plan for a producer as part of the conservation planning process will allow the IPM Plan to directly address identified natural resource concerns as well as provide a broader context to area-wide pest management considerations and habitat management for beneficial species.

It may take several passes through the IPM planning process to achieve all of the producer's goals. An efficient IPM system may still have risks to site-specific natural resource concerns. Some of the risky suppression alternatives may be critical to the function of the overall system. A second pass through the IPM planning process may reveal some additional or alternative IPM techniques that can help prevent or mitigate those site-specific risks to natural resources.

It is important to note that other conservation practices like Crop Rotation, Cover Crop, and Field Borders can also be used to develop an efficient IPM system. Additional conservation practices like filter strips, residue management and irrigation water management can be used in the conservation system along with the 595 conservation practice to provide adequate mitigation.

The IPM mitigation techniques in table 503–47 below are included in most Land Grant University IPM programs, but we have to be careful because NRCS cannot make pesticide recommendations ourselves.

Extension or an appropriately certified farm advisor must support and recommend the use of these techniques, because changing the way a pesticide is applied or substituting a different pesticide is making a pesticide recommendation, and that is not supported by NRCS pest management policy. However, NRCS can fully support the conservation benefits of these IPM mitigation techniques.

Table 503–47 identifies IPM techniques and table 503–48 identifies conservation practices that have the potential to prevent or mitigate pesticide impacts on water and air quality. Water quality is addressed through four separate pesticide loss pathways: leaching, solution runoff, adsorbed runoff, and drift. The pesticide drift pathway also applies to air quality.

Not all IPM techniques and conservation practices will be applicable to a given situation. Relative effectiveness ratings by pesticide loss pathway are indicated with an index value of 5, 10, or 15. The tables also identify how the IPM techniques and conservation practices function and the performance level that the index value is based on. Effectiveness of any IPM technique or conservation practice can be highly variable based on site conditions and how it is designed and maintained. The professional judgment of the planner will ultimately determine the effectiveness of a particular IPM technique or conservation practice for a particular field or planning area.

Tables 503–47 and 503–48 are based on available research specific to IPM technique or conservation practice, related research, and the best professional judgment of NRCS technical specialists. The ratings are relative index values as opposed to absolute values, much like the Conservation Practice Physical Effects (CPPE) matrix ratings. The index values are intended to help planners choose the best combination IPM techniques and conservation practices for their identified resource concerns. The ratings are based on the relative potential for IPM techniques or conservation practices to provide mitigation. The IPM techniques or conservation practices need to be specifically designed, implemented, and maintained for the mitigation potential to be realized. Varying site conditions can influence mitigation effectiveness, but the relative index values indicate which conservation practices or IPM mitigation techniques will generally provide more or less mitigation under a given set of conditions.

A general rule of thumb for IPM techniques or conservation practices having an index value of 5 is that they generally have the potential to reduce losses by 10 to 15 percent. IPM techniques or conservation practices having an index value of 10 generally have the potential to reduce losses by about 25 percent, and IPM techniques or conservation practices having an index value 15 generally have the potential to reduce losses by 50 percent or more.

The original reference for many of the ratings in tables 503–47 and 503–48 is: Aquatic Dialogue Group: Pesticide Risk Assessment and Mitigation, Baker, J.L., Barefoot, A.C., Beasley, L.E., Burns, L.A., Caulkins, P.P., Clark, J.E., Feulner, R.L., Giesy, J.P., Graney, R.L., Griggs, R.H., Jacoby, H.M., Laskowski, D.A., Maciorowski, A.F., Mihaich, E.M., Nelson Jr., H.P., Parrish, P.R., Siefert, R.E., Solomon, K.R., van der Schalie, W.H., editors. 1994. Society of Environmental Toxicology and Chemistry, Pensacola, FL., and table 4–2. This reference provides ranges of effectiveness for various mitigation techniques.

If you have any questions about the material in this publication, please contact the National pest management specialist or your respective State or regional agronomist.

Table 503–47 IPM techniques for reducing pesticide environmental R

IPM techniques[1]	Mitigation index value [4] (by pesticide loss pathway)				Function and performance criteria
	Leaching	**Solution runoff**	**Adsorbed runoff**	**Drift**	
Application timing—ambient temperature				5	Reduces exposure—spraying during cooler temperatures (e.g. early morning, evening or at night) can help reduce drift losses. Avoid spraying in temperatures above 90º F.
Application timing—rain	15	15	15		Reduces exposure—delaying application when significant rainfall events are forecast that could produce substantial leaching or runoff can reduce pesticide transport to ground and surface water.
Application timing—relative humidity				5	Reduces exposure—spraying when there is higher relative humidity reduces evaporation of water from spray droplets thus reducing drift losses.
Application timing—wind				10	Reduces exposure—delaying application when wind speed is not optimal can reduce pesticide drift. Optimal spray conditions for reducing drift occur when the air is slightly unstable with a very mild steady wind between 2 and 9 mph.
Formulations and adjuvants [2,3]	5	5	5	5	Reduces exposure—specific pesticide formulations and/or adjuvants can increase efficacy and allow lower application rates, drift retardant adjuvants can reduce pesticide spray drift.
Monitoring plus economic pest thresholds.	15	15	15	15	Reduces exposure—reduces the amount of pesticide applied with preventative treatments because applications are based on monitoring that determines when a pest population exceeds a previously determined economic threshold.
Partial treatment	15	15	15	10	Reduces exposure—spot treatment, banding and directed spraying reduces amount of pesticide applied. Assumes less than 50% of the area is treated.
Precision application using smart sprayers	10	10	10	10	Reduces exposure—using Smart Sprayer technology (i.e. green sensors, sonar-based sensors, GPS-based variable rate application, computer controlled spray nozzles, etc.) can substantially reduce the amount of pesticide applied.
Set-backs	5	5	5	10	Reduces exposure—reduces overall amount of pesticide applied, reduces offsite pesticide drift. Assumes that the set-backs with no application are at least 30 feet wide.
Soil incorporation [2,3]		15	15		Reduces exposure—reduces solution and adsorbed runoff losses, but potentially increases leaching losses, especially for low K_{OC} pesticides. Applicable to shallow mechanical or irrigation incorporation. Not applicable if pesticide leaching to groundwater is an identified natural resource concern. Not applicable if soil erosion is not adequately managed.

Table 503–47 IPM techniques for reducing pesticide environmental R—continued

IPM techniques[1]	Mitigation index value [4] (by pesticide loss pathway)				Function and performance criteria
	Leaching	**Solution runoff**	**Adsorbed runoff**	**Drift**	
Spray nozzle selection, maintenance and operation.				10	Reduces exposure—selecting appropriate nozzle and pressure for the application, with an emphasis on higher volume spray nozzles run at lower pressures, will produce larger droplets and a narrower droplet size distribution, which reduces spray drift. Proper nozzle spacing, boom height, and boom suspension, along with frequent calibration and replacement of worn nozzles and leaking tubing, can increase efficacy and reduce drift potential.
Substitution—cultural, mechanical or biological controls	15	15	15	15	Reduces risk—substituting alternative cultural, mechanical or biological pest suppression techniques to reduce the application of a pesticide that poses a hazard to an identified natural resource concern. Not applicable if hazards from alternative suppression techniques are not adequately managed.
Substitution—lower risk pesticides [2,3]	15	15	15	15	Reduces risk—substituting an alternative lower risk pesticide to reduce the application of a pesticide that poses a hazard to an identified natural resource concern. Not applicable if the alternative pesticide is not explicitly recommended by extension or an appropriately certified crop consultant because NRCS cannot make pesticide recommendations.
Substitution—semiochemicals	15	15	15	15	Reduces risk—using semiochemicals (e.g., mating disrupting pheromones) to decrease reproductive success or control population density/location to reduce pesticide applications.

1 Additional information on pest management mitigation techniques can be obtained from extension pest management publications including IPM guidelines and crop profiles, pest management consultants, and pesticide labels.

2 The pesticide label is the law - all pesticide label specifications must be carefully followed, including required mitigation. Additional mitigation may be required for NRCS identified natural resource concerns.

3 NRCS does not make pesticide recommendations. All pesticide application techniques must be recommended by extension or an appropriately certified crop consultant and selected by the producer.

4 Numbers in these columns represent index values that indicate relative effectiveness of IPM mitigation techniques to reduce hazardous pesticide losses through the identified pathways.

Table 503–48 Conservation practices for reducing pesticide environmental risk

Pesticide mitigation conservation practices [1, 2]	Mitigation index value [4] (by pesticide loss pathway)				Function and performance criteria
	Leaching	Solution runoff	Adsorbed runoff	Drift	
Alley Cropping (311)	5	5	10	10	Increases infiltration and uptake of subsurface water, reduces soil erosion, can provide habitat for beneficial insects which can reduce the need for pesticides, also can reduce pesticide drift to surface water.
Anionic Polyacrylamide (PAM) Erosion Control (450)		5	15		Increases infiltration and deep percolation, reduces soil erosion.
Bedding (310)	5	5	5		Increases surface infiltration and aerobic pesticide degradation in the rootzone.
Conservation Cover (327)	10	10	10		Increases infiltration, reduces soil erosion, and builds soil organic matter In perennial cropping systems such as orchards, vineyards, berries and nursery stock.
Conservation Crop Rotation (328)	10	10	10		Reduces the need for pesticides by breaking pest lifecycles. The rotation shall consist of at least 2 crops in the rotation and no crop grown more than once before growing a different crop.
Constructed Wetland (656)	5	5	10		Captures pesticide residues and facilitates their degradation.
Contour Buffer Strips (332)		10	10		Increases infiltration, reduces soil erosion.
Contour Farming (330)		5	5		Increases infiltration and deep percolation, reduces soil erosion.
Contour Orchard and Other Fruit Area (331)		5	5		Increases infiltration and deep percolation, reduces soil erosion.
Cover Crop (340) that is incorporated into the soil.	5	5	5		Increases infiltration, reduces soil erosion, builds soil organic matter. Assumes at least 4000 lbs/ac of live biomass at the time of tillage.
Cover Crop (340) for weed suppression that is mulch tilled or no-tilled into for the next crop.	10	10	10	10	Increases infiltration, reduces soil erosion, builds soil organic matter. Assumes at least 4000 lbs/ac of live biomass at the time of tillage and at least 30% ground cover at the time of the pesticide application.
Cross Wind Ridges (588)			5 [3/]		Reduces wind erosion and adsorbed pesticide deposition in surface water. Assumes the pesticide is applied while the field is in the ridged state.
Cross Wind Trap Strips (589C)			10 [3/]		Reduces wind erosion and adsorbed pesticide deposition in surface water, traps adsorbed pesticides.

Table 503–48 Conservation practices for reducing pesticide environmental risk—continued

Pesticide mitigation conservation practices [1, 2]	Mitigation index value [4] (by pesticide loss pathway)				Function and performance criteria
	Leaching	Solution runoff	Adsorbed runoff	Drift	
Deep Tillage (324)		5	5		Increases infiltration and deep percolation. Not applicable if pesticide leaching to groundwater is an identified natural resource concern.
Dike (356)		10	10		Reduces exposure potential - excludes outside water or captures pesticide residues and facilitates their degradation. Not applicable if pesticide leaching to groundwater is an identified natural resource concern.
Drainage Water Management (554)		10	10		Drainage during the growing season increases infiltration and aerobic pesticide degradation in the rootzone and reduces storm water runoff. Managed drainage mode when the field is not being cropped reduces discharge of pesticide residues from the previous growing season. Seasonal saturation may reduce the need for pesticides. Not applicable if pesticide leaching to groundwater is an identified natural resource concern.
Field Border (386)		5	10	5	Increases infiltration and traps adsorbed pesticides, often reduces application area resulting in less pesticide applied, can provide habitat for beneficial insects which reduces the need for pesticides, can provide habitat to congregate pests which can result in reduced pesticide application, also can reduce inadvertent pesticide application and drift to surface water. Assumes 20 foot minimum width.
Filter Strip (393)		10	15	10	Increases infiltration and traps adsorbed pesticides, often reduces application area resulting in less pesticide applied, can provide habitat for beneficial insects which reduces the need for pesticides, can provide habitat to congregate pests which can result in reduced pesticide application, also can reduce inadvertent pesticide application and drift to surface water. Assumes 30 foot minimum width.
Forage Harvest Management (511)	10	10	10	10	Reduces exposure potential - timely harvesting reduces the need for pesticides.
Hedgerow Planting (442)			10 [3/]	10	Reduces adsorbed pesticide deposition in surface water, also can reduce inadvertent pesticide application and drift to surface water

Table 503–48 Conservation practices for reducing pesticide environmental risk—continued

Pesticide mitigation conservation practices [1, 2]	Mitigation index value [4] (by pesticide loss pathway)				Function and performance criteria
	Leaching	Solution runoff	Adsorbed runoff	Drift	
Herbaceous Wind Barriers (1003)			5 [3/]	5	Reduces wind erosion, traps adsorbed pesticides, can provide habitat for beneficial insects which reduces the need for pesticides, can provide habitat to congregate pests which can result in reduced pesticide application, and can reduce pesticide drift to surface water.
Irrigation System, Microirrigation (441)	10	15	15		Reduces exposure potential - efficient and uniform irrigation reduces pesticide transport to ground and surface water.
Irrigation System, Sprinkler (442)	10	10	10		Reduces exposure potential - efficient and uniform irrigation reduces pesticide transport to ground and surface water.
Irrigation System, Surface and Subsurface (443)	5	5	5		Reduces exposure potential - efficient and uniform irrigation reduces pesticide transport to ground and surface water.
Irrigation System Tail Water Recovery (447)		15	15		Captures pesticide residues and facilitates their degradation.
Irrigation Water Management (449)	15	15	15		Reduces exposure potential - water is applied at rates that minimize pesticide transport to ground and surface water, promotes healthy plants which can better tolerate pests.
Mulching (484) with natural materials	10	10	10		Increases infiltration, reduces soil erosion, reduces the need for pesticides.
Mulching (484) with plastic	10	5	5		Reduces the need for pesticides. Not applicable if erosion and pesticide runoff from non-mulched areas is not adequately managed.
Residue Management, No-till and Strip-Till (329)	5	10	15		Increases infiltration, reduces soil erosion, builds soil organic matter. Assumes at least 60% ground cover at the time of application.
Residue Management, Mulch-Till (345)	5	5	10		Increases infiltration, reduces soil erosion, builds soil organic matter. Assumes at least 30% ground cover at the time of application.
Residue Management, Ridge Till (346)	5	5	10		Increases infiltration, reduces soil erosion, builds soil organic matter.
Riparian Forest Buffer (391)	5	15	15	10	Increases infiltration and uptake of subsurface water, traps sediment, builds soil organic matter, and reduces pesticide drift. This assumes 30 foot minimum width.
Riparian Herbaceous Cover (390)	5	10	10	5	Increases infiltration, traps sediment, builds soil organic matter, and reduces pesticide drift. This assumes 30 foot minimum width.

Subpart 503E Crop residue

503.50 Benefits of managing crop residue

Crop residue management is paramount to improving soil quality. Without residue left on or only partially incorporated in the soil surface, there will be continued degradation of soil organic matter levels and soil quality will not be maximized. The concept of leaving only 30 percent of residue on soil surface is out of date as far as improving soil quality. Farmers need to leave as much residue as they can manage to produce high yielding crops, especially in higher rainfall and warmer climates. Lower soil organic matter leads to lower cation exchange capacity, lower pH, lower water holding capacity, greater susceptibility to soil erosion, and poorer soil structure. Poor soil structure results in less pore space, decreased infiltration, and increased surface runoff.

Soil organic matter is an extremely important component of a productive soil. Because organic matter has many exchange sites it is capable of buffering many soil reactions. For example, by holding hydrogen ions, their content is reduced in soil solution that results in less soil acidity. At a pH near neutral (pH 7.0), plant nutrients are most available. In addition, organic matter increases soil aggregate stability and thereby reduces detachment by falling raindrops and surface runoff. Declining levels of soil organic matter over time is a strong indicator of declining soil quality. The NRCS produced information that relates to agronomic practices and effects on soil quality on the NRCS website.

Research in Morris, Minnesota, (Riecosky 1995) reported that as much carbon (C) was lost to the atmosphere as CO_2 in just 19 days after moldboard plowing wheat residue as was produced by the crop. Soil carbon makes up approximately 58 percent of soil organic matter and is therefore a key component of soil organic matter and also serves as an energy source for microbial activity.

Tillage stirs the soil similar to *stoking a fire* that results in more rapid loss of soil carbon. Therefore, the primary reason organic matter levels of continuous cultivated soils have declined to less than half of their original level is directly related to tillage and the resulting loss of carbon to the atmosphere in the form of carbon dioxide. To increase organic matter levels of the soil, crops that produce large amounts of residue and cover crops should be grown with a significant reduction in tillage. Undisturbed root systems are the main contributor to increased soil carbon levels

503.51 Estimating crop residue cover

The line transect method—The line transect method has been proven effective in estimating the percent of the ground surface covered by plant residue at any time during the year.

Estimates of percent cover are used for determining the impact of residue on sheet and rill erosion. When measuring surface residue for where wind erosion is a concern one must not only measure/estimate the flat residue, but also the amount of standing residue. Residue amounts throughout the year are estimated by both the Revised Universal Soil Loss Equation (RUSLE2) and by the Wind Erosion Prediction System (WEPS); however, it is a good practice to measure the actual residue from time to time to ensure the model is predicting the amount of residue correctly based on the planned management system.

Estimates of percent cover obtained using the line transect method to evaluate the impact of residue on sheet and rill erosion are most accurate when the residue is lying flat on the soil surface and is evenly distributed across the field.

The recommended procedures for using the line transect method are:

- Use a commercially available 50- or 100-foot long cable, tape measure, or any other line that has 100 equally spaced beads, knots, or other gradations (marks) at which to sight.
- Select an area that is representative of the field as a whole and stretch the line out across the crop rows. The line may be oriented perpendicular to the rows, or in a direction that is at least 45 degrees off the row direction. The locations in the field where the line is stretched out to make measurements should be selected

randomly from among the areas of the field that are typical of the entire field. End rows, field borders, and parts of the field that appear different are probably not typical of the entire field and should be avoided.

- Walk along the line, stopping at each mark. Position the eye directly over the mark, and look down at it. When sighting, do not look at the entire mark. Rather look at a single point on each mark. A point has an area about like the end of a needle. On commonly used equipment, the knots, beads, or gradations have much larger areas than the end of a needle. A measurement is not based on whether or not some portion of a mark is over the residue. It is based on whether or not a specific point associated with the mark is over residue. If using a commercially available beaded line, one way to accomplish the above is to select as the point of reference the place along the line where a bead begins.
- Determine the percent residue cover by counting the number of points at each mark along the line under which residue is seen. Count only from one side of the line for the single, selected point count at each mark. Do not move the line while counting. Count only that residue that is large enough to intercept raindrops. A rule of thumb is to count only residue that is 3/32 inch in diameter or larger (fig. 503–44). When using a line with 100 points, the percent residue cover is equal to the number of points under which residue is seen.

Three to five transects should be done in each field, using the procedure described in steps 1 through 4. Five transects are recommended. With five measurements, estimates of percent residue cover are accurate to within ±15 percent of the mean. Three measurements will give estimates accurate to within ±32 percent of the mean. For example, if the mean of five measurements was 50 percent cover, you could be confident (at the 95% confidence level) that the true mean was between 42 percent and 57 percent cover. For a 30 percent cover average based on five measurements, you could be confident that the true value was between 25 percent and 34 percent cover.

The documentation of individual transects and computations made to determine average percent residue amounts should be done in a professional manner. Documentation should be done in a way that permits easy tracking from the field measurements to the final answer. The development and use of a documentation worksheet is recommended. Example worksheet formats are illustrated at the end of this section.

Converting pounds of residue to percent cover—For some applications, the weight of the crop residue needs to be known rather than the percent cover. Figure 503–45 illustrates the relationship between residue weight and percent residue cover for various crops. The dashed lines with arrows illustrate the procedure to convert residue weight to percent residue cover. It also illustrates the procedure for estimating the amount of surface cover provided by a known weight of residue.

Figure 503–44 Counting residue pieces along a line transect

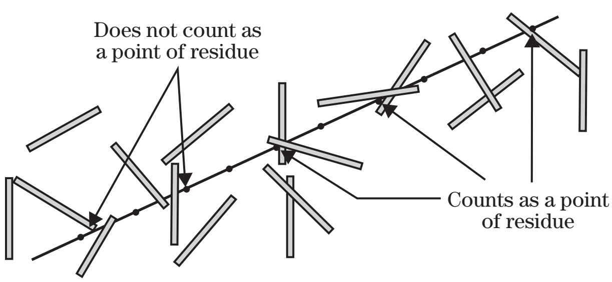
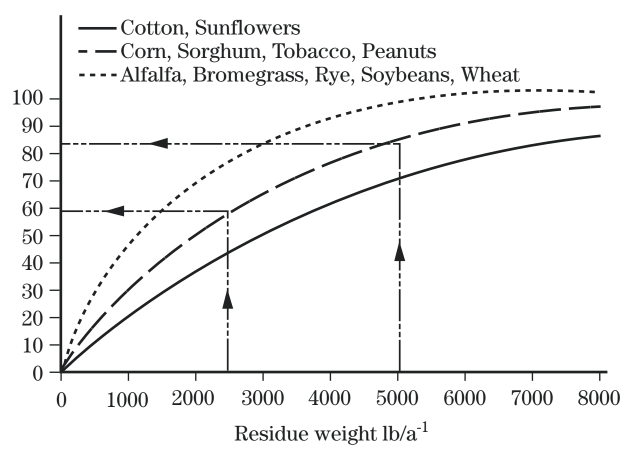


Figure 503–45 Relationship of residue weight to percent residue cover for various crops



503.52 Determining the weight of standing vegetative cover

In many instances, the amount of above-ground biomass needs to be known. The procedures for estimating and measuring the weight of standing vegetation are given in the National Range and Pasture Handbook, Part 600.0401(c).

Part 504 Water Management

Contents

Figures

Tables

Subpart 504A Managing soil moisture on nonirrigated lands

504.00 Soil moisture management overview

Soil moisture management in dryland agriculture is the most critical factor in producing sustainable crop and forage production systems. Without water, no living thing would survive. In relation to crop and forage production, the knowledge of soil water and its proper management has dramatic effects on yields, crop/forage quality, nutrient uptake, and soil health. Climatic factors, crop selection, rotational influences, tillage systems, topography, as well as inherent soil characteristics, all interrelate in assessing the availability of adequate water necessary for successful crop and forage production.

(a) Soil water holding capacity

The potential for a soil to hold water is an important factor in designing a crop production system. Total water held by a soil is called water-holding capacity. However, not all soil water is available for extraction by plant roots. The volume of water available to plants that a soil can store is referred to as available water capacity (AWC).

(b) Available water capacity

Available water capacity is the traditional term used to express the amount of water held in the soil available for use by most plants. It is dependent on crop rooting depth and several soil characteristics. Units of measure are expressed in various terms:

- Volume unit as inches of water per inch or per foot of soil depth
- Gravimetric percent by weight
- Percent on a volume basis

In fine textured soils and soils affected by salinity, sodicity, or other chemicals, a considerable volume of soil water may not be available for plant use.

Water occurs in three forms besides occurring in the form of vapor. *Capillary* water, held in the soil by surface tension, is the water used mostly by plants. When plants begin to wilt, the soil may still contain 2 to 17 percent moisture, depending upon its texture and humus content. Amounts of water below this “permanent wilting point” are largely unavailable to plants. *Gravitational* water is water that moves downward by gravitational forces and may percolate beyond reach of the roots of some plants. *Hydroscopic* water, which is moisture retained by an air-dry soil, is adsorbed on soil particles with such force that it is not available to plants.

Soil-water potential, more correctly, defines water available to plants. It is defined as the amount of work required per unit quantity of water to transport water in soil. The concept of soil-water potential replaces terms such as gravitational, capillary, and hygroscopic water. In the soil, water moves continuously in the direction of decreasing potential energy or from higher water content to lower water content. As a plant takes up water from the soil, the concentration of water in the soil immediately adjacent to its roots is reduced. Water from the surrounding soil then moves into the soil directly around the roots.

For practical reasons, the terms and concepts of field capacity and permanent wilting point are normally used to define the higher and lower limits of available amounts of water. Units of megapascals [MPa (metric units)] or bars or atmospheres (English units) are generally used to express soil water potential. One MPa is equal to 10 bars or atmospheres.

Field capacity of soils, i.e. the amount of water held against the force of gravity, typically ranges from 1 to 2 inches in each foot of soil. The finer the particles (silts and clays) the more water the soil holds. Extremely coarse sandy soils are typically unable to store moisture in sufficient quantities for crop growth under dry land systems.

The field capacity of a well-drained soil is the amount of water held by that soil after free water has drained due to gravity. For coarse textured soil, drainage occurs soon after a rain event because of relatively large pores and low soil particle surface tension. In fine textured soil, drainage takes much longer because of smaller pores and their horizontal shape. Major soil properties that affect field capacity are texture, organic matter content, structure, bulk density, and strata within the profile that restrict water movement. Generally, fine textured soil holds more water than coarse textured soil. Some soils, such as some volcanic and organic soils, are unique in that they can retain significant volumes of water at tensions less than one-tenth bar, thereby giving them a larger available water capacity.

An approximation of field capacity soil-water content level can be made best in the laboratory. It is the water retained in a soil when subjected to a tension of –0.01 MPa [–0.1 atmosphere (bar)] for sandy soils and –0.03 MPa for other finer textured soils.

Absorption—Plants absorb water and also the substances dissolved in it including nitrogen and other mineral elements, largely through root hairs. The root hairs absorb water by osmosis. The more a plant needs water the more vigorously it is absorbed, provided the water supply remains ample. It is also possible for water to be extracted from the roots, as can happen in the case of highly saline soils and saline soil solution.

Nutrients, although taken up by the plant through root hairs (predominantly) are absorbed independently of the rate of water intake, being taken into the plant as ions by diffusion.

Permanent wilting point is the soil-water content at which most plants cannot obtain sufficient water to prevent permanent tissue damage. The lower limit to the available water capacity has been reached for a given plant when it has so exhausted the soil moisture around its roots as to have irrecoverable tissue damage, thus yield and biomass are severely and permanently affected. The water content in the soil is then said to be the permanent wilting percentage for the plant concerned.

Experimental evidence shows that this water content point does not correspond to a unique tension of 1.5 MPa for all plants and soils. The quantity of water a plant can extract at tensions greater than this figure appears to vary considerably with plant species, root distribution, and soil characteristics. Some plants show temporary plant moisture stress during hot daytime periods and yet have adequate soil moisture. In the laboratory, permanent wilting point is determined at 1.5 MPa tension. Unless plant specific data are known, any water remaining in a soil at greater than 1.5 MPa tension is considered unavailable for plant use.

Soil characteristics affecting the available water capacity are texture, structure, bulk density, salinity, sodicity, mineralogy, soil chemistry, and organic matter content. Of these, texture is the predominant factor in mineral soil. Because of the particle configuration in certain volcanic ash soil, the soil can contain very high water content at field capacity levels. This provides a high available water capacity value. Table 508A–1 displays average available water capacity based on soil texture.

Soil pore space

Soil is composed of soil particles, organic matter, water, and air. The pore space (called porosity) found in soil between mineral particles and organic matter is filled with either air or water. The pore space both contains and controls most of the functions of soil. It is not just the total amount of pore space that is importance but also the size and distribution of pores, and the continuity between them that determines function and behavior of soil.

Pore space allows movement of water and air along with the growth of roots. Dense soil (heavy clay) has a low AWC because of decreased pore space. Density can make AWC differences of less than 50 percent to greater than 30 percent compared to average densities. Light (sandy) soils generally have bulk densities greater than soils with high clay content. Sandy soils have less total pore space than silt and clay soils. Gravitational water flows through sandy soils much faster because the pores are much larger. Clayey soils usually contain more water than sandy soils because clay soils have a larger volume of small, flat-shaped pore spaces that hold capillary water. Clay soil particles are flattened or plate-like in shape, thus, soil-water tension is also higher for a given volume of water. When the percent clay in a soil increases over about 40 percent, AWC is *reduced* even though total soil-water content may be greater. Permeability and the ability of a soil to drain are directly related to the volume, size, and shape of pore space.

Uniform plant root development and water movement in soil occurs when the soil profile bulk density is uniform; a condition that seldom exists in the field. Generally, soil compaction occurs in all soils where tillage implements and wheel traffic are used. Soil compaction increases bulk density but decreases pore space, decreasing root development, oxygen content, water movement, and availability.

Compaction—A good soil for crop production contains about 25 percent water and 25 percent air by volume. This 50 percent is referred to as pore space. The remaining 50 percent consists of soil particles. Anything, for example tillage and wheel traffic that reduces pore space, results in a dense soil with poor internal drainage and reduced aeration.

Soil compaction can be a serious production problem. Over the years, field implements have become bigger and heavier, and some cultivation is performed when soil is too moist. Because compacted soil has smaller pores and fewer natural channels, water infiltration can be drastically reduced. This causes greater surface wetness, more runoff, which in turn increases erosion, and longer soil drying time. Wet fields delay planting and harvesting. Plant roots do not grow well in dense or compacted soil resulting in inadequate moisture and nutrients reaching the plant.

Figure 504–1 shows how soil moisture affects compaction depth. A given load and tire size causes greater deep compaction on wet soil than dry. Sod-forming crops such as alfalfa and clover, which in the past were typically included in crop rotations, provide greater support at the soil surface than bare soil.

Table 504–1 Available water capacity (AWC) by soil texture

Texture symbol	Texture	AWC range (in/in)	AWC range (in/ft)	Estimated typical AWC (in/ft)
COS	Coarse sand	0.01–0.03	0.1–0.4	0.25
S	Sand	0.01–0.03	0.1–0.4	0.25
FS	Fine sand	0.05–0.07	0.6–0.8	0.75
VFS	Very fine sand	0.05–0.07	0.6–0.8	0.75
LCOS	Loamy coarse sand	0.06–0.08	0.7–1.0	0.85
LS	Loamy sand	0.06–0.08	0.7–1.0	0.85
LFS	Loamy fine sand	0.09- 0.11	1.1–1.3	1.25
LVFS	Loamy very fine sand	0.10–0.12	1.0–1.4	1.25
COSL	Coarse sandy loam	0.10–0.12	1.2–1.4	1.3
SL	Sandy loam	0.11–0.13	1.3–1.6	1.45
FSL	Fine sandy loam	0.13–0.15	1.6–1.8	1.7
VFSL	Very fine sandy loam	0.15–0.17	1.8–2.0	1.9
L	Loam	0.16–0.18	1.9–2.2	2.0
SIL	Silt loam	0.19–0.22	2.3–2.6	2.45
SI	Silt	0.16–0.18	1.9–2.2	2.0
SCL	Sandy clay loam	0.14–0.16	1.7–1.9	1.8
CL	Clay loam	0.15–0.17	1.8–2.0	1.9
SICL	Silty clay loam	0.17–0.19	2.0–2.3	2.15
SC	Sandy clay	0.15–0.17	1.8–2.0	1.9
SIC	Silty clay	0.15–0.17	1.8–2.0	1.9
C	Clay	0.14–0.16	1.7–1.9	1.8

504.01 Climatic and precipitation

Crops are generally grown most successfully when grown in regions where they are well adapted. Crop production shows patterns of geographic segregation despite the fact that many crops may grow well over wide areas. One of the principal factors that influence localization is climate.

Climate is a major factor for determining the suitability of a crop for any given area. Climatic differences are due chiefly to the variations in latitude, altitude, distances from large water bodies, ocean currents, and direction and intensity of winds.

There are three distinct (major) climatic regions recognized in the US. The first is the narrow strip of territory from the Pacific Coast to the Cascade and Sierra Nevada mountains, an oceanic climate where rainfall ranges from less than 10 inches (Southern California) to over 100 inches per year in the Northwest. Winters are mild in this region, while summers in the northern portion and along the coastline are cooler. The second region is the upland plateau from these mountains eastward to approximately the 100th meridian (fig. 504–2). The climate in this region is characterized by great extremes of temperature between day and night and between winter and summer. It is also characterized by irregular approach of seasons, deficient rainfall, lower humidity, and relatively unobstructed winds. The limited rainfall that occurs can be sporadic and often torrential. The third region is from the 100th meridian east to the Atlantic, where conditions are again modified by the Great Lakes and ocean.

Frost—In many areas, potential frost is a major concern for crop and forage production. Frost not only affects growing tissues, it also has an effect on soil. Frost action can cause upward or lateral movement of soil by formation of ice lenses. Frost can break compact and clayey layers into more granular forms at shallow depths. It can also break large clay aggregates into smaller aggregates that are more easily transported by wind. Frost heaving can have detrimental effects on conservation structures and even destroy taprooted perennial crops.

Precipitation—In dryland systems, rainfall (amount and timing) is the most limiting factor affecting crop production systems. In semi arid regions, such as the Great Plains and Great Basin, managing the scanty precipitation is so vitally important that it takes precedence over all other manageable factors.

Figure 504–1 Effects of compaction

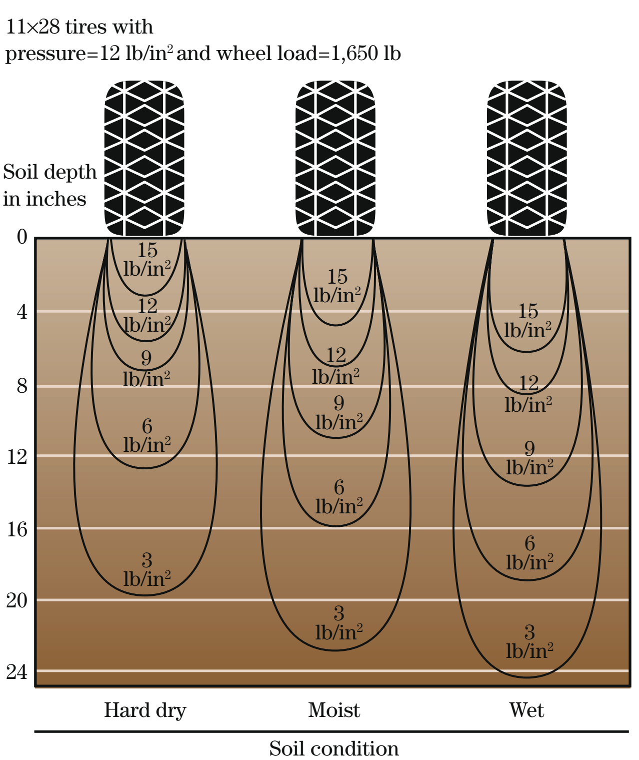
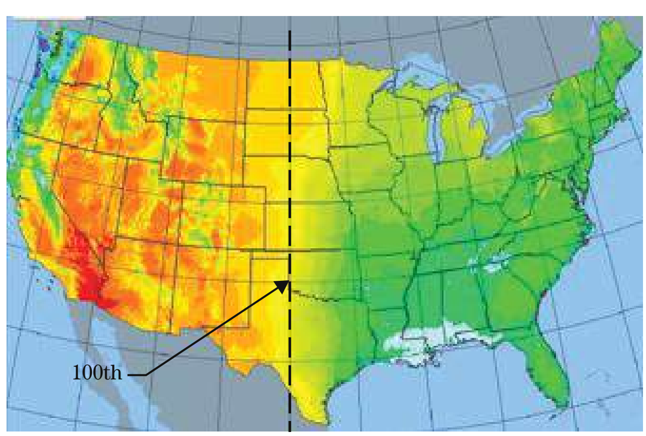


Figure 504–2 Climatic regions of the United States



Crop regions are often classified based on average annual precipitation. The *arid region* is where the average annual precipitation is 10 inches or less. Irrigation is necessary for successful crop production in most of these areas. The *semi arid* region is considered to be that where precipitation varies from 10 to 20 inches. Conservation tillage along with crop varieties and rotations adapted to dry farming regions, and sometimes irrigation, are necessary for successful production. The annual precipitation in *semi-humid* areas ranges from 20 to 30 inches. This amount of precipitation may not be adequate for satisfactory crop yields unless moisture management methods that best utilize growing season soil moisture are followed. For example, in the southern Great Plains, seasonal evapotranspiration is high requiring conservation practices that reduce soil evaporation. The humid region is regarded as the area where annual precipitation is more than 30 inches. Conservation of moisture in this region is not necessarily the dominant factor in crop production systems.

Effective rainfall—The effectiveness of a given amount of rainfall within a crop production system depends upon the time of the year it falls and the intensity of individual rainfall events. Seasonal evaporation may be equally critical.

Total rainfall can fluctuate widely from year to year along with its timeliness. Rainfall has its greatest value when it falls during the growing season, which is typically between April 1 and September 30 in most regions. The critical period for moisture to be available, for most crops, occurs just before or immediately after flowering. For instance, in the Golden Triangle in Montana, where growing season precipitation average about 5 inches of rainfall, a total of less than 1 inch of precipitation had fallen since January. A spring wheat crop was planted in hopes of rains. Due to lack of rainfall, the spring wheat was only 12 inches tall (half of the normal height) when it started into the boot stage. The rain finally came and in one week of continuous, slow rainfall, 4 to 5 inches soaked into the ground. Record yields were harvested with only half of the green vegetation. Conversely, in a year with greater than average soil moisture, the spring wheat planting grew tall and lush only to run out of soil moisture. With no growing season rainfall, seed heads formed on the tall stalks. It was too late when 4 inches of rain poured out of the sky in one day, much of it running off the fields. This type of rainfall is not effective. In dry land farming, timing of precipitation is vitally important.

Soil water—Water is the most important constituent in the soil in relation to crop and forage production. Additionally, physical soil characteristics have a major impact on water infiltration, movement, storage, and availability of water within the soil profile. Some of these characteristics include soil texture, bulk density, structure, pore space, organic matter content, salinity and sodicity as well as other inherent soil characteristics.

Water can move in soils under gravity (i.e. drainage) and under a suction gradient (capillary). The rate of movement is controlled by the size and continuity of the pores containing the water, by the pressure or suction gradient, and by the viscosity of the water. Water can only move through existing water-filled passages. It cannot move across or down an air space except under exact extreme conditions.

Water infiltration—Water infiltration is the process of water entering the soils from the soil surface. The rate at which water enters the soil, considered either infiltration rate or permeability of the soil, depends on the portion of coarser pores on or near the soil surface. The rate itself is controlled by every factor which affects the number and stability of larger pores. Infiltration rates are directly affected by factors that are somewhat controlled by management including tillage practices, amounts of surface residue, soil organic matter, salinity, and sodicity. Infiltration rates are also heavily reduced if the pores at the surface become filled with mud, as may happen if muddy water flows over the land or during heavy rain storms if the surface is not protected from mechanical shattering of the last-falling heavy rain drops.

Infiltration rates change during a rainfall event and typically become slower over time. They may also decrease over the growing season because of cultivation and harvest equipment. This is especially true if operations are completed during higher soil-water levels. Macropores, such as cracks of worm holes affect internal drainage and thus may play significant roles in infiltration rates.

504.02 Crop water requirements

Water is required for all plant growth and is needed in much larger quantities than any essential nutrient. The difference between water and nutrients is that usually a large proportion of nutrients absorbed by the plant are retained, whereas, water is continuously taken up by the plant and then evaporated inside the stomata and diffused into the air.

The rate of water transfer from the soil into the air by the plant is controlled by four separate processes:

- Transfer of water from the soil into the vascular system,
- Transfer from the vascular system through the protoplasm to the leaf cells bounding the stomata,
- Water evaporates in stomata and from leaf surface,
- Transfer of water vapor from inside stomata in the air by diffusion or convection.

Plants *normally* transfer water from the soil to the leaf cells faster than it is dissipated from the leaves as vapor. But, under conditions of high evaporation or limited water supply in the soil, the root cells may not be able to transfer water from the soil to the vascular system as fast as leaf cells are dissipating it. In this situation, the leaves will begin to lose water, causing most species of plants to lose turgor and begin to wilt.

Shortage of water in the leaf has several effects besides causing it to wilt. The stomata close, cutting down on transpiration losses and reducing photosynthesis. Leaf cells loose water causing cell sap to rise, causing death of the cells and eventually the entire leaf (and if continued the entire plant).

Farm crops typically react to prolonged drought by shedding their leaves, thus reducing the amount of water they transpire and hence their demands on the soil water. However, crops differ considerably in the severity of drought they can withstand before all the leaves have been lost or died. Most young plants are very dependent on an adequate supply of water and are unable to withstand any appreciable drought. But, as plants grow older, they can usually survive periods of water shortage without any serious injury. Some crops are capable of going dormant during periods of drought, which is a characteristic of leaf construction. The direct effect of drought on a crop is based on the amount of leaf the crop is able to carry.

Crop evapotranspiration (ETc), sometimes called crop consumptive use, is the amount of water that plants use in transpiration and building cell tissue plus water evaporated from an adjacent soil surface. Seasonal local crop water use requirements are essential for planning crop production systems.

Evaporation—Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Energy is required to change the state of the molecules of water from liquid to vapor. Direct solar radiation and, to a lesser extent, the ambient temperature of the air provide this energy. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if the wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity, and wind speed are climatological parameters to consider when assessing the evaporation process.

Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process. Frequent rains, irrigation, and water transported upwards in a soil from a shallow water table wet the soil surface. Where the soil is able to supply water fast enough to satisfy the evaporation demand, the evaporation from the soil is determined only by the meteorological conditions. However, where the interval between rains (or irrigation) becomes large and the ability of the soil to conduct moisture to the surface is small, the water content in the topsoil drops and the soil surface dries out.

Transpiration—Transpiration consists of the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere. Crops predominately lose their water through stomata. These are small openings on the plant leaf through which gases and water vapor pass. The water, together with some nutrients, is taken up by the roots and transported through the plant. The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the stomatal aperture. Nearly all water taken up is lost by transpiration and only a tiny fraction is used within the plant.

Transpiration, like direct evaporation, depends on the energy supply, vapor pressure gradient, and wind. Hence, radiation, air temperature, air humidity, and wind terms should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do waterlogging and soil water salinity. The transpiration rate is also influenced by crop characteristics, environmental aspects, and cultivation practices. Different kinds of plants may have different transpiration rates. Not only the type of crop, but also the crop development, environment and management should be considered when assessing transpiration.

504.03 Irrigation water and plant growth

Irrigation water is applied to soil to supply adequate water quantities to grow crops and forages that may not otherwise be possible with dryland cropping systems. Irrigation water is applied to replenish water removed from the soil by evaporation, by growing plants (transpiration) and to some extent by drainage below the root zone. In some cases it is used to flush minerals from the root zone (salts) annually.

Water application is completed in a number of different ways. Methods of application depend upon the species of crop or forages being grown, soil characteristics, topography of the land, the cost of the water, and the cost of various delivery systems. The amount of water used and how often it is applied are determined by crop needs, the need for deep leaching (flushing out salts), local climatic conditions, and other interrelated factors. Successful irrigation required careful management of both crops and water.

All water used for irrigation contains some dissolved salts. Suitability of water for irrigation strongly depends on the kinds and amounts of salts present. Needless to say, salts in irrigation water have a direct impact on the plant and soil, and therefore on the properties of soils and the production of plants.

Irrigators should know the effects that their irrigation water and irrigation practices might have on their crops and forages including:

- the salt content of the soil (salinity)
- the sodium status of the soil
- rate of water penetration into the soil
- presence of elements which may be toxic to crops/forages

Water is held largely as film around each soil particle (see National Agronomy Manual Subpart 508A for Agronomic Soil Basics). The thinner these films are, the tighter they are held, and the greater the suction needed to remove the water. Right after an irrigation event, the films of water are thick and *not* held tightly by the soil. After some days, with free drainage, about half of this weakly held water moves deeper into the soil profile and, if additional water is not applied, free drainage ceases. This is the point called *field capacity*. Anytime water is below field capacity, gravity is not longer a significant source of water movement in the profile. Most of the water removed, at this point, is done so by growing plant roots. Plants have the capability of removing about one-half of the water held at field capacity. After that point, the soil holds on to water so tightly that plants cannot extract it, and leads to wilting if additional water is not applied.

(a) When to irrigate

Information pertaining to soil and crop characteristics is also important for irrigated cropping systems. It is vital for proper irrigation water management to accurately determine plant available soil water. Detailed information including soil texture, structure, layering, water-holding capacity, and soil depth, rooting pattern and depths, and crop susceptibility to stress are typically used to determine when to irrigate and how much water to apply.

(b) Tools and techniques

There are several tools and techniques that can be utilized to monitor or measure soil water for purposes of scheduling irrigation including:

- Soil feel and appearance method
- Gravemetric sampling
- Tensiometers
- Porous blocks
- Neutron probe

Scheduling routine sampling is important in any of the methods. Soil and water should be measured or monitored at a minimum of two depths in the expected crop root zone in several locations within a field.

504.04 Methods for determining crop evapotranspiration

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and the canopy completely covers the soil, transpiration becomes the main process. At planting nearly 100 percent of evapotranspiration (ET) comes from evaporation, while at full crop cover more than 90 percent of ET comes from transpiration.

(a) Weather parameters

The principal weather parameters affecting ET are radiation, air temperature, humidity, and wind speed.

(b) Crop factors

The crop type, variety, and development stage should be considered when assessing the ET from crops. Differences in resistance to transpiration, i.e. crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions.

(c) Management and environmental conditions

Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing ET are ground cover, plant density, and the soil water content. The effect of soil water content on ET is conditioned primarily by the magnitude of the water deficit and the type of soil. On the other hand, too much water will result in waterlogging which might damage the root and limit root water uptake by inhibiting respiration.

When assessing the ET rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the ET process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics, or affect the wetting of the soil and crop surface. A windbreak reduces wind velocities and decreases the ET rate of the field directly beyond the barrier. The effect can be significant especially in windy, warm, and dry conditions although evapotranspiration from the trees themselves may offset any reduction in the field. Soil evaporation in a young orchard, where trees are widely spaced, can be reduced by using a well-designed drip or trickle irrigation system. The drippers apply water directly to the soil near trees, thereby leaving the major part of the soil surface dry, and limiting the evaporation losses. The use of mulches, especially when the crop is small, is another way of substantially reducing soil evaporation.

(d) Direct measurement of crop evapotranspiration

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine ET. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel.

Several methods that one can employee to directly measure evapotranspiration including

- lysimetry
- soil-water balance (inflow-outflow)
- energy balance and microclimate method
- others

These methods require localized and detailed measurements of plant water use. Detailed soil moisture monitoring in controlled self contained devices (lysimeters) is probably the most commonly used.

(e) Estimated crop evapotranspiration

There are numerous methods for estimating evapotranspiration based on local crop and climatic factors. The simplest methods are equations that generally use only mean air temperature. The more complex methods are described as energy equations. They require real time measurements of solar radiation, ambient air temperature, wind speed/movement, and relative humidity/vapor pressure. Most of these equations adjust for the reference crop ET with lysimeter data.

Selection of the method used for determining local crop ET depends on location, type, reliability, timeliness, and duration of climatic data; natural pattern of evapotranspiration during the year; and intended use intensity of crop evapotranspiration estimates.

Although any crop can be used as the reference crop, clipped grass is the reference crop of choice. Some earlier reference crop research, mainly in the West, used 2-year-old alfalfa (ETr). With a grass reference crop (ETo) known, ET estimates for any crop at any stage of growth can be calculated by multiplying ETo by the appropriate crop growth stage coefficient (kc), usually displayed as a curve or table. The resulting value is called crop evapotranspiration (ETc).

The following methods and equations used to estimate reference ET_c. ETo methods and equations are described in detail in the National Engineering Field Handbook, Part 623, Chapter 2, Irrigation Water Requirements (1990). The reference crop used is clipped grass. Crop coefficients are based on local or regional growth characteristics. The Natural Resources Conservation Service (NRCS) recommends the following methods:

- Temperature method
  - FAO Modified Blaney-Criddle
  - Modified Blaney-Criddle
- Energy method
  - Penman-Monteith method
- Radiation method
  - FAO Radiation method

Evaporation pan method—The FAO Modified Blaney-Criddle, Penman-Monteith, and FAO Radiation equations represent the most accurate equations for these specific methods. They are most accurately transferable over a wide range of climate conditions.

The intended use, reliability, and availability of local climatic data may be the deciding factor as to which equation or method is used. For estimation of monthly and seasonal crop water needs, a temperature-based method generally proves to be quite satisfactory.

The FAO Modified Blaney-Criddle equation uses long-term mean temperature data with input of estimates of relative humidity, wind movement, and sunlight duration. This method also includes an adjustment for elevation. The FAO Radiation method uses locally measured solar radiation and air temperature.

Crop ET and related tables and maps can be included to replace or simplify crop ET calculations. These maps and tables would be locally developed, as needed.

(f) Critical growth periods

Plants must have ample moisture throughout the growing season for optimum production and the most efficient use of water. This is most important during critical periods of growth and development. Most crops are sensitive to water stress during one or more critical growth periods in their growing season. Moisture stress during a critical period can cause an irreversible loss of yield or product quality. Critical periods must be considered with caution because they depend on plant species as well as variety. Some crops can be moderately stressed during noncritical periods with no adverse effect on yields. Other plants require mild stress to set and develop fruit for optimum harvest time (weather or market). Critical water periods for most crops are displayed in table 504-2.

(g) Rooting depth

The soil is a storehouse for plant nutrients, an environment for biological activity, an anchorage for plants, and a reservoir for water to sustain plant growth. The amount of water a soil can hold available for plant use is determined by its physical and chemical properties. Figure 504–3 provides a typical diagram of how soil water is extracted.

Crops extract water in varying amounts depending on depth into the rooting zone. Crop rooting density with depth is generally not uniform. Additionally, the rate

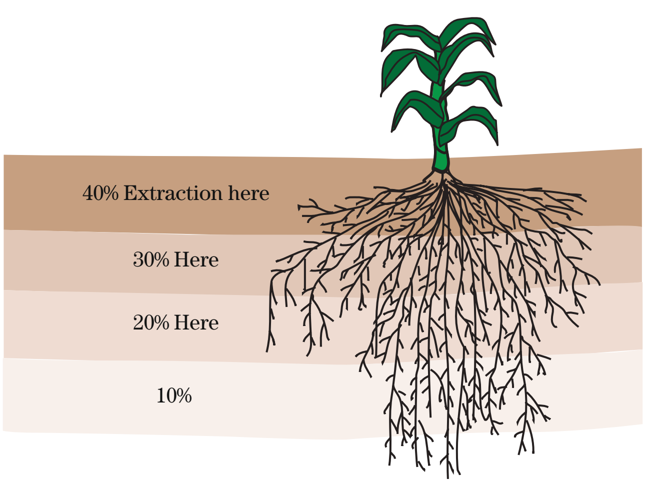
Table 504–2 Critical periods for plant moisture stress

Crop	Critical period	Comments
Alfalfa	At seedling stage for new seedlings, just after cutting for hay, and at start of flowering stage for seed production	Any moisture stress during growth period reduces yield Soil moisture is generally reduced immediately before and during cutting, drying, and hay collecting
Beans, dry	Flowering through pod formation	
Broccoli	During head formation and enlargement	
Cabbage	During head formation and enlargement	
Cauliflower	During entire growing season	
Cane berries	Blossom through harvest	
Citrus	During entire growing season	Blossom and next season fruit set occurs during harvest of the previous crop
Corn, grain	From tasseling through silk stage and kernels become firm	Needs adequate moisture from germination until kernel dent stage for maximum production. Depletion of 80% or more of AWC can occur during final ripening period without impacting yield
Corn, silage	From tasseling through silk stage and kernels become firm	Needs adequate moisture from germination until kernel dent stage for maximum production
Corn, sweet	From tasseling through silk stage and until kernels become firm	
Cotton	First blossom through boll maturing stage	Any moisture stress, even temporary, ceases blossom formation and boll set for at least 15 days after moisture again becomes available
Cranberries	Blossom through fruit sizing	
Fruit trees	During the initiation and early development period of flower buds, the flowering and fruit setting period (may be the previous year), the fruit growing and enlarging period, and the preharvest period	Stone fruits are especially sensitive to moisture stress during last two weeks before harvest
Grain, small	During boot, bloom, milk stage, early head development and early ripening stages	Critical period for malting barley is at soft dough stage to maintain a quality kernel
Grapes	All growth periods, especially during fruit filling	See vine crops
Peanuts	Full Season	
Lettuce	Head enlargement to harvest	Water shortage results in a sour and strong lettuce
Melons	Blossom through harvest	
Milo	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling	
Onions, dry	During bulb formation, near harvest	
Onions, green	Blossom through harvest stress	Strong and hot onions can result from moisture
Nut trees	During flower initiation period, fruit set, and mid-season growth	Pre-harvest period is not critical because nuts form during mid-season period
Pasture	During establishment and boot stage to head formation	

Table 504–2 Critical periods for plant moisture stress—continued

Crop	Critical period	Comments
Peas, dry	At start of flowering and when pods are swelling	
Peas, green	Blossom through harvest	
Peppers	At flowering stage and when peppers are swelling	
Potato	Flowering and tuber formation to harvest	Low-quality tubers result if moisture stress during tuber development and growth
Radish	During period of root enlargement	Hot radishes can be the result of moisture stress
Sunflower	Flowering to seed development	
Sorghum, grain	Secondary rooting and tillering to boot stage, heading, flowering, and grain formation through filling	
Soybeans	Flowering and fruiting stage	
Strawberries	Fruit development through harvest	
Sugar beets	At time of plant emergence, following thinning, and 1 month after emergence	Temporary leaf wilt on hot days is common even with adequate soil water content
Sugarcane	During period of maximum vegetative growth	
Tobacco	Knee high to blossoming	
Tomatoes	When flowers are forming, fruit is setting, and fruits are rapidly enlarging	
Turnips	When size of edible root increases rapidly up to harvest	Strong tasting turnips can be the result of moisture stress
Vine crops	Blossom through harvest	
Watermelon	Blossom through harvest	

Figure 504–3 A typical diagram of how soil water is extracted



and timing of irrigation applications affects root density and distribution with depth. For example, under high frequency irrigation (i.e. center pivot sprinkler systems) crops expected to have a 4 foot rooting depth in uniform soil might only extract water to depths of 18 to 24 inches in the profile, if water is applied too soon after the previous application.

Table 504–3 shows typical rooting depths for various crops on a deep, well-drained soil with good water and soil management. With good soil management and growing conditions, crops can root deeper into the soil profile.

The rooting depth of annual plants varies by stage of growth and must be considered in determining the amount of soil water available.

For most crops and forages, the concentration of moisture absorbing roots is greatest in the upper portion of the root zone. This means that, typically 70 to 80 percent of a crops water uptake will be from the top half of the rooting depth. The upper zone is the area of the most favorable conditions of aeration, biological activity, temperature, and nutrient availability. Water also evaporates from the upper few inches of soil. Therefore, water diminishes most rapidly from the upper portion of the soil. This creates a high soil-water potential gradient. In uniform soils that are at field capacity, plants use water rapidly from the upper part of the root zone and more slowly from the lower parts. About 70 percent of available soil water comes from the upper half of a uniform soil profile. Any layer or area within the root zone that has a low AWC or increased bulk density affects root development and may be the controlling factor for soil moisture availability.

Variations and inclusions are in most soil map units, thus uniformity should not be assumed. Field investigation is required to confirm or determine onsite soil characteristics. Unlike texture, structure and condition of the surface soil can be changed with management.

Very thin tillage pans can restrict root development in an otherwise homogenous soil. Never assume a plant

Table 504–3 Depth to which roots of mature crops will extract available water from a deep, uniform, well drained soil under average unrestricted conditions (depths shown are for 80% of the roots)

Crop	Depth (ft)	Crop	Depth (ft)	Crop	Depth (ft)	Crop	Depth (ft)
Alfalfa	5	Clover, Ladino	2–3	Milo	2–4	Sudan grass	3–4
Asparagus	5	Cranberries	1	Mustard	2	Sugar beets	4–5
Bananas	5	Corn, sweet	2–3	Onions	1–2	Sugarcane	4–5
Beans, dry	2–3	Corn, grain	3–4	Parsnips	2–3	Sunflower	4–5
Beans, green	2–3	Corn, seed	3–4	Peanuts	2–3	Tobacco	3–4
Beets, table	2–3	Corn, silage	3–4	Peas	2–3	Tomato	3
Broccoli	2	Cotton	4–5	Peppers	1–2	Turnips	2–3
Berries, blue	4–5	Cucumber	1–2	Potatoes, Irish	2–3	Watermelon	3–4
Berries, cane	4–5	Eggplant	2	Potatoes, sweet	2–3	Wheat	4
Brussels sprouts	2	Garlic	1–2	Pumpkins	3–4	**Trees**	
Cabbage	2	Grains & flax	3–4	Radishes	1		
Cantaloupes	3	Grapes	5	Safflower	4	Fruit	4–5
Carrots	2	Grass pasture/hay	2–4	Sorghum	4	Citrus	3–4
Cauliflower	2	Grass seed	3–4	Spinach	1–2	Nut	4–5
Celery	1–2	Lettuce	1–2	Squash	3–4		
Chard	1–2	Melons	2–3	Strawberries	1–2		

root zone. Observe root development of present or former crops.

Numerous soil factors may limit the plant's genetic capabilities for root development. The most important factors are:

- soil density and pore size or configuration
- depth to restrictive or confining layers
- soil-water status
- soil aeration
- nutrient availability
- water table
- salt concentrations
- soil-borne organisms that damage or destroy plant root system

Root penetration can be extremely limited into dry soil, a water table, bedrock, high salt concentration zones, equipment and tillage compaction layers, and dense fine texture soils, and hardpans. When root development is restricted, it reduces plant available soil-water use and consequent storage, which in turn limits crop production.

High soil densities that can result from tillage and farm equipment seriously affect root penetration. Severe compacted layers can result from heavy farm equipment, tillage during higher soil moisture level periods, and from the total number of operations during the crop growing season. In many medium to fine textured soils, a compacted layer at a uniform tillage depth causes roots to be confined above the compacted layer at depths usually less than 6 to 10 inches from the surface. Roots seek the path of least resistance, thus do not penetrate a compacted dense layer except through cracks. Every tillage operation causes some compaction.

Even very thin tillage pans restrict root development and can confine roots to a shallow depth, thereby limiting the depth for water extraction. This is probably most common with row crops where many field operations occur and with hayland when soils are at high moisture levels during harvest.

Subsoiling or deep tillage when the soil is dry can fracture compacted layers. However, unless the cause of compaction (typically tillage equipment itself), the number of operations, and the method and timing of the equipment's use are changed, compaction layers will again develop. Only those field operations essential to successfully growing a crop should be used. Extra field operations require extra energy (tractor fuel), labor, and cost because of the additional wear and tear on equipment. Necessary tillage operations should only be performed when the soil surface from 0 to 2 inches or 0 to 3 inches in depth is dry enough not to cause soil smearing or compaction. The lightest equipment with the fewest operations necessary to do the job should

504.05 Tillage systems effect on water conservation

Tillage systems are an important part of sustainable agricultural systems. Tillage systems have evolved over time. Generally speaking, conservation tillage includes a variety of techniques and methods including such systems as no till, ridge till, mulch till, and minimum till. These all involve some form of residue management and only partial soil inversion. Basically, conservation tillage is any system of cultivation that reduces soil or water loss when compared to conventional systems, such as moldboard plowing which turns over the soil completely.

Conservation tillage is designed to conserve soil, water, energy, and protect water quality. Conventional tillage exposes the soil to the erosive actions of wind and water. Conservation tillage systems use residue to buffer the raindrops' energy, so water has less of an erosive force. Protection by residue, along with associated physical factors of conservation tillage, facilitates water infiltration and decreases runoff.

(a) Water conservation under residue management systems.

Tillage practices influence soil moisture throughout the growing season. Reduced and no-till systems that manage residue on the soil surface decrease evaporation losses. Both surface roughness and residue slow water runoff which allows more time for water infiltration. In addition, surface residue prevents soil surface sealing, thus increasing infiltration and the amount of soil water stored. The net effect of tillage systems that leave surface residue is less variation in soil water during the summer months and more plant available water.

The increase in soil moisture, brought on by residue management, improves microbial activity as well, which will, in turn, improve soil organic matter over time.

Evaporation is a primary source of water loss during the first half of the growing season before the crop canopy closes. Crop residue on the soil surface shades the soil surface and reduces the amount of solar energy absorbed, thereby reducing soil temperatures, and evaporation. Residue also reduces air velocity at the soil surface, slowing the rate at which evaporation occurs. Residue cover offers the greatest reduction in evaporation when the soil is moist and not yet shaded by the crop.

The difference in cumulative evaporation between bare soil and soil with a residue cover is related to the frequency and amount of rainfall. For small, infrequent rainfall events, the soil surfaces from conventional and conservation tillage show little difference in cumulative evaporation. However, with larger more frequent rains, less evaporation occurs from soil protected by surface residue than from bare soil. In stubble covered wheat field, evaporation ranges from 60 to 75 percent of that occurring from bare soil. Evaporation from the soil depends on water rising to the surface by capillary action as the soil dries. Shallow incorporation of residue reduces this capillary action however; leaving residue on the soil surface generally reduces evaporation more than shallow incorporation.

Water infiltration is the process of water entering the soil at the soil/air interface. Crop residue affects soil infiltration by intercepting raindrop energy and the associated soil sealing or ponding that occurs thereby increasing infiltration and reducing the amount of runoff. Simulated rainfall studies in Ohio show that infiltration increases with surface residue (table 504–4).

Runoff tillage systems that leave crop residue on the soil surface generally reduce runoff. The factors that influence the differences in runoff are soil characteristics, weather patterns, the presence of macro pores, management, and the amount, kind, and orientation of residue. The residue characteristics that affect water infiltration also affect runoff by increasing the time to initiation of runoff and lowering runoff rates. Residue on the soil surface increases the surface roughness of the soil, reduces runoff velocities, and causes ponding that further delays runoff. In addition, surface residue obstructs and diverts runoff, increasing the length of time in the down slope flow path allowing more time for infiltration.

Another important point is the effect of having both standing and flat residues present. The presence of standing and flat residues reduces the likelihood that small localized flow areas will combine into larger networks, and decreases the velocity and overall transport of runoff from the field. If the climate and soil conditions exclude macro pore development and traffic causes unrelieved reductions in infiltration, runoff rates can increase even with high residue crop production systems such as no-till, particularly in the early years of the systems before surface organic matter has time to accumulate.

Snow catch—Maximizing snow catch is a vital conservation measure in the northern Great Plains, since snow constitutes 20 to 25 percent of the annual precipitation. Stubble height management and orientation are tools used to maximize snow catch. Taller stubble retains more snow, increasing soil water content. Bauer and Black (1990) in a 12 year study reported that increasing small grain stubble height from 2 to 15 inches increased soil water content to a depth of 5 feet by 1.6 inches. In addition to stubble height, scal-

Table 504–4 Effect of tillage and corn residue on infiltration using simulated rainfall (Triplett et al. 1968)

	Total infiltration after 1 hour (inches)	
Treatment	**Initial run**	**Wet run** [1/]
Plowed, bare	0.71	0.41
No-tillage, bare [2/]	0.48	0.25
No-tillage, 40% cover	0.92	0.53
No-tillage, 80% cover	1.73	1.37

1/ Wet run took place 24 hr after initial run.

2/ Residue cover was removed for research purposes.

loping the stubble (varying the height of stubble with each pass) increases the amount of snow trapped by the stubble. Increasing the snow catch on a field may increase spring melt runoff depending on the early spring soil infiltration characteristics. However, in soils on which annual crops are grown, infiltration of snowmelt occurs without runoff due to the soil being frozen while dry or not frozen as deeply due to the snow coverage to permit infiltration. Greb (1979) reported that the efficiency of storing meltwater is often double that of storing water received as rain.

Water storage—Soil moisture savings is of great importance in regions of low rainfall and high evaporation, on soils low in water holding capacity, and in years with below normal rainfall. In some regions, for example the Corn Belt, excessive soil moisture in the spring months may have potential negative effects on crop growth since it slows soil warming and delays planting. However, having more available water during crop pollination and seed filling usually offsets these early season negative effects. Seed zone soil moisture also aids in plant establishment and growth in dry areas of the United States. For a high percentage of the farmland, moisture savings is one of the primary reasons producers consider conservation tillage systems.

Research on the effects of reducing tillage and increasing surface residue have indicated that high amounts of surface residue result in increased soil water stored. Unger (1978) reported that high wheat residue levels resulted in increased water storage during the fallow period and the increased subsequent grain sorghum yields the following year. Similar results of water storage under high residue conditions are shown in table 504–5, summarized by Greb (1983), for 20 crop years from four locations.

Management changes in the Great Plains since 1916 have improved soil water storage, fallow efficiency (percentage of the precipitation received during the fallow period and stored as soil water), and small grain yields. However, fallow efficiencies up to 40 percent were reported in the 1970s and have not improved beyond this value due to the fact (during subsequent research) that a majority of soil moisture recharge is stored early in the year, the time of year directly after harvest operations in the fall up through spring. Very little soil water is stored after that time; in fact, moisture is lost after that time due to evaporation if the soil surface is left unprotected. This indicates that reducing or eliminating fallow from the rotation, intensifying the cropping pattern, and utilizing the soil moisture stored through the rotation, is a means of taking advantage of our increased capability to store water earlier in the cropping cycle with high residue crop production systems.

Excessive soil water—Tillage practices and crop residue management in annual cropping systems play an important role in how soil receives and retains moisture. On perennial crops, such as alfalfa, residue management is not normally a concern as fields are tilled and re-seeded at intervals that are usually 5 years or greater, but annual crops may require some annual tillage.

Tillage practices and crop residue management affect the way water moves into and off of the soil (infiltration and runoff), as well as the way water moves from the soil into the atmosphere evaporation). Especially during drought periods, efficient use of limited water is important.

Management of residues from a previous crop can have significant effect on water movement (including runoff leading to erosion) and the evaporation from the soil surface. Runoff potential exists when precipitation or the rate of irrigation exceeds the infiltration rate of the soil.

Table 504–5 Net soil-water gain at the end of fallow as influenced by straw mulch rates at four Great Plains locations

Location	Years reported	Mulch rate (mg/ha)			
		0	**2.2**	**4.4**	**6.6**
Bushland, TX	3	7.1	9.9	9.9	10.7
Akron, CO	6	13.6	15.0	16.5	18.5
North Platte, NE	7	16.5	19.3	21.6	23.4
Sidney, MT	4	5.3	6.9	9.4	10.2
Mean		10.7	12.7	14.5	15.7
Gain with mulch			2.0	3.8	5.0

Note: Soil water gain units = centimeter

Even low pressure irrigation systems, as may be used on some center pivots, may exceed the infiltration rate of the soil. The presence of crop residues can increase the infiltration rate and decrease the potential for runoff by creating an uneven surface that slows the movement of water.

Runoff can also increase if the soil infiltration rate is reduced over time. A number of factors such as soil texture and structure, excessive surface tillage, and water application or precipitation can cause a reduction in infiltration. As the size and number of water droplets increases, fine soil particles are consolidated on the surface to form a thin crust which reduces infiltration. Soil crusts can reduce infiltration rates up to 75 percent.

One way to combat the negative effects of water droplets is to ensure that crop residues are evenly distributed over the soil surface. Crop residues spread in this manner protect the soil by absorbing energy carried by the falling water droplets. This limits soil crust development, resulting in a more consistent infiltration rate throughout the growing season.

Crop residue on the soil surface reduces evaporation. Most evaporation occurs when the soil is wet. Residue insulates the wet soil from solar energy and reduces evaporation. When the soil is wet more often, as can occur with irrigation, evaporation increases, and the effect of crop residue is even more important in reducing water losses to evaporation. This also demonstrates why irrigating less often, with more volume per application, is more efficient than frequent, light irrigations, which more frequently wet the soil surface. Crop canopies also play a role in reducing evaporation by shading the soil surface.

A study in Nebraska showed that crop residue (6 tons of wheat straw per acre) in an irrigated corn crop reduced evaporation by 2 to 2.5 inches during the growing season. Even lower levels of residue can have a significant impact on reducing evaporation.

Use conservation practices that increase water infiltration and minimize water loss:

- protect the soil surface with plants, cover crops, mulches, and residues
- use buffers to capture snow melt, reduce runoff, and prevent erosion
- use manure, cover crops, and crop residues to increase soil organic matter and build soil quality

To achieve these benefits use cropping practices such as:

- rotations with perennial crops such as grasses and alfalfa
- minimum tillage or no-till to reduce evaporation losses

Soil properties that affect water infiltration, permeability, and drainage must always be properly assessed when making residue management decisions. Research in the Corn Belt has shown that no-till management systems on some poorly drained soils has resulted in lower yields compared to the yields of conventionally tilled systems. Continued research has shown, however, that after 18 years of continued no-till that yields are now equal or greater than conventionally tilled systems. The initial yield reductions on these poorly drained soils may have been attributed to a number of different factors. The positive yield response after continuous no-till on these soils may be attributed to factors including the development of internal drainage characteristics such macropores, increases in organic matter and microbial activity, better soil structure, and the use of disease resistant cultivars.

When dealing with heavier residue amounts from a proceeding crop it may be necessary in no-till or even mulch-till situations to use residue managers that move the residue to the side of the seed trench. Poorly drained soils are not easily adapted to high residue systems and may need to be managed with limited till systems such as ridge-till or fall and spring strip-till methods. Some warm-season species such as corn or sunflower respond to warmer, clean seedbed conditions. This may also be accomplished by including crops in the rotation that produce lower amounts of dark colored residue or including cover crops. Refer to Subpart 506B, Suitability for crop production systems.

Excess water, which can be caused by over irrigation, under utilization of excess soil moisture, improper crop rotations, or excess precipitation, can cause another major resource issue, namely salinization. When excess soil moisture goes unused, it will either evaporate at the soil surface or percolate through the root zone. In arid and semi-arid regions, percolated moisture will often move laterally along an impermeable layer beneath the root zone until it finds its way to the surface where it evaporates. After several years, salt accumulations on the soil surface become elevated enough to become toxic to crops and forages.

Additionally, if irrigation water has even slightly elevated dissolved salts dissolved, salt concentrations will, over time, increase. If concentrations increase enough, it will negatively affect crop and forage production. More discussion on salinization can be found in section 504.06.

Pests—Changes from conventional tillage systems to conservation tillage systems will most likely also change some aspects of pest management. For pathogens, such as fungal and bacterial pathogens, conventional tillage buries crop residue which can destroy many of these pathogens. Many pathogens use surface residue for overwintering, but are then controlled when they are buried. The use of conservation tillage, because of this factor, may cause increases in severity of some diseases and insect populations can increase, requiring more or different controls.

Rather than increasing chemical pest control, an intensive crop rotation will assist in mitigating pest issues. Additionally, integrated pest management systems may need to be adopted at the same time that tillage systems that utilize greater amounts of surface residue are utilized.

(b) Cropping system intensity

Improving the relative water use efficiency in crop production systems is a key goal in achieving sustainable cropping systems. Reducing water losses in cropping systems by changes in tillage, residue management, crop selection, irrigation water management, and crop sequence result in more diverse and intense rotations and greater water use efficiency (WUE).

Historically, crop rotations were much more diverse than they are presently. The loss of crop rotation diversity can be attributed to many factors including economics, farm programs, mechanization, technology, the development of commercial fertilizer, pesticides, and specialization in livestock production leading to fewer cattle operations.

An intense crop rotation can also improve soil health and have a positive effect on the whole farm by reducing weeds and insect infestations and resistance, spreading workloads, diversifying income and spreading weather risks.

The ability of a crop to produce to the physical and chemical limits of the cropping system is largely related to the health of the root system. The health of the root system, in turn, is directly related to the length of the crop rotation, ideally up to 3 or possibly 4 years or more.

The yield of all crops has long been known to decline with monoculture to some level significantly below the original yield of the same crop grown in some rotation system. In many cases this decline can be attributed to root disease and hence loss of absorptive capacity of the root system because of increasing populations of root pathogens.

Any cropping system, rotation or monoculture, depletes the soil of nutrients, starting with nitrogen and then eventually phosphorus, sulfur, potassium, trace elements, and others. Organic matter content of the soil is also reduced as nutrients are mined from the soil. Organic matter is a natural form of slow-release fertilizer for plant growth and it provides the glue or supports the microorganisms that provide the glue for the aggregate structure essential for soil aeration, soil and water conservation, and healthy roots.

Alternating crops that result in an intense, diversified cropping system allows time for the natural soil microbes to displace or destroy root pathogens and other pests of any one crop enabling maximum production while maintaining soil health.

Changes in cropping systems by decreasing tillage, increasing surface residues, making conscious decisions on residue orientation, as well as, strategically placing crops in rotations have produced positive changes in water use efficiency. Cropping system intensification has improved the water use efficiency (WUE), and has increased the productivity of crop production systems.

Continuous cropping may be a viable option for producers in areas where fallow has traditionally been a part of a cropping sequence. With high residue management the inclusion of annual forages, such as sorghums, millet, field peas, or small grains, increase the producers flexibility to maximize WUE. Crop choice affects WUE of the crop production system because each species has a different potential for production.

Several predictive tools (water-use-production functions) have been developed to assist producers in crop selection in several environments across the Great Plains. Black et al. (1981) suggested that a flexible cropping strategy would provide efficient water use to control saline seeps in the northern Great Plains.

Flexible cropping—Flexible cropping is defined as seeding a crop when stored soil water and rainfall probabilities are favorable for satisfactory yield, or fallowing only when prospects are unfavorable. Available soil water can be estimated by measuring moist soil depth with a soil moisture probe or other soil sampling equipment. Brown et al. (1981) have developed soil water guidelines and precipitation probabilities for barley and spring wheat for flexible cropping systems in Montana and North Dakota.

When considering a flexible cropping system a producer should evaluate the amount of plant-available soil water at seeding time, the precipitation probabilities for the seasonal needs of a given crop, and management factors such as variety, crop rotation, weed and insect problems, soil fertility, and planting date.

Current information in the Great Plains at various locations includes yield water-use-production functions for winter wheat, spring wheat, barley, oats, millet, corn, sunflower, dry beans, canola, crambe, soybean, and safflower given soil moisture and rainfall-probability information (Brown and Carlson 1990; Vigil et al. 1995; Nielson 1995). This information can assist a producer in crop selection in a given year; however users of these water use/yield relationships need to understand that the final crop yield is influenced by the timing of precipitation as well as the amount of water used.

Another tool was designed by the Dakota Lakes Research Farm in South Dakota. The Crop Intensity and Diversity Index can be used to assist the development of appropriate alternative rotations. The tool assigns relative values to crops within a rotation depending upon differing characteristics in terms of their impacts on various aspects of crop production used in a given environment by a particular producer.

Irrigation effects—Tillage practices and crop residue management affect the way water moves into and off of the soil (infiltration and runoff), as well as the way water moves from the soil into the atmosphere (evaporation).

Under sprinkler irrigation systems, management of residues from the previous crop can have significant effect on water movement (including runoff leading to erosion) and evaporation from the soil surface. Runoff potential exists when the rate of irrigation exceeds the infiltration rate of the soil.

Low pressure irrigation systems, as may be used on some center pivots, may also exceed the infiltration rate of the soil. The presence of crop residues can increase infiltration rate and decrease the potential for runoff by creating an uneven surface that slows the movement of water. There are certain tillage operations and other management practices that also may affect the movement of water including the use of the dammer-diker implement or farming on the contour.

Runoff can also increase if the soil infiltration rate is reduced over time. Factors such as soil texture and structure, excessive tillage, and water application can cause a reduction in infiltration. As the size and number of water droplets increases, fine soil particles are consolidated on the surface to form a thin crust which reduces infiltration. Soil crusts formed during the growing season can reduce infiltration by as much as 75 percent.

One way to combat the negative effects of water droplets is to ensure that crop residues are evenly distributed over the soil surface. Crop residue spread in this manner protects the soil by absorbing energy carried by the falling water droplets. This limits soil crust development, resulting in a more consistent infiltration rate throughout the growing season.

Crop residue on the soil surface reduces evaporation. Most evaporation occurs when the soil is wet. Residue insulates the wet soil from solar energy and reduces evaporation.

When the soil is wet more often, as occurs with irrigation, evaporation increases, and the effect of crop residue is even more important in reducing water losses. This also demonstrates why irrigating less often, with more water volume per application, is more efficient than frequent than frequent, light irrigations, which more frequently wet the soil surface. Crop canopies also play a role in reducing evaporation by shading the soil.

A study in Nebraska showed that crop residue (6 tons per acre) reduced evaporation by 2 to 2.5 inches during the growing season. However, even lower levels of residue can have a significant role in reducing evaporation.

Conservation practices that increase water infiltration and minimize water loss are:

- protect soil with plants, cover crops, mulches, and residues
- use buffers to capture snow melt, reduce run-off, and prevent erosion
- use manure, cover crops, and crop residues to increase organic matter and build soil quality
- rotate with perennial crops
- use minimum tillage or no-till

504.06 Saline Seeps

(a) Development of saline seeps

Saline seep describes a salinization process accelerated by dryland farming practices. Saline seep is an intermittent or continuous saline water discharge at or near the soil surface downslope from a recharge area under dryland farming conditions that reduces or eliminates crop growth in the affected area because of increased soluble salt concentration in the root zone. Saline seeps are differentiated from other saline soil conditions by their recent and local origin, saturated root zone in the soil profile, shallow perched water table, and sensitivity to precipitation and cropping systems. In the recharge area, water percolates to zones of low hydrologic conductivity at depths of 2 to 60 feet below the soil surface and flows internally downslope to emerge at the point where the transport layer approaches the soil surface or soil permeability is reduced.

The saline-seep problem stems from surface geology, above-normal precipitation periods, and farming practices that allow water to move beyond the root zone. Under native vegetation, grasses and forbs used most of the water before it had a chance to percolate below the root zone to the water table. With sod plow-up, subsoil became wetter and fallow kept the land relatively free of vegetation for months at a time. Beginning in the forties, soil water storage efficiency during fallow improved with the advent of large tractors, good tillage equipment, effective herbicides, and timely tillage operations. This extra water filled the root zone to field capacity and allowed some water to move to the water table and downslope to emerge as a saline seep.

Several factors that may individually or in combination contribute water to shallow water table include: fallow, high precipitation periods, poor surface drainage, gravelly and sandy soils, drainageways, constructed ponds and dugouts, snow accumulation, roadways across natural drainageways, artesian water, and crop failures resulting in low use of stored soil water. Saline-seep formation begins with a root zone filled to its water-holding capacity. Some of this water runs off the surface, some evaporates, and the rest moves into the soil. Once the soil is filled to field capacity, any additional water that moves through the root zone may contribute to saline seepage.

Water percolating through salt-laden strata dissolves salts and eventually forms a saline water table above an impermeable or slowly permeable layer. The underground saline water moves downslope and dissolves more salts, adding to the perched water table at the site of the seep. Whenever, the water table rises to within 3 feet of the surface the water plus dissolved salts then move to the soil surface by capillary action were the discharge water evaporates, concentrating salt on or near the soil surface. As a result, crop growth in the affected area is reduced or eliminated and the soil is too wet to be farmed.

(b) Identification of saline seeps

Early detection and diagnosis of a saline-seep problem are important in designing and implementing control and reclamation practices to prevent further damage. By early detection, a producer may be able to change his or her cropping system to minimize the damage. Detection of discharge areas may be accomplished by visual or by electrical conductivity detection. Visual symptoms of an impending saline seep may include:

- vigorous growth of kochia or foxtail barley in small areas where the soil would normally be too dry to support weed growth
- scattered salt crystals on the soil surface
- prolonged periods of soil surface wetness in small areas
- poor seed germination or rank wheat or barley growth
- accompanied by lodging in localized areas
- stunted trees in a shelterbelt accompanied by leaf chlorosis
- a sloughed hillside in native vegetation adjacent to a cultivated field

Soil electrical conductivity (EC), which is proportional to soil salinity, can be determined in the field using resistivity. This technique can be used to identify and confirm an encroaching or developing saline seep. Soil salinity in the discharge area may be low near the soil surface, but increases considerably with depth. Once the discharge area is identified, the next step is to locate the recharge area. Most remedial treatments for controlling the seep must be applied to the recharge area, which is always at a higher elevation than the discharge area. The approximate size of the recharge area must be determined to be successful. Most recharge areas are within 2,000 feet and many are within 100 to 600 feet of the discharge area, depending on the geology involved.

Several procedures for identifying the recharge area include: visual, soil probing, soil surveys, drilling, soil resistivity, and electromagnetic techniques. Even if the previously mentioned equipment is not available, a visual approximation of the recharge area can be made, and strategies implemented to correct the saline-seep problem. Some facts to remember are that the recharge areas are higher in elevation than the seep or discharge area, the recharge areas are generally within 2,000 feet of the discharge area, and that seeps in glacial till areas expand downslope, laterally, and upslope toward the recharge area. Saline seeps in non-glaciated areas tend to expand downslope, away from the discharge area. After the recharge area has been located, a management plan should be designed to control the saline-seep problem.

(c) Effects of salinity on yields

Saline soil is a term used to characterize soil containing sufficient salts to adversely affect the growth of most crop plants. One or more of the following may cause these adverse effects.

- Direct physical effects of salts in preventing soil water uptake by the plant roots because of increased osmotic tension.
- Direct chemical effects of salt in disrupting the nutritional and metabolic processes of the plant.
- Indirect effect of salt in altering soil structure, permeability, and aeration.

Agricultural crops differ significantly in their response to excessive concentrations of soluble salts in the root zone. This ability of the plant to produce economic yields in a saline environment is termed salt tolerance. Crop selection is one of the primary options available to growers to maximize productivity under saline conditions. Table 504–6 lists the salinity threshold and yield decrease of several selected agricultural crops. The threshold salinity level is the maximum allowable salinity that does not reduce yield below that of nonsaline conditions. The yield decrease is reported as a percent yield reduction for every whole unit increase in salinity measured as electrical conductivity (EC) mmho/cm. For example, alfalfa yields decrease about 7.3 percent per unit of salinity increase above 2.0 mmho/cm. Therefore, at a soil salinity of 5.4 mmho/cm, alfalfa yield would be 25 percent lower than at soil salinity levels less than 2.0 mmho/cm.

Crop production has been reduced on approximately 2 million dryland acres in the northern Great Plains of the United States and Canada. Brown (1982) reported that this production loss on 2 million acres in the northern Great Plains could be translated into $120 million in lost annual farm income.

(d) Management practices for control of saline seeps

Saline-seeps are caused by water moving below the root zone in the recharge area. Because of this movement of water though the recharge area, there will be no permanent solution to the saline-seep problem unless control measures are applied to the recharge area.

These measures vary according to the soil texture and underlying geologic material, water table fluctuations, depth to the low hydraulic conductivity zone, occurrences of potholes and poorly drained areas, and annual precipitation and frequency of high precipitation periods.

Two general procedures are available for managing saline seeps: either make agronomic use of the water for crop production before it percolates below the root zone; or mechanically drain either surface or subsurface water before it reaches the discharge area. Mechanical drainage is generally not performed either because of current farm bill legislation or because of constraint that subsurface water is excessively contaminated with salts and downstream disposal is difficult because of physical or legal limitations. However, before any control measures are implemented an evaluation of the land capability class should be determined. All control measures should be compatible with the land capability class involved.

The most effective solution to the saline-seep problem is to use as much of the current precipitation as possible for crop or forage production before it percolates beyond the root zone. Forage crops, such as alfalfa, use more water than cereal grains and oil crops because they have deep root systems, are perennial, and have longer growing seasons. Planting alfalfa in the recharge area of a saline seep is often the most effective way to draw down stored subsoil moisture and stop water flow to a saline-seep. Alfalfa can use all current precipitation plus a substantial amount of water from the deep subsoil.

Halvorson and Reule (1976, 1980) found that alfalfa growing on approximately 80 percent of the recharge area effectively controlled several saline seeps. They also found that a narrow buffer strip of alfalfa (occupying less than 20 percent of the recharge area) on the immediate upslope side of a seep did not effectively control the water in the discharge area. Grasses may also effectively draw down subsurface water if the depth to the low hydraulic conductivity zone is less than 15 feet. After terminating alfalfa or grass production, the recharge area should be farmed using a flexible cropping system. Flexible cropping is defined as seeding a crop when stored soil water and rainfall probabilities are favorable for satisfactory yield or fallowing when prospects are unfavorable.

Available soil water can be estimated by measuring moist soil depth with a soil moisture probe or other soil sampling equipment. Black et al. (1981) suggested that this cropping strategy would provide efficient water use to control saline seeps in the northern Great Plains. Brown et al. (1981) have developed soil water

Table 504–6 Salt tolerance of selected crops [1/]

Common name	Botanical name	Salt tolerance threshold (mmhos/cm	Yield decline (% per mmhos/cm)
Alfalfa	*Medicago sativa*	2.0	7.3
Barley	*Hordeum vulgare*	8.0	5.0
Sorghum	*Sorghum bicolor*	6.8	16.0
Soybean	*Glycine max*	5.0	20.0
Wheat	*Triticum aestivum*	6.0	7.1
Wheatgrass, tall	*Agropyron elongatum*	7.5	4.2
Wildrye, beardless	*Leymus triticoides*	2.7	6.0

1/ Maas and Hoffman (1977) and Maas (1990) guidelines and precipitation probabilities for barley and spring wheat for flexible cropping systems in Montana and North Dakota.

After successful application of control measures to the recharge area, the seep area and surrounding area can then be seeded to a grass or grass/legume mixture tolerant to the saline conditions present in the discharge area. A return to a cropping system that does not adequately utilize stored soil water in the recharge area may reactivate the seep.

Once the water flow from the recharge area to the seep has been stopped or controlled and the water table in the seep has dropped enough to permit cultivation, cropping in the seep area can begin. Crop selection is important when initiating crop production on the discharge area. In the northern Great Plains, six-row barley is the most salinity-tolerant cereal available, and it is normally the first crop seeded. As the reclamation processes continues, comparing yields in and outside the seep area can be used to monitor progress. The water table depth should be closely monitored during the reclamation period.

Another approach that can be used on discharge areas is to manage salt-tolerant grasses seeded on the area. If the water table is above 4 feet the grasses should be mowed and completely removed to prevent excess snow accumulation and the subsequent rise in the water table. If the water table is below 4 feet, the grass can be left to catch snow. The resulting snowmelt will leach the salt downward into the soil and improve subsequent grass growth. Snow trapping using grass strips or crop stubble will enhance water movement through the profile in the discharge area and hasten the reclamation process.

These practices will not be effective until hydrologic control is achieved in the recharge area and the water table is significantly lowered in the discharge area. Research and farmer experience have shown that yields will generally return to normal in 3 to 5 years.

In saline-seep areas, observation wells are useful for monitoring water table levels during the control, reclamation, and post-reclamation periods. Water tables fluctuate seasonally and annually. Reclaimed saline seeps may be reactivated by a significant rise in the water table, which persists for several weeks or months. If a saline water table is less than 3 feet below the soil surface, saline water can move to the surface by capillary rise and create a salt problem. To alleviate this problem, monitoring wells at least 10 feet in depth should be installed in discharge areas, along drainageways, and in recharge areas. Ideally, the water table should be at least 6 feet in depth. Water table levels should be monitored monthly, especially during and after snowmelt, and rainy seasons. A rising water table that persists into the summer months indicates that cropping practices should be intensified to increase soil water use.

504.07 Irrigation related agricultural salt problems

The major solutes comprising dissolved salts are the cations (sodium, calcium, magnesium, and potassium) and the anions (sulfate, chloride, bicarbonate, carbonate, and nitrate). Dissolved minerals might also include other constituents including manganese, boron, lithium, fluoride, barium, strontium, aluminum, rubidium, and silica.

Irrigation can bring about the salinization of soils and waters and the subsequent threat to the sustainability of irrigated agroecosystems. Over the course of history, thriving civilizations declined in part due to their inability to sustain food production on lands that had been salinized. Worldwide, the trend of decreasing crop production capacity, attributed to soil degradation and the effects of salinity continues. It has been estimated that in the United States yield reductions due to salinity and associated waterlogging occur on an estimated 30% of all irrigated land.

There are three principles regarding irrigation and salinity that are important to understand;

- all waters used for irrigation contain salts of some kind in some varying amount
- salinization of soil and water is inevitable to some extent
- irrigated agroecosystems cannot be sustained without drainage, either natural or artificial

The primary origin of salts in the hydrosphere and soils is from two sources; a broad category that called hydrogeological and the second category that describes the contributing processes of human activities as anthropogenic.

As an anthropogenic source of salinity, irrigation has a profound effect on introducing soluble salts into irrigated agroecosystems that is driven by plant communities (crops/forage) and climate factors associated directly with evapotranspiration and compounded by the excessive application of water. The causes contributing to the excessive application of water are inefficient irrigation distribution systems, poor on-farm management practices, and inappropriate management of drainage water.

Application of irrigation water

Application of irrigation water results in the addition of soluble salts. The primary soluble salt constituents of interest are sodium, calcium, magnesium, potassium, sulfate, and chloride dissolved from geologic materials with which the waters have been in contact and alkalinity, i.e. bicarbonate and carbonate, principally from atmospheric and soil zone dissolution of carbon dioxide. Therefore, water quality needs to be evaluated in terms of assessing the combined effects of salinity, infiltration/permeability (sodicity), and nutritional imbalance/toxicity.

Salinity
Sometimes called evapo-concentration, the concentrations of soluble salts increase in soils as the soil water is removed to meet its atmospheric demand by evaporation and transpiration. The salts, which are left behind concentrate in the shrinking soil-water volume with each successive applied irrigation. This adverse effect of soil solution salinity is the reduction of transpiration at a threshold where biochemical energy is diverted away from dry matter production which suppresses yield once the average root zone soil salinity exceeds the crop dependent threshold value unless adequate leaching and drainage are provided. This illustrates another important principle that for soils that have reached cation exchange equilibrium that the salt load (i.e. volume x concentration) of the soil profile where water is being consumed by plants is solely dependent upon the salt load of the infiltrating water volume and the salt burden of the root zone outfall water volume as represented by the leaching fraction.

Not all crop plants respond to salinity in the same way. Some produce acceptable yields at higher soil salinity levels than others. Each crop species has an inherent ability to make the needed osmotic adjustments enabling them to extract more water from a saline soil. This ability for some crops to adjust to salinity is extremely useful. In areas where the accumulation of salinity within the soil profile cannot be controlled at acceptable levels, an alternative crop can be selected that is more tolerant resulting in the production of better economical yields.

Infiltration/permeability problems
Although crop yield is primarily limited by EC level of the irrigation water, the application of irrigation water with a sodium imbalance can further reduce yield under certain soil texture conditions. Generally, high salinity water increases infiltration, low salinity water decreases infiltration, and water with a high sodium content relative to the calcium and magnesium content decrease infiltration. This latter potential adverse effect of certain natural waters on soils is the soil property termed “sodicity.”

Managing the impacts of irrigated-related salt problems.

There is usually not one single prescription for an effective salinity management strategy. Rather, different practices and approaches need to be combined into a management scheme that satisfactorily addresses an existing salinity problem or preventing one from manifesting itself into the irrigated ecosystem.

There are seven requisite management elements or objectives in formulating a comprehensive management strategy. These essential elements are:

- assess the source of irrigation water for its suitability
- deliver irrigation water to fields efficiently
- apply irrigation water to fields in an efficient manner that minimizes the leaching fraction and resulting minimized deep percolation
- provide adequate drainage
- use planting and tillage procedures that prevent excessive salinity accumulation
- know your cropping and soil limitations
- monitor irrigation adequacy and soil profile salinity

Assess the suitability of irrigation water sources.
In order to develop the most effective salinity control strategy for a given situation, evaluation of a given source of water must be considered.

A complete inventory of the necessary parameters is essential to support the criteria to be used in judging suitability that create adverse soil conditions to crop use. The established criteria of a water suitability have already been discussed; namely salinity, sodicity, and, toxicity.

Deliver irrigation water to fields efficiently.
For conveyance of irrigation and drainage waters to and away from the points of application, seepage losses must be minimized. Controlling seepage losses and maintaining drainage systems are critical. Excessive loss of irrigation water from canals constructed in permeable soil contributes to not only the mineral dissolution of the underlying geologic materials, but contributes significantly to the manifesting of high water tables and soil salinization. Poor drainage system maintenance potentially impedes flow of drainage waters that also contributes to high water table hazards and additional soil salinization.

Apply irrigation water in a manner that minimizes leaching and deep percolation.
Another keystone principle is that Irrigation water management is not a product, but a process of determining and controlling the volume, frequency, and application rate of irrigation water in a planned, efficient manner.

It is the soluble salts that, if not managed in the soil profile, will eventually build up to the point that crop yields are adversely affected. Leaching, as the key factor in controlling the soluble salts, is accomplished by applying an amount of water that is in excess of the crops seasonal evapotranspiration and runoff. Too little leaching results in excessive soil profile accumulation while too much leaching contributes to the probable excessive percolation of groundwater into underlying geological formations that can result in additional salt dissolution. This in turn increases the salt loading of alluvial water sources and sometimes further degradation of downstream aquifers that contributes to regional salinization.

Provide adequate drainage.
Inappropriate management of drainage water exasperates the potential salinity hazards from excessive use of water. In order to provide an adequate salt balance within the root zone the flux of water must be in the downward direction so as to remove salts by leaching. Therefore, there must not be any marked upward flux of water such that which occurs from shallow water tables along with additional salts transported into the vadose zone.

Steps must be taken to ensure that the necessary minimum depth to water table is provided so that the continuous downward flux of both water and salts is maintained. The resulting drainage must then be discharged either naturally or artificially. Where drainage waters are discharged through artificial engineered systems of subsurface and surface drains from irrigated regions, it is important that drainage waters from shallow water tables be intercepted, collected, and then subsequently returned to open water bodies as quickly as possible; be reused; or transported to an appropriate disposal site.

Know your cropping and soil limitations and grow suitable salt tolerant crops.
Strategies for managing irrigation-related agricultural salt problems include the exhaustion of the consumptive use capacity of water. The goal is for the crop to consume the maximum amount of water by transpiration so as to accumulate the greatest amount of dry matter. This applies to the use of low-salinity water as well as with high salinity water sources or drainage water for crops that are sufficiently salt-tolerant.

Salt tolerance of crops not only differs considerably but also differs phonologically in that there are certain stages of growth where crops become more tolerant. This leads to greater attention given to developing crop rotations that offer opportunities of using poor quality water separately or sequentially.

Use planting and tillage procedures that prevent excessive salinity accumulation.
As a general rule most plants are salt tolerant during germination. After germination, plants become sensitive during emergence and development of the seedling. Stand losses can occur when planting configurations allow salt accumulation progressively towards the surface and center of raised beds or ridges, par-

ticularly in regions of the seedbed where water flows converge and subsequently evaporate.

Monitor irrigation adequacy and soil profile salinity.
Fundamental to the planning process are the inventory and collection of necessary natural resource information and the evaluation of the effectiveness of an implemented strategy. These are important in managing the impacts of irrigation-related agricultural salt problems and the evaluation of the strategy and continued monitoring that ensures that the objectives are being achieved.

A primary consideration in achieving a sustainable irrigated agro-ecosystem susceptible to salinity hazards soils requires knowledge of the concentration and distribution of soluble salts in the soil. This includes information on spatial and temporal trends in soil salinity status and water table depths. This can be accomplished with periodic assessments and inventories that serve as a framework to guide management decisions concerning leaching adequacy and drainage.

If the outcomes identified within this framework are to be achieved traditional observation methods are no longer appropriate. The framework requires the need for repeated measurements in both time and space that accurately describe salinity patterns. Obtaining the needed information using conventional soil sampling and laboratory analysis procedures is not usually practical and certainly cost prohibitive. One of several options of practical field salinity assessment procedures and *in situ* techniques should be considered where large intensive and extensive data sets can be collected consisting of geospatial measurement of the bulk soil electrical conductivity (EC_a) directly in the field (Rhoades, et al., 1997; Lesch, et al., 1998). The methodology and instrumental techniques can be integrated into systems that are rapid and mobile (Corwin and Lesch, 2005) provide systematic means for not only describing salinity conditions but also detailed information of various agricultural practices and management effects (Lesch, *et al.*, 2005).

504.08 References

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Part 506 Plant Attributes

Contents

Tables

Subpart 506A Vegetative stabilization

506.00 Structures

Structures are engineered earthen water retention, conveyance, or other conservation practice components. This section deals with establishing vegetation on typical erosion control structures such as Public Law 566 dams, diversions, waterways, emergency watershed program structures, and others. These structures are designed and constructed for soil and slope stability with vegetative treatment to protect and maintain the integrity of the structure.

506.01 General considerations

(a) Plants

Protecting structures is typically accomplished with grasses enhanced by a legume component for some nitrogen generation. Landscaping with shrubs and trees blend structures into the surrounding landscapes. Species and cultivar selection and effective planting techniques are key to successful establishment. Select plants to meet the existing site conditions including internal soil drainage, soil texture, and percent fine particles present, organic matter, density, pH and nutrients available from the soil, exposure and aspect, temperature zone, and plant hardiness factors. Recommended plant lists are available in each state.

Proper plant selection to meet the existing and future site use will minimize future maintenance. Cultivars that have been released through the NRCS Plant Materials program should receive first consideration. Consider using native plants if they are known to be effective. Avoid using plants known to be invasive, such as kudzu, multiflora rose or phragmites.

(b) Soil

Soil is the medium in which seeds germinate and roots grow. The condition of the soil may well determine the success or failure of seedings or plantings. Soil texture, structure, tilth, organic matter, drainage, and chemical composition need to be reviewed to be certain that compatible plants have been selected. Soil amendments should be specified to meet site and plant needs.

If topsoil is salvaged onsite, use it on the most sensitive area(s) of the structure, such as emergency spillways or faces of dams. Blend the topsoil into the surface of the structure to avoid a sharp contrast between compacted fill material and the topsoil.

(c) Water and wind management

Potential erosion problems need to be considered when selecting appropriate species and establishment techniques. Water as rainfall or snowmelt, spring ice flows in streams, surface runoff, or seepage areas may require special attention. Diversions and waterways may need to be established to manage excess surface water, or subsurface drains may need to be installed to dry out seeps. Exposed areas subject to wind should be treated with adequate protection to insure establishment of the planting. This may include mulch anchoring, temporary windbreaks or using wind barrier plants.

Combinations of geotextiles, soil bioengineering (live fascines, brush mattresses) and biotechnical stabilization may be desirable to handle special conditions of erosive water velocities or areas of temporary high flows.

(d) Land use

Land use surrounding the structure(s) should be evaluated to blend the disturbed area into as natural setting as possible. Plantings should be planned based on anticipated growth and appearance of the species. Blending structures with the environment will enhance the visual appearance and present a positive effect to the public.

(e) Geology

Geologic investigations include the overburden material and the underlying parent material. Bedrock, changes of soil texture at various depths, and saline areas can be addressed early in the planning process when identified from the geologic review.

(f) Existing vegetation

Existing vegetation can be a source of potential species that should be included in the seeding of constructed structures. It may be desirable to select species from several successional stages to include in the revegetation plan. Using species that grow on surrounding areas will help blend the structure into the landscape. Caution is needed when doing this, because local species may not tolerate transplanting or may not perform well on disturbed sites. Local ecotypes, where available commercially, would be preferred sources of plant material.

(g) Present and proposed use

Consideration of the proposed future use of the structure is important in species selection. If people and vehicles will be using the area, traffic patterns should be planned. Paths should be designed to minimize erosion potential. Plants that impede recreational activities, such as vines or dense, tangled growth, should be avoided. Select vegetation that will enhance the long-term use of the area as well as provide erosion control cover needed. For example, if fishing will be allowed after a large dam is constructed, leave some grass areas without shrubs at the water's edge. Where recreational abuse of the site causes soil erosion, select plant species that will discourage the use of these areas.

(h) Climate

Select species for the local climate. Rainfall and temperature vary greatly within a State. Exposure to wind may create a sandblasting problem on the plants or may result in desiccation of the plants. Site aspect (north facing slopes) may result in several degrees difference in temperature. The USDA Plant Hardiness Zone Map, Misc. Pub. No. 1475, 1990, can serve as a general guide for selecting plants. The Plant Zone map may be viewed online at: *http://www.usna.usda.gov/Hardzone/*

However, local conditions may offer protection or may create exposure that will influence the plant performance.

(i) Shade tolerance

Where structures will be shaded for part or all day, be sure the species are tolerant for the anticipated condition. If canopy cover closure is anticipated in the future, then include appropriate ground cover species to meet the future site condition.

(j) Site preparation

The area before construction should be reviewed to select and preserve any highly desirable plants or section of plants near the perimeter or edge of the construction zone. Endangered, threatened, or declining species considerations must be met before construction. Install any temporary wind or water control measures. If topsoil or other organic matter is available onsite, salvage as much as is economically feasible for reuse. Do not waste it by burial or other loss.

506.02 Seeding and planting process

Seeding should be done as construction is completed or at intervals during construction. Daily or regular time interval seedings may be mandatory where site location or local laws require frequent seeding. Frequently, daily seedings are planned for temporary erosion control until the work for the entire project is completed. Then the areas will be reseeded to permanent vegetation at an appropriate planting date.

(a) Seedbed preparation

The objective in seedbed preparation is to create a condition where seed can be planted, emerging seedlings will have a favorable microenvironment, and the surface area will be such as to allow the type of maintenance required to support protective vegetative cover.

During this operation, soil amendments such as lime, gypsum or fertilizer should be applied. Also, remove large stones (generally greater than 1 to 2 inches in diameter in areas that will be lawns or parks, greater than 4 to 6 inches in diameter for other areas) and debris that will hinder seeding or planting and future operations and maintenance.

Seedbed scarification may be required unless seeding is accomplished within 24 hours of final grading. Sand and gravel (sites with less than 20% fines passing a 200 mesh) do not require scarification as long as moisture is adequate. When the surface soil is powdery, the soil is too dry for seeding. If clumps of mud stick to the planting equipment, the soil is too wet unless a hydroseeder or other suitable equipment is used.

Areas of compaction should be identified and ripped or scarified to a depth of at least 9 to 12 inches to create a more favorable rooting zone. Topsoil (if available) should be applied and blended with the surface of the structure. All tillage operations should be performed on or as close to the contour as possible. The balance of the area should be scarified or loosened to a minimum of 3 inches to allow good soil to seed contact. Scarification may be waived if the seeding is accomplished immediately after the final grading is finished and site conditions warrant this approach.

506.03 Seed, plant, and amendment application rates

(a) Seed and plant rates

General seeding rates and planting quantities of adapted species or mixtures are available in the NRCS Field Office Technical Guide (FOTG), Section IV, Critical Area Planting Standard 342.

(b) Seed or plant specifications, or both

To ensure the quality of all planting material, specify genus, species, cultivar (if applicable), specific inoculant, and percent pure live seed or minimum seed germination. All seed should meet Federal and state seed laws for proper labeling and noxious weed content. Criteria for shrub and tree quality, size and type of plant material should be based on standards in the publication "American Standards for Nursery Stock", developed by the American Association of Nurserymen.

(c) Time of seeding or planting

Specify appropriate planting dates. Spring seedings may be adequate where normal rainfall is available. However, the effect of annual weeds and midsummer droughts should be considered. Fall seedings in many parts of the country have the advantage of more reliable precipitation and favorable temperatures. In addition, in the northern states, the annual weeds are generally winter killed.

Cool-season grasses generally do best when seeded in the fall. However, construction will often be completed during periods of the year when seedings should not be made. In these cases, temporary seeding or mulching should be done and the permanent seeding made at the optimum time of year for the species used. In some cases cool season grasses can be planted during otherwise adverse periods if mulch is applied to conserve moisture and mitigate soil temperature extremes.

Warm-season grasses are normally seeded in the spring. Some fall seedings are successful providing weather conditions remain cold and the seed remains dormant. In general, warm-season grasses should have about 100 days of growing season remaining after planting.

Where soil or site conditions limit available moisture, such as sandy or rocky soils, a temporary irrigation system can help insure adequate establishment of vegetative cover. Irrigation can be used on earth-fill structures if care is taken to apply only amounts necessary. If the system is not operated properly, irrigation-induced erosion can occur. Steep slopes (3:1 or steeper) are generally too hazardous on which to set pipe, plus the erosion potential is too great.

(d) Soil amendments

The desired soil pH will depend on the plant species selected and long-term goal of species composition. Acid soil should generally have the pH adjusted to 5.5 or higher for grasses and 6.0 if legumes are to be used. This will allow the rhizobium bacteria associated with legume roots to function. Ground agricultural limestone, either calcitic (high Ca) or dolomitic (high Mg) is used to increase the soil pH. The most desirable ratio is a Ca:Mg ratio of 10:1; however wider ratios are acceptable. High pH or saline soil may require a gypsum ($CaSO_4 .2H_2O$) application. A detailed soil analysis should be used to determine the type and amount of nutrients needed. Unusually high levels of some elements may be toxic, and special steps may be needed to amend these areas. Add only the amount of nutrients required to produce adequate vegetative cover.

(e) Method of seeding or planting

Many techniques are available that have proven successful. Site conditions will dictate options.

Steep slopes on which regular seeding equipment cannot be safely operated must be seeded by broadcasting the seed, blowing it on, or by hydroseeding (applying seed, and sometimes soil amendments and mulch, in a water slurry or suspension). For hydroseeders, coverage is limited by the size of equipment, wind conditions, and stream load. Centrifugal seeding equipment requires dry weather conditions and limited wind interference. High-velocity blowers are normally used for sites where it is difficult to hold seed in place or sites that are inaccessible by large equipment. These blowers will force some of the seed into the soil and crevices for germination. For this method to work properly, the soil must be moist. Some delicate seeded species may experience seed damage.

Calibration of these units is difficult. Experienced operators usually will be able to uniformly apply seed by estimating the land area and apply tank loads at acceptable rates. Hydroseeders frequently add colored hydromulch to mark the area covered.

Another technique for steep slopes is to use a track type bulldozer to incorporate seed and amendments. Operate the bulldozer up and down the slope. The cleat tracks create areas in which seed may be trapped. Soil migrating down the slope will cover the seed and the indentations in the bank hold additional moisture. This works well on sands and gravel.

On flatter areas, additional equipment is available to better place the seed into the soil and in arid regions, to better take advantage of soil moisture.

Imprinting works well to allow for deep placement of seed. This allows for access to moisture and affords the germinating seedling some wind protection.

Special grass drills with packing wheels and other special features are available. Warm season grass boxes are available to handle the fluffy prairie grass seed. These units have devices within the boxes to prevent the bridging of seed, resulting in even seed flow.

Broadcast seeding with an airflow spreader is an acceptable seeding method for some species and purposes.

Herbaceous planting material, such as bermudagrass sprigs
American beachgrass cuttings or trees, requires special knowledge and handling. Internal heating of this material frequently occurs during shipping and storage. The damage to the growing points may go undetected by an untrained person until the plants do not grow. During delivery and planting, every effort should be made to keep the plants cool and moist to insure good survival and growth.

Mulching
Mulching is an important process in establishing vegetation (especially cool-season grasses) on structures or other critical areas. Mulch cover will help maintain favorable moisture conditions, prevent soil erosion by water or wind, hold seed in place, and maintain cooler, more constant soil temperatures. Mulch should be applied immediately after seeding (within a few hours or less). It should be uniformly applied at the specified rate.

Mulch material is not all equal in providing the optimum conditions for germinating seeds (table 506–1). Small grain straw is the preferred material for most sites. This material generally has few weed seeds and provides the best results of any tested material. Grass or mixed legume and grass hay is good but frequently has weed and hay seeds that may also grow and compete with the desired seeded species for moisture, nutrients, and light. It does not make much sense to use certified seed and then throw weedy mulch over the seeding. Other fibrous material such as coconut fiber, excelsior fiber and wood fiber all may be used. Economics will sometimes dictate which mulch material is used. Many latex compounds and commercial products will control erosion and hold seed in place under some moisture and temperature regimes.

Competition is a problem with warm-season grass plantings. Consider alternatives to mulching when warm-season grasses are seeded in northern regions. An oat cover crop, seeded in the fall, will grow enough to protect the soil. Because it will winter kill, the residue will be present in the spring to prevent erosion, but not compete with the warm season grass seedlings.

Mulch material can be selected from table 506–1. Use appropriate materials for the location. The optimum mulch material for cool season grasses and legumes are small grain straw at 4,000 pounds per acre, anchored with 500 to 750 pounds wood fiber hydromulch. This will provide optimum conditions for rapid germination and establishment.

Mulch anchoring—Once mulch is applied, it must remain in place. Few if any of the seeded species will establish in bare areas from which the mulch has moved. On critical sites that are droughty and wind swept, mulch anchoring must be performed to obtain uniform establishment. The cost of establishing erosion control cover is frequently justified, and reducing the area needing reseeding offsets this cost. Mulch anchoring material selection and application rate is important to establish some species.

Material for anchoring fibrous material ranges from wood fiber hydromulch to latex compounds to asphalt emulsion, to mesh netting, to mulch blankets. All are excellent for specific situations. Follow manufactures recommendations for use. Selection is dependent on the intended use, cost, and available labor or equipment.

A wide assortment of implements is available to anchor mulch by incorporating some of the mulch into the soil surface.

Ultimately, the local growing conditions will dictate the outcome of the seeding. If a short-term drought occurs as the seed is germinating, allowing the mulch to be blown around or removed from the site during this time may result in a seeding failure. This is especially critical on droughty soils and for spring seedings.

506.04 Disturbed land

(a) Planning principles

Vegetative treatment of disturbed land areas requires some planning to overcome many potential problems. These include water and wind management concerns, sedimentation, potential limiting or excess elements

Table 506–1 Common mulch material

Mulch material	Quality standard	Application rate	Remarks
Hay, small grain straw	Air-dried; free of mold; free of noxious weeds	2 tons per acre	Subject to wind blowing unless anchored; cover about 90% of soil surface
Wood excelsior	Green or air-dried burred wood fiber	2 tons per acre	Decomposes slowly; subject to blowing unless anchored; packaged in 80–90 lb bales
Wood fiber cellulose	Partially digested wood fiber; usually with green dye and a dispersing agent	2,000 lb per acre	Apply with hydroseeder; used as an anchoring material for mulches subject to blowing
Jute mat - twisted yarn	Undyed, unbleached plain weave; warp 78 ends/yd; weft 41 ends/yd; 60–90 lb rolls	48 in by 50 yd or 48 in by 75 yd	Use without additional mulch; secure as per manufacturers' specification
Excelsior wood fiber mats	Interlocking web of excelsior fibers with photodegradable plastic netting	48- by 100-in 2-sided plastic or 48- by 180-in 1-sided plastic	Use without additional mulch; secure as per manufacturers' specification
Straw or coconut or combined mats	Photodegradable plastic net on one or two sides	6.5 by 83.5 ft, 81 rolls per acre	Designed to withstand fiber individually specific water velocities

on site, intended land use, length of time the area or partial area must be exposed for continued construction, existing slope and planned slope and slope length, and presence or absence of vegetation. The kind of soil and drainage class will influence the type of plant desired.

Water and wind erosion concerns must be dealt with before establishing vegetation. Plants tolerant to wind may be used to protect areas before establishing more permanent and desirable species, or temporary wind breaks (wind fence) may be used. Plants tolerant of inundation or wetness may be required along with regrading or shaping portions of the site to divert or retain water. If the site requires grading and leveling, salvage as much topsoil and existing plants as possible. Shape and grade for intended future use. Areas planned for sports or other types of recreation require considerably more attention and detail than an area being reclaimed for wildlife habitat.

If a site is barren of vegetation, or nearly so, the cause needs to be determined before trying to establish vegetation. Past use or history of industry may provide clues to the lack of vegetation. Old garage areas or motor pool areas may have petroleum contamination or battery acid spills. Mining operations or industrial sites may have dumps associated with them, in which chemicals associated with the industry were disposed. By asking questions about the past use, the planner can then begin piecing the puzzle together. Testing for residual material or chemicals is the only way to confirm what is present.

Soil physical barriers such as restrictive or compacted layers in the rooting zone need to be identified and corrected. Soil sample analysis for particle size distribution may be required. Several plants may be available for use on soil that has 40 percent fines but fewer are suitable if the fines are less than 15 percent. Select plants for the long term, not ones that will grow well for 1 or 2 years. For example, use of ryegrass and cool season grasses on sand and gravel areas will grow and provide temporary cover. However, when the fertilizer is depleted and moisture becomes deficient, the cool season plants will die off. If switchgrass and other warm season grasses are used, they will persist for more than 20 years while natural succession occurs.

Fertility levels need to be assessed before selecting the appropriate plants. Percent organic matter, potentially toxic levels of elements, and pH are interrelated, and they need to be quantified before treatment.

The natural plant succession for the area should be considered, especially when selecting species to use. It may be desirable to select species from several successional stages to include in the revegetation plan. Use plants that blend to the surrounding areas. Avoid selecting invasive species.

Biotechnical or bioengineering options should be evaluated for unstable slopes. The use of live fascines or brush layering techniques should be considered in lieu of more expensive stone gabion baskets and riprap. Chapters 16 and 18 of the Engineering Field Handbook detail these techniques.

(b) Unique critical areas

Strip-mined areas

Strip mining is the removal of overburden to gain access to some mineral or fuel. The spreading or dumping of this overburden material frequently exposes contaminants. Coal mining in the Appalachian Mountains frequently exposes sulfur and iron, the oxidation of which results in the formation of acid materials. The best solution is to cover this acid-forming material during the mining process. If left exposed, the soil pH can be extremely low, causing any aluminum in the soil to become available for plant uptake. When this occurs, the plants selected must be tolerant to potential aluminum toxicity. Because of exposure, slope, and rock, these sites are frequently very droughty.

The sequence of mining operations can be the best management practice and provide for minimizing future toxic areas through proper closing of mined areas. This requires saving the overburden and replacing it on the surface in proper sequence before vegetating the area.

Mine tailings

Areas covered with waste material from mining operations may be high in heavy metals, or have other chemical or physical conditions that make vegetative establishment difficult or impossible. Covering this material with a minimum of six inches of borrow material from surrounding areas may be needed to establish vegetation, stabilize the site and help ensure the long-term survival of desirable vegetation.

Coastal and inland sands and sand dunes
Areas of blowing sand need wind erosion control measures. This may be accomplished using plants such as American beachgrass or with windbreaks or other physical structures. On inland sands, planting single or double rows of American beachgrass or other appropriate plants, perpendicular to the prevailing wind erosion direction, will provide protection for establishing more permanent vegetation. Spacing between rows should be ten times the anticipated height of the plants after one growing season. Wait one year before seeding the permanent vegetation.

Subpart 506B Suitability for crop production systems

506.20 Suitability for crop production

Crop selection in a properly designed rotation is critical to maximize rotational benefits. A properly designed crop rotation provides an excellent tool in breaking insect, weed, and disease cycles (Part 503, Subpart 503A, Crop rotation).

In the past 10 years there has been a major shift in agriculture toward crop production systems using higher amounts of surface residue. In the United States between 1989 and 1997, there has been a 13.5 percent increase in cropland acres involved in some form of residue management. During this same time period the acres in no-till crop production systems have increased 10.1 percent. One of the consequences of this change in crop production systems is that less seedbed modification though tillage is occurring while placing greater reliance on crop selection and variety or hybrid characteristics. Conservation tillage or no-till methods require changes in machinery, fertility programs, and pesticide use. In addition, crop and seed selection must also be reevaluated. Selecting a more desirable variety or hybrid should not be a substitution for properly designed crop rotation.

After a proper rotation has been designed, two primary areas of crop selection need to be evaluated in depth: variety or hybrid performance and after-harvest seedbed characteristics for the next crop in the rotation.

(a) Variety or hybrid performance characteristics

In crop production systems using higher amounts of surface residue, the importance of desirable variety or hybrid characteristics varies among crops. Some important characteristics to consider are high-quality seed, the right maturity for the geographic area, good early season emergence, good early season seedling vigor, consistent performance across soil types, vigorous root development and disease and insect resistance.

Of these characteristics, choosing high-quality seed, those with the right maturity for the geographic area, and that consistent performance are not just characteristics for high residue situations but are universal among tillage systems. However, because of the cooler and wetter seedbeds normally encountered in high residue situations, these characteristics are not only important, but may also need to be modified. An example would be a warm-season grass such as corn. Selecting hybrids 5 to 10 days earlier in maturity may be necessary when planting into heavy residues. In addition, consistent performance across various soil types is important because it is a sign that the hybrid can withstand stress under varied environmental conditions.

Early season emergence and seedling vigor become of greater importance specifically with warm-season crop species when cooler, wetter soil conditions are the rule. Selecting varieties or hybrids with good early emergence and early seedling vigor is necessary where soil conditions that have more stored soil moisture and will be cooler and wetter. Crops under these conditions must germinate quickly and have good early season growth potential to provide the necessary competitive edge required against early weed competition. Treating crop seeds with fungicides can help offset these potential negative effects of planting in high residue conditions.

The selection of varieties or hybrids that can develop vigorous root systems without the help from conventional cultivation is also a very important characteristic for reduce till or no-till system. Some hybrids or varieties also produce a stronger stem or stalk that translates into consistent performance and may contribute to a more durable residue cover following harvest. When selecting varieties and hybrids for superior root and stem characteristics, inquire whether these characteristics have been evaluated under reduced tillage or no-till conditions.

Tolerance to common insect and disease can be important depending on the area and crop rotation. This can be especially true when the crop to be planted is closely related to the preceding crop in the rotation, such a cool-season grass planted into a cool-season grass. Another example might be planting soybeans in field with heavy surface residues and poorly drained soils. Selecting soybean varieties for phytophthora root rot resistance may be a major advantage in these fields. An important point to mention again is that the selection of varieties with insect or disease tolerance is not a substitution for rotation.

(b) After harvest seedbed characteristics for the next crop in the rotation

Previously, modifying the seedbed in preparation for the next crop was done with tillage, either conventionally (plow, disk, harrow), or in recent years, by building ridges (ridge till) or fall and spring strip till methods. In high-residue cropping systems, residue characteristics such as the amount, color, resistance to decay, and stubble height of residue left after harvest can affect the seedbed characteristics for the next crop. These characteristics can be an advantage if properly managed, or they can be an obstacle to good production if not properly incorporated into a cropping system. Residue levels and residue color affect soil temperature. High levels of residue keep the soil cool longer because the residue absorbs or reflects the sun's energy. After crops such as corn or grain sorghum, which can produce high levels of surface cover, the soil will warm up slower. When dealing with heavier residue amounts from the preceding crop it may be necessary in no-till situations to use of residue managers that move the residue of to the side of the seed trench. Dark-colored residue, such as that produced by oilseed and legume crops, absorb the sun's energy and transfer it to the soil, causing it to warm up faster than if the residue was lighter colored.

Warm-season species such as corn or sunflower respond to warm, clean seedbed conditions. These conditions can be obtained by managing the type and amount of residue from the preceding crop residue. For example, soybeans produce relatively low amounts of residue that is dark-colored. After soybeans, the seedbed for subsequent crops will be mellow, warm, and very conducive to fast, uniform emergence.

Other crop species may benefit from the micro-environmental conditions produced by high amounts of surface residue. Cool soil conditions are not a concern when seeding winter wheat. However surface moisture and sufficient standing stubble to catch snow are important factors to consider. Surface residue helps prevent the soil from drying out or cooling down too rapidly, extending the fall growing period for winter wheat. For another example, soybeans are sensitive to heat, drought, and high soil temperatures. Heavier surface residue levels improve soybean performance under these conditions.

When higher amounts of surface residues are desirable for crop production, the inclusion of a crop with more durable residue characteristics may be necessary. As surface residues increase, microbial populations in the upper one or two inches of soil also increase, which increases the rate of decay of these residues. Including a crop whose residue is more resistant to decay, such as corn, sorghum, or sunflowers, will help increase surface residue levels.

Stubble height of previous crop residues can be very beneficial in increasing soil moisture and can increase the survival of fall-planted crops. In the northern Great Plains, increasing stubble height traps more snow on the field, increasing the available water for crop production. Stubble height can be increased by setting the combine header higher, or by using stripper headers to harvest grain.

Taller stubble heights can also moderate air and soil temperatures, improving the survival of winter wheat and increasing the effective range of the crop further north. The maximum winter wheat hardiness is obtained with winter wheat planted into standing small grain stubble. However, when winter wheat is planted following another small grain, varieties with tolerance to leaf spotting diseases should be considered in some environments. Managing stubble height coupled with selecting disease-tolerant varieties allows higher-yielding varieties with less winter hardiness to be planted further north than was previously possible.

506.21 References

American Nursery and Landscape Association. 2004. American Standard for Nursery Stock. Washington, DC. *www.anla.org* 57 pp.

Part 507 Cropland Conservation Management Systems

Contents

Figures

Tables

Part 507 Cropland Conservation Management Systems

Subpart 507 Cropland Conservation Management Systems

507.00 Cropland conservation management systems

The development of sustainable cropland conservation management systems involves effective conservation planning. This conservation planning process views the agro-ecosystem as an integration of complex natural physical, chemical, and biological functions. A look back at history provides evidence that undertaking to manage agro-ecosystems as a natural resource must consider the entire system rather than just the parts. Nothing less than managing for the whole or health of the agro-ecosystem is acceptable. Managing for the health of the agro-ecosystem requires acceptance of a holistic approach to conservation planning to achieve some degree of sustainability.

As Hugh Hammond Bennett stated in his address to the American Geographical Society in 1948 proper conservation treatment mandates the "use of land in accordance with its capabilities and the treatment in accordance with its needs." The same general principles that Dr. Bennett set forth in 1948 are still applicable in the development of effective conservation management systems on cropland. NRCS's National Planning Procedures Handbook outlines the process for implementation of these principles through the "nine steps of conservation planning." The principles are summarized as follows:

- Consideration and focus on the producer's goals. As part of this goal setting process, an evaluation is made of the producer's farm and livestock facilities, machinery, and economic situation. The product of this principle results in the establishment of three action statements that further define the goal. The statements are:
  - — the quality of life that the producer wants derived from the agro-ecosystem
  - — the forms of production and management tools required to deliver the quality of life
  - — a description as to what the farm's landscape or the desired future condition is to look like (ATTRA, 2001)

In addition to the three action statements, the following evaluations and considerations must be part of the planning process:

- evaluation of the resource needs and capability of each cropland acre
- incorporation of the producer's willingness to implement and adapt new technology and practices
- consideration of the landscapes relationship and function to the entire farm and watershed
- continual presence of the conservationist with the producer. In any holistic approach to management of the agro-ecosystem there is a requisite for monitoring and assessment of the function of the system.

In addition, there will be assessment indicators and events that will demand re-planning and adjustments in the conservation management system. In many cases the specific management tools will need to be altered or in some cases a current tool is abandoned and a different one implemented, particularly with changes in technologies, producer objectives, and ecosystem components.

507.10 Cropland conservation management systems—humid east and other humid areas of the United States

Environmental sustainability has the same basic meaning in all eco-regions, though treatments to ensure sustainability may differ. The humid east and other humid areas of the United States have numerous and varied ecological composites, each having its specific resources and needs. These variations occur not only over wide landscapes through the region but may also occur within small watersheds and even within specific land treatment units. The contrasting ecosystems and the specific resources (e.g. soils, rainfall, etc.) of these contrasting ecosystems can be an asset in the number of alternative crops and the abundance of production. However, the variations can also provide greater challenges for resource management planning. As with the resources, there typically are multiple resource needs. Commonly treatment of a specific need impacts other resources and treatment needs. Thus, holistic concepts are essential to ensure the adequacy of treatments and the sustainability of resources.

507.11 Typical cropland resource concerns in the humid east and other humid areas of the United States

One or more of the resource problems listed below are typically a concern on cropland in the humid east and other humid areas of the United States and on irrigated cropland throughout all eco-regions. The additional planning considerations must also be taken into account in planning of conservation management systems for cropland that are sustainable and are compatible to the situation and the producer's objectives.

Typical resource problems:

- erosion from water or wind, or both
- soil quality (organic matter depletion or organic soil subsidence)
- water quantity (too much or too little available water)
- water quality (excessive sediment in surface water, excessive nutrients, excessive pesticides, or bacterial contaminants in surface or ground water)
- air quality (objectionable odors, excessive ammonia, or particulate matter)
- undesirable plant productivity and health (plant species or ecotypes not adapted or unsuited; abrasion by windblown soil particles, soil compaction, and inadequate fertility)
- plant pest (weeds, insects, diseases and other organisms that impede plant growth and production)

Additional planning considerations:

- energy use
- social and cultural
- economics
- laws and regulation
- optimizing production

507.12 Purposes, effects, and impacts of the major cropland conservation management systems

Practices and treatments used to address specific resource concerns about cropland situations often have complimentary effects on other resource concerns. For example, by selecting a rotation of different crops (conservation crop rotation practice) to meet soil erosion, soil quality, and producer needs; the practice can also have complimentary effects on reducing weed, disease, and insect pressures (integrated pest management practice). Likewise, a practice or treatment selected to treat one concern may have an adverse effect on another resource concern. For example, the use of the residue management, no till/strip till/direct seed practice may be effective to reduce erosion, improve soil quality, and reduce nutrient and pesticide runoff; but no-till may have an adverse effect on the production system if a proper crop rotation and nutrient and pest management are not implemented at the same time. Therefore, as a cropland management system is planned, it is critical to understand all the effects of the practices/treatments being considered on the total production system.

Table 507-1 provides examples of some of the major purposes and expected effects of the most commonly used practices and treatments on cropland. The purposes identified are expressed in the National Practice Standards as well as additional considerations and effects for local consideration.

Conservation management systems for cropland include a combination of practices and treatments necessary to address existing and anticipated soil, water, air, plant, animal and human resource concerns, and treat all the concerns to a minimum acceptable level. Cropland involves the growing of annual or a mixture of annual and perennial crops. To produce crops requires the continued management of soil, water, air, plants, and their associated components to meet the objectives of the producer and to maintain a sustainable production base.

A large number of potential practices and treatments can be used on cropland. However, there are few major practices and treatments that form the foundation (or core) of most cropland conservation management systems. The major practices and treatments that form

Table 507–1 Example of major purposes and expected effects of commonly used conservation practices on cropland

Practice /Treatment	Purposes of practice	Effects [1/]
Conservation Crop Rotation (Code 328)	• Reduce erosion from wind and water • Maintain or improve soil organic matter content • Manage the balance of plant nutrients • Improve water use efficiency • Manage saline seeps • Manage plant pests (weeds, insects, and diseases) • Provide food for domestic livestock • Provide food and cover for wildlife • Provide energy use	• water erosion → m – su • wind erosion → m – su • soil quality → sl – m • water quality → sl – su • water quant.→ sl – m • air quality → sl – m • plant health → m – su • water erosion → sl – m • conservation → sl - m
Contour Buffer Strips (Code 332)	• Reduce sheet and rill erosion • Reduce transport of sediment and other water-borne contaminants • Increase water infiltration	• wind erosion → n/a • soil quality → sl – m • water quality → sl – su • water quant. → sl • air qual. & plt. health → sl • energy conservation → sl–m
Contour Farming (Code 330)	• Reduce sheet and rill erosion • Reduce transport of sediment, other solids and attached contaminants • Increase water infiltration	• wind erosion → n/a • soil quality → sl – m • water quality → sl – su • water quant. → sl • air qual. & plt. health → sl
Cover Crop (Code 340)	• Reduce erosion from wind and water • Increase soil organic matter content • Capture and recycle or redistribute nutrients in the soil profile • Promote biological nitrogen fixation • Increase biodiversity; Provide weed suppression • Provide supplemental forage; Manage soil moisture • Reduce particulate emissions into the atmosphere • Minimize and reduce soil compaction • Reduce energy use	• water erosion → m – su • wind erosion → m – su • soil quality → sl – m • water quality → sl – m • water quant. → sl – m • air quality → sl – m • plant health → sl – m • energy conservation→ sl – m
Field Border (Code 386)	• Reduce erosion from wind and water • Protect soil and water quality • Manage pest populations • Provide wildlife food and cover • Increase carbon storage • Improve air quality	• Water & wind er → sl – su • soil quality → sl – su * • water quality → sl – m • water quant. → sl – m • air quality → n/a – sl • plant health → su [2/]
Filter Strips (Code 393)	• Reduce suspended solids and associated contaminants in runoff • Reduce dissolved contaminant loadings in runoff • Reduce suspended solids and associated contaminants in irrigation tail water	• Water & wind er → n/a • soil quality → su [2/] • water quality → sl – su

Table 507–-1 Example of major purposes and expected effects of commonly used conservation practices on cropland—continued

Practice /Treatment	Purposes of practice	Effects [1/]
Herbaceous Wind Barriers (Code 603)	• Reduce soil erosion and/or particulate generation from wind. • Protect growing crops from damage by wind-borne soil particles. • Manage snow to increase plant-available moisture. • Provide food and cover for wildlife.	• water erosion → sl inc. • wind erosion → sl – su • soil quality -> n/a – sl • water quality → n/a – sl • water quant. → sl – m • air quality → sl – m • plant health → sl – su
Integrated Pest Management (Code 595)	• Prevent or mitigate pesticide risks to water quality from leaching, solution runoff, and adsorbed runoff losses. • Prevent or mitigate pesticide risks to soil, water, air, plants, animals, and humans from drift and volatilization losses. • Prevent or mitigate on-site pesticide risks to pollinators and other beneficial species through direct contact. • Prevent or mitigate cultural, mechanical, and biological pest suppression risks to soil, water, air, plants, animals, and humans.	• water erosion → sl – su • wind erosion → sl – su • soil quality → sl – m • water quality → n/a – su • water quant. → n/a – sl • air quality → n/a – m • plant health → su
Nutrient Management (Code 590)	• Budget and supply nutrients for plant production. • Properly utilize manure or organic by-products as a plant nutrient source. • Minimize nutrient nonpoint source pollution of surface and ground water resources. • Protect air quality by reducing nitrogen emissions (ammonia and NO_x compounds) and the formation of atmospheric particulates. • Maintain or improve the physical, chemical, and biological condition of soil.	• water and wind er → n/a • soil quality → sl – m • water quality → n/a – su • water quant.→ n/a • air quality → sl – su • plant health → sl – su
Residue Management, No-Till/StripTill/ Direct Seed Code (Code 329)	• Reduce erosion from wind and water. • Improve soil organic matter content. • Reduce CO_2 losses from the soil. • Reduce soil particulate emissions. • Increase plant-available moisture. • Provide food and escape cover for wildlife. • Reduce energy use	• water and wind er → m – su • soil quality → sl – su • water quality → sl – su • water quant. → sl – m • air quality → n/a – su • plant health → sl – m • energy conservation → sl – su
Stripcropping (Code 585)	• Reduce soil erosion from wind and water. • Reduce transport of sediment and other water-borne contaminants. • Protect growing crops from damage by wind-borne soil particles.	• water and wind er → m – su • soil quality → sl – m • water quality → sl – su • water quant. → n/a – m • air quality → n/a – su • plant health → sl – su

1 er = erosion; n/a = not applicable; sl = slight; m = moderate; su = substantial
2 on footprint

the core of cropland management systems involve those that relate to the:

- selection and rotation of crops
- tillage or planting system (crop establishment)
- residue management
- fertility management
- pest management

To successfully produce crops in an economical and sustainable manner requires an accurate assessment of the resources (soil, water, air, plants, animals, human, and energy) capabilities and limitations. The core practices of crop rotation, timing and type of tillage, how the residue is managed, nutrient management, and pest management are almost always involved to address the capabilities and limitations (resource concerns) of any cropland management system.

Cropland management systems must address the following:

- crop(s) to be grown within the resource capabilities and limitations
- producer's needs and concerns
- crop(s) establishment
- residue management
- nutrient management
- pest management
- soil water management
- sustainability of the management system

Thus the core conservation practices in the cropland conservation management system almost always include conservation crop rotation, residue management, nutrient management, and pest management. Other major practices and treatments used in cropland management systems include:

- contour buffer strips
- contour farming
- cover crops
- crosswind strips
- deep tillage
- drainage water management
- field border
- filter strip
- grassed waterway
- irrigation water management
- stripcropping
- terraces
- water and sediment control basins (control concentrated flow/gully erosion)

In some situations, special components such as irrigation or habitat for beneficial insects and/or pollinators may be essential to facilitate achieving the production goals of the producer. In addition, vegetative practices, such as critical area planting, and structural practices, such as surface drainage, may be needed to support the planned management practices. Also, where wildlife habitat and/or grazing are secondary land uses, additional practices, and treatments may be needed to facilitate those uses.

The first step in developing a cropland management system is to fully assess the resource capabilities and limitations (a resource assessment) and determine the producer's capabilities, limitations, and objectives. This will establish the baseline to begin to build an effective conservation management system for cropland. One must also keep in mind that although different cropland systems may have the same practices planned, the treatment within those practices may be different to meet different purposes and resource conditions. Cropland systems with the same combination of practices but planned for different purposes will have different effects on the resources and concerns.

507.13 Economics of the major agronomic practices/treatments

To assess the economics of the agronomic practices is often difficult. Both short-term and long-term costs and benefits must be considered. Short-term costs and benefits are certainly important considerations in assessing the immediate viability of the practice(s) and the impacts of their application on the enterprise. Further the probability of successful implementation and costs associated with maintenance of the practice(s) must be evaluated. Never-the-less, assessment of the long-term costs and benefits is critical to insuring sustainability of the resources and the continued viability of the enterprise.

The cost and benefit considerations of agronomic practices include both facets related to profit to the enterprise and to resource protection. Consequently, the impacts of the practices on optimizing production must be evaluated. While technologies and methods may facilitate maximizing production, the merits of the agronomic practices must be evaluated based contributions and compatibility with optimal production, i.e. the production level providing the greatest net value to the enterprise.

The traditional method used to assess the economics of various agronomic practices is to compare different methods to achieve a given treatment or purpose. For example, to compare the economics of preparing a seedbed for planting, one method would be to compare the cost of a mulch-till system vs. the cost of a no-till system. It is critical that the costs involved in agronomic practices and treatments be carefully analyzed. For example, in the mulch-till vs. no-till scenario mentioned previously, if the producer owns both mulch-till tools and no-till tools, one can only evaluate operation and maintenance costs of the equipment because the costs of the equipment are already incurred regardless of the system used.

Most agronomic type practices and treatments do not require a direct or major outlay of cash. Many of the practices and treatments are often more of a change in management techniques rather than a structural installation.

507.14 New and emerging technologies and crop production systems

The application of the “holistic” approach to planning conservation management systems on cropland values the merits of proven practices and treatments. However, to meet the producer objectives and to maintain compatibility with current production system and markets the planning system must have the flexibility to incorporate new and emerging technologies such as precision application of nutrients and/or pesticides, adaptive nutrient management, and precision irrigation.

Typically the conservation management system will need revision as new and emerging technologies are incorporated. Further the process must be broad enough in scope to facilitate development of specific conservation management systems across a vast array of resource conditions, production systems, and producer objectives, including traditional systems and more unique systems such as “organic production.” Never-the-less the core components of the cropland conservation management system have been and will continue to be related to maintaining cover on the land and the management of the cover.

507.15 Combining practices and treatments into conservation management systems

Alternative conservation management systems consist of combinations of specific practices and treatments that when applied as a system will treat identified resource concerns to acceptable treatment levels, be compatible with the production system, and meet the producer’s objectives. The producer selects the conservation management system to be applied from the alternative systems developed in conjunction with the planner. A key consideration in the producer’s decision is certainly the most cost-effective system.

To select the most cost-effective cropland management system, first develop two or more alternative management systems that adequately treat the resources and meet the producer’s objectives. Then evaluate each system, comparing the total costs to implement each system to the expected impacts and returns of that system.

507.20 Resource concerns and effects—dryland regions of the Great Plains and western United States

In describing major cropland management practices within the Great Plains and western regions of the United States, a distinction must be made between the term's dryland and rain fed. Rain-fed agricultural systems can be used to describe agricultural systems that exclude irrigation as a water source and generally fall into two categories. The first category of rain-fed agricultural systems consist of those that emphasize maximum crop yields, significant production inputs, and disposal of excess water, while the second category of rain-fed agricultural systems characterize the dryland systems (Stewart 1988; Stewart and Burnett 1987).

Several investigators have proposed various definitions of dryland or dry farming (Duley and Coyle 1955; Hargreaves 1957; Higbee 1958). Common to all definitions, these dryland systems are those which describe production techniques under limited precipitation and usually severe resource concern constraints. The resource constraints include soil erosion by both wind and water; periods of water stress of significant duration; and limited production inputs. Another distinction is that the dryland systems focus on crop yield sustainability and water conservation and water harvesting techniques. To further define dryland, Oram (1980) has suggested six criteria to be used in describing dryland regions and systems:

- occurrence of very high intensity rainstorms
- potential evapotranspiration exceeds the precipitation for a minimum of 7 months during the year
- decreased reliability and increased precipitation variability as annual precipitation decreases
- low total annual precipitation accompanied with at least one pronounced dry season
- large annual precipitation variations from year-to-year
- large monthly variations in precipitation

507.21 Defining and describing dryland regions

A number of attempts have been made to quantitatively describe and categorize dryland regions. The older accepted approaches which generally included some form of the Thornthwaite precipitation effectiveness index (P–E) are presented and reviewed elsewhere (Brengle 1982).

Stewart (1988) reviews two methods hereby referred to as the United Nations Educational, Scientific, and Cultural Organization (UNESCO) method and the Food and Agriculture Organization of the United Nations (FAO) method. Based on the length of growing season the FAO method delineates dryland climatic regions as dry, arid, and semiarid. The UNESCO method delineates four dryland zones (hyperarid, arid, semiarid, and subhumid) based on an index, called the climatic aridity index. Both methods use daily values of precipitation (P) and potential evapotranspiration (ETp). Since daily values are evaluated, an appropriate energy balance method for estimating ETp for short time steps should be used. This would include the Penman method or one of its several variations based on local conditions and available data.

UNESCO method

The UNESCO method uses the climatic aridity index. The climatic aridity index (CAI) is the ratio of the precipitation (P) to the potential evapotranspiration (ETp) (CAI=P/ETp). The four climatic zones are delineated in table 507–2.

FAO method

The length of the growing period in the FAO method is the number of days that have a mean daily temperature greater than 44 degrees Fahrenheit (6.5 °C) during the year when P is greater than 50 percent of ETp (0.5 ETp), plus the number of days required to use about 4 inches (10 cm) of stored soil profile water. Regions

Table 507–2 Climatic zone delineation

Zone	CAI
Hyperarid	CAI < 0.03
Arid	O.03 <CAI < 0.20
Semiarid	0.20 <CAI < 0.50
Subhumid	0.50 <CAI < 0.75

classified as dry are those where P never exceeds 0.5 ETp; arid where the length of the growing period is between 1 and 74 days; and, semiarid where the growing period is between 75 and 119 days.

507.22 Regional resource settings of dryland cropping areas of the United States

In the United States and Canada, six distinct dryland-farming regions can be identified. The six regions are the Southern Great Plains, Central Great Plains, Northern Great Plains, Canadian Prairies, Pacific Northwest, and the Pacific Southwest (fig. 507–1). Also shown are the five specific areas of dryland production.

Common to all of the regions is the non-beneficial use of soil water through evaporation and the practice of summer fallow. There are, however, a number of general distinctions other than crop adaptability that can be made between the regions. The distribution and types (snow versus rainfall) of precipitation differ greatly. Snow management can be used effectively to increase soil water storage in the northern regions. Detailed descriptions of these regions are in Cannell and Dregne (1983).

507.23 Principles and guidelines of dryland conservation management systems

(a) Basic principles

In natural ecosystems the succession process advances until something limits it. Moreover, as succession continues, the complexity, diversity, and stability increases (Savory 1988). The result of a complex, diverse, and stable ecosystem is increased productivity. Secondly, everything that occurs within an ecosystem can be described in terms of the effectiveness, or lack of effectiveness in the water cycle, nutrient cycle, succession itself, and the flow of carbon (energy) through the ecosystem.

The same concepts can certainly be applied to dryland agroecosystems. The succession process in a natural system is analogous to the sequence of crops in rotation. Like natural systems, the succession process of dryland systems can advance until something limits it. In most cases, this limiting factor is climate. The holistic approach, though, teaches us that there may be additional limitations. The most common of these include economics and market forces.

The underlying principles directed at the development of a sustainable dryland cropping system include three elements. These elements are:

- rotation intensity
- rotation diversity
- management

First, any given crop rotation must have a crop succession of sufficient intensity to assure maximum use of effective precipitation.

Second, the crop rotation must have sufficient diversity, which is central to the whole-system management philosophy. Agroecosystem diversity is more than the interaction and manifestation of physical and biochemical processes. It includes all of the concepts related to the promotion of effective nutrient cycling and expansion of disease and weed control strategies. Diversity also considers human and economic factors, in that the crop rotation must have sufficient diversity for distributing workloads and economic risks. Crop species and ecotypes in the rotation are chosen for "specific eco-agro purposes and are included at proper timing and intervals in the rotation to manage water resources and the maximize nitrogen fixation and nutrient cycling and to reduce erosion. Gleissman (1998) outlines six specific benefits and characteristics of diverse eco-agro systems. The following can be identified and applied to the dryland areas:

Greater stability and diminished external input requirements. Stability not only includes the lack of fluctuating crop yields; but also includes the ability to spread out workload and fixed costs; and the reduction in weather and price risks.

- Greater harvestable biomass production potential
- Larger soil carbon pool resulting from increased total biomass

Figure 507–1 Major dryland regions and production areas of the United States and Canada (Cannel and Dregne 1988)

- — Diminished need for external nutrient inputs resulting from efficient nutrient cycling.
- — Reduced risk of economic crop loss resulting from greater species diversity.
- — Increased opportunity to break insect and disease cycles; and potential for effective application biological control strategies.

Third, the crop rotation that has sufficient intensity and diversity must be managed properly. The proper management levels include using tillage and planting methods that reduce soil disturbance and renewing dependence on cultural practices that will reduce reliance on costly technology.

(b) Intensity

The intensity of crop rotations in the dryland areas of the United States can be based on the water use patterns of the various crops (Beck and Doerr 1992; Beck 1997). The higher the water use the greater the intensity. Crops can be divided into high water use crops and low water use crops. High water use crops are those full-season summer-grown crops such as corn, sunflower, soybean, and cotton. Low water use crops are those classified as short-season and cool-season crops. Examples include small grains, flax, millet, canola, brown mustard, camelina, and lentils. The application of this method gives arbitrary increasing values with increasing crop water use; respectively:

- fallow (no crop water use) has a zero (0) value
- low water use crops have a value of one (1)
- high water use crops have a value of two (2)

The intensity is equal to the sum of all of the crop water-use values and divided by the number of crops and fallow in the rotation. For example, a winter wheat-fallow rotation has an intensity of only 0.50 (0+1=1 divided by 2); and a spring wheat-winter wheat-corn-sunflower rotation has an intensity of 1.50 (1+1+2+2=6 divided by 4).

(c) Diversity

Ecologists have developed several measures of diversity. The most widely used procedures are the Shannon, Simpson, and Margalef diversity indices (Gleissman 1998). The NRCS has made several attempts at describing the influence of crops and tillage on productivity and sustainability (Soil Conservation Service 1976; King 1977). A much simplified and holistic approach to describing diversity has been proposed by Beck (1996). Beck's system was demonstrated as reliable in the Northern Great Plains. However, its validity has not been substantiated outside this region; however, the principles reflected in Beck's system should be universal in application.

The system proposed by Beck for evaluating crop rotation diversity first determines the average crop interval. The average crop interval value is then adjusted to give a diversity index that credits characteristics which bring additional diversity to the rotation.

The diversity index accounts for the different crop types and their intervals within the rotation. The crop types considered are as follows:

- cool-season grasses (winter wheat, spring barley)
- warm-season grasses (corn, millet, sorghum)
- cool-season broadleaf (flax, lentils, canola)
- warm-season broadleaf (soybean, cotton, dry bean, sunflower)

In addition, the index accounts for ecological considerations such as those relating to weed and disease pressures, as well as workload distribution and the conflicts between operational interferences. These include planting interference of one crop with the harvest of another crop in the rotation. Diversity values generally range from –0.50 (winter wheat-fallow) to nearly 4.0 for highly diverse rotations such as spring wheat-winter wheat-soybean-corn.

Calculation of the diversity index involves two steps:

- In the first step the average interval between crop types is determined.

  Count back the number of years between crop types for each crop in the rotation and divide by the length of the rotation, e.g. wheat-fallow = (1 + 1)/2 = 1.0 or wheat – wheat – canola = (1 + 0 + 2)/3 = 1.0.

  If a second crop in the rotation is from the same "crop type group", value the second crop as 0.5 rather than 1, e.g. wheat – barley – canola = (1.5 + 0.5 + 2)/3 =1.33.

- In the second step a diversity index is determine by adjusting the interval average from step 1 to account for work-loading spreading and pest concerns.

  If both a grass and a broadleaf are used in the rotation add 0.5. If both a fall and a spring seeded crop are used in the rotation, add 0.5. If both cool and warm-season crops are used add 0.5.

  Adjust for broadleaf intervals by assigning and adding a value of 0 if the broadleaf to broadleaf interval is 2 years; 0.5 for each broadleaf interval of 3 years or more; -0.5 for an interval of 1 year; and -1.0 for back to back broadleaf sequences.

  Adjust for workload spreading benefits by determining the proportion of crops (largest value) with a shared seeding time and deducting that value from the score.

  A further deduction is made for harvest interference of one crop interferes with seeding of another crop. The deduction used in one-half the proportion of the conflicting acreage seeded to harvest acreage.

Both of the described intensity and diversity indices offer tools that can be used to evaluate rotations. The utility of these tools is particularly useful during the initial planning phases.

507.24 Factors in planning dryland cropping systems

The following factors need to be considered in planning dryland-cropping systems:

- historic precipitation patterns and rainfall probabilities
- crop marketability and potential profitability
- insect cycles and potential disease organisms
- crop water use patterns
- snow management
- weed control options and evaluation of ability to rotate herbicide types
- optimum row widths
- potential phytotoxicity
- equipment needs
- energy use

507.25 Major cropping systems and technologies for the dryland regions of the United States

As previously mentioned, the resource constraints of the dryland regions of the United States are three-fold:

- soil erosion by both wind and water
- periods of water stress of significant duration
- limited production inputs

Probably the most important factor affecting the constraint associated with limited production inputs is soil fertility. The inability to make precise fertilizer recommendations under diverse and variable precipitation patterns limits efforts in obtaining maximum economic returns.

The focus of dryland systems is on crop yield sustainability and water conservation and water harvesting techniques. Thus, the sequence of crops and the characteristics of each crop control every other aspect of the cropping system.

Briefly, table 507-3 identifies the major crops, crop rotations, and management technologies.

Table 507–3 Major cropping systems and water and soil conservation management technologies for U.S. dryland agricultural regions

U.S. dryland agricultural regions	**Cropping systems**		**Water and soil conservation management technologies**	
	Crops [1/]	**Crop rotations**		
Southern Great Plains	Winter wheat (WW) Grain sorghum (SO) Cotton (OC) Sunflower (SF) Forage sorghum (SD) Alfalfa (AL) Guar (GU)	OC-SF con't OC con't WW WW-fallow WW-SO/SD-fallow WW-OC-fallow con't SO/SD WW(3)-OC(3)-fallow	• Bench terraces • Contouring • Delayed planting dates • Furrow diking • Furrow blocking • Nutrient management • Pest management, including weed control • Summer fallow • Terrace	• Alternate irrigation/dryland • Residue management, no-tillage/strip tillage/direct seed • Residue management, mulch tillage • Variable rate planting • Vertical mulching
Central Great Plains	Winter wheat (WW) Grain sorghum (SO) Sunflower (SF) Forage sorghum (SD) Grain corn (CG) Millet (MO) Dry bean (BD)	WW-fallow WW-SO/SD-fallow WW-CG-fallow WW-SF-fallow con't SO/SD WW-MO-fallow SF/SG-BD con't BD	• Contouring • Terrace • Pest management, including weed control • Residue management, no-tillage/strip tillage/direct seed • Residue Management, Mulch tillage	• Snow management – tall wheatgrass barriers – annual crop barriers • Nutrient management • Stripcropping • Summer fallow
Northern Great Plains	Barley (BA) Winter Wheat (WW) Spring Wheat (WS) Oats (OT) Flax (FL) Safflower (SA) Sunflower (SF) Grain Corn (CG) Soybean (SB) Alfalfa (AL) Millet (MO)	WW/WS-fallow BA-fallow WW/WS-BA-fallow WS-WW-fallow WW-BA-SB WS-SF/SA/SB WS-OT-SF/SA/FL-BA WS-WW-CG-SB/SF BA-WW-CG-SB/SF WW-CG-MO-fallow WW-SF-fallow CG-SB WS-FL/SF/SA-fallow BA-CG WW-LDw	• Summer fallow • Nutrient management • Stripcropping • Pest management, including weed control • Residue management, no-tillage/strip tillage/direct seed	• Residue management, mulch tillage • Snow management • Tall wheatgrass • Barriers • Annual crop barriers • Field shelterbelts/tree windbreaks bench terraces w/grassed dikes

Table 507–3 Major cropping systems and water and soil conservation management technologies for U.S. dryland agricultural regions

U.S. dryland agricultural regions	Cropping systems		Water and soil conservation management technologies	
	Crops [1/]	Crop rotations		
Pacific Northwest	Spring lentil (LDs) Winter lentil (LDw) Spring Barley (BAs) Rapeseed (RB) Green Pea (PG) Austrian winter Pea (AW) Winter wheat (WW) Spring wheat (WS) Spring pea (PF)	BAs-fallow BAs-PF RB-fallow PG-RB AW-WW-BAs WW-AW-BAs/WS WS-fallow WW-fallow	• Contouring • Slot mulching • Nutrient management • Pest management, including weed control • Stripcropping	• Residue management, no-tillage/strip tillage/direct seed • Residue management, mulch tillage • Summer fallow • Terrace
Pacific Southwest	Winter wheat (WW) Pasture (PT) Spring barley (BAs) WW-PT-fallow BAs-fallow BAs-BAs-fallow	WW-fallow	• Water harvesting • Summer fallow • Nutrient management • Terrace • Pest management, including weed control	• Residue management, no-tillage/strip tillage/direct seed • Residue management, mulch tillage • Snow melt control w/flyash

1 AL = alfalfa
AW = Austrian winter pea
BAs = spring barley
BD = dry bean
CG = grain corn
FL = flax
LDs = spring lentil
LDw = winter lentil
GU = guar
MO = millet
OC = cotton
Ot = oats
PG = spring pea
PT = pasture
RB = rapeseed
Sa = safflower
SB = soybean
SD = forage sorghum
SF = sunflower
SO = grain sorghum
WS = spring wheat
WW = winter wheat

507.26 References

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Part 508 Soils

Contents

Subpart 508A **Agronomic Soil Basics** **508–1**

Figures

Part 508 Soils

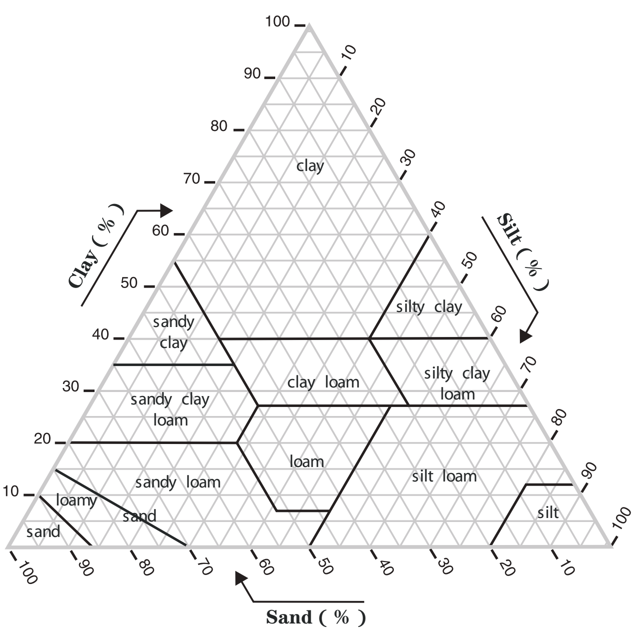
Subpart 508A Agronomic Soil Basics

508.00 Soil texture

Soils are composed of particles with a large variety of sizes and shapes. On the basis of size, individual particles (or separates) are divided into three categories; sand, silt, and clay. This defines the “fineness” or “coarseness” of a soil. Soil class is recognized on the basis of the relative percentages of these separates (fig. 508–1). The principal classes pertaining to texture are sand, loamy sand, sandy loam, silt loam, clay loam, silty clay loam, and clay, in increasing order of their content of fine separates. Particles larger than 2 millimeters are considered rock fragments, and those that are less than 2 millimeters are considered fine earth fraction.

Figure 508–1 displays what is commonly referred to as the USDA textural triangle. It describes the proportions of sand, silt, and clay in the basic textural classes. Texture determines the amount of surface area on the soil particles within the soil mass. Clay and humus both exist in colloidal state and have an extremely high surface area per unit weight. They also carry surface electrical charges to which ions and water are attracted.

Figure 508–1 USDA soil textural triangle



A textural class description of a soil reveals a lot about soil-plant interactions, since the physical properties of soils are determined largely by the texture. In mineral soils, the exchange capacity (ability to hold plant nutrient elements) is related closely to the amount and kind of clay in the soil. The water holding capacity is determined largely by the particle size distribution. Therefore you find that fine-textured soils (high in silt and clay) hold more water than coarse textured soils (sandy). Water percolates more quickly and more deeply into light soils, but heavier soils have the greater water holding capacity per cubic foot. Finer textured soils are also more compact, have slower movement of water and air can be more difficult to till.

Soil texture has an important influence upon crop production. From the stand point of plant growth, medium-textured soils, such as loams, sandy loams, and silt loams, are probably the most ideal.

508.01 Soil structure

Soil structure is the arrangement and organization of soil particles into natural units of aggregation. Except for sand, soil particles do not exist singularly in the soil, but rather are arranged into aggregates or groups of particles. Soil aggregates are formed both by physical forces and by binding agents which are principally products of decomposition of organic matter. Aggregates formed by binding agents are more stable and able to resist the destructive forces of water and cultivation. Aggregates formed by physical forces such as wetting and drying cycles as well as freezing and thawing, are relatively unstable and are subject to quicker decomposition.

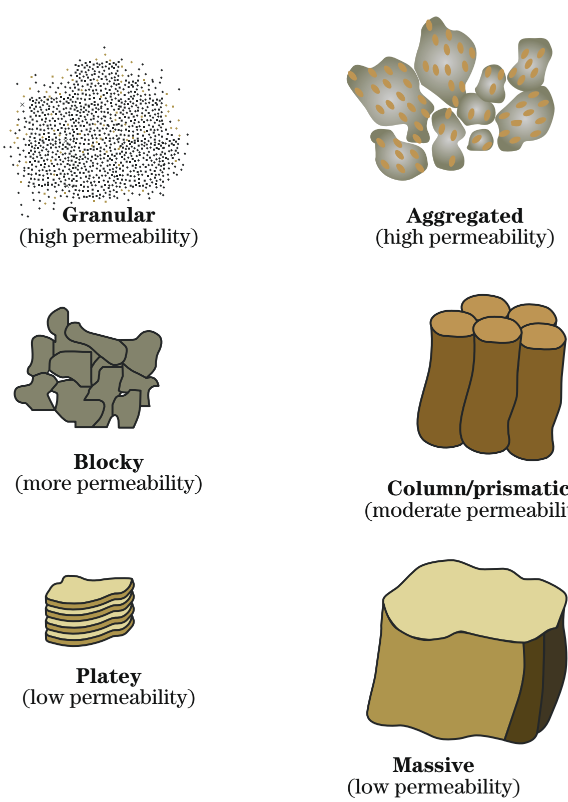
Soil aggregation normally occurs when ample organic matter is present. Aggregation sharply increases with increases in soil carbon content from 0 to 2 percent or more. However, soil aggregation can also be easily destroyed by flooding or by compaction or working the soil when it is too wet.

Structure type refers to the particular kind of grouping that predominates in a soil horizon. Single-grained and massive soils are structureless. In these types of soils, such as sands, water percolates rapidly. Water moves slowly through most clay soils.

There are (in general) four primary types of structure, based upon shape and arrangement of aggregates; granular, blocky, columnar or prismatic, and platey. Figure 508–2 shows a diagram of each of these and also includes two additional aggregates, massive and granular, which are considered to be structureless.

The most favorable water relationships occur with soils that are columnar, blocky, or aggregated granular structures. Platey structure, in fine and medium soils, will impede downward movement of water.

Figure 508–2 Types of aggregates



Soil structure has an important influence on plant growth, primarily as it affects moisture relationships, aeration, heat transfer, and mechanical impedance of root growth. For example, good seedbed preparation is directly related to moisture and heat transfer. A fine granular structure is ideal in this respect. The movement of water and air through the soil is dependent on porosity, which is highly influenced by structure. Good granular structure provides adequate porosity for moisture infiltration (and air exchange). However, where surface crusting or subsurface claypans or hardpans exist, plant growth is hindered because of restricted porosity.

Structure can be improved with proper cultural practices, such as reducing tillage, improving internal drainage, cover crops, liming or adding sulfur to soil, using grasses, or deep rooted crops in rotation, incorporating crop residue, and adding organic material or soil amendments. Structure can easily be destroyed by heavy tillage equipment or excess operations.

(a) Soil bulk density

Bulk density is the weight per unit volume of dry soil, which includes the volume of solids and pore space. Units are expressed as the weight at oven-dry and volume at field capacity water content, expressed as grams per cubic centimeter (g/cc) or pounds per cubic foot (lb/ft^3). Bulk density is used to convert water measurements from a weight basis to a volume basis. Other factors affecting soil bulk density include freeze/thaw process, plant root growth and decay, wormholes, and organic matter.

(b) Soil tilth

Simply defined, tilth refers to the physical condition of the soil in its relation to plant growth.

Tilth not only depends on granulation and its stability, but also on moisture content, degree of aeration, rate of water infiltration, drainage, and capillary-water capacity. Tilth can change often and markedly. For example, working properties of fine texture soils may be altered by a slight change in moisture. One of the objectives of cultivation is to encourage and maintain good tilth. However, when improperly administered tillage operations may seriously impair tilth directly or set the stage for later deterioration especially in the upper furrow slice.

(c) Organic matter

Soil organic matter (SOM) is the organic fraction of the soil. It consists of plant and animal residues in various stages of decomposition, living soil organism, and substances synthesized by these organisms.

Practically every soil property is affected by soil organic matter. Organic matter beneficially influences soil structure, soil condition, soil bulk density, water infiltration, plant growth and root development, permeability, total water holding capacity, biological activity, oxygen availability, nutrient availability, and tilth, as well as many other factors that make the soil a healthy natural resource for plant growth.

Soils in the western part of the United States vary considerably in organic matter content from region to region. Since the western climate is predominantly semi arid, the average organic matter content is quite low, usually less than 2.0 percent. Soil organic matter content in the higher rainfall areas may range upwards to 10 to 15 percent. In some areas of the United States, where soils contain centuries old accumulations of aquatic vegetation, reeds and sedges, may be predominantly organic soils (peats and mucks).

The amount of organic matter that may accumulate in the soil depends upon temperature, moisture, aeration, soil pH, microbial population and the quantity and chemical make-up of the plant residues returned to the soil.

The chemical composition of SOM is categorized into three major groups: polysaccharides, lignins, and proteins. The polysaccharides include cellulose, hemicelluloses, sugars, and starches and pectic substances. Lignins are derived from woody tissues of plants. Proteins are the principal nitrogen-containing constituents of organic matter and exist in all life forms. These three classes of materials are sources of food for soil micro-organisms.

Residues are decomposed in the soil by living organisms, primarily bacteria, fungi, and actinomycetes. Each of these groups of organisms is important at various stages of decomposition. These and larger organisms, such as earthworms and insects, ingest residues and soil, thereby binding together soil particles into stable aggregates.

Soil microbes require nutrients just as plants do. In the process of breaking down an introduced supply of residues, microbes will populate quickly and rob (tie up) the soil of available nitrogen. This will temporarily reduce plant growth if the soil supply of nitrogen is not sufficient to take care of the needs of both the microbes and growing plants. By applying nitrogen fertilizer, both the growing crop and soil organisms can have a plentiful supply to meet their needs.

The dark-colored organic residue, typically found nearer the soil surface, is called humus. Humus increases friability of soils, improves tilth, and facilitates aeration and water infiltration.

(d) Soil depth

Soil depth is the dimension from the soil surface to bedrock, hardpan, or water table; to a specified soil depth; or to a root growth restrictive layer. The depth from the soil surface to bedrock influences the soil's potential for plant growth and agronomic practices. The deeper the soil the more total soil-water storage is available for plant use. Crop rooting depth and the resulting total AWC control the length of time plants can go between rainfall events before reaching moisture stress. A shallow depth to bedrock results in a lower available water capacity and thus drier conditions for plants. Equipment induced compaction layers or naturally-occurring impervious layers restrict the downward movement of water and root penetration.

An abrupt change in soil texture with depth can restrict downward water movement. For example, coarse sand underlying medium or fine textured soil requires saturation at the textural interface before substantial amounts of water will move into the coarser soil below. When a coarse textured soil abruptly changes to a medium or fine textured soil, a temporary perched water table develops above the less permeable soil. Stratified soils or shallow soils over hardpans or bedrock can also hold excess gravitational water at their interface. The excess water can move upward because of the increased soil particle surface tension as the soil water in the upper profile is used by plants or capillary action resulting from surface evaporation. Thus, an otherwise shallow soil with low total AWC can have characteristics of a deeper soil.

The depth of a soil also has implications pertaining to salinity. High levels of salinity in the lower portion of a root zone has lesser influence on yield since crops can compensate for reduced uptake of water from a zone of highly salinity by increasing uptake from a zone low in salinity. Therefore, the deeper the soil, the greater the capacity to store salt with minimal yield reduction.

Root restrictive layers

Some soils have layers that roots and water cannot easily penetrate. Physical root restriction may be expected in hard or soft bedrock and some soil layers, such as fragipan or cemented hardpan. Intensive management may be required to reduce the effects of poor rooting depth, a high water table, and lower available water capacity.

Some restrictive layers, such as a cemented hardpan, are ripped with deep tillage to improve root and water penetration.

(e) Water tables

Water tables can be a barrier for root development because of restricted oxygen availability. Most crops grow best where the water table is greater than six feet below the soil surface. Adequate soil drainage must be present for sustained growth of most plants. Additionally, when ground water is saline, upward movement and its subsequent evaporation at the surface of the soil adds to the salinization of soils. Providing artificial drainage for poorly drained soils (see the provisions of the 1985/1990 Food Security Act for cropland soils considered “hydric” when considering artificial drainage) and for soils with high concentrations of salt increases the soil depth for potential root development.

In other situations, where water tables are not a barrier to root development, planned water table control and management of shallow ground water can supply all or part of the seasonal crop water needs. The water must be high quality, salt free, and held at or near a constant elevation. The water table level should be controlled to provide water according to crop needs.

(f) Chemical properties

The physical and chemical weathering of materials on the Earth’s surface forms soil. These materials may have been rock or they may have materials that transported from elsewhere and deposited over rock. Exposure of the surface to water, oxygen, organic matter, and carbon dioxide brings about chemical alterations to the material. Oxidation, reduction, hydration, hydrolysis, and carbonation contribute to chemical and physical changes in the surface material. If it is rock, the material gradually breaks down into smaller particles, forming a mineral soil. If it is a transported material, such as glacial till or loess, weathering can affect soil chemistry and mineralogy. The chemical and mineralogical composition of the soil varies with respect to depth or horizon. Weathering intensity decreases with depth from the surface. The longer the weathering has proceeded, the thicker the weathered layer and the greater the dissimilarity from the original material. In mineral soils, organic matter content generally decreases with depth.

Major elements

Eight chemical elements comprise the majority of the mineral matter in soils. Of these eight elements, oxygen, a negatively-charged ion (anion) in crystal structures, is the most prevalent on both a weight and volume basis. The next most common elements, all positively-charged ions (cations), in decreasing order are silicon, aluminum, iron, magnesium, calcium, sodium, and potassium. Ions of these elements combine in various ratios to form different minerals. More than 80 other elements also occur in soils and the Earth's crust, but in much smaller quantities.

Soils are chemically different from the rocks and minerals from which they are formed in that soils contain less of the water soluble weathering products, calcium, magnesium, sodium, and potassium, and more of the relatively insoluble elements such as iron and aluminum. Old, highly weathered soils normally have high concentrations of aluminum and iron oxides.

The organic fraction of a soil, although usually representing much less than 10 percent of the soil mass by weight, has a great influence on soil chemical properties. Soil organic matter is composed chiefly of carbon, hydrogen, oxygen, nitrogen and smaller quantities of sulfur and other elements. The organic fraction serves as a reservoir for the plant essential nutrients, nitrogen, phosphorus, and sulfur, increases soil water holding and cation exchange capacities, and enhances soil aggregation and structure.

The most chemically active fraction of soils consists of colloidal clays and organic matter. Colloidal particles are so small (< 0.0002 mm) that they remain suspended in water and exhibit a very large surface area per unit weight. These materials also generally exhibit net negative charge and high adsorptive capacity.

Microbiological activity is greatest near the surface where oxygen, organic matter content, and temperature are the highest.

Cation exchange capacity (CEC)
Clays and organic matter typically possess net negative charge. Positively-charged cations are attracted to these negatively-charged particles, just as opposite poles of magnets attract one another. Cation exchange is the ability of soil clays and organic matter to adsorb and exchange cations with those in soil solution (water in soil pore space). A dynamic equilibrium exists between adsorbed cations and those in soil solution. Cation adsorption is reversible if other cations in soil solution are sufficiently concentrated to displace those attracted to the negative charge on clay and organic matter surfaces. The quantity of cation exchange is measured per unit of soil weight and is termed cation exchange capacity. Organic colloids exhibit much greater cation exchange capacity than clays. Various clays also exhibit different exchange capacities. Thus, cation exchange capacity of soils is dependent upon both organic matter content and content and type of clays.

Cation exchange capacity is an important phenomenon for two reasons:

- exchangeable cations such as calcium, magnesium, and potassium are readily available for plant uptake
- cations adsorbed to exchange sites are more resistant to leaching, or downward movement in soils with water

Movement of cations below the rooting depth of plants is associated with weathering of soils. Greater cation exchange capacities help decrease these losses. Pesticides or organics with positively charged functional groups are also attracted to cation exchange sites and may be removed from the soil solution, making them less subject to loss and potential pollution.

Calcium (Ca^{++}) is normally the predominant exchangeable cation in soils, even in acid, weathered soils. In highly weathered soils, aluminum (Al^{+3}) may become the dominant exchangeable cation.

The energy of retention of cations on negatively charged exchange sites varies with the particular cation. The order of retention is: aluminum > calcium > magnesium > potassium > sodium > hydrogen. Cations with increasing positive charge and decreasing hydrated size are most tightly held. Calcium ions, for example, can rather easily replace sodium ions from exchange sites. This difference in the replaceability is the basis for the application of gypsum ($CaSO_4$) to reclaim sodic soils.

The cations of calcium, magnesium, potassium, and sodium produce an alkaline reaction in water and are termed bases or basic cations. Aluminum and hydrogen ions produce acidity in water and are called acidic cations. The percentage of the cation exchange capacity occupied by basic cations is called percent base saturation. The greater the percent base saturation, the higher the soil pH.

Soil pH is a commonly measured soil chemical property and also one of the more informative. Soil pH implies certain characteristics that might be associated with a soil. Since pH (the negative log of the hydrogen ion activity in solution) is an inverse, or negative, function, soil pH decreases as hydrogen ion, or acidity, increases in soil solution. Soil pH increases as acidity decreases.

A soil pH of 7 is considered neutral. Soil pH values greater than 7 signify alkaline conditions, whereas those with values less than 7 indicate acidic conditions. Soil pH typically ranges from 4 to 8.5, but can be as low as 2 in materials associated with pyrite oxidation and acid mine drainage. In comparison, the pH of a typical cola soft drink is about 3.

Soil pH has a profound influence on plant growth. Soil pH affects the quantity, activity, and types of microorganisms in soils which in turn influence decomposition of crop residues, manures, sludges and other organics. It also affects other nutrient transformations and the solubility, or plant availability, of many plant essential nutrients. Phosphorus, for example, is most available in slightly acid to slightly alkaline soils, while all essential micronutrients, except molybdenum, become more available with decreasing pH. Aluminum, manganese, and even iron can become sufficiently soluble at pH < 5.5 to become toxic to plants. Bacteria which are important mediators of numerous nutrient transformation mechanisms in soils generally tend to be most active in slightly acid to alkaline conditions.

Electrical conductivity (EC) is commonly used to check the salt content of soils. EC measurements are used to monitor changes in the salt content of the soil in both dryland and irrigated cropping systems. It is also useful in evaluating the relative tolerance of plants to salt and the suitability of a soil for certain crops.

(g) Salt-affected soils

Salt-affected soils are unique in that they have variations in levels of salinity, different kinds of salts, differences in climatic patterns, and varying materials. Salts in the soil-water solution decrease the amount of water available for plant uptake. Salt-affected soils have been internationally classified into general categories:

- Saline Soils

  EC > 4 mmhos/cm at 25 °C
  SAR 0–13
  pH < 8.5
  ESP < 15

- Saline-sodic soils

  EC > 4 mmhos/cm at 25 °C
  SAR ≥ 13
  pH < 8.5
  ESP < 15

- Sodic Soils

  EC44 mmhos/cm at 25 °C
  SAR ≥13
  pH > 8.5
  ESP ≥ 15

Salt-affected soils are generally classified using electrical conductivity (ECe) of the soil-water extract corrected to 25 °C. Units are expressed in decisiemens per meter (dS/m) or millimhos per centimeter (mmhos/cm).

The adverse effects of salts in depressing plant growth are caused by at least one of three factors:

- Direct physical effects of salt in preventing soil water uptake by plant roots because of increased osmotic tension
- Direct chemical effects of salts in disrupting the nutritional and metabolic processes of plants
- The indirect effect of salt in altering soil structure, permeability, and aeration.

Suitability of a soil for cropping depends heavily on the soils ability to conduct water and air (permeability) and on physical properties of the seedbed (tilth). Saline soils generally have “normal” physical properties. However, in sodic soils, physiochemical reactions cause aggregates to slake and clay minerals to swell and disperse, leading to reduced permeability and poor tilth.

Salinity—The direct source of all salt constituents are the primary minerals found in soils and in the exposed rocks of the earth’s crust. Although weathering of the primary minerals is the indirect source of nearly all soluble salts, there are few instances where sufficient salts accumulated in place to form a saline soil. Saline soils usually occur in areas that receive salts from other locations, and water is the primary carrier.

Management techniques, which allow excess soil moisture to migrate beneath the rooting zone, create a saline shallow groundwater flow system that moves down gradient to a discharge area, where the salinized water evaporates, creating a saline seep. The most common land use creating saline seeps is a cropping system that involves summer fallow.

Because of the uniqueness of saline soils, onsite investigations are usually required to document actual conditions and gather supporting data for developing plans to resolve the salt problem. Once a seep has been identified, the next step is to locate the recharge area. The recharge area must be accurately determined if treatment is to be successful. When the recharge area is determined methods of controlling excess soil moisture must be implemented which typically includes establishing perennial deep-rooted species on a significant portion (~80%) of the recharge area. Treatment should continue until groundwater moisture has been removed, which may take between 10 to 15 years or longer. An intensive cropping system should then be applied to prevent the buildup of excess groundwater.

Sodicity—Dispersion, the release of individual clay platelets from aggregates, and slaking, the breakdown of larger aggregates in smaller aggregates, lodge in soil pore spaces, reducing permeability and decreasing porosity, which leads to soil crusting and poor tilth.

Adding gypsum to the soil surface or even to irrigation water can effectively avoid or even alleviate problems with reduced infiltration rate and seedling emergence (through crusted soil). A sulfur source can also be added to enhance acidification of the soil.

For soils already saturated with calcium (carbonate), the addition of gypsum or sulfur is ineffective in treating sodicity. Increasing organic matter levels by continuous cropping, residue management, establishing tolerant plant species and removing excess water is more sustainable.

Part 509 Data Management

Contents

Figures

Subpart 509A Introduction and responsibilities

509.00 Background

U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) agronomic data exists in both electronic and hard copy formats, and is maintained at many different locations by a large number of people. Efforts are currently underway to organize a database structure among those who maintain the data to facilitate data sharing and to ensure against duplication of effort in data collection. This data will eventually be stored on a server that will be accessible to NRCS and other potential non-agency and private users of the data.

Coordination is needed among all those in NRCS who manage, collect, and use data to share similar data sets that may apply to the use of one or more models used for resource assessment and planning in more than one state or region. This will reduce workloads and ensure data accuracy and integrity.

A large portion of the agronomic data used by NRCS is contained in data files developed for the implementation of various tools at the state and field office level, such as erosion prediction, nutrient management and pest management tools.

509.01 Responsibilities

The national agronomist is responsible for preparation of national policy and instructions pertaining to data management.

The national database manager, agronomist on the National Soil Survey Center (NSSC) staff, is responsible for developing and maintaining data for the implementation and application of wind and water erosion prediction models and soil quality models. This includes the national vegetation and operation databases used in these erosion prediction models. The NSSC agronomist is to work directly with the NRCS national wind and water erosion specialists for wind and water erosion to develop and maintain the databases used in these models. The NSSC agronomist provides national coordination, in cooperation with the national wind and water erosion specialists, for the development of climate zones, crop management zones, crop management templates, and assist in assigning dates of operations used in developing crop management templates for erosion prediction tools.

Revised Universal Soil Erosion version 2 (RUSLE2) and Wind Erosion Prediction System (WEPS) regional specialists at the National Technical Support Centers (NTSC) serve as the liaisons with other state agronomists and/or erosion specialists in their respective regions and with the NRCS national wind and water erosion specialists. They are responsible for maintaining consistency, both within their regions and between regions, in data used for erosion prediction tools.

The national nutrient management specialist is responsible for developing and maintaining databases for assisting States with implementation and application of nutrient management tools.

The national pest management specialist is responsible for developing and maintaining databases for assisting States with implementation and application of Integrated Pest Management tools.

At the State level, the appropriate State specialist (agronomist, nutrient/pest management specialist, or water quality specialist) is responsible for proper use of NRCS databases in field office applications. They are also responsible for identifying if different or additional types of data are needed at the field level.

Subpart 509B Database management

509.10 Databases for erosion prediction tools

(a) Crop and field operations databases

(1) A core set of plant and operation data records has been developed under the leadership of Agricultural Research Service (ARS). These data records serve as guides for developing additional plant data records. Additional data records will be added to include all plant types and field implements and operations needed by NRCS. Currently, a national set of databases for the RUSLE2 and WEPS 1.0 models, known as the NRCS Crop Database and the NRCS Operation Database, is maintained by the agency. These official NRCS databases are to be used by NRCS to provide technical assistance to our clients. The data records needed for the operations used and crops grown in the local area will be downloaded from the official databases for local use with the RUSLE2 and WEPS erosion models.

Efforts are currently underway to combine all the land operations, crop, climate, wind data into a Land Operations Management Database (LMOD) that will support the current and future erosion models and other resource assessment and planning models to simplify database management and duplication.

(2) The national database manager, the agronomist on the (NSSC) staff, is responsible for adding, modifying, and revising all parameter values in the Crop and Operation Databases. This should be done in consultation with the national wind and water erosion specialists. State agronomists or other state and local designated erosion specialists, in coordination with the NTSC regional contacts, can submit additions or revisions to the NRCS Crop or Operation databases to the national database manager. The database coordinator will coordinate the development of the record and issue it for peer review and eventual posting to the official NRCS database. All agronomists or designated erosion specialists will be notified when new records have been posted.

(b) Climate databases

(1) For RUSLE2, the average monthly temperature and precipitation from one designated climate station will be used to represent each Climatic Zone. Local climate data records will be developed using these temperature and precipitation values, but location-specific R factor and 10-year storm EI values will be used in that local climate record.

The national database coordinator will provide national coordination and assist the States in developing local climate records. Only official NRCS RUSLE2 Climate Databases are to be used by NRCS and those providing assistance on behalf of NRCS to our clients. The data records for the local area will be downloaded from the official NRCS Climate Database for use by NRCS.

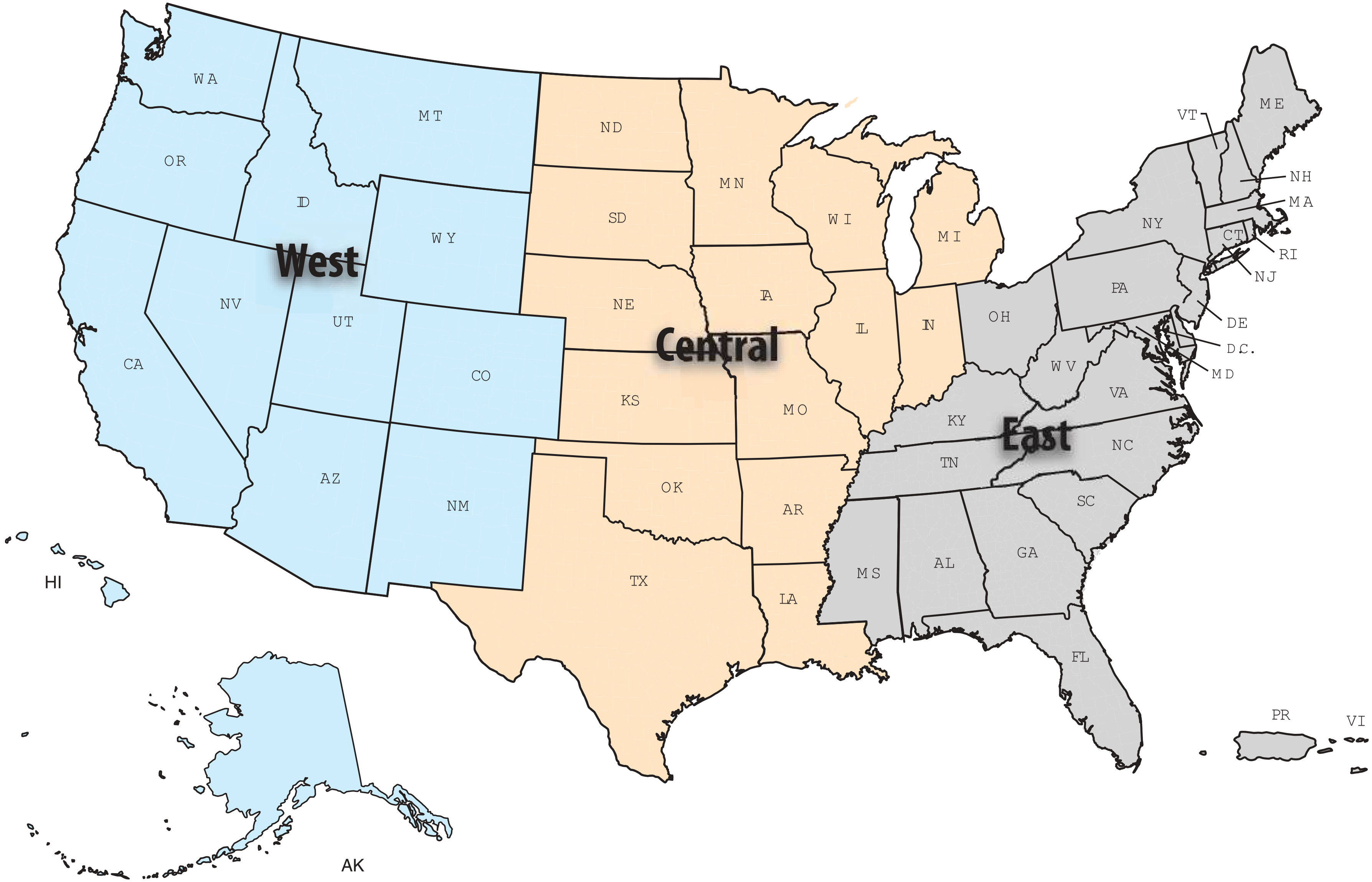
(2) For WEPS and other process based models, either simulated climate data (using WINDGEN and CLIGEN weather generators imbedded in the model) or actual climate data (stored in the model) will be used. Climate stations for the western states (see figure 1) have been designated and placed in a GIS shape file internal to the WEPS model to select the correct stations. The Central and Eastern states (fig. 1) will use the closest climate station location to run CLIGEN (temperature. and precipitation.) and an interpolated wind station from the three closest wind station locations for WINDGEN.

The Central and Eastern regional states will use a county wide station location based on the centroid of the county for Windgen. States have the option to further subdivide the county if needed with the help and concurrence of the national database manager and the appropriate national model specialist. An appropriate map will be developed and incorporated into the existing shape map in WEPS.

(c) Soil databases

A soil data download from the National Soils Information System (NASIS) will be created and placed on the field office computer in a Microsoft Access database in conjunction with the Customer Service Toolkit. The NASIS database will contain soil data to be used in that field office as inputs for RUSLE2 and WEPS 1.0. The soil database downloaded to each field office will be the official NRCS Soil Database and will be updated only as supported by agency policy.

Figure 509–1 NRCS Regional Map



509.11 Pesticide properties database

The pesticide properties database is used by the National Agricultural Pesticide risk Analysis (NAPRA) model and the Windows-Pesticide Screening Tool (WIN_PST). These environmental risk screening tools are used to predict the potential for pesticides to move with water and eroded soil/organic matter and affect non-target organisms.

The national pest management specialist will work with the Agricultural Research Service and representatives of companies that produce pesticides to keep this database current.

509.12 Plant nutrient content database

The plant nutrient content database contains estimates of the nitrogen, phosphorus, and potassium content in plant biomass for many agricultural crops. This information is useful to nutrient management planners who need estimates of plant nutrient content to develop nutrient management plans and nutrient budgets. It becomes particularly valuable when nutrient are applied in quantities that are a function of the nutrient content of plant biomass.

The plant nutrient database is currently included in the "Crop Nutrient Tool" on the USDA Plants Data Center website as the official database. This database may be added to the Land Operation Management Database (LMOD) in the future.

The national nutrient management specialist will work with the Agricultural Research Service and Land Grant Universities to update and expand this database.

Glossary

A factor — The computed longtime average annual soil loss carried by runoff from specific field slopes in specified cropping and management systems. It is expressed in the RUSLE2 model in tons/acre/year.

Abrasion — Breakdown of clods, crusts, and plant material by the impact of particles moved by wind in saltation. The impacting particles may also abrade. Abrasion causes soil aggregates to break down progressively as wind erosion continues.

Accelerated erosion — Erosion of soil resulting from disturbance of the natural landscape. It results largely from the consequences of human activity, such as tillage, grazing, and removal of vegetative cover.

Adsorption — The process by which atoms, molecules, or ions are taken up from the soil solution or soil atmosphere and retained on the surfaces of solids by chemical or physical binding.

Aggregate stability — The ability of a soil aggregate to resist various destructive forces, such as tillage, abrasion by wind or flowing water, or raindrop force.

Aggregation, soil — The cementing or binding together of primary soil particles (sand, silt, and clay) into a secondary unit, which unit contributes to the soil structure.

Agronomic rate — The rate at which fertilizers, organic wastes or other amendments can be added to soils for optimum plant growth.

Air-dry weight — Weight of a substance after it has been allowed to dry to equilibrium with the atmosphere.

Amendment — A substance added to the soil to improve plant growth, such as lime.

Allelopathy — Production of a substance by one organism that inhibits one or more other organisms.

Angle of deviation — The angle between prevailing wind erosion direction and a line perpendicular to: (1) the long side of the field or strip, when determining unsheltered distance using a wind erosion direction factor, or (2) row direction when determining effect of wind direction on the ridge roughness factor.

Available water holding capacity — The capacity of a soil to hold water in a form available to plants, usually expressed in inches of water per inch of soil depth. Commonly defined as the amount of water held between field capacity and wilting point.

Avalanching — The increase in rate of soil flow with distance downwind across an area being eroded by wind.

Biomass — The total mass of living organisms in a given volume or mass of soil, or in a particular environment.

Biochemical oxygen demand (BOD) — The amount of oxygen required by aerobic organisms to carry out oxidative metabolism in water containing organic matter, such as sewage. BOD is used as an indirect measure of the concentration of biologically degradable material present in organic wastes. Also known as Biological Oxygen Demand.

Bioremediation — The use of biological agents to reclaim soil and water polluted by substances hazardous to the environment or human health.

Buffer strip A narrow strip of grass or other close-growing vegetation that, when placed along the contour on a slope, traps sediment that was produced on the hillslope above.

Bulk density, soil The mass of dry soil per unit bulk volume. The value is expressed as Mg per cubic meter, Mg m^{-3}.

C factor—Water erosion Cover and management factor in RUSLE. It combines the effects of prior land use, crop canopy, surface cover, surface roughness, and soil moisture to predict a soil loss ratio for a crop or other vegetation, cropping period, or season.

C factor—Wind erosion Climatic factor in WEQ. It is an index of climatic erosivity, specifically wind speed and surface soil moisture. The factor for any given location is based on long-term climatic data and is expressed as a percentage of the C factor for Garden City, KS, which has been assigned a value of 100.

Calcareous soil Soil containing sufficient free calcium carbonate or magnesium carbonate to effervesce visibly when treated with cold 0.1 N hydrochloric acid. High content of lime (up to about 5 percent), particularly in the clay fraction, appreciably increases erodibility by wind.

Calcium carbonate equivalent The content of carbonate in a liming material or calcareous soil calculated as if all of the carbonate is in the form of CaCO3. See also lime, agricultural.

Canopy The vertical projection downward of the aerial portion of plants, usually expressed as percent of ground so occupied.

Carbon cycle The sequence of transformations whereby carbon dioxide is converted to organic forms by photosynthesis or chemosynthesis, recycled through the biosphere (with partial incorporation into sediments), and ultimately returned to its original state through respiration or combustion.

Carbon-nitrogen ratio The ratio of the mass of organic carbon to the mass of organic nitrogen in soil, organic material, plants, or microbial cells.

Cation exchange capacity (CEC) The sum of exchangeable bases plus total soil acidity at a specific pH values, usually 7.0 or 8.0. It is usually expressed in centimoles of charge per kilogram of exchanger (cmolckg-1) or millimoles of charge per kilogram of exchanger.

Classical gully erosion. Erosion caused by the action of runoff water in concentrated flow channels. These flow channels are well-defined, permanent drainageways that cannot be crossed by ordinary farming operations

Climatic erosivity The relative influence of climate on field erodibility by wind in different regions, specifically the effects of average wind speed and effective soil surface moisture.

Clod A compact, coherent mass of soil greater than 2 millimeters in equivalent diameter, often created by tillage or other mechanical disturbance of the soil.

Coarse fragments Rock or mineral particles greater than 2 millimeters in diameter.

Compost Organic residues, or a mixture of organic residues and soil, that have been mixed, piled, and moistened, with or without addition of fertilizer and lime, and generally allowed to undergo thermophilic decomposition until the original organic materials have been substantially altered or decomposed.

Contour farming The practice of using ridges and furrows left by tillage to redirect runoff from a path directly downslope to a path around the hillslope.

Cover crop Close-growing crop that provides soil protection, seeding protection and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When incorporated into the soil, cover crops may be referred to as green manure crops.

Critical wind erosion period Period of the year when the greatest amount of wind erosion can be expected to occur from a field under an identified management system. It is the period when the combination of vegetative cover, soil surface conditions, and expected erosive winds result in the greatest potential for wind erosion.

Crop residue management Maintaining stubble, stalks, and other crop residue on the soil surface or partially incorporated into the surface layer to reduce erosion, conserve soil moisture, and improve soil tilth.

Crop rotation A planned sequence of several different crops grown on the same land in successive years or seasons, done to replenish the soil, reduce insect, weed and disease populations, or to provide adequate feedstocks for livestock operations.

Crop tolerance to wind erosion Ability of crop plants to tolerate wind blown soil particles when in the seedling stage or exposure of plant roots where soil is eroded away, or burial of plants by drifting soil, or desiccation and twisting of plants by the wind.

Crust A thin surface layer, where aggregates are bound together and the surface is sealed. It is more compact and mechanically stable than the soil material immediately beneath it. Crust is characterized by its dense, platey structure that becomes less distinct with depth until it merges with the soil below. Crust is a transitory condition.

Deposition The accumulation of eroded soil material on the land surface when the velocity of the transporting agent (wind or water) is reduced.

Desert pavement A non-erodible soil surface devoid of erodible materials or consisting of gravel or stones left on the land surface. It occurs in desert regions as a result of the removal of fine materials by wind or water erosion. Desert pavement is virtually non-erodible.

Detachment The removal of transportable fragments of soil material from the soil mass by an eroding agent, usually falling raindrops, running water, wind, or windblown soil particles. Detachment is the process that makes soil particles or aggregates available for transport.

Drought year Any year when precipitation is less than 80 percent of the long-term normal.

Dry aggregate A compound or secondary air-dry soil particle that is not destroyed by dry sieving.

Dryland farming Crop production without irrigation (rainfed agriculture).

Dust storm A strong turbulent wind carrying large amounts of soil particles in suspension.

E tables Tables derived from computer solutions (WEROS) of the Wind Erosion Equation that display values of average annual wind erosion per acre (E) for various combinations of soil erodibility (I), ridge roughness (K), climate (C), unsheltered distance (L), and vegetative cover (V).

Effective precipitation That portion of the total rainfall precipitation which becomes available for plant growth.

Electrical conductivity (ECe) The electrical conductance of an extract from a soil saturated with distilled water, normally expressed in units of siemens or decisiemens per meter at 25 °C.

Ephemeral gully erosion Erosion that occurs from the action of runoff water which concentrates in shallow flow channels when rills converge. These flow channels are alternately filled with soil by tillage operations and re-formed in the same general location by subsequent runoff events.

Erodibility The susceptibility of soil to erode. Soils with low erodibility include fine textured soils high in clay that are resistant to detachment, and coarse textured soils high in sand that have low runoff. Soils having a high silt content are highly susceptible to erosion. The K factor in RUSLE expresses the erodibility of soil.

Erosive wind energy The capacity of winds above the threshold velocity to cause erosion. Erosive wind energy is a function of the cube of wind speed and the duration of erosive winds.

Erosive wind energy distribution The distribution of erosive wind energy over time at any geographic location.

Erosivity The energy (amount) and intensity of rainstorms that cause soil to erode. Erosivity includes the effects of raindrop impact on the soil and the amount and rate of runoff likely to be associated with the rain.

Evapotranspiration The combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants.

Eutrophication A process that increases the amount of nutrients, especially nitrogen and phosphorus, in a marine or aquatic ecosystem. Eutrophication occurs naturally over geological time but may be accelerated by human activities, such as waste disposal or land drainage, leading to an increase in algae and a decrease in diversity.

Fallow The practice of leaving land uncropped, either weed-free or with volunteer vegetation, during at least one period when a crop would normally be grown; done to control weeds, or accumulate water or available plant nutrients.

Fertility, soil The quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants or crops.

Fertilizer Any organic or inorganic material of natural or synthetic origin (other than liming materials) that is added to a soil to supply one or more plant nutrients essential to the growth of plants.

Fertilizer analysis The percent composition of a fertilizer as determined in a laboratory and expressed as total N, available phosphoric acid (P_2O_5) equivalent, and water-soluble potash (K_2O) equivalent.

Fibric organic soil materials The least decomposed of all the organic soil materials containing very high amounts of fiber that are well preserved and readily identifiable as to botanical origin.

Field capacity (Field water capacity) The content of water, on a mass or volume basis, remaining in a soil two to three days after being saturated with water, and from which free drainage is negligible.

Friable A term describing soils that when either wet or dry can be easily crumbled between the fingers.

Geologic erosion The wearing away of the Earth's surface by the forces of water and wind. Sometimes referred to as natural erosion, it is responsible for the natural topographic cycles, as it wears away higher points of elevation and constructs valleys and alluvial plains.

Green manure crop Any crop grown for soil improvement by being incorporated into the soil while green or soon after maturity.

Greenhouse effect The absorption of solar radiant energy by the Earth's surface and its release as heat into the atmosphere; longer infrared heat waves are absorbed by the air, principally by carbon dioxide and water vapor, thus, the atmosphere traps heat much as does the glass in a greenhouse.

Groundwater That portion of the water below the surface of the ground at a pressure equal to or greater than atmospheric. See also water table.

Hard seed Seed that is dormant due to a seed coat impervious to either water or oxygen.

Hemic organic soil materials Intermediate in degree of decomposition between the less decomposed fibric and the more decomposed sapric materials.

Hydrologic cycle The fate of water from the time of precipitation until the water has been returned to the atmosphere by evaporation and is again ready to be precipitated.

Hydroseeding Planting seed in a water mixture by pumping through a nozzle that sprays the mixture onto a seedbed. The water mixture may also contain addends such as fertilizer and mulches.

Inoculate To treat, usually seeds, with microorganisms to create a favorable response. Most often refers to the treatment of legume seeds with Rhizobium or Bradyrhizobium to stimulate dinitrogen fixation.

Isolated field A field where the rate of soil flow is zero at the windward edge of the field due to the presence of a stable border. An isolated field is not protected by barriers and is exposed to open wind velocities. The Wind Erosion Equation applies to conditions on an isolated field.

Isoline A line on a map or chart along which there is a constant value of a variable such as wind velocity or climatic erosivity.

K factor—Water Erosion Soil erodibility factor in RUSLE that quantifies the susceptibility of soil particles to detachment and movement by water. The K value is the soil-loss rate per erosion index unit for a specified soil as measured on a standard plot, which is defined as a 72.6-foot length of uniform 9 percent slope in continuous clean-tilled fallow.

K factor—Wind Erosion The soil roughness factor K, for WEQ. It is a measure of the effect of oriented roughness (ridges) and random roughness (cloddiness) on erosion. See Random Roughness and Ridge Roughness

Knoll An abrupt change in topography characterized by windward slope change greater than 3 percent and windward slope less than 500 feet long.

Knoll erodibility The increase in wind erosion potential resulting from the compression of wind flowlines and accompanying increased velocity over the crest of knolls. A knoll erodibility factor is used to adjust estimated erosion where these conditions occur.

Land capability The suitability of land for use without permanent damage. Land capability, as ordinarily used in the USA, is an expression of the effect of physical land conditions, including climate, on the total suitability for use, without damage, for crops that require regular tillage, for grazing, for woodland, and for wildlife. Land capability involves consideration of the risks of land damage from erosion and other causes and the difficulties in land use owing to physical land characteristics, including climate.

Land capability class One of the eight classes of land in the land capability classification of NRCS; distinguished according to the risk of land damage or the difficulty of land use; they include:

Land suitable for cultivation and other uses

- Class I—Soils that have few limitations restricting their use.
- Class II—Soils that have some limitations, reducing the choice of plants or requiring moderate conservation practices.
- Class III—Soils that have severe limitations that reduce the choice of plants or require special conservation practices, or both.
- Class IV—Soils that have very severe limitations that restrict the choice of plants, require very careful management or both.
- Class V—Soils that have little or no erosion hazard, but that have other limitations, impractical to remove, that limit their use largely to pasture, range, woodland, or wildlife food and cover.

Land generally not suitable for cultivation (without major treatment)

- Class VI—Soils that have severe limitations that make them generally unsuited for cultivation and limit their use largely to pasture or range, woodland, or wildlife food and cover.
- Class VII—Soils that have very severe limitations that make them unsuited to cultivation and that restricts their use largely to grazing, woodland, or wildlife.
- Class VIII—Soils and landforms that preclude their use for commercial plant production and restrict their use to recreation, wildlife, water supply, or aesthetic purposes

Leaching The removal of soluble materials from one zone in soil to another via water movement in the profile.

Liebig's Law The growth and reproduction of an organism is dependent on the nutrient substance that is available in minimum quantity.

Lime, agricultural A soil amendment containing calcium carbonate, magnesium carbonate and other materials, used to neutralize soil acidity and furnish calcium and magnesium for plant growth. Classification, including calcium carbonate equivalent and limits in lime particle size, is usually prescribed by law or regulation.

Loess soil Material transported and deposited by wind, consisting predominantly of silt-sized particles.

LS factor The RUSLE factor that accounts for the combined effects of length and steepness of slope on soil loss. The factor value represents the ratio of soil loss on a given slope length and steepness to soil loss from a slope that has a length of 72.6 feet and a steepness of 9 percent, where all other conditions are the same.

Management period A period of time during a cropping sequence when cover and management effects are approximately uniform or otherwise result in uniform rates of erosion during the period.

Mineral soil A soil composed mainly of, and having its properties determined by, mineral matter, with less than 20 percent organic matter. Compare Organic soil.

Mineralization The conversion of an element from an organic form to an inorganic state as a result of microbial activity.

Mulch Any material such as straw, sawdust, leaves, plastic film, loose soil, or similar material that is spread or formed upon the surface of the soil to protect the soil and/or plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc.

Mulch tillage Managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round, while growing crops where the entire field surface is tilled prior to planting.

Nitrogen cycle The continuous process by which nitrogen circulates among the air, soil, water, plants, and animals of the earth. Nitrogen in the atmosphere is converted by bacteria into forms that green plants can absorb from the soil; animals eat these plants (or eat other animals that feed on the plants); the animals and plants die and decay; the nitrogenous substances in the decomposed organic matter return to the atmosphere and the soil.

No-till/Strip till Managing the amount, orientation and distribution of crop and other plant residues on the soil surface year-round, while growing crops in narrow slots, or tilled or residue free strips in soil previously untilled by full-width inversion implement

Northwestern Wheat and Range Region (NWRR) Areas of non-irrigated cropland in the Pacific Northwest and mountainous regions of the west. It includes portions of eastern Washington, north central Oregon, northern and southeastern Idaho, western Montana, western Wyoming, northern Utah and northern California. Rainfall and erosion processes in this region are dominated by winter events.

Organic farming A crop production system that reduces, avoids or largely excludes the used of synthetically-produced fertilizers, pesticides, growth regulators and livestock feed additives.

Organic soil A soil that contains a high percentage (greater than 20 percent) of organic matter throughout the solum. Compare Mineral soil

Oven-dry weight The weight of a substance after it has been dried in an oven at 105 °C, to equilibrium.

P factor The support practice factor in RUSLE. It is a measure of the soil loss with a specific support practice to the corresponding loss with upslope and downslope tillage. On cultivated land, support practices considered in RUSLE include contouring, stripcropping, buffer strips, and terraces. These practices principally effect erosion by modifying the flow pattern, grade or direction of surface runoff and by reducing the amount and rate of runoff.

Permanent wilting point (Wilting coefficient) The largest water content of a soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber. Often estimated by the soil water content at –1.5 MPa (–15 bars) soil matric potential.

Permeability The ease with which water, air, or plant roots penetrate or pass through a soil horizon.

Precipitation-effectiveness (PE) index An index of the effectiveness of precipitation, calculated from mean monthly precipitation and mean monthly temperature at a specific geographical location. A modified P-E index is used to represent effective surface soil moisture in calculation of the WEQ climatic factor C.

Preponderance A ratio which expresses how much of the erosive wind energy occurs parallel to the prevailing wind erosion direction, as compared to the amount of erosive wind energy occurring perpendicular to the prevailing direction. A preponderance of 1.0 indicates that as much wind erosion force occurs perpendicular to the prevailing direction as occurs parallel to that direction. A higher preponderance indicates more of the force is parallel to the prevailing wind erosion direction.

Prevailing wind direction The direction from which winds most commonly occur. This may not be the same as the prevailing wind erosion direction.

Pure live seed Percentage of pure germinating seed: (pure seed percentage × germination percentage)/100.

Prevailing wind erosion direction The direction of erosive winds where there is potential for the greatest amount of soil to be moved, relative to the erosive force of winds from other directions.

R equivalent (Req) factor The factor used in place of the RUSLE R factor in the Northwestern Wheat and Range Region of the United States to measure the unique effects of melting snow, rain on snow, and/or rain on thawing soil. Much of this soil loss occurs by rilling when the surface part of the soil profile thaws and snowmelt or rain occurs on the still partially frozen soil.

R factor The rainfall and runoff factor in RUSLE that accounts for the energy and intensity of rainstorms. It is a measure of total storm energy times the maximum 30-minute intensity.

Random roughness The standard deviation of the soil surface elevations when changes because land slope or nonrandom (oriented) tillage marks are removed from consideration. Roughness ponds water in small localized depressions and reduces erosivity of raindrop impact and surface water flow.

Reference condition A standard wind tunnel condition for small grain equivalent determination where small grain stalks 10 inches long are lying flat on the soil surface in 10-inch rows which are perpendicular to the wind direction, with stalks oriented parallel to the wind direction.

Relative field erodibility An index of relative erodibility under field conditions. Wind tunnel erodibility is adjusted for the effect of unsheltered distance and of the resistance of soil textural classes to breakdown of surface crusts by abrasion and avalanching. Compared to the wind tunnel, erodibility of a field surface is greater because the longer unsheltered distance allows abrasion and avalanching to occur.

Ridge roughness The degree of oriented roughness determined by the height and width of ridges formed by tillage and planting implements. Ridges provide sheltered zones that trap moving soil particles.

Rill A small, intermittent water course with steep sides; usually only several centimeters deep.

Rhizobia Bacteria able to live symbiotically in roots of leguminous plants, from which they receive energy and often utilize molecular nitrogen. Collective common name for the genus Rhizobium.

Runoff That portion of precipitation or irrigation on an area which does not infiltrate, but instead is discharged from the area.

Revised Universal Soil Loss Equation version 2 (RUSLE2) An empirical model that predicts long-term average annual soil loss for a given set of climatic conditions, on a defined land slope, and under a specified cropping and tillage management system. RUSLE is an update of the USLE, and contains a computer program to facilitate calculations.

Saline seep Intermittent or continuous saline water discharge at or near the soil surface under dryland conditions that reduces or eliminates crop growth. It is differentiated from other saline soil conditions by recent and local origin, shallow water table, saturated root zone, and sensitivity to cropping systems and precipitation.

Saline soil A nonsodic soil containing sufficient soluble salt to adversely affect the growth of most crop plants. The lower limit of saturation extract electrical conductivity of such soils is conventionally set at 4 dS m-1 (at 25 °C). Actually, sensitive plants are affected at half this salinity and highly tolerant ones at about twice this salinity.

Saltation Soil movement in wind where particles skip or bounce along the soil surface in response to wind forces. Particles in the size range from 0.1 to 0.5 mm (0.004 to 0.02 in) usually move in this manner.

Salt-affected soil Soil that has been adversely modified for the growth of most crop plants by the presence of soluble salts, with or without high amounts of exchangeable sodium.

Salt tolerance The ability of plants to resist the adverse, nonspecific effects of excessive soluble salts in the rooting medium.

Sapric organic soil materials The most highly decomposed of the organic materials, having the highest bulk density, least amount of plant fiber, and lowest water content at saturation.

Seasonally variable K factor The average annual soil erodibility K factor value that has been adjusted to reflect the temporal variability associated with freezing and thawing or wetting and drying cycles during the year.

Sheet erosion A form of water erosion in which a very thin layer is removed from the soil surface by detachment and overland flow.

Small grain equivalent (SGe) The wind erosion control equivalent of vegetative cover, compared to a small grain standard. The standard (reference condition) is defined as small grain stalks 10 inches long lying flat on the soil surface in 10-inch rows which are perpendicular to the wind direction, with stalks oriented parallel to the wind direction. The small grain equivalent value is a function of kind, amount, and orientation of growing plants or plant residues on the soil surface.

Soil erodibility index (I) The potential soil loss, in tons per acre per year, from a wide, level, unsheltered, isolated field with a bare, smooth, loose, and non-crusted surface, under climatic conditions like those in the vicinity of Garden City, Kansas.

Soil loss tolerance (T) The average annual soil erosion rate (tons/acre/year) that can occur in a field with little or no long-term degradation of the soil resource thus permitting crop productivity to be sustained for an indefinite period of time.

Soil surface moisture Adsorbed water films surrounding surface soil particles that increase the soil resistance to erosion. In developing the climatic factor, soil surface moisture is assumed to be proportional to the Thornthwaite Precipitation-Effectiveness (P-E) Index.

Sorting Separation of various size classes of soil particles or aggregates during wind erosion. Soils tend to become coarser in response to continued sorting by erosion.

Sprigging Vegetative establishment of herbaceous species using stolons, rhizomes, or tillers with soil. Vegetative material may be broadcast and then lightly covered with soil, or planted using a sprigging implement.

Stable border A stable border defines the upwind boundary of an isolated field. It is an area with sufficient protection to prevent saltation from starting, and capable of trapping and holding incoming saltation from eroding areas upwind, thus preventing saltating soil particles from entering areas downwind.

Stripcropping The practice of growing two or more crops in alternating strips along contours to control erosion.

Surface armor A layer of coarse fragments or other non-erodible particles resistant to abrasion that remain on the soil surface after the removal of fine particles by erosion.

Surface creep Soil movement by wind in which the coarser fractions are transported by rolling and sliding along the ground surface, primarily by the impact of particles in saltation rather than by direct force of the wind. Particles greater than 0.5 mm (0.02 in) in size are usually moved in this manner.

Suspension Soil movement in wind whereby the finer fractions are transported over long distances floating in the windstream. Suspension is usually initiated by the impact of saltating particles. Particles moving in this manner are usually less than 0.1 mm (0.004 in) in size. Many suspension-size particles are created by abrasion during erosion.

Threshold velocity The minimum velocity at which wind will begin moving soil particles from a smooth, bare, non-crusted surface. The threshold velocity is usually considered to be 13 mph at 1 foot above the soil surface, or 18 mph at 30 feet height.

Tillage, Conventional Primary and secondary tillage operations normally performed in preparing a seedbed and/or cultivating for a given crop grown in a given geographical area, usually resulting in little or no crop residues remaining on the surface after completion of the tillage sequence.

Inversion Reversal of vertical order of occurrence of layers of soil, or of the soil within a layer.

Non-inversion Tillage that does not mix (or minimizes the mixing of) soil horizons or does not vertically mix soil within a horizon.

Subsoiling Any treatment to non-inversively loosen soil below the Ap horizon with a minimum of vertical mixing of the soil. Any treatment to fracture and/or shatter soil with narrow tools below the depth of normal tillage without inversion and with a minimum mixing of the soil. This loosening is usually performed by lifting action or other displacement of soil dry enough so that shattering occurs.

Tilth The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

Total Maximum Daily Load (TMDL) The maximum quantity of a particular water pollutant that can be discharged into a body of water without violating a water quality standard.

Transport The movement of detached soil material across the land surface or through the air by wind or running water. Transport of soil particles in wind is by three modes: (l) saltation, (2) suspension, and (3) surface creep.

Transport capacity The maximum amount of soil material that can be carried by wind or running water under given conditions.

Trap strip A strip of grass or other erosion-resisting vegetation, planted between cultivated strips or fields and having sufficient width, height, and density to trap and store incoming saltation. Trap strips are usually not tall enough to create significant barrier effects.

Unit plot A standard plot used to experimentally determine factor values in USLE and RUSLE. It is arbitrarily defined as being 72.6 feet long, with a uniform slope of 9 percent, in continuous fallow, tilled up and down the slope.

Unsheltered distance The distance across an erodible field, measured along the prevailing wind erosion direction, beginning at a stable border on the upwind side and continuing downwind to a non-erodible or stable area, or to the downwind edge of the area being evaluated.

Unsheltered field A field or portion of a field characterized by the absence of windbreaks or barriers and fully exposed to open wind velocity.

Universal Soil Loss Equation (USLE) An empirical model that predicts long-term average annual soil loss for a given set of climatic conditions, on a defined land slope, and under a specified cropping and tillage management system.

Vegetative wind barrier Narrow strips of annual or perennial vegetation planted at intervals across fields for wind erosion control, snow management, or protection of sensitive crops. Barriers have sufficient height and density to create a sheltered zone downwind. In the protected zone, wind velocities are reduced enough to prevent saltation from beginning. Vegetative barriers may also trap incoming saltation, but this is a secondary function.

Water erosion The detachment, transport, and deposition of soil particles by rainfall and runoff.

Water table The upper surface of ground water or that level in the ground where the water is at atmospheric pressure.

Wide field Any field with sufficient width to allow the rate of soil flow to reach the maximum that an erosive wind can sustain. This distance is the same for any erosive wind. It varies only and inversely with erodibility of the field surface. That is, the more erodible the surface, the shorter the distance in which maximum flow is reached.

Windbreak A living barrier of trees or combination of trees and shrubs designed to reduce wind erosion, conserve energy or moisture, control snow deposition, or provide shelter for livestock or wildlife. When used to control wind erosion, windbreaks deflect wind forces and reduce wind velocity in the downwind sheltered zone below the threshold required for initiation of soil movement.

Wind erodibility group A grouping of soils that have similar properties affecting their resistance to wind erosion.

Wind erosion The detachment, transport, and deposition of soil by wind.

Wind erosion direction factor A numerical factor used to calculate the equivalent unsheltered distance. The factor accounts for field shape (length/width ratio), field width, preponderance, and angle of deviation of the prevailing wind erosion direction from a line perpendicular to the long side of the field or strip.

Wind erosion equation (WEQ) An equation used to estimate wind erosion and design wind erosion control systems. E=(IKCLV) where E is the average annual soil loss expressed in tons per acre per year; I is the soil erodibility; K is the soil ridge roughness factor; C is the climatic factor; L is the equivalent unsheltered distance across the field along the prevailing wind erosion direction; and V is the equivalent vegetative cover.

Wind stripcropping A method of farming whereby erosion-resistant crop strips are alternated with strips of erosion-susceptible crops or fallow. Erosion-resistant strips reduce or eliminate saltation and act as soil traps designed to reduce soil avalanching. Strips are perpendicular or nearly so to the direction of erosive winds.

Wind tunnel A duct in which experimental situations are created and tested by exposure to air streams under controlled conditions. Both laboratory and portable field wind tunnels are used in wind erosion research.

Yield The amount of a specified substance produced (e.g., grain, straw, total dry matter) per unit area.