



NUTRIENT CYCLING IN PASTURES

LIVESTOCK SYSTEMS GUIDE

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Abstract: Good pasture management practices foster effective use and recycling of nutrients. Nutrient cycles important in pasture systems are the water, carbon, nitrogen, and phosphorus cycles. This publication provides basic descriptions of these cycles, and presents guidelines for managing pastures to enhance nutrient cycling efficiency — with the goal of optimizing forage and livestock growth, soil health, and water quality. Includes 19 Tables and 14 Figures.

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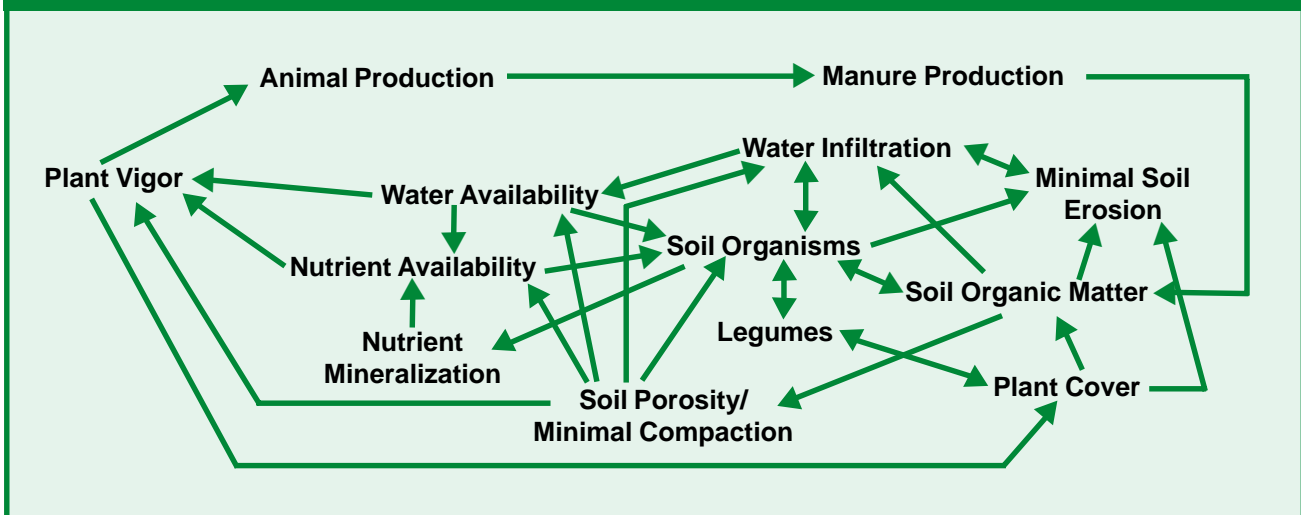
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Introduction and Summary

As a pasture manager, what factors do you look at as indicators of high production and maximum profitability? You probably look at the population of animals stocked within the pasture. You probably look at the vigor of plant regrowth. You probably also look at the diversity of plant species growing in the pasture and whether the plants are being grazed uniformly. But do you know how much water seeps into your soil or how much runs off the land into gullies or streams? Do you monitor how efficiently your plants are taking in carbon and forming new leaves, stems, and roots through photosynthesis? Do you know how effectively nitrogen and phosphorus are being used, cycled, and conserved on your farm? Are most of these nutrients being used for plant and animal growth? Or are they being leached into the groundwater or transported through runoff or erosion into lakes, rivers, and streams? Do you know how to change your pasture management practices to decrease these losses and increase the availability of nutrients to your forages and animals?

Figure 1. Nutrient Cycles in Pastures.



Healthy plant growth provides plant cover over the entire pasture. Cover from growing plants and plant residues protects the soil against erosion while returning organic matter to the soil. Organic matter provides food for soil organisms that mineralize nutrients from these materials and produce gels and other substances that enhance water infiltration and the capacity of soil to hold water and nutrients.

Effective use and cycling of nutrients is critical for pasture productivity. As indicated in [Figure 1](#) above, nutrient cycles are complex and interrelated. This document is designed to help you understand the unique components of water, carbon, nitrogen, and phosphorus cycles and how these cycles interact with one another. This information will help you to monitor your pastures for breakdowns in nutrient cycling processes, and identify and implement pasture management practices to optimize the efficiency of nutrient cycling.

WATER

Water is necessary for plant growth, for dissolving and transporting plant nutrients, and for the survival of soil organisms. Water can also be a destructive force, causing soil compaction, nutrient leaching, runoff, and erosion. Management

practices that facilitate water movement into the soil and build the soil's water holding capacity will conserve water for plant growth and groundwater recharge, while minimizing water's potential to cause nutrient losses. Water-conserving pasture management practices include:

- Minimizing soil compaction by not overgrazing pastures or using paddocks that have wet or saturated soils
- Maintaining a complete cover of forages and residues over all paddocks by not overgrazing pastures and by implementing practices that encourage animal movement across each paddock
- Ensuring that forage plants include a diversity of grass and legume species with a variety of root systems capable of obtaining water and nutrients throughout the soil profile

CARBON

Carbon is transformed from carbon dioxide into plant cell material through photosynthesis. It is the basic structural material for all cell life, and following the death and decomposition of cells it provides humus and other organic components that enhance soil quality. Plant nutrients such as nitrogen and phosphorus are chemically bound to carbon in organic materials. For these nutrients to become available for plant use, soil organisms need to break down the chemical bonds in a process called *mineralization*. If the amount of carbon compared to other nutrients is very high, more bonds will need to be broken and nutrient release will be slow. If the amount of carbon compared to other nutrients is low, fewer bonds will need to be broken and nutrient release will proceed relatively rapidly. Rapid nutrient release is preferred when plants are growing and are able to use the nutrients released. Slower nutrient release is preferred when plants are not actively growing (as in the fall or winter) or if the amount of nutrients in the soil is already in excess of what plants can use. Pasture management practices that favor effective carbon use and cycling include:

- Maintaining a diversity of forage plants with a variety of leaf shapes and orientations (to enhance photosynthesis) and a variety of root growth habits (to enhance nutrient uptake). A diversity of forages will provide a balanced diet for grazing animals and a variety of food sources for soil organisms
- Promoting healthy regrowth of forages by including a combination of grasses with both low and elevated growing points, and by moving grazing animals frequently enough to minimize the removal of growing points
- Maintaining a complete cover of forages and residues over all paddocks to hold soil nutrients against runoff and leaching losses and ensure a continuous turnover of organic residues

NITROGEN

Nitrogen is a central component of cell proteins and is used for seed production. It exists in several chemical forms and various microorganisms are involved in its transformations. Legumes, in association with specialized bacteria

called rhizobia, are able to transform atmospheric nitrogen into a form available for plant use. Nitrogen in dead organic materials becomes available to plants through mineralization. Nitrogen can be lost from the pasture system through the physical processes of leaching, runoff, and erosion; the chemical process of volatilization; the biological process of denitrification; and through burning of plant residues. Since it is needed in high concentration for forage production and can be lost through a number of pathways, nitrogen is often the limiting factor in forage and crop production. Productive pasture management practices enhance the fixation and conservation of nitrogen while minimizing the potential for nitrogen losses. Practices that favor effective nitrogen use and cycling in pastures include:

- Maintaining stable or increasing percentages of legumes by not overgrazing pastures and by minimizing nitrogen applications, especially in the spring
- Protecting microbial communities involved in organic matter mineralization by minimizing practices that promote soil compaction and soil disturbance, such as grazing of wet soils and tillage
- Incorporating manure and nitrogen fertilizers into the soil, and never applying these materials to saturated, snow-covered, or frozen soils
- Avoiding pasture burning. If burning is required, it should be done very infrequently and by using a slow fire under controlled conditions
- Applying fertilizers and manure according to a comprehensive nutrient management plan

PHOSPHORUS

Phosphorus is used for energy transformations within cells and is essential for plant growth. It is often the second-most-limiting mineral nutrient to plant production, not only because it is critical for plant growth, but also because chemical bonds on soil particles hold the majority of phosphorus in forms not available for plant uptake. Phosphorus is also the major nutrient needed to stimulate the growth of algae in lakes and streams. Consequently, the inadvertent fertilization of these waterways with runoff water from fields and streams can cause

degradation of water quality for drinking, recreational, or wildlife habitat uses. Regulations on the use of phosphorus-containing materials are becoming more widespread as society becomes increasingly aware of the impacts agricultural practices can have on water quality. Pasture management practices must balance the need to ensure sufficient availability of phosphorus for plant growth with the need to minimize movement of phosphorus from fields to streams. Pasture management practices that protect this balance include:

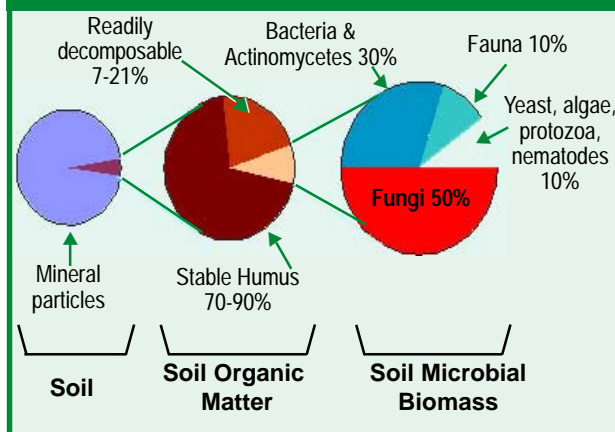
- Minimizing the potential for compaction while providing organic inputs to enhance activities of soil organisms and phosphorus mineralization
- Incorporating manure and phosphorus fertilizers into the soil and never applying these materials to saturated, snow-covered, or frozen soils
- Relying on soil tests, phosphorus index guidelines, and other nutrient management practices when applying fertilizers and manure to pastures

SOIL LIFE

Soil is a matrix of pore spaces filled with water and air, minerals, and organic matter. Although comprising only 1 to 6% of the soil, living and decomposed organisms are certainly of the essence. They provide plant nutrients, create soil structure, hold water, and mediate nutrient transformations. Soil organic matter is composed of three components: stable humus, readily decomposable materials, and living organisms — also described as the very dead, the dead, and the living components of soil (1).

Living organisms in soil include larger fauna such as moles and prairie dogs, macroorganisms such as insects and earthworms, and microorganisms including fungi, bacteria, yeasts, algae, protozoa, and nematodes. These *living* organisms break down the *readily decomposable* plant and animal material into nutrients, which are then available for plant uptake. Organic matter residues from this decomposition process are subsequently broken down by other organisms until all that remains are complex compounds resistant to decomposition. These complex end products of decomposition are known as *humus*.

Figure 2. Components of Soil Organic Matter.



Soil contains 1-6% organic matter. Organic matter contains 3-9% active microorganisms. These organisms include plant life, bacteria and actinomycetes, fungi, yeasts, algae, protozoa, and nematodes.

Humus, along with fungal threads, bacterial gels, and earthworm feces, forms glues that hold soil particles together in *aggregates*. These constitute soil structure, enhance soil porosity, and allow water, air, and nutrients to flow through the soil. These residues of soil organisms also enhance the soil's nutrient and water holding capacity. Lichens, algae, fungi, and bacteria form biological crusts over the soil surface. These crusts are important, especially in arid rangelands, for enhancing water infiltration and providing nitrogen fixation (2). Maintaining a substantial population of legumes in the pasture also ensures biological nitrogen fixation by bacteria associated with legume roots.

Effective nutrient cycling in the soil is highly dependent on an active and diverse community of soil organisms. Management practices that maintain the pasture soil as a habitat favorable for soil organisms include:

- Maintaining a diversity of forages, which promotes a diverse population of soil organisms by providing them with a varied diet
- Adding organic matter, such as forage residues and manure, to the soil to provide food for soil organisms and facilitate the formation of aggregates
- Preventing soil compaction and soil saturation, and avoiding the addition of amendments that might kill certain populations of soil organisms

Publication Overview

This publication is divided into five chapters:

1. *Nutrient cycle components, interactions, and transformations*
2. *Nutrient availability in pastures*
3. *Nutrient distribution and movement in pastures*
4. *The soil food web and pasture soil quality*
5. *Pasture management and water quality*

The first chapter provides an overview of nutrient cycles critical to plant production and water-quality protection: the water, carbon, nitrogen, phosphorus, and secondary-nutrient cycles. The components of each cycle are explained, with emphasis on how these components are affected by pasture management practices. The description of each cycle concludes with a summary of pasture management practices to enhance efficient cycling of that nutrient.

The second chapter focuses on the effects of soil chemistry, mineralogy, and land-management practices on nutrient cycle transformations and nutrient availability. Management impacts discussed include soil compaction, organic matter additions and losses, effects on soil pH, and consequences of the method and timing of nutrient additions. The chapter concludes with a summary of pasture management practices for enhancing nutrient availability in pastures.

The third chapter discusses nutrient balances in grazed pastures and the availability of manure, residue, and fertilizer nutrients to forage growth. Factors affecting nutrient availability include nutrient content and consistency of manure; manure distribution as affected by paddock location and layout; and forage diversity. These factors, in turn, affect grazing intensity and pasture regrowth. A graph at the end of the chapter illustrates the interactions among these factors.

The fourth chapter describes the diversity of organisms involved in decomposing plant residues and manure in pastures, and discusses the impact of soil biological activity on nutrient cycles and forage production. The impacts of pasture management on the activity of soil organisms are explained. A soil health card developed for pastures provides a tool for qualitatively assessing the soil's ability to support healthy populations of soil organisms.

The publication concludes with a discussion of pasture management practices and their effects on water quality, soil erosion, water runoff, and water infiltration. Several topical water concerns are discussed: phosphorus runoff and eutrophication, nutrient and pathogen transport through subsurface drains, buffer management, and riparian grazing practices. A guide for assessing potential water-quality impacts from pasture-management practices concludes this final chapter.



Chapter 1

Nutrient Cycle Components, Interactions, and Transformations

The water, carbon, nitrogen, phosphorus, and sulfur cycles are the most important nutrient cycles operating in pasture systems. Each cycle has its complex set of interactions and transformations as well as interactions with the other cycles. The water cycle is essential for photosynthesis and the transport of nutrients to plant roots and through plant stems. It also facilitates nutrient loss through leaching, runoff, and erosion. The carbon cycle forms the basis for cell formation and soil quality. It begins with photosynthesis and includes respiration, mineralization, immobilization, and humus formation. Atmospheric nitrogen is fixed into plant-available nitrate by one type of bacteria, converted from ammonia to nitrate by another set of bacteria, and released back to the atmosphere by yet another group. A variety of soil organisms are involved in decomposition processes that release or mineralize nitrogen, phosphorus, sulfur, and other nutrients from plant residues and manure. Balances in the amount of these nutrients within organic materials, along with temperature and moisture conditions, determine which organisms are involved in the decomposition process and the rate at which it proceeds.

Pasture management practices influence the interactions and transformations occurring within nutrient cycles. The efficiency of these cycles, in turn, influences the productivity of forage growth and the productivity of animals feeding on the forage. This chapter examines each of these cycles in detail and provides management guidelines for enhancing their efficiency.

WATER CYCLE

Water is critical for pasture productivity. It dissolves soil nutrients and moves them to plant roots. Inside plants, water and the dissolved nutrients support cell growth and photosynthesis. In the soil, water supports the growth and reproduction of insects and microorganisms that decompose organic matter. Water also can degrade pastures through runoff, erosion, and leaching, which cause nutrient loss and water pollution. Productive pastures are able to absorb and use water effectively for plant growth. Good pasture management practices promote water absorption by maintaining forage cover over the entire soil surface and by minimizing soil compaction by animals or equipment.

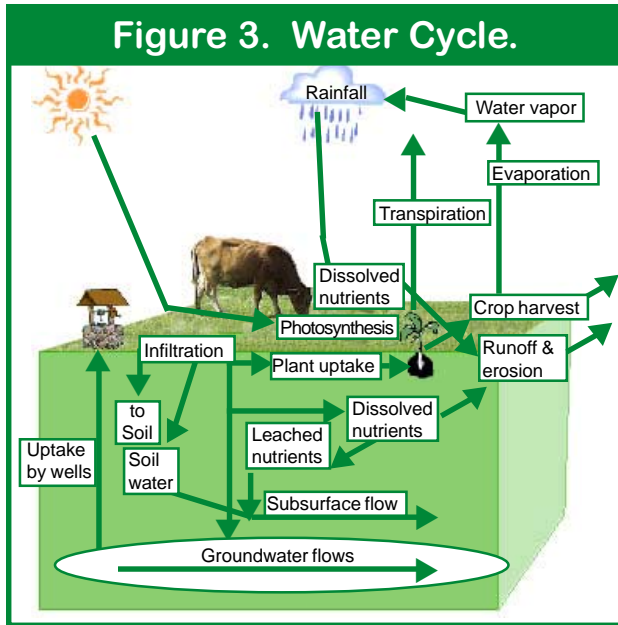
A forage cover over the entire paddock promotes water infiltration and minimizes soil compaction.

Geology, soil type, and landscape orientation affect water absorption by soils and water movement through soils. Sloping land encourages water runoff and erosion; depressions and footslopes are often wet since water from upslope collects in these areas. Clay soils absorb water and nutrients, but since clay particles are very

small, these soils can easily become compacted. Sandy soils are porous and allow water to enter easily, but do not hold water and nutrients against leaching. Organic matter in soil absorbs water and nutrients, reduces soil compaction, and increases soil porosity. A relatively small increase in the amount of organic matter in soil can cause a large increase in the ability of soils to use water effectively to support plant production.

INFILTRATION AND WATER HOLDING CAPACITY

Water soaks into soils that have a plant or residue cover over the soil surface. This cover cushions the fall of raindrops and allows them to slowly soak into the soil. Roots create pores that increase the rate at which water can enter the soil. Long-lived perennial bunch-grass forms deep roots that facilitate water infiltration by conducting water into the soil (3). Other plant characteristics that enhance water infiltration are significant litter production and large basal coverage (4). In northern climates where snow provides a substantial portion of the annual water budget, maintaining taller grasses and shrubs that can trap and hold snow will enhance water infiltration.



The Water Cycle. Rain falling on soil can either be absorbed into the soil or be lost as it flows over the soil surface. Absorbed rain is used for the growth of plants and soil organisms, to transport nutrients to plant roots, or to recharge ground water. It can also leach nutrients through the soil profile, out of the reach of plant roots. Water flowing off the soil surface can transport dissolved nutrients as runoff, or nutrients and other contaminants associated with sediments as erosion.

Soils with a high water holding capacity absorb large amounts of water, minimizing the potential for runoff and erosion and storing water for use during droughts. Soils are able to absorb and hold water when they have a thick soil profile; contain a relatively high percentage of organic matter; and do not have a rocky or compacted soil layer, such as a hardpan or plowpan, close to the soil surface. An active population of soil organisms enhances the formation of aggregates and of burrowing channels that provide pathways for water to flow into and through the soil. Management practices that enhance water infiltration and water holding capacity include:

- a complete coverage of forages and residues over the soil surface
- an accumulation of organic matter in and on the soil
- an active community of soil organisms involved in organic matter decomposition and aggregate formation
- water runoff and soil erosion prevention
- protection against soil compaction

SOIL SATURATION

Soils become saturated when the amount of water entering exceeds the rate of absorption or drainage. A rocky or compacted lower soil layer will not allow water to drain or pass through, while a high water table prevents water from draining through the profile. Water soaking into these soils is trapped or perched above the hard

layer or high water table. Soils prone to saturation are usually located at the base of slopes, near waterways, or next to seeps.

Impact on crop production. Soil saturation affects plant production by exacerbating soil compaction, limiting air movement to roots, and ponding water and soil-borne disease organisms around plant roots and stems. When soil pores are filled with water, roots and beneficial soil organisms lose access to air, which is necessary for their healthy growth. Soil compaction decreases the ability of air, water, nutrients, and roots to move through soils even after soils have dried. Plants suffering from lack of air and nutrients are susceptible to disease attack since they are under stress, and wet conditions help disease organisms move from contaminated soil particles and plant residues to formerly healthy plant roots and stems.

Runoff and erosion potential. Soil saturation enhances the potential for runoff and erosion by preventing entry of additional water into the soil profile. Instead, excess water will run off the soil surface, often carrying soil and nutrients with it. Water can also flow horizontally under the surface of the soil until it reaches the banks of streams or lakes. This subsurface water flow carries nutrients away from roots, where they could be used for plant growth, and into streams or lakes where they promote the growth of algae and eutrophication.

Artificial drainage practices are often used on soils with a hardpan or a high water table to decrease the duration of soil saturation following rainfalls or snowmelts. This practice can increase water infiltration and decrease the potential for water runoff (5). Unfortunately, most subsurface drains were installed before water pollution from agriculture became a concern and thus empty directly into drainage ways. Nutrients, pathogens, and other contaminants on the soil surface can move through large cracks or channels in the soil to drainage pipes where they are carried to surface water bodies (6).

SOIL COMPACTION

Soil compaction occurs when animals or equipment move across soils that are wet or saturated, with moist soils being more easily compacted than saturated soils (7). Compaction can also occur when animals or equipment continually move across a laneway or stand around watering tanks and headlands or under shade. Animals trampling over the ground press down on soils, squeezing soil pore spaces together. Trampling also increases the potential for compaction by disturbing and killing vegetation.

Soils not covered by forages or residues are easily compacted by the impact of raindrops. When raindrops fall on bare soil, their force causes fine soil particles to splash or disperse. These splash particles land on the soil surface, clog surface soil pores, and form a crust over the soil. Clayey soils are more easily compacted than sandy soils because clay particles are very small and sticky.

Animals trampling over the ground press down on soils, squeezing soil pores together, which limits root growth and the movement of air, water, and dissolved nutrients.

Compaction limits root growth and the movement of air, water, and dissolved nutrients through the soil. Compressing and clogging soil surface pores also decreases water infiltration and increases the potential for runoff. The formation of hardpans, plowpans, traffic pans, or other compacted layers decreases downward movement of water through the soil, causing rapid soil saturation and the inability of soils to absorb additional water. Compaction in pas-

tures is remediated by root growth, aggregate formation, and activities of burrowing soil organisms. In colder climates, frost heaving is an important recovery process for compacted soils (8).

RUNOFF AND EROSION

Runoff water dissolves nutrients and removes them from the pasture as it flows over the soil surface. Soil erosion transports nutrients and any contaminants, such as pesticides and pathogens, attached to soil particles. Because nutrient-rich clay and organic matter particles are small and lightweight, they are more readily picked up and moved by water than the nutrient-poor, but heavier, sand particles. Besides depleting pastures of nutrients that could be used for forage production, runoff water and erosion carry nutrients and sediments that contaminate lakes, streams, and rivers.

Landscape conditions and management practices that favor runoff and erosion include sloping areas, minimal soil protection by forage or residues, intense rainfall, and saturated soils. While pasture managers should strive to maintain a complete forage cover over the soil surface, this is not feasible in practice because of plant growth habits and landscape characteristics. Plant residues from die-back and animal wastage during grazing provide a critical source of soil cover and organic matter. As mentioned above, forage type affects water infiltration and runoff. Forages with deep roots enhance water infiltration while plants with a wide vegetative coverage area or prostrate growth provide good protection against raindrop impact. Sod grasses that are short-lived and shallow-rooted inhibit water infiltration and encourage runoff. Grazing practices that produce clumps of forages separated by bare ground enhance runoff potential by producing pathways for water flow.

Runoff water and erosion carry nutrients and sediments that contaminate lakes, streams, and rivers.

EVAPORATION AND TRANSPIRATION

Water in the soil profile can be lost through evaporation, which is favored by high temperatures and bare soils. Pasture soils with a thick cover of grass or other vegetation lose little water to evaporation since the soil is shaded and soil temperatures are decreased. While evapo-

ration affects only the top few inches of pasture soils, transpiration can drain water from the entire soil profile. Transpiration is the loss of water from plants through stomata in their leaves. Especially on sunny and breezy days, significant amounts of water can be absorbed from the soil by plant roots, taken up through the plant, and lost to the atmosphere through transpiration. A diversity of forage plants will decrease transpiration losses and increase water-use efficiency.

This is because forage species differ in their ability to extract water from the soil and conserve it against transpiration (9). Some invasive plant species, however, can deplete water stores through their high water use (4). Water not used for immediate plant uptake is held within the soil profile or is transported to groundwater reserves, which supply wells with water and decrease the impacts of drought.

Table 1. Water Cycle Monitoring.

If you answer no to all the questions, you have soils with high water-use efficiency. If you answer yes to some of the questions, water cycle efficiency of your soil will likely respond to improved pasture management practices. See Table 2, next page.

	YES	NO
<u>Water infiltration / Water runoff</u>		
1. Do patches of bare ground separate forage coverage?		
2. Are shallow-rooted sod grasses the predominant forage cover?		
3. Can you see small waterways during heavy rainfalls or sudden snowmelts?		
4. Are rivulets and gullies present on the land?		
<u>Soil saturation</u>		
5. Following a rainfall, is soil muddy or are you able to squeeze water out of a handful of soil?		
6. Following a rainfall or snowmelt, does it take several days before the soil is no longer wet and muddy?		
7. Do forages turn yellow or die during wet weather?		
<u>Soil compaction</u>		
8. Do you graze animals on wet pastures?		
9. Are some soils in the pasture bare, hard, and crusty?		
10. Do you have difficulty driving a post into (non-rocky) soils?		
<u>Water retention /Water evaporation and transpiration</u>		
11. Do you have a monoculture of forages or are invasive species prominent components of the pasture?		
12. Do soils dry out quickly following a rainstorm?		
13. During a drought, do plants dry up quickly?		

Table 2. Pasture Management Practices for Efficient Water Cycling in Pastures.

Ensure forage and residue coverage across the entire pasture

- Use practices that encourage animal movement throughout the pasture and discourage congregation in feeding and lounging areas
- Use practices that encourage regrowth of forage plants and discourage overgrazing
- Use a variety of forages with a diversity of root systems and growth characteristics

Pasture management during wet weather

- Use well-drained pastures or a “sacrificial pasture” that is far from waterways or water bodies
- Avoid driving machinery on pastures that are wet or saturated
- Avoid spreading manure or applying fertilizers

Artificial drainage practices

- Avoid grazing animals on artificially drained fields when drains are flowing
- Avoid spreading manure or applying fertilizers when drains are flowing
- Ensure that drains empty into a filter area or wetland rather than directly into a stream or drainage way

CARBON CYCLE

Effective carbon cycling in pastures depends on a diversity of plants and healthy populations of soil organisms. Plants form carbon and water into carbohydrates through photosynthesis. Plants are most able to conduct photosynthesis when they can efficiently capture solar energy while also having adequate access to water, nutrients, and air. Animals obtain carbohydrates formed by plants when they graze on pastures or eat hay or grains harvested from fields. Some of the carbon and energy in plant carbohydrates is incorporated into animal cells. Some of the carbon is lost to the atmosphere as carbon dioxide, and some energy is lost as heat, during digestion and as the animal grows and breathes.

Humus maintains soil tilth and enhances water and nutrient absorption.

Carbohydrates and other nutrients not used by animals are returned to the soil in the form of urine and manure. These organic materials provide soil organisms with nutrients and energy. As soil organisms use and decompose organic materials, they release nutrients from these materials into the soil. Plants then use the released, inorganic forms of nutrients for their growth and reproduction. Soil organisms also use nutrients from organic materials to produce substances that bind soil particles into aggregates. Residues of organic matter that resist further decomposition by soil organisms form *soil humus*. This stable organic material is critical for maintaining soil tilth and enhancing the ability of soils to absorb and hold water and nutrients.

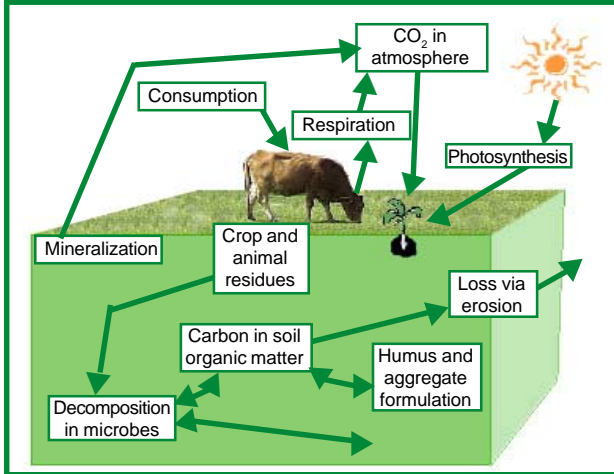
CARBOHYDRATE FORMATION

For productive growth, plants need to effectively capture solar energy, absorb carbon dioxide, and take up water from the soil to produce carbohydrates through photosynthesis. In pastures, a combination of broadleaf plants and grasses allows for efficient capture of solar en-

ergy by a diversity of leaf shapes and leaf angles. Taller plants with more erect leaves capture light even at the extreme angles of sunrise and sunset. Horizontal leaves capture the sun at midday or when it is more overhead.

Two methods for transforming carbon into carbohydrates are represented in diversified pas-

Figure 4. Carbon Cycle.



The Carbon Cycle begins with plants taking up carbon dioxide from the atmosphere in the process of photosynthesis. Some plants are eaten by grazing animals, which return organic carbon to the soil as manure, and carbon dioxide to the atmosphere. Easily broken-down forms of carbon in manure and plant cells are released as carbon dioxide when decomposing soil organisms respire. Forms of carbon that are difficult to break down become stabilized in the soil as humus.

tures. Broadleaf plants and cool-season grasses have a photosynthetic pathway that is efficient in the production of carbohydrates but is sensitive to dry conditions. Warm-season grasses have a pathway that is more effective in producing carbohydrates during hot summer conditions. A combination of plants representing these two pathways ensures effective forage growth throughout the growing season. A diversity of root structures also promotes photosynthesis by giving plants access to water and nutrients throughout the soil profile.

ORGANIC MATTER DECOMPOSITION

Pasture soils gain organic matter from growth and die-back of pasture plants, from forage waste during grazing, and from manure deposition. In addition to the recycling of aboveground plant parts, every year 20 to 50% of plant root mass dies and is returned to the soil system. Some pasture management practices also involve the regular addition of manure from grazing animals housed during the winter or from poultry, hog, or other associated livestock facilities.

A healthy and diverse population of soil organisms is necessary for organic matter decomposition, nutrient mineralization, and the formation of soil aggregates. Species representing almost every type of soil organism have roles in the breakdown of manure, plant residues, and dead organisms. As they use these substances for food and energy sources,

they break down complex carbohydrates and proteins into simpler chemical forms. For example, soil organisms break down proteins into carbon dioxide, water, ammonium, phosphate, and sulfate. Plants require nutrients to be in this simpler, decomposed form before they can use them for their growth.

To effectively decompose organic matter, soil organisms require access to air, water, and nutrients. Soil compaction and saturation limit the growth of beneficial organisms and promote the growth of anaerobic organisms, which are inefficient in the decomposition of organic matter. These organisms also transform some nutrients into forms that are less available or unavailable to plants. Nutrient availability and nutrient balances in the soil solution also affect the growth and diversity of soil organisms. To decompose organic matter that contains a high amount of carbon and insufficient amounts of other nutrients, soil organisms must mix soil-solution nutrients with this material to achieve a balanced diet.

Balances between the amount of carbon and nitrogen (C:N ratio) and the amount of carbon and sulfur (C:S ratio) determine whether soil organisms will release or immobilize nutrients

when they decompose organic matter. *Immobilization* refers to soil microorganisms taking nutrients from the soil solution to use in the decomposition process of nutrient-poor materials. Since these nutrients are within the bodies of soil

A healthy and diverse population of soil organisms is necessary for organic matter decomposition, nutrient mineralization, and the formation of soil aggregates.

organisms, they are temporarily unavailable to plants. In soils with low nutrient content, this can significantly inhibit plant growth. However, immobilization can be beneficial in soils with excess nutrients. This process conserves nutrients in bodies of soil organisms, where they are less likely to be lost through leaching and runoff (10).

Populations of soil organisms are enhanced by soil that is not compacted and has adequate air and moisture, and by additions of fresh residues they can readily decompose. Soil-applied pesticides can kill many beneficial soil organisms, as will some chemical fertilizers. Anhydrous ammonia and fertilizers with a high chloride content, such as potash, are particularly detrimental to soil organisms. Moderate organic or synthetic fertilizer additions, however, enhance populations of soil organisms in soils with low fertility.

In soils with low nutrient content, nutrient immobilization inhibits plant growth. In soils with excess nutrients, immobilization conserves nutrients in the bodies of soil organisms, where they are less likely to be lost through leaching and runoff.

SOIL HUMUS AND SOIL AGGREGATES

Besides decomposing organic materials, bacteria and fungi in the soil form gels and threads that bind soil particles together. These bound particles are called soil aggregates. Worms, beetles, ants, and other soil organisms move partially decomposed organic matter through the soil or mix it with soil in their gut, coating soil particles with organic gels. As soil particles become

aggregated, soil pore size increases and soils become resistant to compaction. The organic compounds that hold aggregates together also increase the ability of soils to absorb and hold water and nutrients.

As soil organisms decompose manure and plant residues, they release carbon dioxide and produce waste materials, which are further decomposed by other soil organisms. Because carbon is lost to respiration at each stage of this decomposition process, the remaining material increases in relative nitrogen content. The remaining material also increases in chemical complexity and requires increasingly specialized species of decomposers. Efficient decomposition of organic matter thus requires a diversity of soil organisms. Humus is the final, stable product of decomposition, formed when organic matter can be broken down by soil organisms only slowly or with difficulty. Humus-coated soil particles form aggregates that are soft, crumbly, and somewhat greasy-feeling when rubbed together.

PREVENTING ORGANIC MATTER LOSSES

Perennial plant cover in pastures not only provides organic matter inputs, it also protects against losses of organic matter through erosion. Soil coverage by forages and residues protects the soil from raindrop impact while dense root systems of forages hold the soil against erosion while enhancing water infiltration. Fine root hairs also promote soil aggregation. In addition, a

Table 3. Typical C:N, C:S, and N:S Ratios.

Typical C:N, C:S, and N:S ratios of plant residues, excreta of ruminant animals, and biomass of soil microorganisms decomposing in grassland soils (based on values for % in dry matter)

	%N	C:N	%S	C:S	N:S
Dead grass	1.8	26.6:1	0.15	320:1	12:1
Dead clover	2.7	17.7:1	0.18	270:1	15:1
Grass roots	1.4	35:1	0.15	330:1	9:1
Clover roots	3.8	13.2:1	0.35	140:1	10:1
Cattle feces	2.4	20:1	0.30	160:1	8:1
Cattle urine	11.0	3.9:1	0.65	66:1	17:1
Bacteria	15.0	3.3:1	1.1	45:1	14:1
Fungi	3.4	12.9:1	0.4	110:1	8.5:1

From Whitehead, 2000 (reference #11)

dense forage cover shades and cools the soil. High temperatures promote mineralization and loss of organic matter, while cooler temperatures promote the continued storage of this material within the plant residues and the bodies of soil organisms.

Table 4. Pasture Management Practices for Efficient Carbon Cycling.

Ensure forage and residue coverage and manure deposition across the entire pasture

- Use practices that encourage animal movement throughout the pasture and discourage congregation in feeding and lounging areas

Promote healthy forage growth and recovery following grazing

- Use a variety of forages with a diversity of leaf types and orientations
- Use a combination of cool- and warm-season forages with a diversity of shoot and root growth characteristics
- Conserve sufficient forage leaf area for efficient plant regrowth by monitoring pastures and moving grazing animals to another pasture in a timely manner
- Maintain soil tilth for healthy root growth and nutrient uptake

Encourage organic matter decomposition by soil organisms

- Use management practices that minimize soil compaction and soil erosion
- Minimize tillage and other cultivation practices
- Maintain a diversity of forage species to provide a variety of food sources and habitats for a diversity of soil organisms
- Avoid the use of soil-applied pesticides and concentrated fertilizers that may kill or inhibit the growth of soil organisms

Encourage soil humus and aggregate formation

- Include forages with fine, branching root systems to promote aggregate formation
- Maintain organic matter inputs into the soil to encourage the growth of soil organisms
- Maintain coverage of forages and plant residues over the entire paddock to provide organic matter and discourage its rapid degradation

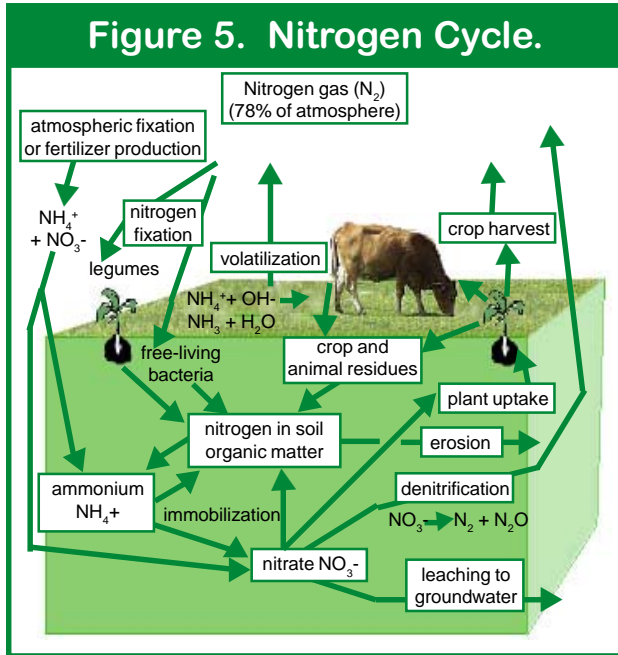
NITROGEN CYCLE

Nitrogen is a primary plant nutrient and a major component of the atmosphere. In a pasture ecosystem, almost all nitrogen is organically bound. Of this, only about 3% exists as part of a living plant, animal, or microbe, while the remainder is a component of decomposed organic matter or humus. A very small percentage of the total nitrogen (less than 0.01%) exists as plant-available nitrogen in the form of ammonium or nitrate (12).

Nitrogen becomes available for the growth of crop plants and soil organisms through nitrogen fixation, nitrogen fertilizer applications, the

return of manure to the land, and through the mineralization of organic matter in the soil. Nitrogen fixation occurs mainly in the roots of legumes that form a symbiotic association with a type of bacteria called *rhizobia*. Some free-living bacteria, particularly cyanobacteria (“blue-green algae”), are also able to transform atmospheric nitrogen into a form available for plant growth. Fertilizer factories use a combination of high pressure and high heat to combine atmospheric nitrogen and hydrogen into nitrogen fertilizers. Animals deposit organically-bound nitrogen in feces and urine. Well-managed pastures accu-

Figure 5. Nitrogen Cycle.



The Nitrogen Cycle. Nitrogen enters the cycle when atmospheric nitrogen is fixed by bacteria. Nitrogen in the ammonical form is transformed into nitrite and nitrate by bacteria. Plants can use either ammonia or nitrate for growth. Nitrogen in plant cells can be consumed by animals and returned to the soil as feces or urine. When plants die, soil organisms decompose nitrogen in plant cells and release it as ammonia. Nitrate nitrogen can be lost through the physical process of leaching or through the microbially-mediated process of denitrification. Nitrogen in the ammonical form can be lost to the atmosphere in the chemical process of volatilization.

mulate stores of organic matter in the soil and in plant residues. Decomposition and mineralization of nutrients in these materials can provide significant amounts of nitrogen to plants and other organisms in the pasture system.

Plants use nitrogen for the formation of proteins and genetic material. Grazing animals that consume these plants use some of the nitrogen for their own growth and reproduction; the remainder is returned to the earth as urine or manure. Soil organisms decompose manure, plant residues, dead animals, and microorganisms, transforming nitrogen-containing compounds in their bodies into forms that are available for use by plants.

Nitrogen is often lacking in pasture systems since forage requirements for this nutrient are high and because it is easily lost to the environment. Nitrogen is lost from pasture systems through microbiological, chemical, and physical processes. Dry followed by wet weather provides optimal conditions for bacteria to transform nitrogen from plant-available forms into atmospheric nitrogen through *denitrification*. Chemical processes also transform plant-available nitrogen into atmospheric nitrogen through *volatilization*. In pastures, this often occurs after manure or nitrogen fertilizers are applied to the soil surface, especially during warm weather. Physical processes are involved in the downward movement of nitrogen through the soil profile during *leaching*.

NITROGEN FIXATION

Plants in the legume family, including alfalfa, clover, lupines, lespedeza, and soybeans, form a relationship with a specialized group of bacteria called *rhizobia*. These bacteria have the ability to fix or transform atmospheric nitrogen into a form of nitrogen plants can use for their growth. Rhizobia form little balls or nodules on the roots of legumes. If these balls are white or pinkish on the inside, they are actively fixing nitrogen. Nodules that are grey or black inside are dead or no longer active. Legume seeds should be dusted with inoculum (a liquid or powder containing the appropriate type of rhizobia) prior to planting to ensure that the plant develops many nodules and has maximal ability to fix nitrogen. Other microorganisms that live in the soil are also able to fix and provide nitrogen to plants.

Table 5. Nitrogen Fixation by Legumes.

	#N/acre/ year
Alfalfa -----	150-350
White clover -----	112-190
Hairy vetch -----	110-168
Red clover -----	60-200
Soybeans -----	35-150
Annual lespedeza -----	50-193
Birdsfoot trefoil -----	30-130

From Joost, 1996 (Reference # 13)

Legumes require higher amounts of phosphorus, sulfur, boron, and molybdenum than non-legumes to form nodules and fix nitrogen. If these nutrients are not available in sufficient amounts, nitrogen fixation will be suppressed. When nitrogen levels in the soil are high due to applications of manure or nitrogen fertilizers, nitrogen fixation by legumes decreases because nitrogen fixation requires more energy than does root uptake of soluble soil nitrogen. Nitrogen fixed by legumes and rhizobia is available primarily to the legumes while they are growing. When pasture legume nodules, root hairs, and aboveground plant material dies and decomposes, nitrogen in this material can become available to pasture grasses (14).

However, while legumes are still growing, mycorrhizal fungi can form a bridge between the root hairs of legumes and nearby grasses. This bridge facilitates the transport of fixed nitrogen from legumes to linked grasses. Depending on

Legumes can transfer up to 40% of their fixed nitrogen to grasses during the growing season.

the nitrogen content of the soil and the mix of legumes and grasses in a pasture, legumes can transfer between 20 and 40% of their fixed nitrogen

to grasses during the growing season (15). A pasture composed of at least 20 to 45% legumes (dry matter basis) can meet and sustain the nitrogen needs of the other forage plants in the pasture (16).

Grazing management affects nitrogen fixation through the removal of herbage, deposition of urine and manure, and induced changes in moisture and temperature conditions in the soil. Removal of legume leaf area decreases nitrogen fixation by decreasing photosynthesis and plant competitiveness with grasses. Urine deposition decreases nitrogen fixation by adjacent plants since it creates an area of high soluble-nitrogen availability. Increased moisture in compacted soils or increased temperature in bare soils will also decrease nitrogen fixation since rhizobia are sensitive to wet and hot conditions.

NITROGEN MINERALIZATION

Decomposition of manure, plant residues, or soil organic matter by organisms in the soil re-

sults in the formation of ammonia. Protozoa, amoebas, and nematodes are prolific nitrogen mineralizers, cycling 14 times their biomass each year. While bacteria only cycle 0.6 times their biomass, because of their large numbers in soil they produce a greater overall contribution to the pool of mineralized nitrogen (17). Plants can use ammonical nitrogen for their growth, but under aerobic conditions two types of bacteria usually work together to rapidly transform ammonia first into nitrite and then into nitrate before it is used by plants.

Mineralization is a very important source of nitrogen in most grasslands. As discussed above, for efficient decomposition (and release of nitrogen), residues must contain a carbon-to-nitrogen ratio that is in balance with the nutrient needs of the decomposer organisms. If the nitrogen content of residues is insufficient, soil organisms will extract nitrogen from the soil solution to satisfy their nutrient needs.

NITROGEN LOSSES TO THE ATMOSPHERE

Under wet or anaerobic conditions, bacteria transform nitrate nitrogen into atmospheric nitrogen. This process, called denitrification, reduces the availability of nitrogen for plant use. Denitrification occurs when dry soil containing nitrate becomes wet or flooded and at the edges of streams or wetlands where dry soils are adjacent to wet soils.

Volatilization is the transformation of ammonia into atmospheric nitrogen. This chemical process occurs when temperatures are high and ammonia is exposed to the air. Incorporation of manure or ammonical fertilizer into the soil decreases the potential for volatilization. In general, 5 to 25% of the nitrogen in urine is volatilized from pastures (11). A thick forage cover and rapid manure decomposition can reduce volatilization from manure.

NITROGEN LEACHING

Soil particles and humus are unable to hold nitrate nitrogen very tightly. Water from rainfall or snowmelt readily leaches soil nitrate downward through the profile, putting it out of reach of plant roots or moving it into the groundwater. Leaching losses are greatest when the water table is high, the soil sandy or porous, or when rainfall or snowmelt is severe. In pastures, probably the most important source of nitrate leaching is from

urine patches (18). Cattle urine typically leaches to a depth of 16 inches, while sheep urine leaches only six inches into the ground (19). Leaching may also be associated with the death of legume nodules during dry conditions (20).

Methods for reducing nitrate leaching include maintaining an actively growing plant cover over the soil surface, coordinating nitrogen applications with the period of early plant growth, not applying excess nitrogen to soils, and encouraging animal movement and distribution of manure across paddocks. Actively growing plant roots take up nitrate from the soil and prevent it from leaching. If the amount of nitrogen applied to the soil is in excess of what plants need or is applied when plants are not actively growing, nitrate not held by plants can leach through the soil. Spring additions of nitrogen to well-managed pastures can cause excessive plant growth and increase the potential for leaching. This is because significant amounts of nitrogen are also being mineralized from soil organic matter as warmer temperatures increase the activity of soil organisms.

Nitrate levels in excess of 10 ppm in drinking water can cause health problems for human infants, infant chickens and pigs, and both infant and adult sheep, cattle, and horses (21). Pasture forages can also accumulate nitrate levels high enough to cause health problems. Conditions conducive for nitrate accumulation by plants include acid soils; low molybdenum, sulfur, and phosphorus content; soil temperatures lower than 55°F; and good soil aeration (22).

Nitrate poisoning is called methemoglobinemia, commonly known as “blue baby syndrome” when seen in human infants. In this syndrome, nitrate binds to hemoglobin in the blood, reducing the blood’s ability to carry oxygen through the body. Symptoms in human infants and young animals include difficulty breathing. Pregnant animals that recover may abort within a few days. Personnel from the Department of Health can test wells to determine whether nitrate levels are dangerously high.

Table 6. Estimated Nitrogen Balance (pounds/acre) for Two Grassland Management Systems.

	Moderately managed grass-clover	Extensively grazed grass
Inputs		
Nitrogen fixation	134	9
Atmospheric deposition	34	19
Fertilizer	0	0
Supplemental feed	0	0
Recycled nutrients		
Uptake by herbage	270	67
Herbage consumption by animals	180	34
Dead herbage to soil	90	34
Dead roots to soil	56	34
Manure to soil	134	28
Outputs		
Animal weight gain	28	4
Leaching/runoff/erosion	56	6
Volatilization	17	3
Denitrification	22	2
Gain to soil	56	13

From Whitehead, 2000 (Reference # 11)

Table 7. Pasture Management Practices for Efficient Nitrogen Cycling.

Ensure effective nitrogen fixation by legumes

- Ensure that phosphorus, sulfur, boron, and molybdenum in the soil are sufficient for effective nitrogen fixation
- Apply inoculum to legume seeds when sowing new pastures to ensure nodulation of legume roots
- Ensure that legumes represent at least 30% of the forage cover
- Maintain stable or increasing ratios of legumes to grasses and other non-legumes in pastures over time
- Establish forages so that legumes and grasses grow close to one another to allow for the transfer of nitrogen from legumes to grasses

Encourage nitrogen mineralization by soil organisms

- Use management practices that minimize soil compaction and soil erosion
- Minimize tillage and other cultivation practices
- Maintain a diversity of forage species to provide a variety of food sources and habitats for a diversity of soil organisms
- Use grazing management practices that encourage productive forage growth and that return and maintain residues within paddocks
- Avoid application of sawdust, straw, or other high-carbon materials unless these materials are mixed with manure or composted prior to application
- Avoid the use of soil-applied pesticides and concentrated fertilizers that may kill or inhibit the growth of soil organisms

Avoid nitrogen losses

- Minimize nitrogen volatilization by avoiding surface application of manure, especially when the temperature is high or there is minimal forage cover over the soil
- Minimize nitrogen leaching by not applying nitrogen fertilizer or manure when soil is wet or just prior to rainstorms and by encouraging animal movement and distribution of urine spots across paddocks
- Minimize nitrogen leaching by not applying nitrogen fertilizer or manure to sandy soils except during the growing season
- Rely on mineralization of organic residues to supply most or all of your forage nitrogen needs in the spring. Minimize the potential for nitrogen leaching by limiting spring applications of nitrogen
- Minimize nitrogen losses caused by erosion by using management practices that maintain a complete cover of forages and residues over the pasture surface

Ensure effective use of nitrogen inputs

- Use management practices that encourage the even distribution of manure and urine across paddocks
- Rely on soil tests and other nutrient management practices when applying fertilizers and manure to pastures

NITROGEN LOSS THROUGH RUNOFF AND EROSION

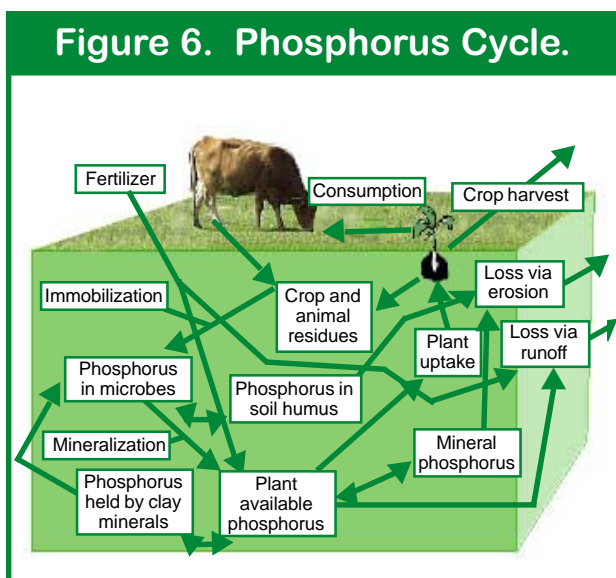
Runoff and erosion caused by rainwater or snowmelt can transport nitrogen on the soil surface. Erosion removes soil particles and organic matter containing nitrogen; runoff transports dissolved ammonia and nitrate. Incorporation of manure and fertilizers into the soil reduces the exposure of these nitrogen sources to rainfall or snowmelt, thus reducing the potential for erosion. In pasture systems, however, incorporation is usually impractical and can increase the potential for erosion. Instead, a complete cover

of forages and plant residues should be maintained over the soil surface to minimize raindrop impact on the soil, enhance water infiltration, help trap sediments and manure particles, and reduce the potential for runoff and erosion. A healthy and diverse population of soil organisms, including earthworms and dung beetles that rapidly incorporate manure nitrogen into the soil and into their cells, can further reduce the risk of nitrogen runoff from manure. Since increased water infiltration decreases the potential for runoff but increases the potential for leaching, risks of nitrate losses from runoff need to be balanced against leaching risks.

PHOSPHORUS CYCLE

Like nitrogen, phosphorus is a primary plant nutrient. Unlike nitrogen, phosphorus is not part of the atmosphere. Instead, it is found in rocks, minerals, and organic matter in the soil. The mineral forms of phosphorus include apatite (which may be in a carbonate, hydroxide, fluoride, or chloride form) and iron or aluminum phosphates. These minerals are usually associated with basalt and shale rocks. Chemical reactions and microbial activity affect the availability of phosphorus for plant uptake. Under acid conditions, phosphorus is held tightly by aluminum and iron in soil minerals. Under alkaline conditions, phosphorus is held tightly by soil calcium.

Plants use phosphorus for energy transfer and reproduction. Legumes require phosphorus for effective nitrogen fixation. Animals consume phosphorus when they eat forages. Phosphorus not used for animal growth is returned to the soil in manure. Following decomposition by soil organisms, phosphorus again becomes available for plant uptake.



The Phosphorus Cycle is affected by microbial and chemical transformations. Soil organisms mineralize or release phosphorus from organic matter. Phosphorus is chemically bound to iron and aluminum in acid soils, and to calcium in alkaline soils. Soil-bound phosphorus can be lost through erosion, while runoff waters can transport soluble phosphorus found at the soil surface.

MYCORRHIZAE

Mycorrhizal fungi attach to plant roots and form thin threads that grow through the soil and wrap around soil particles. These thin threads increase the ability of plants to obtain phosphorus and water from soils. Mycorrhizae are especially important in acid and sandy soils where phosphorus is either chemically bound or has limited availability. Besides transferring phosphorus and water from the soil solution to plant roots, mycorrhizae also facilitate the transfer of nitrogen from legumes to grasses. Well aerated and porous soils, and soil organic matter, favor mycorrhizal growth.

SOIL CHEMISTRY AND PHOSPHORUS AVAILABILITY

Phosphorus is tightly bound chemically in highly weathered acid soils that contain high concentrations of iron and aluminum. Active calcium in neutral to alkaline soils also forms tight bonds with phosphorus. Liming acid soils and applying organic matter to either acid or alkaline soils can increase phosphorus availability. In most grasslands, the highest concentration of phosphorus is in the surface soils associated with decomposing manure and plant residues.

PHOSPHORUS LOSS THROUGH RUNOFF AND EROSION

Unlike nitrogen, phosphorus is held by soil particles. It is not subject to leaching unless soil levels are excessive. However, phosphorus can move through cracks and channels in the soil to artificial drainage systems, which can transport it to outlets near lakes and streams. Depending on the soil type and the amount of phosphorus already in the soil, phosphorus added as fertil-



izer or manure may be readily lost from fields and transported to rivers and streams through runoff and erosion. The potential for phosphorus loss through runoff or erosion is greatest when rainfall or snowmelt occurs within a few days following surface applications of manure or phosphorus fertilizers.

Continual manure additions increase the potential for phosphorus loss from the soil and the contamination of lakes and streams. This is especially true if off-farm manure sources are used to meet crop or forage nutrient needs for nitrogen. The ratio of nitrogen to phosphate in swine or poultry manure is approximately 1 to 1, while the ratio of nitrogen to phosphate taken up by forage grasses is between 2.5 to 1 and 3.8 to 1. Thus, manure applied for nitrogen requirements will provide 2.5 to 3.8 times the amount of phosphorus needed by plants (23). While much of this phosphorus will be bound by chemical bonds in the soil and in the microbial biomass, continual additions will exceed the ability of the soil to store excess phosphorus, and the amount of soluble phosphorus (the form available for loss by runoff) will increase. To decrease the potential for phosphorus runoff from barnyard manure or poultry litter, alum or aluminum oxide can be added to bind phosphorus in the manure (24).

Supplemental feeds are another source of phosphorus inputs to grazing systems, especially for dairy herds. Feeds high in phosphorus increase the amount of phosphorus deposited on pastures as manure. To prevent build up of excess phosphorus in the soil, minimize feeding of unneeded supplements, conduct regular soil tests on each paddock, and increase nutrient removals from excessively fertile paddocks through haying.

Phosphorus runoff from farming operations can promote unwanted growth of algae in lakes and slow-moving streams. Regulations and nutrient-management guidelines are being developed to decrease the potential for phosphorus movement from farms and thus reduce risks of lake eutrophication. Land and animal management guidelines, called “phosphorus indices,” are being developed across the U.S. to provide farmers with guidelines for reducing “non-point” phosphorus pollution from farms (25). These guidelines identify risk factors for phosphorus transport from fields to water bodies based on the concentration of phosphorus in the

Phosphorus index guidelines consider:

- the amount of phosphorus in the soil
- manure and fertilizer application rates, methods, and timing
- runoff and erosion potential
- distance from a water body

soil, timing and method of fertilizer and manure applications, potential for runoff and erosion, and distance of the field from a water body (26). Although the total amount of phosphorus lost from fields is greatest during heavy rainstorms, snowmelts, and other high-runoff events, relatively small amounts of phosphorus running off from fields into streams at low water level in summer pose a higher risk for eutrophication. This is because phosphorus is more concentrated in these smaller flows of water (27). Conditions for concentrated flows of phosphorus into low-flow

streams include location near streams of barnyards or other holding areas without runoff containment or filtering systems, extensive grazing of animals near streams without riparian buffers, and unlimited animal access to streams.



Table 8. Pasture Management Practices for Efficient Phosphorus Cycling.

Encourage phosphorus mineralization by soil organisms

- Use management practices that minimize soil compaction and soil erosion
- Minimize use of tillage and other cultivation practices
- Maintain a diversity of forage species to provide a variety of food sources and habitats for a diversity of soil organisms
- Avoid application of sawdust, straw, or other high-carbon materials unless these materials are mixed with manure or composted prior to application
- Avoid the use of soil-applied pesticides and concentrated fertilizers that may kill or inhibit the growth of soil organisms

Avoid phosphorus losses

- Minimize phosphorus losses caused by erosion by using management practices that maintain a complete cover of forages and residues over the pasture surface
- Minimize phosphorus losses caused by runoff by not surface-applying fertilizer or manure to soil that is saturated, snow-covered, or frozen
- Avoid extensive grazing of animals in or near streams especially when land is wet or saturated or when streams are at low flow

Ensure effective use of phosphorus inputs

- Use management practices that encourage the even distribution of manure and urine across paddocks
- Rely on soil tests, phosphorus index guidelines, and other nutrient management practices when applying fertilizers and manure to pastures

SECONDARY NUTRIENTS

Potassium and the secondary nutrients, calcium, magnesium, and sulfur, play a critical role in plant growth and animal production. Potassium, calcium, and magnesium are components of clay minerals. The soil parent-material primarily influences the availability of these plant nutrients. For example, soils derived from granite contain, on the average, nine times more potassium than soils derived from basalt, while soils derived from limestone have half the amount. Conversely, soils derived from limestone have, on the average, four times more calcium than soils derived from basalt and thirty times more than soils derived from granite (11).

POTASSIUM

Potassium, like all plant nutrients, is recycled through plant uptake, animal consumption, and manure deposition. The majority of potassium is found in urine. Potassium levels can become excessive in fields that have received repeated high applications of manure. Application of fertilizer nitrogen increases the potassium uptake by grasses if the soil has an adequate supply of potassium. Consumption of forages that contain more than 2% potassium can cause problems in breeding dairy cattle and in their recovery following freshening (28). High potassium levels, especially in lush spring forage, can cause nutrient imbalance resulting in grass tetany.

CALCIUM AND MAGNESIUM

Calcium and magnesium are components of liming materials used to increase soil pH and reduce soil acidity. However, the use of lime can also be important for increasing the amount of calcium in the soil or managing the balance between calcium and magnesium. Increasing the calcium concentration may enhance biological activity in the soil (29). Managing this balance is especially important for decreasing the occurrence of grass tetany, a nutritional disorder of ruminants caused by low levels of magnesium in the diet. Magnesium may be present in the soil in sufficient amounts for plant growth, but its concentration may be out of balance with the nutrient needs of plants and animals. When calcium and potassium have a high concentration

Phosphorus fertilization of tall fescue decreased the incidence of grass tetany in cattle since it stimulated grass growth and increased the availability of magnesium during cool wet spring conditions.

in the soil compared to magnesium, they will limit the ability of plants to take up magnesium. Under these conditions, the magnesium concentration needs to be increased relative to calcium. Dolomite lime, which contains magnesium carbonate, can be used to both lime soils and increase the availability of magnesium. Phosphorus fertilization of tall fescue in Missouri was also shown to increase the availability of magnesium sufficiently to decrease the incidence of grass tetany in cattle (30). This probably resulted from the stimulation of grass growth during cool wet spring conditions that are conducive to the occurrence of grass tetany.

SULFUR

Sulfur increases the protein content of pasture grasses and increases forage digestibility and effectiveness of nitrogen use (31). In nature, sulfur is contained in igneous rocks, such as granite and basalt, and is a component of organic matter. In areas downwind from large industrial and urban centers, sulfur contributions from the atmosphere in the form of acid rain can be considerable. Fertilizer applications of nitrogen as ammonium sulfate or as sulfur-coated urea also contribute to sulfur concentration in soils. However, pasture needs for sulfur fertilization will increase as environmental controls for acid rain improve, as other sources of nitrogen fertilizer are used, and as forage production increases.

Microbial processes affect sulfur availability. As with nitrogen, the sulfur content of organic matter determines whether nutrients will be mineralized or immobilized. Also as with nitrogen, the sulfur content of grasses decreases as they become older and less succulent. Thus, soil organisms will decompose younger plants more rapidly and thereby release nutrients while they will decompose older plant material more slowly

and may immobilize soil nutrients in the process of decomposition.

Chemical and biological processes are involved in sulfur transformations. In dry soils that become wet or waterlogged, chemical processes transform sulfur from the sulfate to sulfide form. If these wet soils dry out or are drained, bacteria transform sulfide to sulfate. Like nitrate, sulfate is not readily absorbed by soil minerals, especially in soils with a slightly acid to neutral pH. As a result, sulfate can readily leach through soils that are sandy or highly permeable.



Table 9. Pasture Management Practices for Efficient Cycling of Potassium, Calcium, Magnesium, and Sulfur.

Encourage nutrient mineralization by soil organisms

- Use management practices that minimize soil compaction and soil erosion
- Minimize use of tillage and other cultivation practices
- Maintain a diversity of forage species to provide a variety of food sources and habitats for a diversity of soil organisms
- Avoid the use of soil-applied pesticides and concentrated fertilizers that may kill or inhibit the growth of soil organisms
- Encourage animal movement across paddocks for even distribution of manure nutrients

Avoid nutrient losses

- Minimize sulfur losses by using management practices that decrease the potential for leaching
- Minimize nutrient losses caused by erosion by using management practices that maintain a complete cover of forages and residues over the pasture surface

Maintain nutrient balances in the pasture

- Ensure magnesium availability to minimize the potential for grass tetany. This can be done by balancing the availability of magnesium with the availability of other soil cations, particularly potassium and calcium. Phosphorus fertilization of pastures in spring can also enhance magnesium availability
- Guard against a buildup of potassium in pastures by not overapplying manure. High potassium levels can cause reproductive problems, especially in dairy cows

Chapter 2

Nutrient Availability in Pastures

Nutrient balances and nutrient availability determine the fate of nutrients in pastures. In the simplest of grazing systems, forage crops take up nutrients from the soil; haying and grazing remove forage crops and their associated nutrients; and animal manure deposition returns nutrients to the soil. Continual nutrient removals deplete soil fertility unless fertilizers, whether organic or synthetic, are added to replenish nutrients. Nutrients may be added to pastures by providing animals with feed supplements produced off-farm.

Chemical and biological interactions determine the availability of nutrients for plant use. Both native soil characteristics and land management practices affect these interactions. Phosphorus can be held chemically by iron or aluminum bonds while potassium can be held within soil minerals. Practices that erode topsoil and deplete soil organic matter decrease the ability of soils to hold or retain nutrients. All crop nutrients can be components of plant residues or soil organic matter. The type of organic matter available and the activity of soil organisms determine the rate and amount of nutrients mineralized from these materials. Nutrient availability and balance in forage plants affect the health of grazing animals. Depleted soils produce unhealthy, low-yielding forages and unthrifty animals; excess soil nutrients can be dangerous to animal health and increase the potential for contamination of wells, springs, rivers, and streams.

SOIL PARENT MATERIAL

Chemical, physical, geological, and biological processes affect nutrient content and availability in soils. As discussed in the previous chapter, soils derived from basalt and shale provide phosphorus to soils, granite contains high concentrations of potassium, and limestone is a

source of calcium and magnesium. Some clay soils and soils with high percentages of organic matter contain a native store of nutrients in addition to having the capacity to hold nutrients added by manure, crop residues, or fertilizers. Soils formed under temperate prairies or in flood plains have built up fertility through a long history of organic matter deposition and nutrient accumulation. Sandy soils and weathered,

reddish clay soils contain few plant nutrients and have a limited ability to hold added nutrients. Soils formed under desert conditions are often saline, since water evaporating off the soil surface draws water in the soil profile upward. This water carries nutrients and salts, which are deposited on the soil surface when water evaporates. Tropical soils generally have low fertility since they were formed under conditions of high temperatures, high biological activity, and high rainfall that caused rapid organic matter decomposition and nutrient leaching.

SOIL CHEMISTRY

Many clay minerals are able to hold onto water and nutrients and make them available for plant growth. The pH, or level of acidity or alkalinity of the soil solution, strongly influences the strength and type of bonds formed between soil minerals and plant nutrients. Soil pH also affects activities of soil organisms involved in the decomposition of organic matter and the dissolution of plant nutrients from soil minerals. Many clay soil particles are able to bind large amounts of nutrients because of their chemical composition and because they are very small and have a large surface area for forming bonds. Unfortunately, this small size also makes clay particles prone to compaction, which can reduce nutrient and water availability. Sandy soils are porous and allow water to enter the soil rapidly.

Nutrient-depleted soils produce low-yielding forages and unthrifty animals.

Excess soil nutrients can be dangerous to animal health and increase the potential for contamination of wells, springs, rivers, and streams.

But these soils are unable to hold water or nutrients against leaching. Organic matter has a high capacity to hold both nutrients and water. Soil aggregates, formed by plant roots and soil organisms, consist of mineral and organic soil components bound together in soft clumps. Aggregates enhance soil porosity, facilitate root growth, allow for better infiltration and movement of water and nutrients through soil, and help soils resist compaction.

PRIOR MANAGEMENT PRACTICES

In pastures, continual removal of nutrients through harvests or heavy grazing without return or addition of nutrients depletes the soil. Land management practices that encourage soil erosion — such as heavy grazing pressure, plowing up and down a slope, or leaving a field bare of vegetation during times of heavy rains or strong winds — also result in depletion of soil fertility. Some pasture management practices involve the use of fire to stimulate growth of native forages (32). Burning readily mineralizes phosphorus, potassium, and other nutrients in surface crop residues. It also volatilizes carbon and nitrogen from residues and releases these nutrients into the atmosphere, thus minimizing the ability of organic matter to accumulate in the soil. Loss of residues also exposes soil to raindrop impact and erosion. Hot uncontrolled fires increase the potential for erosion by degrading natural biological crusts formed by lichens, algae, and other soil organisms, and by promoting the formation of physical crusts formed from melted soil minerals (33, 34). The continual high application of manure, whey, sludge, or other organic waste products to soils can cause nutrients to build up to excessive levels. Pasture management practices that influence soil compaction, soil saturation, the activity of soil organisms, and soil pH affect both soil nutrient content and availability.



Compacted soils do not allow for normal root growth. This root grew horizontally when it encountered a compacted layer.

SOIL COMPACTION

Animal movement compacts soil pores, especially when soils are wet or saturated. Continual trampling and foraging, especially in congregation areas and laneways, also depletes plant growth and produces bare spots.

Soil compaction increases as soil moisture, animal weight, animal numbers, and the length of stay in the paddock increase.

Resistance to compaction increases as forage establishment and the percentage of plants with fibrous roots increase.

Soil compaction reduces nutrient availability for plant uptake by blocking nutrient transport to roots and restricting root growth through the soil profile. Treading and compaction can substantially reduce forage yields. One study showed that the equivalent of 12 sheep treading on mixed ryegrass, white clover, and red clover pasture reduced yields by 25% on dry soil, 30% on moist soil, and 40% on wet soil compared to no treading. On wet soils, root growth was reduced 23% (35).

Compaction also decreases the rate of organic matter decomposition by limiting the access soil organisms have to air, water, or nutrients. In addition, compacted soils limit water infiltration and increase the potential for water runoff and soil erosion. In Arkansas, observers of overgrazed pastures found that manure piles on or near bare, compacted laneways were more readily washed away by runoff than were manure piles in more vegetated areas of the pasture (24).

The potential for animals to cause soil compaction increases with soil moisture, the weight of the animal, the number of animals in the paddock, and the amount of time animals stay in the paddock. The potential for a

paddock to resist compaction depends on the duration of forage establishment and the type of forage root system. Established forages with strong and prolific root growth in the top six to 10 inches of the soil profile are able to withstand treading by grazing animals. Grasses with extensive fibrous root systems, such as bermuda grass, are able to withstand trampling better than grasses like orchardgrass that have non-branching roots or legumes like white clover that have taproots (36). Bunch grasses expose more soil to raindrop impact than closely seeded non-bunch grasses or spreading herbaceous plants. However, these grasses enhance water infiltration by creating deep soil pores with their roots (3). Combining bunch grasses with other plant varieties can increase water infiltration while decreasing the potential for soil compaction and water runoff.

The risk of soil compaction can also be reduced by not grazing animals on paddocks that are wet or have poorly-drained soils. Instead, during wet conditions, graze animals on paddocks that have drier soils and are not adjacent to streams, rivers, seeps, or drainage ways. Soils that are poorly drained should be used only in the summer when the climate and the soil are relatively dry.

Compacted soils can recover from the impacts of compaction, but recovery is

slow. Periods of wet weather alternating with periods of dry weather can reduce compaction in some clay soils. Freezing and thawing decreases compaction in soils subjected to cold weather. Taproots are effective in breaking down compacted layers deep in the soil profile while shallow, fibrous roots break up compacted layers near the soil surface (37). Active populations of soil organisms also reduce soil compaction by forming soil aggregates and burrowing into the soil.

ORGANIC MATTER

NUTRIENT RELEASE FROM ORGANIC MATTER DECOMPOSITION

Manure and plant residues must be decomposed by soil organisms before nutrients in these materials are available for plant uptake. Soil organisms involved in nutrient decomposition require a balance of nutrients to break down organic matter efficiently. Manure and wasted forages are succulent ma-

Time required for organic matter decomposition is affected by:

- the carbon to nitrogen ratio of organic matter
- temperature
- moisture
- pH
- diversity of soil organisms

Table 10. Effects of 11 Years of Manure Additions on Soil Properties.

	Manure application rate (tons/acre/year)			
	<u>None</u>	<u>10 tons</u>	<u>20 tons</u>	<u>30 tons</u>
Organic Matter (%)	4.3	4.8	5.2	5.5
CEC (me/100g)	15.8	17.0	17.8	18.9
PH	6.0	6.2	6.3	6.4
Phosphorus (ppm)	6.0	7.0	14.0	17.0
Potassium (ppm)	121.0	159.0	191.0	232.0
Total pore space (%)	44.0	45.0	47.0	50.0

From Magdoff and van Es, 2000 (Reference #1)

materials that have high nitrogen content and a good balance of nutrients for rapid decomposition.

Dried grasses, such as forages that died back over winter or during a drought, or manure mixed with wood bedding, have lower nitrogen contents and require more time for decomposition. In addition, soil organisms may need to extract nitrogen and other nutrients from the soil to balance their diet and obtain nutrients not available in the organic matter they are decomposing. Composting these materials increases the availability of nutrients and decreases the potential for nutrient immobilization when materials are added to the soil. Temperature, moisture, pH, and diversity of soil organisms affect how rapidly organic matter is decomposed in the soil.

Nutrient release from organic matter is slow in the spring when soils are cold and soil organisms are relatively inactive. Many farmers apply phosphorus as a starter fertilizer in the spring to stimulate seedling growth. Even though soil tests may indicate there is sufficient phosphorus in the soil, it may not be readily available from organic matter during cool springs.



NUTRIENT HOLDING CAPACITY OF ORGANIC MATTER

Besides being a source of nutrients, soil organic matter is critical for holding nutrients against leaching or nutrient runoff. Stabilized organic matter or humus chemically holds positively-charged plant nutrients (cations). The ability of soil particles to hold these plant nutrients is called *cation exchange capacity* or *CEC*. Continual application of organic materials to soils increases soil humus (38) and enhances nutrient availability, nutrient holding capacity, and soil pore space.

SOIL AGGREGATES

Soil humus is most effective in holding water and nutrients when it is associated with mineral soil particles in the form of soil aggregates.

Soil aggregates are small, soft, water-stable clumps of soil held together by fine plant-root hairs, fungal threads, humus, and microbial gels. Aggregates are also formed through the activities of earth-



worms. Research has shown that several species of North American earthworms annually consume 4 to 10% of the soil and 10% of the total organic matter in the top 7 inches of soil (39). This simultaneous consumption of organic and mineral matter by earthworms results in casts composed of associations of these two materials. Earthworms, as well as dung beetles, incorporate organic matter into the soil as they burrow.

Besides enhancing the nutrient and water holding capacity, well-aggregated soils facilitate water infiltration, guard against runoff and erosion, protect against drought conditions, and are better able to withstand compaction than less aggregated soils. Since aggregated soils are more granular and less compacted, plant roots grow more freely in them, and air, water, and dissolved plant nutrients are better able to flow through them. These factors increase plant access to soil nutrients.

To enhance aggregation within pasture soils, maintain an optimum amount of forages and residues across paddocks, avoid the formation of bare areas, and minimize soil disturbance. Grazing can degrade soil aggregates by encouraging mineralization of the organic glues that

hold aggregates together. In areas with a good cover of plant residues, animal movement across pastures can enhance aggregate formation by incorporating standing dead plant materials into the soil (40).



SOIL pH

Soil mineralogy, long-term climatic conditions, and land-management practices affect soil pH. The acidity or alkalinity of soils affects nutrient availability, nitrogen fixation by legumes, organic matter decomposition by soil organisms, and plant root function. Most plant nutrients are most available for uptake at soil pH of 5.5 to 6.5. Legume persistence in pastures is enhanced by soil pH of 6.5 to 7.0. In low-pH or acid soils, aluminum is toxic to root growth; aluminum and iron bind phosphorus; and calcium is in a form with low solubility. In high-pH or alkaline soils, calcium carbonate binds phosphorus while iron, manganese, and boron become insoluble.

Application of some synthetic nitrogen fertilizers acidifies soils. Soil microorganisms involved in nitrification rapidly transform urea or ammonia into nitrate. This nitrification process releases hydrogen ions into the soil solution, causing acidification, which decreases nutrient availability, thus slowing the growth of plants and soil organisms. Nitrification also occurs in urine patches when soil microorganisms transform urea into nitrate.

Another fertilizer that acidifies the soil is superphosphate. Superphosphate forms a highly acid (pH 1.5) solution when mixed with water. The impact of this acidification is temporary and only near where the fertilizer was applied, but, in this limited area, the highly acid solution can kill rhizobia and other soil microorganisms (9).

The type and diversity of forage species in pastures can alter soil pH. Rangeland plants such as saltbush maintain a neutral soil pH. Grasses and non-legume broadleaf plants tend to increase pH, while legumes tend to decrease it. The impact of plant species on pH depends on the type and amounts of nutrients they absorb. Rangeland plants absorb equal amounts of cation (calcium, potassium, magnesium) and anion (nitrate) nutrients from the soil. Grasses and non-legume broadleaf plants absorb more anions than cations since they use nitrate as their primary source of

nitrogen. Legumes that actively fix nitrogen use very little nitrate; consequently, they reduce soil pH by taking more cations than anions (9). A combination of legumes and non-legumes will tend to stabilize soil pH.

Pasture soils should be tested regularly to determine soil nutrients, soil organic matter, and pH. Based on test results and forage nutrient requirements, management practices can adjust soil pH. Lime and organic matter increase soil pH and decrease soil acidity. Soil organic matter absorbs positive charges, including hydrogen ions that cause soil acidity (41). Lime increases soil pH by displacing acid-forming hydrogen and aluminum bound to the edges of soil particles and replacing them with calcium or magnesium. Limestone that is finely ground is most effective in altering soil pH since it has more surface area to bind to soil particles. All commercial limestone has label requirements that specify its capacity to neutralize soil pH and its reactivity, based on the coarseness or fineness of grind.

“Lime” refers to two types of materials, calcium carbonate and dolomite. Dolomite is a combination of calcium and magnesium carbonate.

Calcium carbonate is recommended for soils low in calcium; where grass tetany or magnesium deficiency is an animal health problem, dolomite limestone should be used. In sandy soils or soils with low to moderate levels of potassium, the calcium or magnesium in lime can displace potassium from the edges of soil particles, reducing its availability. Therefore, these soils should receive both lime and potassium inputs to

prevent nutrient imbalances.

The timing of nutrient additions to fields or pastures determines how effectively plants take up and use nutrients while they are growing and

Lime soils with calcium carbonate if the soil is low in calcium. Use dolomite limestone if grass tetany or magnesium deficiency is an animal health problem.

TIMING OF NUTRIENT ADDITIONS

setting seed. Different nutrients are important during different stages of plant development. Nitrogen applied to grasses before they begin flowering stimulates tillering, while nitrogen applied during or after flowering stimulates stem and leaf growth (9). However, fall nitrogen applications

for cool-season grasses are more effective and economical than spring applications. In most years, nutrient releases through mineralization are sufficient to stimulate forage growth in the spring. Applications of nitrogen in the late summer and fall allow cool-season grasses to grow and accumulate nutrients until a killing frost. This provides stockpiled growth for winter grazing (42).

Both potassium and phosphorus are important for increasing the nutrient quality of forages, extending stand life, and enhancing the persistence of desirable species in the forage stand (42). Phosphorus is critical for early root growth, for seed production, and for effective nitrogen fixation by legume nodules. Potassium is important during the mid-to-late growing season. It increases the ability of plants to survive winter conditions, by stimulating root growth and reducing water loss through stomata or leaf pores (43). It also is important for legume vigor and for enhancing plant disease resistance (42).

Nutrient uptake by plants corresponds to their growth cycle. Warm-season forages exhibit maximum growth during the summer, whereas cool-season forages exhibit maximum growth during the spring and early fall (32). Pastures containing a diverse combination of forages will use nutrients more evenly across the growing season while less-diverse pastures will show spikes in nutrient uptake requirements.

Legumes provide nitrogen to the pasture system through their relationship with the nitrogen-fixing bacteria, rhizobia. If nitrogen levels in the

Nitrogen fertilization depresses fixation by legumes since they require less energy to take up nitrogen from the soil than they need to fix nitrogen.

soil are low, newly planted legumes require nitrogen fertilization until rhizobia have developed nodules and are able to fix nitrogen. Once they start fixing nitrogen, nitrogen fertilization depresses fixation by legumes since they require less energy to take up nitrogen from the soil than they need to fix nitrogen. Legumes can fix up to 200 pounds of nitrogen per year, most of which becomes available to forage grasses in the following years. Phosphorus is essential for effective

nodule formation and nitrogen fixation. In acid soils, liming may make phosphorus already in the soil more available, thereby decreasing the need for fertilization.

As discussed above, the type of organic material added to the soil, as well as temperature, moisture, pH, and diversity of soil organisms, determines how rapidly soil organisms decompose and release nutrients from organic matter. Synthetic fertilizers are soluble and immediately available for plant uptake. Therefore, these fertilizers should be applied during periods when plants can actually use nutrients for growth. A lag time of two to 21 days may pass after fertilizers are applied before increased forage production is observed.

Organic material releases nutrients over a period of several years. On average, only 25 to 35% of the nitrogen in

manure is mineralized and available for plant use during the year of application. Another 12% is available in the following year, 5% in the second year

A lag time of two to 21 days may pass after fertilizers are applied before increased forage production is observed.

following application, and 2% in the third year (44). Manure deposited in pastures causes an increase in forage growth approximately 2 to 3 months after deposition, with positive effects on growth extending for up to two years (11). Alfalfa can supply approximately 120 pounds of nitrogen to crops and forages in the year after it is grown, 80 pounds of nitrogen during the following year, and 10 to 20 pounds in the third year (44). Because of this gradual release of nutrients from organic materials, continual additions of manure or legumes will compound the availability of nutrients over time. Accounting for nutrients available from previous years is critical for developing appropriate applications rates for manure and fertilizers during each growing season. Not accounting for these nutrients can result in unnecessary fertilizer expenses and risks of nutrient losses to the environment.

Nutrients from both organic and synthetic fertilizers can be lost through leaching, runoff, or erosion. The potential for nutrient losses is greatest if these materials are applied in the fall or winter, when plants are not actively growing

or during times when soils are frozen, snow-covered, or saturated. During times of high rainfall, nitrate may leach through the soil since it does not bind to soil particles. Rainfall also facilitates the transport of phosphorus to water bodies in runoff water or through artificial drainage tiles. Rainfall or snowmelt water flowing over bare soil causes soil erosion and the transport of nutrients attached to soil particles.

Table 11. Pasture Management Practices for Enhancing Nutrient Availability.

Ensure plant cover and diversity across pastures

- Use management practices that maintain a complete cover of forages and residues across pastures
- Combine bunch-grass species with a diversity of forage species, including plants with prostrate growth habit, to provide both good water infiltration and protection against erosion and soil compaction

Grazing management practices during wet weather

- Use well-drained pastures or a “sacrificial pasture” that is far from waterways or water bodies
- Avoid driving machinery on pastures that are wet or saturated
- Avoid spreading manure or applying fertilizers on soil that is saturated, snow-covered, or frozen

Ensure effective use of nutrient inputs

- Use management practices that encourage the even distribution of manure and urine across paddocks
- Rely on soil tests and other nutrient management practices when applying fertilizers and manure to pastures
- Account for nutrients available from manure and legume applications during prior years when developing fertilizer or manure application rates for the current year
- Sample the nutrient content of added manure to determine appropriate rates of application
- Choose the appropriate type of limestone to apply for pH adjustment based on calcium and magnesium needs and balances in pastures
- Either avoid the use of fertilizers that decrease soil pH or use lime to neutralize soils acidified by these fertilizers
- Apply nitrogen fertilizer in the fall to enhance the amount of forages stockpiled for winter grazing
- Apply sufficient phosphorus and potassium while limiting additions of nitrogen in order to favor growth of legumes in your pastures

Chapter 3

Nutrient Distribution and Movement in Pastures

Farmers and ranchers graze animals using a variety of management methods. In this document, *extensive grazing* refers to the practice of grazing animals continuously or for extended periods of time on a large land area. *Rotational grazing* is a management-intensive system that concentrates animals within a relatively small area (a paddock) for a short period of time — often less than a day for dairy animals. The animals are then moved to another paddock, while the first paddock is allowed to recover and regrow. Animals are moved according to a flexible schedule based on the herd size, the amount of land available, quality of forages in the paddock, and forage consumption. Grazing managers determine when and how long to graze animals in specific paddocks based on climatic conditions, soil characteristics, land topography, and the distance the paddock is from streams or rivers.

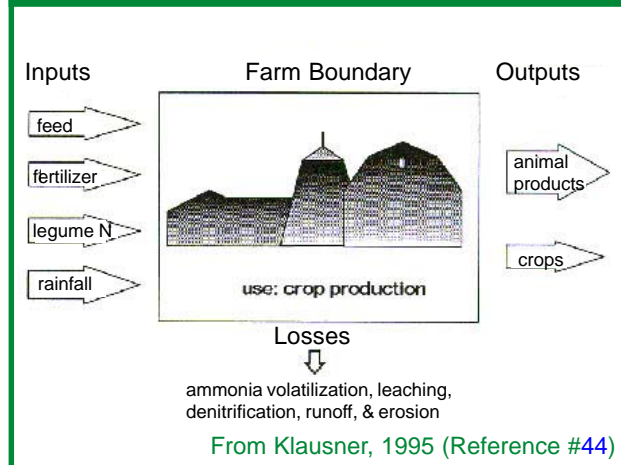
Pasture size, shape, and topography; stocking rate; grazing duration; and time of day all affect how animals graze, lounge, drink water, and use feed or mineral supplements. Also, different animal species vary in their use of nutrients and their herding behavior. These factors, along with soil characteristics, climate, and forage and soil management practices, affect nutrient cycling in pastures, animal growth and productivity, and potential of manure nutrients to contaminate ground or surface water.

PASTURE NUTRIENT INPUTS AND OUTPUTS

NUTRIENT BALANCES

Maintaining a balance between nutrients removed from pastures and nutrients returned to pastures is critical to ensure healthy and productive forage growth, as well as to control nutrient runoff and water-body contamination. Nutrient balances in pastures are determined by subtracting *nutrient removals* in the form of hay harvested, feed consumed, and animals sold, from *nutrient inputs* including feed, fertilizer, and manure.

Figure 7. Pasture Nutrient Inputs and Outputs.



Grazing animals that receive no mineral or feed supplements will recycle between 75 and 85% of forage nutrients consumed. If no fertilizer or outside manure inputs are applied, continual grazing will cause a gradual depletion of plant nutrients. Animals provided feed or mineral supplements also deposit 75 to 85% of the nutrients from these inputs as urine and feces (42). These nutrients represent an input into the pasture system. Nutrient inputs from non-forage feeds can be substantial for dairy and other animal operations that use a high concentration of grain and protein supplements, importing into the pasture approximately 148 lbs. N, 32 lbs. P, and 23 lbs. K per cow per year (42). Winter feeds also form a substantial input into the pasture nutrient budget when animals are fed hay while being kept on pasture.

MANURE DEPOSITION AND DISTRIBUTION

A cow typically has 10 defecations per day, with each manure pile covering an area of approximately one square foot (47). They will also urinate between eight and 12 times per day (48). Each urination spot produces a nitrogen application equivalent to 500 to 1,000 lbs./acre while each defecation represents a nitrogen application rate of 200 to 700 lbs./acre (42). An even distribution of nutrients throughout a paddock is required for productive plant and animal growth.

Table 12. Nutrient Consumption and Excretion by Grazing Animals.

	Dairy cows	Beef /Sheep
Feed consumption/day	18–33 lbs.	
Nutrients used for growth and reproduction	17% N 26% P	15 -25% N 20% P, 15% K
Nutrients removed from pasture in form of milk and meat	N 84 lbs./cow P 15 lbs./cow K 23 lbs./cow	N 10 lbs./cow-calf P 3 lbs./cow-calf K 1 lbs./cow-calf
Nutrients/ton manure	6–17 lbs.N 3–12 lbs.P ₂ O ₅ 2-15 lbs. K ₂ O	
Nitrogen content of feces	2.0–3.6%	3.4–3.6%
Nitrogen excreted as feces	55 lbs./year	
Nitrogen content of urine	0.42–2.16%	0.30–1.37%
Nitrogen excreted as urine	165 lbs./year	
From Stout, et al. (45), Detling (46), Russelle (17), Wells and Dougherty (47) , Haynes and Williams (41), Klausner (44), Lory and Roberts (42)		

Unfortunately, grazing animals do not naturally deposit urine and feces evenly across the paddocks where they graze. In one rotational grazing study, urine spots occupied 16.7% of the pasture, while manure spots occupied 18.8%, following 504 grazing days per acre (49). Intensity of grazing rotations affects the distribution of manure coverage in paddocks. Under continuous, extensive grazing practices, 27 years would be needed to obtain one manure pile on every square yard within a paddock; if a two-day rotation were used instead only two years would be needed (42).

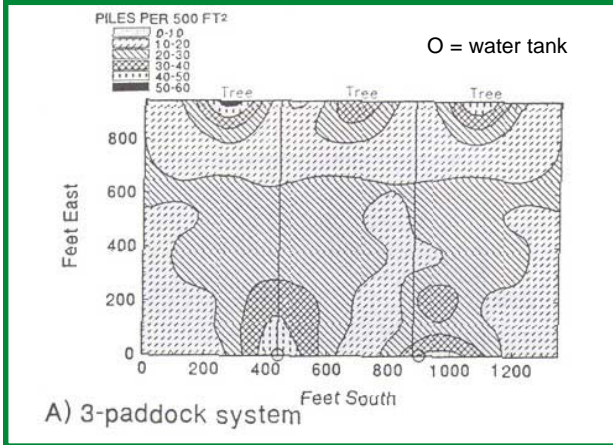
Nutrient concentration within pastures results from the tendency of grazing animals to congregate. They tend to leave manure piles or urine spots around food and water sources, on side hills, in depressions, along fence lines, and under shade. Sheep have a greater tendency than cattle to congregate and deposit manure in these areas (50). Prevailing wind direction and exposure to sunlight can also affect animal movement, congregation, and manure deposition (51). Laneways that connect pastures or lead to watering areas are another area of animal congregation and manure deposition. When animals have to walk more than 400 feet from the pas-

ture to water, they deposit between 13 and 22% of their manure on laneways (47, 52).

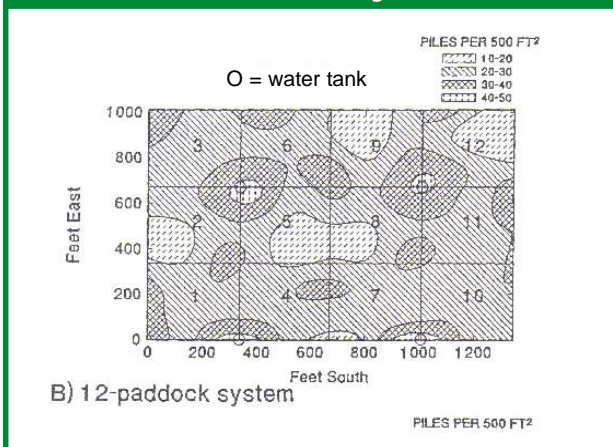
A study conducted in Iowa showed a buildup of nutrients extending 30 to 60 feet into the pasture around water, shade, mineral supplements, and other areas where cattle congregated (53). Nutrients are concentrated in these congregation areas because animals transport nutrients from areas where they graze. Consequently, they also deplete nutrients from the grazing areas. Grazing practices that encourage foraging and manure distribution across paddocks and discourage congregation in limited areas will improve nutrient balances within pastures.

The time of day when animals congregate in different areas determines the amount and type of nutrients that accumulate in each area. Animals tend to deposit feces in areas where they rest at night or ruminate during the day, while they urinate more in the areas where they graze during the day (47). Nitrogen is present in both feces and urine while phosphorus is primarily deposited as feces, and potassium is found mostly in urine. While most urine is deposited during the day, urine that is deposited at night has a higher nutrient content than urine deposited while grazing (41). As a result of these fac-

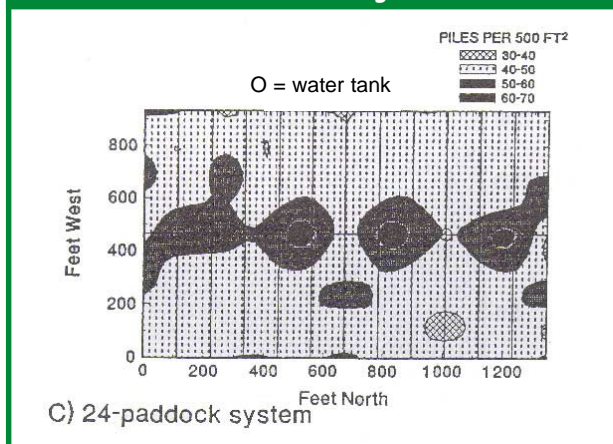
**Figure 8.
3-Paddock System.**



**Figure 9.
12-Paddock System.**



**Figure 10.
24-Paddock System.**



Manure deposition as affected by paddock size (from Peterson and Gerrish, Reference 52).

tors, phosphorus will accumulate in resting areas (13) while nitrogen and potassium will accumulate in both resting and grazing areas.

MINIMIZING ANIMAL CONGREGATION

By working with the normal foraging and herding behavior of grazing animals, distribution of animals across paddocks can be encouraged. In larger paddocks, animals tend to graze and lounge as a herd, while they distribute themselves more evenly across smaller paddocks (41). In larger paddocks, animals visit water, minerals, shade, and fly-control devices as a herd, whereas animals concentrated within small paddocks tend to visit these areas one-by-one. Locating nutrients, shade, and pest-control devices farther apart in the paddock further discourages concentration of animals and manure. If a particular area of a paddock is deficient in nutrients, placement of supplemental feeds in that area can be used to encourage congregation and manure deposition there.

Subdividing depressions, side hills, and shady areas among several paddocks can enhance nutrient distribution across the landscape. Research conducted in Missouri showed that manure nutrients were distributed more evenly across the landscape when a field was managed using 12 or 24 paddocks rather than only three paddocks (54). Animals in the smaller paddocks concentrated around favored areas for less time than did animals in larger paddocks. Since animals tend to graze along the perimeter of fence lines, they distribute nutrients most evenly across paddocks that are small, square, and have water available (55). An efficiently designed paddock allows animals to graze and drink with a minimum amount of time, effort, and trampling of the pasture sod.

MANURE NUTRIENT AVAILABILITY

While feces contain nitrogen predominantly in the organic form, 60 to 70% of cow-urine nitrogen and 70 to 80% of sheep-urine nitrogen is in the form of urea. Urea and potassium in urine are soluble and therefore immediately available for plant uptake. Phosphorus in feces is predominantly in the organic form and must undergo decomposition before it is available to plants. Soil

organisms will decompose moist, nitrogen-rich manure piles derived from succulent grasses relatively quickly. They will have difficulty breaking down manure derived from hay or older forages that is stiff, dry, and crusty. When a hard crust forms on manure piles during dry weather, both physical breakdown and biological decomposition are inhibited (41). By treading on manure piles as they move around a pasture, animals physically break these piles into smaller pieces that are more easily consumed by soil organisms.

Because nutrients are released slowly from manure, forage plants in the vicinity of manure piles will grow slowly for about two months following manure deposition (41, 42). However, as decomposition of manure piles by soil organisms makes nutrients available for plant use, greater pasture regrowth and forage production occurs in the vicinity of manure and urine compared to other pasture areas (49, 54, 56). Increases in nitrogen availability in areas near manure piles can favor the growth of grasses compared to legumes (9), an impact that can last for up to two years (41).

Animals naturally avoid grazing near dung sites, but will feed closer to manure piles (41) and use forages more efficiently as grazing pressure intensifies. In multispecies grazing systems, sheep do not avoid cattle manure as much as cattle do (57). While both sheep and cattle avoid sheep manure, the pellet form of sheep manure has a large surface area, and thus breaks down more rapidly than cattle manure. Consequently, forages are used more effectively when cattle are combined with sheep.

PASTURE FERTILIZATION

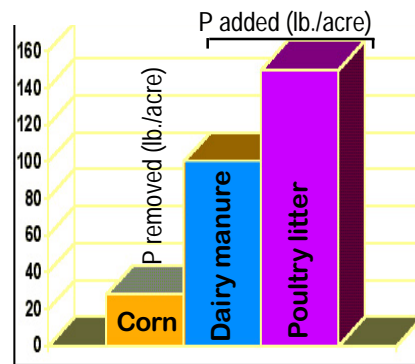
Manure and fertilizers are applied to pastures to provide nutrients necessary to obtain effective plant growth and animal production. Applications should be based on regular soil testing, the ability of soil to provide and retain nutrients, plant needs, grazing intensity, and nutrient removals through

Fertilizer and manure applications should be based on regular soil testing, the ability of soil to provide and retain nutrients, plant needs, and grazing intensity.

haying. Prior to the current concerns over water quality, manure application recommendations were made to meet forage needs for nitrogen. Continued nitrogen-based applications result in a phosphorus build-up in the soil since manure usually contains about the same concentration of phosphorus and nitrogen, while plants only require one-half as much phosphorus as nitrogen. In diverse pastures that contain a combination of grasses and legumes, decreasing or eliminating manure applications can lower phosphorus imbalances while maintaining forage yields. Nitrogen fixation by legumes helps satisfy forage nitrogen requirements while using excess soil phosphorus.

Figure 11. P Added in Manure/Removed by Crop.

Applying manure to meet the nitrogen needs of corn (about 200 lbs. N/acre) adds much more phosphorus than corn needs.



From Sharpley, et al. (Reference 58)

On some farms, manure is applied to soil as a waste product. Instead of being applied according to crop needs, manure is primarily applied according to the need to dispose of manure, the location of fields in relation to the barn, and the accessibility of fields during bad weather. These “waste application” practices present a high potential for nutrient buildup and movement of excess nutrients to ground or surface waters.

To ensure that manure is used effectively as a source of plant nutrients and poses minimal risks to the environment, it should be applied according to a nutrient management plan. Natural Resources Conservation Service or Soil and Water Conservation District personnel, as well

as many commercial crop consultants, are trained in the development of nutrient management plans. Software programs to develop your own nutrient management plan may be available from Cooperative Extension Service educators or Agronomy and Soil Science specialists at land grant universities.

Table 13. Components of a Comprehensive Nutrient Management Plan.

Components of a Comprehensive Nutrient Management Plan

- Soil tests on all fields or paddocks
- Manure tests
- Load-capacity and rate-of-application of manure spreading equipment
- Timing and method of manure and fertilizer applications
- Prior land management practices including manure applications, legumes used as green manures, fallows, or hay removal
- Assessments of runoff, erosion, and flooding potentials for each field or paddock
- Crops or forages to be produced
- Current pasture management practices, including stocking rates and hay removal

Format of a nutrient management plan for each paddock or field

- Soil and manure test results
- Risk factors such as excess nutrient levels, or high runoff, erosion, or flooding potential
- Recommended time, method, and rate for fertilizer and manure applications
- Recommended time for grazing, especially on pastures with moderate to high potentials for runoff, erosion, or flooding
- Management practices to minimize risk factors and maximize nutrient availability to forages

GRAZING INTENSITY

DEFINITION

Grazing intensity refers to the impact animals have on forage growth and reproduction and on soil and water quality. It is influenced by animal foraging habits, stocking rates, the length of time animals are allowed to graze within a given paddock, and the relation these factors have to soil characteristics and climatic conditions. Continuous high-intensity grazing depletes soil nutrients, decreases the diversity of forage species, inhibits the ability of some forage plants to regrow and reproduce, and increases the potential for nutrient runoff and erosion. Conversely, short-term high-intensity grazing combined with a resting period (as in rotational grazing practices) causes an increase in the diversity of forage spe-

Short-term high-intensity grazing combined with a resting period (as in rotational grazing practices) causes an increase in the diversity of forage species, enhances the dispersal of forage seeds, and helps conserve nutrient resources within the soil-plant system.

cies, enhances the dispersal of forage seeds, and helps conserve nutrient resources within the soil-plant system.

GRAZING BEHAVIOR, PLANT GROWING POINTS, AND PLANT LEAF AREA

Grazing habits of different animal species have different impacts on forage species composition in pastures. For example, horses graze more closely to the ground than cattle; sheep graze at soil level and can take away the base of grass plants below the area of tiller emergence (59); while cattle tend to graze taller grasses that sheep may reject. Animal grazing behavior, the location of a plant's growing point, and the amount of

leaf area remaining when animals are rotated to another pasture affect the ability of plants to regrow. If grazing animals remove the growing point and substantial leaf area of grasses, new leaf growth must come from buds that have been dormant and the energy for this growth must

come from stored carbohydrates rather than from photosynthesis (60).

Early in the growing season, all grasses have their growing points at or near ground level. Ryegrass, tall fescue, Kentucky bluegrass and many other species of cool-season grasses have growing points that remain at or below ground level throughout most of the growing season. Other, predominantly native, grass species — including smooth broomgrass, timothy, reed canarygrass, switchgrass, and gamagrass — have stems that elongate below the growing point above the soil level (60). As long as the growing point remains intact, the plant is capable of producing new leaves. Grasses with low growing points are able to recover from grazing relatively quickly because the growing point is not disturbed. If the growing point is removed, growth recommences from the emergence of new tillers. Under continuous, intensive grazing practices, warm-season grasses recover more slowly than cool-season grasses, especially during the spring (61). As a result, continuous grazing practices or grazing too early in the season tends to favor the growth of non-native grasses and decrease the diversity of forages in pastures (62).

Continuous grazing tends to favor the growth of cool-season grasses since grazing animals remove the elevated growing points of native warm-season grasses more readily than they remove the lower growing points of non-native, cool-season grasses.

For areas with moderate rainfall, leaf area remaining after grazing is more critical for forage recovery than the location of a forage plant's growing point (J. Gerrish, personal communication). Most forbs and legumes, such as alfalfa and red clover, have aerial growing points relatively high up on the plant, which are easily removed by grazing animals. This is not detrimental to plant growth unless a majority of the leaf area or the basal portion of the plant is removed. For optimal recovery, at least 3 to 4 inches of residual leaf area should remain on cool-season grasses while 4 to 8 inches of leaf area should remain for warm-season grasses following grazing (61). Other factors that affect plant regrowth

include treading impact on leaf and root growth, forage composition impact on the ability of plants to intercept sunlight for photosynthesis, and soil conditions (35).

NUTRIENT UPTAKE

Forage plants that are cut or regrazed frequently during the growing season take up more nutrients than forages that are not cut or grazed. Research conducted in Kansas indicated that cutting pasture forage six times during the growing season resulted in 4.3 times greater nitrogen content and 5.2 times greater phosphorus content in cut forages compared to uncut plots (63). Cutting pastures in the spring when seed heads are forming can also increase the productivity and nutrient uptake of pasture forages (64). Other studies (56, 65) demonstrated that increased grazing intensity resulted in younger, more succulent plants with a higher nitrogen content compared to plants growing in ungrazed areas. The higher nitrogen content was attributed to return of nitrogen to the system through urine and to the availability of nitrogen fixed by legumes. In these studies legumes remained prevalent in the more intensely grazed plots while their populations decreased in the more lightly grazed paddocks (65).

YIELD

During the first year of intensive grazing, increasing the intensity of cutting or grazing increases the amount of forage produced. Following grazing, photosynthesis is stimulated and plants take up more nutrients. This permits leaf regrowth in broadleaf plants and increased tillering in grasses. Increased leaf area then allows for greater photosynthesis. As photosynthesis and the formation of carbohydrates increase, nutrient uptake by roots and subsequent movement of nutrients from roots to leaves also increase. However, as more energy and nutrients are allocated to leaf production and increased photosynthesis, less energy and nutrients are provided for root growth (63).

Frequently grazed plots exhibit high biomass production and nutrient uptake during the initial grazing season. But if grazing intensity is too great, forage production will decrease in the following years.

While frequently mowed or grazed plots exhibit high biomass production and nutrient uptake during the initial grazing season, if the intensity of grazing is too high, forage production will decrease in following years (63, 66). This production decline results from decreased plant ability to take up nutrients because of decreased root growth and depletion of soil nutrients. Severe grazing will also impact plant diversity, since grazing during flowering removes seed heads and flowers, limiting the reseeding of forage plants (64).

A sufficient resting period allows plants to regrow and produce adequate leaf area for photosynthesis. It also allows plants and soil organisms to reduce soil compaction and increase the availability of nutrients through mineralization.

Root growth is critical for water and nutrient uptake. Plants can also store food reserves in roots to allow for regrowth during periods of stress. Plants grazed too frequently or cut too short have difficulty producing more leaves because of limited growth and food reserve storage by roots. In one study, plants that were not cut until they reached eight inches tall produced more growth than plants cut every time they reached two inches tall. Similarly, grasses subjected to continuous intensive grazing by sheep produced less vegetation than lightly grazed pastures. In both cases, a longer resting period resulted in better plant growth, since the resting period allowed plants to regrow and produce adequate leaf area for photosynthesis (63). Grass tiller population and pasture production markedly increased in an extensively grazed pasture that was fallowed for one year. This resting period allowed plants and soil organisms to reduce soil compaction and increase the availability of nutrients through mineralization (67).

Cutting grasses short not only depresses plant regrowth, it also increases soil temperature. As soil temperature increases so does nutrient mineralization by soil organisms. While mineralization is necessary to release nutrients from plant and animal residues, if mineralization is too rapid, it can cause a loss of organic matter

(65). Grazing or cutting pastures too short can also expose bare soil to the impact of rainfall, increasing the potential for soil compaction and the loss of topsoil and nutrients through erosion. Nutrient cycling and effective nutrient use by plants depend on pasture management practices that minimize soil compaction, conserve organic matter, and do not hinder plant regrowth following grazing.

Nutrient cycling and effective nutrient use by plants depend on pasture management practices that minimize soil compaction, conserve organic matter, and do not hinder plant regrowth following grazing.

The nutrient content of forage plants affects animal feeding habits, the amount of nutrition animals obtain, and the type of manure they produce. Succulent, nutritionally balanced pastures provide good animal productivity and cause animals to deposit moist manure piles (36). Animals feeding on dry, older, or overgrazed forages will obtain limited nutrient value. Manure piles produced from these forages will be stiff because of their high fiber content. Dry, stiff manure piles are difficult for soil organisms to decompose since there is little air within the pile (68). Conversely, animals often deposit very liquid manure as they begin feeding on pastures in the spring after a winter of eating hay. The high moisture content of the pasture forages results in a very wet manure pile that disperses across the soil. Soil organisms are able to decompose manure that has relatively high nitrogen and moisture content more readily than manure that is drier and more carbon-rich.

DIVERSITY AND DENSITY OF PASTURE PLANTS

Diverse forage mixtures of both broadleaved plants and grasses use solar energy efficiently. The shape and orientation of plant leaves affect how and when the plant can best conduct photosynthesis. Tall plants and upright grasses cap-

ture light at the extreme angles of sunrise and sunset while horizontal leaves of broadleaf plants use sunlight better at midday. A combination of tall sun-loving plants with shorter shade-tolerant plants allow for the capture of both direct and filtered sunlight. A combination of warm- and cool-season grasses allows for effective photosynthesis throughout the growing season. Warm-season grasses like big bluestem are better able to grow and use solar energy at temperatures between 90 and 100°F, while cool-season grasses like tall fescue grow best between 75 and 90°F (32).

PERSISTENCE OF PASTURE LEGUMES

Maintaining legumes as part of the forage mix is necessary if nitrogen fixation is to provide most of the nitrogen input to the pasture system. Legumes with a deep taproot and a woody crown, such as alfalfa, red clover, and birdsfoot trefoil, are able to persist in a well-drained pasture because they are able to obtain water and nutrients from deep below the soil surface. They also tolerate drought and cold, and are able to regrow unless their growing points are elevated and exposed to defoliation. Rotational grazing has been shown to increase the proportion of red clover and alfalfa in mixed pastures (69).

White clover has rhizomes rather than a taproot. This growth habit allows it to colonize bare soils (64) by forming additional plants through the growth of stolons.

White clover is competitive with grass at low production densities while legumes with taproots are more competitive at high production densities (70).

The diversity of forage species also affects the persistence of legumes within a pasture. When six to eight forage species were planted

Timing of grazing affects species composition and diversity in pastures.

together in a Missouri pasture, pasture plant diversity remained high after three years of grazing. Pastures with a diversity of forage species also maintained a higher

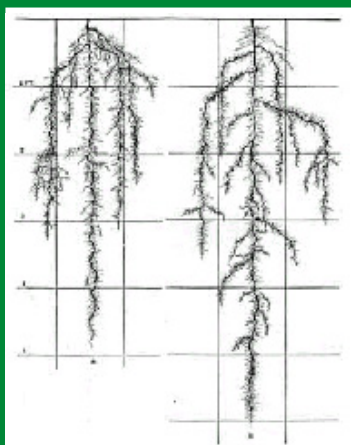
percentage of forage cover during this time than pastures planted to monocultures or simple mixtures of forages (72). Productivity within pastures is more stable when forages provide a diversity of function and structure, such as height, root growth habit, life cycle, and habitat requirements (4).

Nitrogen transfer between grasses and legumes is greatest when there is a close population balance between these species and they are growing close together.

Nitrogen fixation is directly related to the ability of legumes to accumulate energy through photosynthesis. Thus, leaf removal decreases nitrogen fixation, and leaf regrowth increases the potential for nitrogen fixation. Legumes not only fix nitrogen for their own needs, but are also able to supply nitrogen to non-nitrogen-fixing forage crops. They primarily supply nitrogen to forage plants following decomposition. Pastures dominated by clover produce around 200 pounds nitrogen per acre per year through nitrogen fixation.

Legumes can also provide nitrogen to companion grass species during the growing season. In New Zealand, perennial ryegrass obtained 6 to 12% of its nitrogen from associated white clover. Alfalfa and birdsfoot trefoil provided up to 75% of the nitrogen used by reed canarygrass in Minnesota. This nitrogen transfer occurs when roots die, nodules detach, or neighboring grasses and legumes become interconnected by their roots or through mycorrhizae. Nitrogen transfer between grasses and legumes is greatest when there is a close population balance between these species and they are growing close together (15). In the first year of legume establishment, nitrogen transfer is relatively low and is derived predominantly from nodule decomposition; it increases in the second year as direct-transfer mechanisms through mycorrhizae become established (14).

**Figure 12.
Root Growth.**



Root growth of alfalfa under irrigated (left) and dry (right) conditions (Weaver, Reference 71).

NUTRIENT USE EFFICIENCY

A diverse plant community uses soil nutrients more effectively than a monoculture or simple plant mixtures. Native grasses have a lower requirement for nitrogen and subsequently a lower concentration of nitrogen in their leaf tissue compared to non-native cool-season grasses. As a result, these grasses thrive under low nutrient conditions but they provide lower-quality feed and recycle nutrients more slowly back to the soil system. The low nitrogen content of the plant litter results in slow decomposition, immobilization of nitrogen by organisms involved in decomposition, and a decrease in the nitrogen available for plant uptake.

Just as a diverse plant canopy covers the entire soil surface, a diversity of root systems occupies the entire soil profile.

Broadleaf plants require higher nitrogen inputs for productive growth and have higher nitrogen content in their plant tissues than grasses

(73). Due to their high nitrogen content, decomposition of residues from these plants stimulates the mineralization or release of nutrients into the soil solution. Cool-season and warm-season forages grow and take up nutrients at different times of the year. A combination of cool- and warm-season forages ensures a relatively even uptake of nutrients throughout the growing season.

Just as a diverse plant canopy covers the entire soil surface, a diversity of root systems occupies the entire soil profile, from the soil surface down as far as 15 feet. Grasses generally have fine bushy roots. Legumes such as alfalfa or red clover have taproots. Some plants have longer or deeper root systems while other plants have a root system that grows primarily in the surface soil. Pastures that contain plants with a diversity of root systems will be better able to harvest and use nutrients from the soil than a less diverse community. Plants with more shallow roots are effective in recycling nutrients released through the decomposition of thatch and manure on the soil surface, while deep-rooted plants are able to scavenge nutrients that have been leached down through the soil profile.



Manure is unevenly distributed, concentrated near the fence line

Table 14. Enhance Nutrient Balances within the Farm and across Paddocks.

Balance nutrient inputs and outputs

- Replenish nutrients removed by grazing animals
- Recognize that feed supplements, particularly for dairy cows, represent significant nutrient inputs onto farms
- Replace nutrients based on a comprehensive nutrient management plan that takes into account prior manure additions, nitrogen contributions from legumes, and soil tests
- Apply manure based on the phosphorus needs of forages in order to avoid phosphorus build up on pastures; rely on legumes to supply much of the nitrogen needed for forage growth

Promote even distribution of manure nutrients across paddocks

- Subdivide pastures to distribute congregation areas among several paddocks
- Keep paddock dimensions as close to square as possible
- Provide animals with water in every paddock; avoid use of laneways to access water
- Locate nutrient supplements, shade, water, and pest-control devices far apart from one another

Enhance nutrient availability

- Enhance growth of soil organisms involved in the decomposition of manure by maintaining good soil quality and minimizing use of soil-applied insecticides and high-salt fertilizers
- A combination of cattle and sheep enhances the amount of land available for grazing since sheep graze closer to cattle manure than cattle do and feed on coarser vegetation than cattle will use

Encourage a diversity of forage species within paddocks

- Maintain a diversity of forages representing a variety of leaf and root growth habits, life cycles, and habitat preferences
- Rotate pastures while at least 4 inches of the leaf area remains. This allows plants to regrow rapidly and roots to recover
- Maintain a high percentage of legumes in the forage mix by not overgrazing and by minimizing nitrogen fertilizer additions
- Provide paddocks with sufficient rest time to allow forages to regrow

Chapter 4: The Soil Food Web and Pasture Soil Quality

DIVERSITY OF THE SOIL FOOD WEB

Soil organisms play a critical role in nutrient cycling. Not only are they responsible for decomposing organic matter, forming soil aggregates, solubilizing mineral nutrients, and adjusting soil pH; they are also responsible for nitrogen fixation, nitrification, phosphorus uptake through mycorrhizae, degradation of soil minerals, and formation of plant hormones. A healthy soil contains millions of or-

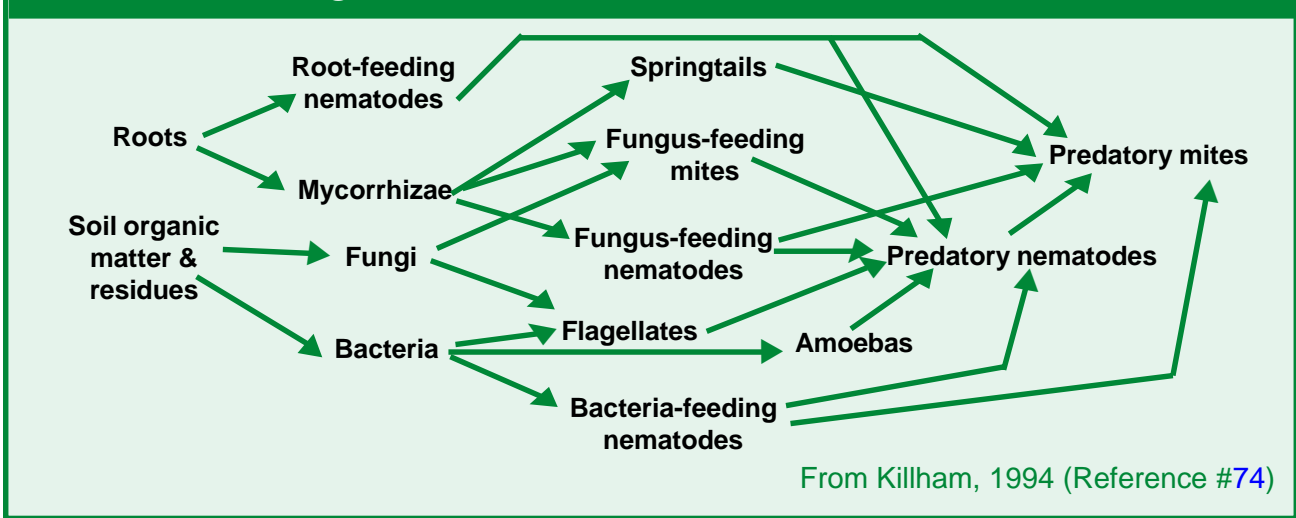
Soil food web refers to the network of dynamic interactions among these organisms as they decompose organic materials and transform nutrients.

ganisms, ranging from visible insects and earthworms to microscopic bacteria and fungi. An acre of living soil may contain 900 pounds of earthworms, 2400 pounds of fungi, 1500 pounds of bacteria, 133 pounds of protozoa, and 890 pounds of arthropods and algae, as well as small mammals. The term *soil food web* refers to the network of dynamic interactions among these organisms as they decompose organic materials and transform nutrients.

While some of the organisms in this diverse community are plant pests, many more serve as antagonists of plant pests and diseases. Other soil organisms, particularly bacteria, are able to use toxic chemicals, such as pesticides, as a source of food. As they consume these toxic chemicals, they break them down into substances, such as carbon dioxide, water, and atmospheric nitrogen, that are either non-toxic or less-toxic to plants, animals, and humans.

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Figure 13. Foodweb of Grassland Soil.



ORGANIC MATTER DECOMPOSITION

SOIL ORGANISMS

Many soil organisms are involved in the decomposition of organic matter. Larger soil organisms, including small mammals, insects, and earthworms, are *primary decomposers*, involved in the initial decomposition and cycling of nutri-

ents. Primary decomposers make greater use of carbon than of nitrogen in their growth and respiration processes. As a result, the feces and casts deposited by them have a lower carbon content and a lower ratio of carbon to nitrogen than the original organic matter. By transforming organic matter into a simpler chemical form as well as physically breaking it down into smaller pieces, primary decomposers make these materials more available to microorganisms or *secondary decom-*

posers for further breakdown. Because the dead bodies of earthworms and insects are high in nitrogen, they are easily decomposed by soil microorganisms (75). Fungi and bacteria are predominant secondary decomposers, but algae, protozoa, amoebas, actinomycetes, and nematodes also play important roles in transforming soil nutrients.

The chemistry of organic materials and environmental conditions determines how rapidly organic matter is broken down, which soil organisms are involved in the decomposition process, and whether organic matter decomposition will cause an initial decrease or increase in available nutrients. The soil environment determines which soil organisms are dominant and which soil organisms are less active. Some bacterial species thrive under flooded, anaerobic conditions but most soil organisms require access to oxygen. Earthworms and some soil insects require soil that is aggregated and relatively uncompacted so they can burrow through it. Environments with limited nitrogen availability are dominated by organisms that are able to fix nitrogen from the atmosphere, such as algae, lichens, and rhizobia associated with legumes. Many soil organisms are killed by non-specific insecticides as well as by highly concentrated fertilizers such as anhydrous ammonia.

As discussed previously, organic materials that are old or woody, such as tree branches, old roots, or dried grass, contain a large amount of carbon compared to nitrogen. To decompose these materials, soil organisms may need to extract nitrogen from the soil solution in order to balance their carbon-rich diet, thus temporarily reducing the amount of nitrogen available for plant use. Young, succulent, “first-growth” plant materials, fresh manure, and materials that have gone through primary decomposition processes by larger soil organisms contain a higher concentration of nitrogen in relation to carbon. Soil organisms more readily decompose these materials and make the nutrients in them available for plant uptake.

The type of organic matter will influence the type of soil organisms involved in the decomposition process. As each decomposer feeds, it uses some nutrients for its own growth and reproduction and releases other nutrients into the soil solution where they are available for plant growth and production. Decomposer organisms may also excrete organic materials that can either be

further broken down by other soil organisms or become part of the soil humus.

In general, bacteria require more nitrogen in order to break down organic matter than do most fungi. Fungi are the dominant decomposer in forest environments since they require less nitrogen in their diet and are able to feed on woody, older, or more

fibrous materials. They are also able to survive and replicate in environments that are less moist than those required by bacteria. Bacteria are more prevalent in garden and pasture environments because they require higher amounts of nitrogen and moisture, and because they feed readily on fresh manure, young grasses, legumes, and other easy-to-decompose materials (10).

The chemistry of organic materials and environmental conditions determines:

- **how rapidly organic matter is broken down**
- **which soil organisms are involved in the decomposition process**
- **whether nutrient availability will increase or decrease in the short term**

PRIMARY DECOMPOSERS

Earthworms are primary decomposers of leaf litter and manure piles. Research conducted in Denmark showed that earthworms were responsible for 50% of the breakdown and disappearance of cow manure, while dung beetle larvae accounted for between 14 and 20% (76). These organisms also consume fresh organic materials, then deposit their feces in the soil. When they burrow, they move manure and other organic

Earthworms and dung beetles are visible indicators of soil health: their presence shows that nutrient decomposition processes are occurring and the soil food web is effectively operating.

materials into the soil, where it is more accessible to other organisms involved in decomposition. Burrowing organisms also aerate the soil. Good aeration promotes the growth of the majority of organisms involved in organic matter decomposition. For this reason, earthworms and dung beetles are visible indicators of soil health: their presence shows that nutrient decomposition processes are occurring and the soil food web is effectively operating.

EARTHWORMS

According to research studies, the weight of earthworms in the soil is directly related to pasture productivity (77). In healthy soils with abundant earthworms, these organisms consume between 65 and 80 tons of manure per acre per year (39). Earthworms also break down pasture thatch and incorporate organic matter from the thatch into the soil. Where few or no earthworms are present, pastures develop a thick thatch layer, slow rates of organic matter decomposition, and a poor crumb structure (39).



Decomposition of organic matter by earthworms speeds up the breakdown and release of plant nutrients, particularly nitrogen and phosphorus. Earthworms consume low-nitrogen plant materials as well as high-nitrogen manure (39). Under pasture conditions, earthworms have been shown to mineralize 10 pounds per acre per year of phosphorus in their casts (5). Earthworms also facilitate the transformation of straw and leaf litter into soil humus (78). The earthworm gut combines decomposed organic matter with particles of mineral soil and microorganisms, forming soil aggregates and humus-coated soil minerals.

Through their feeding and burrowing activities, earthworms move organic matter through the soil enhancing soil aeration, water infiltration, and soil structure. They also improve root growth by creating channels lined with nutrients (79) and help till the soil. They can completely

Through their feeding and burrowing activities, earthworms

- break down large residues
- produce nutrient-rich casts
- move organic matter through the soil
- enhance soil aeration, water infiltration, and soil structure
- improve root growth

mix the top six inches of a humid grassland soil in 10 to 20 years (80).

Factors that contribute to an abundant population of earthworms include inputs of fresh organic matter, a medium-textured soil, thick topsoil, a near-neutral pH, moist but well-aerated soil, and moderate temperatures. Tillage, acid-producing fertilizers, insecticides, and poorly-drained soils inhibit earthworm survival (79).

DUNG BEETLES

Dung beetles improve nutrient cycling, enhance soil aeration, and improve forage growth while feeding on manure and using it to provide housing and food for their young. Adult dung beetles

An adequate population and mix of dung beetle species can remove a complete dung pile from the soil surface within 24 hours.

are drawn to manure by odor. They use the liquid contents for nourishment and the roughage to form a brood ball in which the female lays a single egg. This brood ball is buried in the soil where the larva grows, eating about 40 to 50% of

the interior contents of the ball while depositing its own excrement. After the larva emerges, secondary decomposers readily break down the remaining dung ball (81).

An adequate population and mix of dung beetle species can remove a complete dung pile from the soil surface within 24 hours (82).

This process decreases the potential for ammonia volatilization and nutrient runoff while making manure nutrients available to secondary decomposers within the soil profile. While moving dung into the soil, dung beetles create tunnels that enhance soil aeration and water infiltration. Dung removal also increases forage availability, since it minimizes the areas that animals are avoiding because of the presence of manure.



Environmental conditions that enhance activities of dung beetles include adequate soil moisture levels and warm temperatures. Dung beetle larvae are susceptible to some insecticides used for fly and internal-parasite control for cattle. Both injectable and pour-on formulations of Ivermectin (Ivomec and Doramectin), applied to cattle at the recommended dosages, reduce survival of the larvae for one to three weeks. However, when administered as a bolus, effects on dung beetle populations last up to 20 weeks (83).

SECONDARY DECOMPOSERS

Soil organisms are not only responsible for the mineralization and release of nutrients from organic material; they are also important for retaining nutrients in the soil, improving soil structure through the formation of aggregates and humus, degrading toxic substances, and suppressing diseases. Nutrients held in the bodies of soil organisms gradually become available for plant uptake and meanwhile they are protected against being lost through leaching, runoff, or other processes. Soil organisms involved in nutrient cycling release nutrients as they defecate and die. While they are still alive, these organisms conserve nutrients within their bodies.

Soil microorganisms are responsible for

- mineralizing nutrients
- retaining nutrients in the soil
- forming aggregates
- degrading toxic substances
- suppressing diseases

BACTERIA AND FUNGI

Bacteria and fungi are the most prevalent soil organisms. Bacterial decomposers feed on root exudates as well as on plant litter and manure. Maintaining actively growing soil roots provides a nutrient-rich habitat for the growth of many bacterial species. Some species of bacteria are able to detoxify pollutants while other species, particularly rhizobia and cyanobacteria (“bluegreen algae”), are able to fix nitrogen. Bacterial gels are an important component of soil aggregates. Fungi decompose complex or more

carbon-rich forms of organic matter. They also form soil aggregates by binding them with fungal threads or *hyphae*.

Mycorrhizal fungi enhance the nutrient and water uptake of plants by extending the length and surface-area of root uptake.

In dry rangelands, crusts composed of green algae, bacteria, cyanobacteria, lichens, and fungi form over

the soil surface. These crusts provide surface cover, erosion control, and soil aggregation. They are also involved in nitrogen fixation and nutrient decomposition. Crust organisms are most active during the cooler, moister part of the year when plant cover is minimal (2).

AMOEBAS, NEMATODES, AND PROTOZOA

Amoebas, nematodes, and protozoa feed on bacteria and fungi. Nematodes may consume up to 25% of the bacteria in the soil (84). According to one study, nematodes feeding on bacteria accelerated litter decomposition by 23% (85). Both protozoa and nematodes release nutrients to the soil system, making them available to plants and other soil organisms.

MUTUALISTIC RELATIONSHIPS

In undisturbed ecosystems, plants and soil organisms have coevolved to form mutualistic relationships. Plants provide carbohydrates and other nutrient-rich substances through their root system, providing an excellent source of food for soil organisms. As a result, populations of soil organisms involved in nutrient decomposition are greatest next to plant roots (85). These organisms provide plants with nutrients necessary for their growth, produce hormones and other chemicals that improve plant vigor, and protect the plant against diseases. When the plant’s need for nutrients is low, soil organisms will hold nutrients in their bodies rather than release them into the soil solution (10). This mutualistic relationship is disturbed by cultivation and harvesting. When plant roots are removed, populations of soil organisms decrease since they no longer have a source of nourishment and habitat.



SOIL ORGANISMS AND SOIL HEALTH

Soil health refers to the ability of soils to function as a productive environment for plant growth, an effective filter, and an efficient regulator of water flow. Soil mineralogy and chemistry form the basis for soil composition and soil health. However, much of soil health and function depends on an active community of diverse soil organisms. Nutrient cycling, aggregate for-

mation, degradation of toxins, creation of soil pores, and absorption of water and nutrients are all functions of soil organisms.

The activities of soil organisms serve as effective indicators of current land productivity and its ability to withstand degradation. By monitoring these indicators, farmers, soil conservationists, and other land managers can implement appropriate practices to minimize soil or nutrient losses, enhance nutrient cycling, and increase plant productivity. The Soil Quality Institute has taken the lead in developing and promoting the use of soil health indicators (86).

Table 15. Pasture Soil Health Card.

Indicator	Good	Medium	Poor
Pasture cover	Complete cover of forages and litter over entire pasture.	Limited bare patches. No extensive bare areas near drainage areas.	Extensive bare patches especially near watering or other congregation areas.
Plant diversity	Diversity of plant species, including forbs, legumes, and grasses, and differences in leaf and root growth habits.	Limited number of species and limited diversity of growth habit. Some invasive plants present.	Less than three different species, or invasive species are a major component of the plant mix.
Plant roots	Abundant vertical and horizontal roots.	More horizontal roots than vertical.	Few roots; most are horizontal.
Soil life – macroorganisms	Many dung beetles and earthworms present.	Few dung beetles and earthworms present.	No dung beetles or earthworms present.
Soil compaction	Wire flag enters soil easily, and does not encounter hardened area at depth.	Wire flag pushed into soil with difficulty, or encounters hardened area at depth.	Wire flag cannot be pushed into soil.
Erosion	No gullies present; water running off pasture is clear.	Small rivulets present; water running off pasture is somewhat muddy.	Gullies present; water running off pasture is very muddy.
Soil aggregation	Soil in clumps; holds together when swirled in water.	Soil breaks apart after gentle swirling in water.	Soil breaks apart within one minute in water.
Water infiltration	Water soaks in during moderate rain; little runoff or water ponding on soil surface.	Some runoff during moderate rainfall, some ponding on soil surface.	Significant runoff during moderate rainfall; much water ponding on soil surface.

Adapted from the Georgia, Mon-Dak, and Pennsylvania Soil Health Cards (86) Sullivan (88) and USDA (89).

Qualitative “farm-based” and “farmer friendly” indicators are incorporated into soil health cards specific to location and farming practice (87). These cards can be used to monitor the relative health and productivity of soils, identify areas

of concern, and enhance awareness of the relationships between soil health and crop production. Below is a soil health card for pastures based on a compilation of indicators from soil health cards developed in various locations.

Table 16. Soil Organisms.

Bacteria – the most numerous microorganism in the soil. Every gram of soil contains at least a million of these tiny one-celled organisms. Decompose simple or nitrogen-rich organic matter. Require moist environments. Also responsible for nitrogen fixation, soil aggregate formation, and detoxification of pollutants.

Actinomycetes – thread-like bacteria, which look like fungi. They are decomposers and are responsible for the sweet, earthy smell of biologically active soil.

Fungi – multicellular microorganisms that usually have a thread-like structure. Mycorrhizae form extensions on roots, increasing their ability to take up nutrients and water. They also transport nitrogen from legumes to grasses. Yeasts, slime molds, and mushrooms are other species of fungi.

Algae – microorganisms that are able to make their own food through photosynthesis. They often appear as a greenish film on the soil surface following a rainfall.

Protozoa – free-living animals that crawl or swim in the water between soil particles. Many soil protozoan species are predatory and eat other microorganisms. By feeding on bacteria they stimulate growth and multiplication of bacteria and the formation of gels that produce soil aggregates.

Nematodes – small wormlike organisms that are abundant in most soils. Most nematodes help decompose organic matter. Some nematodes are predators on plant-disease-causing fungi. A few species of nematodes form parasitic galls on plant roots or stems, causing plant diseases.

Earthworms – multicellular organisms that decompose and move organic matter through the soil. Earthworms thrive where there is little or no tillage, especially in the spring and fall, which are their most active periods. They prefer a near neutral pH, moist soil conditions, an abundance of plant residues, and low light conditions.

Other species of soil organisms – Many other organisms, including dung beetles, sowbugs, millipedes, centipedes, mites, slugs, snails, springtails, ants, and birds facilitate nutrient cycling. They make residues more available to smaller organisms by breaking them down physically and chemically and by burying them in the soil.

Table 17. Pasture Management Practices to Maintain a Healthy Soil Food Web.

Provide soil organisms with a balanced diet

- Manure and perennial pastures provide food for soil organisms
- Succulent materials that are more nitrogen-rich are more rapidly decomposed than materials that are older and woodier and contain less nitrogen

Provide soil organisms with a favorable environment

- Most beneficial soil organisms prefer a well-aerated environment
- Decomposer bacteria generally prefer an environment that is moist, has a near neutral pH, and has easy-to-decompose materials
- Decomposer fungi generally prefer an environment that is acid, moderately dry, and has more carbon-rich, complex organic materials
- Continuous plant growth maintains environment of actively growing roots in the soil. The root or rhizosphere environment is a very nutrient-rich habitat for the growth of many soil organisms

Use practices that favor the growth of soil organisms

- Maintain a balance between intense grazing and adequate rest or fallow time
- Encourage movement of grazing animals across pastures to feed and distribute manure evenly as well as to kick and trample manure piles
- Maintain a diversity of forage species to provide a variety of food sources and habitats for a diversity of soil organisms

Avoid practices that kill or destroy the habitat of soil organisms

- Avoid the use of Ivomectin deworming medications, soil-applied insecticides, and concentrated fertilizers such as anhydrous ammonia and superphosphate
- Minimize tillage and other cultivation practices
- Minimize practices that compact the soil, such as extended grazing practices or grazing wet soils



Chapter 5: Pasture Management and Water Quality

Judicious applications of fertilizers and manure enhance plant growth. However, if nutrients are applied at the wrong time or in excess of what plants can use, they increase the potential contamination of nearby rivers and lakes. Similarly, grazing practices can degrade water quality if grazing intensity is too great, if paddocks are used when the soil is too wet, or if the duration of rest periods is too short. Long-term intensive grazing practices can negatively affect water quality, especially when combined with heavy fertilization with either mineral or manure nutrients. Likely impacts include contamination of groundwater with nitrates and contamination of surface water with phosphate, sediments, and pathogens (90, 91).

RISK FACTORS FOR NUTRIENT LOSSES

NUTRIENT LOSS PATHWAYS

If more manure or fertilizer nutrients are applied to pastures than are used in the growth of forage crops, excess nutrients will either accumulate in the soil or be lost through leaching, runoff, or erosion. Nutrient accumulation occurs when minerals in the soil have the ability to bind or hold particular nutrients. Sandy or silty soils or soils with a near-neutral pH do not bind phosphorus well. When more phosphorus is applied to these soils than is used for plant growth, the excess phosphorus can easily be dissolved and carried away by runoff water to lakes and streams. Both acid clay soils and soils with a high calcium carbonate content have a strong ability to bind large amounts of phosphorus. If only moderate excesses of phosphorus are applied to these soils or if excess phosphorus is applied to the soil only occasionally, these soils will be able to bind the excess phosphorus and hold it against leaching. However, if phosphorus fertilizers or manure are continually applied at high rates, phosphorus levels will eventually build up in the soil to the extent that soils will no longer be able to hold onto the additional phosphorus and these excesses will be susceptible to loss through run-

off. High levels of phosphorus in surface water cause eutrophication and algal blooms. When sources of drinking water have significant algal growth, chlorine in the water-treatment process reacts with compounds in the algae to produce substances that can increase cancer risks.

Unlike phosphorus, nitrogen does not readily bind to soil minerals or organic matter. As a result, it easily leaches through the soil, especially if high rainfall follows manure or nitrogen fertilizer applications and the soil is sandy or gravelly. High levels of nitrate in ground water used for drinking can cause health problems for human babies and immature animals. Management practices that minimize the potential for nitrogen leaching include not applying excessive nitrogen and avoiding manure or nitrogen fertilizer applications during times when plants are not actively growing.

Erosion occurs when water or wind moves soil particles, resulting in the loss of topsoil and of the nutrients, toxins, and pathogens attached to these particles. Erosion by water can also transport surface-applied manure into lakes, rivers, and streams. Water quality concerns associated with erosion include siltation, fish kills, eutrophication, and degraded quality for recreational and drinking-water uses.

NUTRIENT BALANCES

Water contamination problems associated with farming are becoming an increasing societal and political concern. The Federal Clean Water Act mandates states to minimize non-point-source pollution or pollution associated with runoff and erosion, much of this originating from agricultural lands (92). Currently, water quality regulations are primarily focused on larger farms that have a high concentration of animals and use high inputs of purchased feeds. Societal concerns about farming operations are increasing as more non-farm families move into rural areas and urban growth decreases the distance between farm and non-farm community members.

On farms that have high numbers of animals, a limited land area, and high use of feeds that are not grown on the farm, nutrient imbalances exist. This is because the amount of nutrients

that accumulate in the animal manure is greater than the needs of all crops being grown on the farm. Maintaining a balance between the amount of nutrients added to the soil as manure and fertilizer and the amount of nutrients removed as forages, hay, crops, or livestock is critical for productive crop growth and water quality protection. If more nutrients are removed than are returned to the system, crop production will decline. If more nutrients are added than can be used for productive crop growth, nutrients will build up in the soil, creating a high risk for leaching, runoff, and water contamination.

While environmental regulations primarily target large farms, these are not the only livestock operations at risk for contaminating water quality. Often, smaller livestock farms pose more risk than larger operations. For instance, on smaller dairy farms the barn is commonly located near a stream because it was built prior to rural electrification and the ability to pump water from wells or streams to watering troughs. On many small livestock operations, animals have access to paddocks located near a well head or over highly permeable soils because land area is limited. Riparian areas are less likely to be protected by fencing or buffer areas. On farms without adequate manure storage facilities, manure is often applied to poorly drained or frozen fields during the winter, resulting in a high potential for surface water contamination. In addition, on smaller farms, necessary equipment or labor is often not available to properly apply manure according to a nutrient management plan. Careful management of grazing and manure-handling practices is critical on all farms in order to protect water resources.

Manure or fertilizers should be applied when the nutrients in these materials can be most effectively used for plant growth and production, and never to ground that is snow-covered, frozen, or saturated.

PATHOGENS

PATHOGENS IN MANURE

Although not directly related to nutrient cycling, pathogens are a critical water quality con-

cern associated with manure management. Animal grazing and manure applications can contaminate water bodies not only with excess nutrients but also with parasites in feces. Parasites of greatest concern are *E. coli*, *Giardia*, and *Cryptosporidium*. *E. coli* is of most concern to rural residents dependent on well water and of limited concern to public water users since this parasite is killed by municipal water purification and treatment processes. Typically, this parasite causes mild to moderate gastrointestinal problems. However, new strains of *E. coli* have killed people who are very young, very old, or have weakened immune systems. *Giardia* and *Cryptosporidium* are pathogens with a dormant stage that is very resistant to purification treatment. Almost all municipal water treatment facilities are required to use secondary filtration processes that remove these resistant forms from the water supply. Most private wells, however, do not have the capability of filtering out these pathogens. Like the virulent strain of *E. coli*, *Giardia* and *Cryptosporidium* cause gastrointestinal problems that can be fatal for people with weak or undeveloped immune systems.

Minimizing the risk of pathogen movement into water bodies involves ensuring that animals, especially young calves, are not exposed to, or kept in conditions that make them susceptible to, these diseases. Any manure that potentially contains pathogens should either be completely composted before application, or applied to land far from streams and at low risk of erosion or runoff (93).

PASTURE MANAGEMENT PRACTICES TO REDUCE RISKS OF PATHOGEN CONTAMINATION

Manure or fertilizers should be applied when the nutrients in these materials can be most effectively used for plant growth and production, and never to ground that is snow-covered, frozen, or saturated. Under such wet or frozen conditions, manure or fertilizer nutrients are not bound by soil particles. Instead, these nutrients are lying unbound on the soil surface where they have a high potential to be carried away by runoff into lakes or streams. Pathogens in manure applied to frozen or snow-covered soil will not be in contact with other soil organisms. In addition, most predatory soil organisms will be in a

dormant state and unable to decrease pathogen numbers before snowmelts or heavy rainfalls cause runoff.

Areas that need to be protected from contamination by nutrients and parasites in animal feces include well heads, depressions at the base of hills, drainage ways, rivers, streams, and lakes. Well heads and water bodies need protection because they serve as drinking and recreational water sources, while foot slopes and drainage ways have a high potential for nutrient runoff and transport of contaminants to water bodies.

NITRATE CONTAMINATION

Nitrate is not held by soil particles and is easily leached, especially through porous soils, such as sandy soils or soils with cracks or fissures that allow for rapid movement of excess nitrogen through the soil profile. Where excess nitrogen is not applied, nitrate leaching in pastures is minimal. High nitrate leaching losses were observed, however, when orchard-grass pastures in Pennsylvania were fertilized with 200 pounds per acre of nitrogen as ammonium nitrate (45). These researchers also calculated that a stocking rate for Holstein dairy cows of 200 animal days would result in nitrate leaching from urine in excess of drinking-water standards (10 mg/liter) (45). In pastures where nitrogen was provided by nitrogen-fixing legumes, nitrate leaching was minimal when environmental conditions were normal. But high nitrate leaching was observed when a severe drought followed good growing conditions, causing legume nodules to die and release nitrogen into the soil (20).

Nitrate concentrations greater than 10 ppm in well water may cause nitrate toxicity or methemoglobinemia. This ailment, which affects infant children as well as young chickens and pigs, and both infant and adult sheep, cattle, and horses, increases nitrate concentration in the bloodstream and prevents the uptake and use of oxygen, thus causing suffocation. Pregnant animals that are affected may recover, then abort within a few days (21). Personnel associated with

local health departments can test wells to determine nitrate concentrations.

PHOSPHORUS CONTAMINATION

Phosphorus can be transported from fields or pastures into lakes or streams either as a component of erosion or within runoff water. Phosphorus that is dissolved in runoff water has a greater effect on water quality than phosphorus that is attached to soil particles transported to water bodies by erosion (94). This is because the dissolved phosphorus is more available for use by algae and other aquatic organisms that cause eutrophication, noxious greening of water bodies, and fish kills. Phosphorus associated with soil particles tends to settle to the lake or river bottom where it remains biologically stable or only slowly available for use by aquatic organisms.

DISSOLVED PHOSPHORUS

In pastures, sources of dissolved phosphorus include manure or phosphorus fertilizers lying on the soil surface, and wet soils that have a high phosphorus concentration. Runoff water can readily dissolve soluble phosphorus in manure or phosphorus fertilizers. When the amount of phosphorus in soil exceeds the ability of soil particles to bind onto it, the excess phosphorus can readily be dissolved and transported by runoff water, especially when soils are saturated. Dissolved phosphorus has the greatest potential for being transported from pastures into water bodies when rainfall is heavy, when high levels of phosphorus are present either on the surface of the soil or within the soil, and when pastures are located within 350 feet of water bodies (95).

Increasing forage diversity generally decreases runoff potential. Care should be taken to combine species, such as bunch-grasses, that enhance water infiltration but expose the soil surface between clumps (96), with closer-growing species such as tall fescue or prostrate species such as white clover. A combination of native

High nitrate leaching occurs when a severe drought follows good growing conditions, causing legume nodules to die and release nitrogen into the soil.

When the amount of phosphorus in soil exceeds the ability of soil particles to bind onto it, the excess phosphorus can readily be dissolved and transported by runoff water, especially when soils are saturated.

forages and low-growing, shade-tolerant plants could enhance both water infiltration and cattle production (D. Brauer, personal communication). Setting up paddocks on the contour can also allow downslope paddocks that are regenerating after grazing to serve as buffer strips for upslope paddocks that are currently being grazed. Potential runoff from manure can also be reduced by applying it to alternate paddocks set up as contour strips (D.E. Carman, personal communication).

PHOSPHORUS ASSOCIATED WITH EROSION

Soil-attached phosphorus can be transported to water bodies by erosion. Low-level sheet erosion contributes more phosphorus than higher-impact rill or gully erosion. This is because sheet erosion primarily transports nutrient-enriched topsoil, manure, and plant residues while gully erosion transports more nutrient-poor subsoil (27). As with runoff, the amount of phosphorus transported by erosion is greatest during intense rainfalls or snowmelts. Pasture soils that are completely covered by vegetation are protected against the forces of erosion. Erosion occurs primarily when soils are bare and land is sloping.

IMPACT OF PHOSPHORUS

CONTAMINATION ON WATER QUALITY

The impact of phosphorus runoff on stream or lake water quality is greatest during summer and fall. While spring rains or snowmelts may transport a greater total amount of phosphorus, the large amount of water in the runoff dilutes the phosphorus so that it is in a relatively low concentration when it reaches water bodies. In contrast, intense rains falling on soils and pastures during the summer are likely to run off rather than soaking into dry, hard soils. When intense rains fall on pastures with surface-applied manure or phosphorus fertilizers, runoff water will carry a high concentration of dissolved phosphorus into streams. If these streams have relatively low water flows, the runoff water will create a high concentration of phosphorus in

streams, which then causes algae and other nuisance plants to grow (27).

Table 18. Impacts of excess phosphorus on water quality.

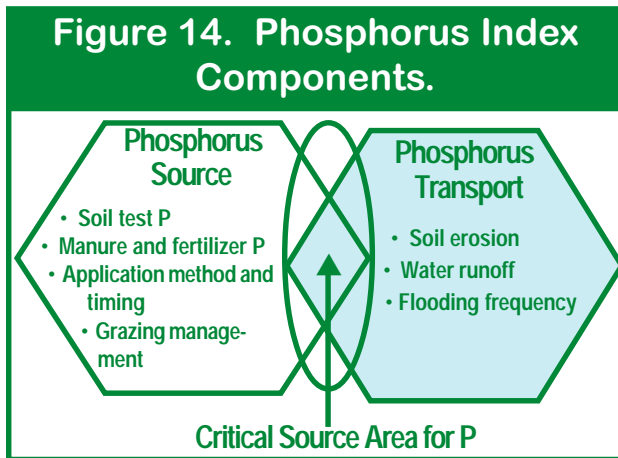
- **Excessive phosphorus stimulates growth of algae and aquatic weeds in lakes and streams**
- **Rapid algal and aquatic-weed growth depletes oxygen from water, leading to death of fish**
- **Outbreaks of certain aquatic organisms dependent on high phosphorus levels can cause health problems in humans, livestock, and other animals**
- **When water that has high algal growth is chlorinated for use as drinking water, carcinogenic substances are formed**

The type of phosphorus fertilizer used influences the potential risk of water contamination. Highly soluble fertilizers such as superphosphate present a greater short-term potential for phosphorus loss since they are easily dissolved and transported. In the long term, however, less-soluble fertilizers, such as dicalcium phosphate, may pose a greater risk. This is because less-soluble fertilizer remains on the soil surface and available for dissolution and runoff for a longer time (27). Impacts on water quality from sediment-attached phosphorus fertilizer have been observed to persist for up to six months (97). Runoff risks can be substantially decreased if fertilizers are incorporated into soil and applied according to a nutrient management plan.

PHOSPHORUS INDEX

The phosphorus index was developed to address federal and state water quality guidelines while recognizing that phosphorus movement is influenced by local environmental conditions and land management practices. Each state is developing their own phosphorus index to ensure that it is appropriate to local conditions. Each phosphorus index contains a component related to phosphorus sources, soil-test phosphorus, manure phosphorus, and fertilizer phosphorus. (Soil-test phosphorus accounts for the plant-

available or soluble phosphorus in the soil, derived either from the mineral base of the soil or from decomposing organic matter.) The potential for manure or fertilizer phosphorus to be lost through runoff depends on the amount applied, how it was applied, and when it was applied. Manure and fertilizer incorporated into the soil at rates required for crop growth, and at or just prior to the time of crop production, pose minimal risk to water quality. Conversely, surface-applying excessive amounts of manure or fertilizer when crops are not actively growing or when the soil is saturated, frozen, or snow-covered will pose high risks for phosphorus runoff. However, a high concentration of phosphorus in the soil or applied to the soil will not pose a risk to water quality unless there is a means of transporting this phosphorus to water bodies. Methods for transporting phosphorus from farm fields to water bodies include erosion, runoff, and flooding. Locations that have a high source of phosphorus and a high risk of transport are *critical source areas* or locations where land managers need to carefully consider risks of phosphorus losses.



SUBSURFACE DRAINAGE

Artificial subsurface drainage makes normally wet soils drier, and decreases the wet period for seasonally wet soils, by allowing more water to seep into the soil profile. Subsurface drainage has been shown to decrease water runoff by 72% and total phosphorus losses due to runoff by 50% (5).

CONTAMINANT TRANSPORT THROUGH DRAINS

Unfortunately, the advantage that subsurface drainage provides in decreasing runoff potential may be overshadowed by the ability of drainage systems to directly transport nutrients from fields to waterways. Most subsurface drainage systems were installed primarily for production reasons: to allow farmers to work their fields earlier in the year and to minimize plant stunting and disease problems associated with saturated soils. Since many of these systems were installed before agricultural impacts on water quality became a societal concern, agricultural drains often empty directly into streams and rivers.

During wet periods of the year, artificially drained fields should be managed as though they were not drained. Grazing, manure spreading, and fertilizer applications should be avoided while drains are flowing.

Because artificial drainage makes fields drier, farmers can drive tractors or other equipment onto these fields earlier in the year. Farmers who have a full manure-storage system to empty, or who have time constraints for spreading manure in advance of planting, may be tempted to apply manure and fertilizers to these fields during times when the soil would be wet if it were not drained. Farmers with a limited land base may want to graze these fields when the weather is wet. However, to protect water quality, these fields should be managed as though artificial drainage had not been installed. Nutrients in fertilizers or manure can leach through the soil to drainage pipes. If artificially drained fields are used for nutrient applications or grazing while water is flowing out of drainage outlets, drainage water can carry these leached nutrients directly to streams or rivers.

In soils with subsurface drainage, cracks and channels provide a direct pathway for nitrate, phosphorus, or soluble manure to move from the soil surface to subsurface drains (6, 78). Because these channels are relatively large, contaminants are not absorbed by soil particles or biologically treated by soil organisms (27). Soil cracks or

Tile drainage water should be directed to a grassed filter or buffer area, or treated in a wetlands area where biological and chemical processes lower contaminant levels.

channels develop through earthworm burrowing, death and decomposition of taproots, and soil drying. The direct connection of cracks or channels in soils to artificial drainage pipes can transport phosphorus and pathogens from manure applications directly to drainage outlets within an hour after the onset of a heavy rain (6). One research study showed that a single rotational grazing event doubled the amount of sediment and increased the amount of dissolved phosphorus in tile drainage water 15-fold compared to an ungrazed site (5).

MANAGEMENT PRACTICES

To minimize the potential for water contamination, land that is artificially drained should not be grazed or have fertilizer or manure applied during times when drainage water is flowing from the field or just prior to a rainstorm. Alternatively, contaminated water flowing out of tile drains should not be allowed to empty directly into rivers or streams. Instead, it should be directed to a grassed filter or buffer area, or treated in a wetlands area where biological and chemical processes lower contaminant levels through sedimentation and absorption (27).

RIPARIAN BUFFERS

A well-designed buffer with a combination of trees, shrubs, and herbaceous plants has the ability to trap sediments and nutrients associated with the sediments. Buffers also provide habitat for river-bank and aquatic animals. An effective buffer for trapping sediments contains a combination of grasses and herbaceous plants that are able to catch sediments in their foliage or residues. The root channels around actively growing plants will also absorb slow-moving runoff water and plants in the buffer area will use transported nutrients for their growth. Regular harvest and removal of buffer vegetation can delay or prevent the buildup of nutrients in the buffer area. However, harvests must be conducted in a manner that does not decrease the ability of buff-

ers to capture sediments and absorb runoff water.

Riparian buffers are limited in their ability to remove soluble phosphorus and nitrate from runoff water, especially if flows are intense (98). During heavy rainstorms or rapid snowmelts, buffers generally have limited effectiveness for controlling the movement of runoff-borne nutrients into water bodies. This is because water from these heavy flows concentrates into rapidly moving channels that can flow over or through buffer areas.

As phosphorus is continually transported into buffers, soils in the buffer area will eventually lose their ability to hold additional phosphorus, thus limiting their effectiveness to control phosphorus movement into streams.

The continual transport of phosphorus-rich sediments into buffers will cause a buildup of high concentrations of phosphorus in buffer areas. Eventually, these areas will lose their ability to hold additional phosphorus. Buffer areas can actually become a *source* of phosphorus entering water bodies, rather than an area that captures phosphorus before it enters water bodies (99).

RIPARIAN GRAZING

When grazing animals have continuous, unlimited access to riparian areas, their activities break down stream banks, alter stream flow, cause decreased vigor of stream-bank vegetation, and diminish the species diversity and populations of fish and aquatic wildlife (100, 101). Cattle



grazing in riparian areas trample on streamside and aquatic organisms, disturb the habitat of these organisms, decrease oxygen availability by suspending bottom sediments, and contaminate streams by directly depositing manure and urine (102). Animal movement along streambanks or within streams also contributes to bank erosion. In addition, grazing activities alter the amount and type of plant residues available for the growth and reproduction of riparian organisms (90).

Limiting animal access to riparian areas allows a thick vegetative turf to develop throughout the paddock, which stabilizes stream banks and reduces stream-bank erosion.

Managed grazing of riparian areas can protect water quality and improve riparian habitat. In Wisconsin, researchers studying intensive rotational grazing practices restricted livestock access to riparian areas to 5 to 20 days per season. Limiting animal access to riparian areas allowed a thick vegetative turf to develop throughout the paddock, which stabilized stream banks and reduced streambank erosion (102). For dairy cattle, each grazing period should last only 12 to 24 hours, while beef cattle and sheep can be grazed for 3 to 4 days each time (103). Grazing should not be allowed to reduce herbage stubble to less than 4 to 6 inches in height. This will protect water quality by providing adequate plant

growth, bank protection, and sediment entrapment (104).

Pasture management practices should discourage animals from congregating in the stream or on the stream bank, where their manure can pollute water. Shade, salt licks, and other sources of supplemental nutrients should be located at least 15 feet from the stream bank to provide a buffer between areas of manure deposition and the stream (100).

The season in which riparian areas are grazed is also an important consideration if water quality is to be protected. Grazing in the spring or early summer followed by complete livestock removal in the summer allows riparian plant regrowth to occur before the dormant period in the fall. Animals will damage stream banks if they are allowed to graze riparian areas in the winter when soils are freezing and thawing or in the spring when soils are wet. During drought conditions, streambanks should not be grazed since vegetation will be slow to recover. Animals should not be allowed to graze riparian areas in the summer, when hot dry conditions would encourage cattle to congregate in the water (103). Stream banks that have a high soil moisture content or a fine soil texture, or that are prone to erosion, are subject to early-season grazing damage and should not be grazed in the spring or not until they have dried (104). Use of floating fences and graveled access areas can control animal access to water, minimizing the impacts on stream-bank stability and ecology.



Table 19.
Pasture Management Practices to Protect Water Quality.

Minimize congregation of animals in pastures

- Use practices that encourage the movement of animals across paddocks
- Avoid overgrazing of pastures

Minimize the potential for nitrate leaching

- Encourage animal movement across paddocks
- Maintain a healthy cover of actively growing forages across paddocks
- Rotate pastures to maximize nutrient uptake by plants

Minimize the potential for nutrient runoff

- Do not apply fertilizers or manure to saturated, snow-covered, or frozen ground
- If possible, compost manure before applying it to soil. This will minimize pathogen populations while transforming nutrients into more stable compounds
- Do not use pastures that are wet, flooded, or saturated
- Use practices that favor populations of soil organisms that rapidly incorporate manure into the soil
- During cold or wet weather, do not use pastures that are located next to a river, stream, or waterway
- Recognize that buffers are not effective in controlling the movement of nutrients carried by runoff water, especially when flows are intense

Minimize the potential for erosion

- Maintain a complete cover of forages and residues across the surface of all paddocks
- Use practices that minimize the congregation of animals or the repeated trampling of animals on the same lounging area or pathway
- Riparian areas should only be grazed using short-term intensive grazing practices, and then only during spring and early summer
- Maintain riparian buffers (including a combination of herbaceous plants, trees, and shrubs) adjacent to rivers, streams, and lakes to act as a filter for eroded soil and other contaminants

Minimize water contamination from artificial drainage systems

- During wet weather, do not use pastures that are on artificially-drained land
- Modify outlets from drainage ways to treat drainage water in wetlands or on filter areas before it flows into streams or other water bodies

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Resource List

AGENCIES AND ORGANIZATIONS

American Forage and Grassland Council. Gerorgetown, TX.

Mission statement: "To promote the use of forages as economically and environmentally sound agriculture through education, communication, and professional development of producers, scientists, educators and commercial representatives and through communication with policy makers and consumers in North America" <<http://www.afgc.org>>.

Grazing Lands Conservation Initiative

A national effort to provide high-quality technical assistance on privately owned grazing lands and increase the awareness of the importance of grazing land resources. <<http://www.glci.org/>>.

Grazing Lands Technology Institute (GLTI) Provides technical excellence to the Natural Resources Conservation Service (NRCS) and other appropriate customers in the acquisition, development, coordination, and transfer of technology that meets the needs of grazing land resources, landowners and managers, and the public. <<http://www.ncg.nrcs.usda.gov/glti/homepage.html>>, or contact your county or regional NRCS office.

Cooperative Extension Service.

Educational and technical assistance that links farmers and ranchers with university research expertise. Many county or regional offices address grazing practices. To identify your local office see <<http://www.reeusda.gov/1700/statepartners/usa.htm>>.

Natural Resource, Agriculture, and Engineering Service. Ithaca, NY.

Coordinates and publishes proceedings from conferences on agricultural and environmental issues. Also publishes technical and practical documents on manure management, composting, and animal housing. <<http://www.nraes.org>>.

General Grazing

Clark, E.A. and R.P. Poincelot. 1996. **The Contribution of Managed Grasslands to Sustainable Agriculture in the Great Lakes Basin.** The Haworth Press Inc., New York.

An easy-to-read but technically-based discussion of the relations between grazing management, forage production, and soil quality.

PUBLICATIONS IN PRINT

Emmick, D.L. and D.G. Fox. 1993. **Prescribed Grazing Management to Improve Pasture Productivity in New York.** United States Department of Agriculture Soil Conservation Service and Cornell University. <<http://www.wscas.cit.cornell.edu/forage/pasture/index.html>>.

Gerrish, J. and C. Roberts (eds.) **1996 Missouri Grazing Manual.** University of Missouri. Columbia, MO.

Short papers addressing forage production and nutrient management in pastures.

Pearson, C.J. and R.L. Ison. 1987. **Agronomy of Grassland Systems.** Cambridge University Press. Cambridge.

Technical discussion of forage biology and production, nutrient availability, and animal nutrition on forages.

Stockman Grass Farmer Magazine

The nation's leading publication on grass-based livestock systems. Order information <<http://stockmangrassfarmer.com/>>.

Terrill, T. and K. Cassida. 2001. **American Forage and Grassland Council Proceedings.** American Forage and Grassland Council. Georgetown, TX.

Unsander, D., B. Albert, P. Porter, A. Crossley, and N. Martin. No date. **Pastures for Profit. A Guide to Rotational Grazing.** University of Wisconsin Extension. Madison, WI. Available at <<http://www.uwrf.edu/grazing/>>.

Soil Quality and Soil Conservation

Magdoff, F. and H. van Es. 2000. **Building Soils for Better Crops, Second Edition.** Sustainable Agriculture Network. Handbook Series Book 4. Beltsville, MD.

Easy-to-read descriptions of concepts regarding soil quality and agricultural management practices to enhance soil quality. Although many of the practical management descriptions are oriented more towards field crops than to grazing systems, the concepts of soil quality protection and management are the same.

Edwards, C. 1999. **Soil Biology Primer.** United States Department of Agriculture, Natural Resources Conservation Service. Washington, D.C. Order information <http://www.statlab.iastate.edu/survey/SQI/soil_biology.htm>

A well-illustrated overview of soil organisms and their impact on soil quality.

Cavigelli, M.A., S.R. Deming, L.K. Probyn, and R.R. Harwood (eds). 1998. **Michigan Field Crop Ecology: Managing biological processes for productivity and environmental quality.** MSU Extension Bulletin E-2646. Michigan State University Extension Service, East Lansing, MI.

A well-illustrated overview of nutrient cycles in agricultural systems, the organisms that affect these systems, and the impact of environmental conditions and management practices on the activities of these organisms.

Journal of Soil and Water Conservation.

Technical articles on soil conservation research and practices. Many articles pertain to grazing systems. Order information: <http://www.swcs.org/f_pubs_journal.htm>

Whitehead, D.C. 2000. **Nutrient Elements in Grassland Soil-Plant-Animal Relationships.** CAB International Publishing. Wallingford, Oxon, UK.

An excellent technical resource on nutrient cycle components and interactions in grazing systems.

Undersander, D. and B. Pillsbury. 1999. **Grazing Streamside Pastures.** University of Wisconsin Extension. Madison, WI.

An easy-to-read overview of the potential risks and benefits associated with riparian grazing practices.

Water Quality Protection

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 1999. **Agricultural Phosphorus and Eutrophication.** ARS-149. United States Department of Agriculture / Agricultural Research Service. Washington, D.C. Order information: <<http://www.soil.ncsu.edu/sera17/publicat.htm>>.

An illustrated, easy-to-read discussion describing the impact of environmental conditions and land management practices on the risk for phosphorus runoff from agricultural lands.

Daniels, M., T. Daniel, D. Carman, R. Morgan, J. Langston, and K. VanDevender. 1998. **Soil Phosphorus Levels: Concerns and Recommendations.** University of Arkansas. Division of Agriculture. Cooperative Extension Service. Accessed at: <<http://www.soil.ncsu.edu/sera17/publicat.htm>>.

NRAES. 2000. **Managing Nutrients and Pathogens from Animal Agriculture.** Natural Resource, Agriculture, and Engineering Service. Ithaca, NY.

Proceedings from a conference that included research reports, field experience, and policy discussions. Available from <<http://www.nraes.org>>.

WEB RESOURCES

Rotational Grazing – University Programs

Center for Grassland Studies - University of Nebraska-Lincoln <<http://www.grassland.unl.edu/index.htm>>.

Purdue Pasture Management Page- Purdue University Cooperative Extension <<http://www.agry.purdue.edu/ext/forages/rotational/>>.

Texas Agricultural Extension Service. Extension Resource Center <<http://texaserc.tamu.edu/catalog/query.cgi?id=433>>.

Controlled Grazing of Virginia's Pastures – Virginia Cooperative Extension <<http://www.ext.vt.edu/pubs/livestock/418-012/418-012.html>>.

Grazing Dairy Systems at the Center for Integrated Agricultural Systems – University of Wisconsin – Madison <<http://www.wisc.edu/cias/research/livestoc.html#grazing>>.

Pasture Management & Grazing – University of Wisconsin Extension <<http://www.uwrf.edu/grazing/>>.

Grasslands Watershed Management – Clemson University <<http://grasslands.clemson.edu/>>.

Focuses on the role pasture and forage crop production can play in helping insure a clean, safe water supply.

Rotational Grazing – Organizations and Agencies

Grazing Lands Conservation Initiative

A national effort to provide high-quality technical assistance on privately owned grazing lands and increase the awareness of the importance of grazing land resources <<http://www.gpci.org/>>.

Grazing Lands Technology Institute - Grazing information from the Natural Resources Conservation Service. <<http://www.ncg.nrcs.usda.gov/glti/homepage.html>>.

Stockman Grass Farmer Magazine - The nation's leading publication on grass-based livestock systems <<http://stockmangrassfarmer.com/>>.

American Farmland Trust information site on grass-based farming systems <<http://grassfarmer.com/>>.

Sustainable Farming Connection's Grazing Menu- good links to grazing sites <<http://www.ibiblio.org/farming-connection/grazing/home.htm>>.

Why Grassfed Is Best - Jo Robinson explores the many benefits of grassfed meat, eggs, and dairy products <<http://www.eatwild.com/>>.

Archived listings from Graze-L, an international forum for the discussion of rotational grazing and seasonal dairying <<http://grazel.taranaki.ac.nz/>>.

Soil Quality

Soil Quality Institute. United States Department of Agriculture. Natural Resources Conservation Service. <<http://www.statlab.iastate.edu/survey/SQI/>>.

Soil quality information sheets, soil quality indicators, and soil quality assessment methods

Rangeland Soil Quality. Soil Quality Institute. United States Department of Agriculture Natural Resources Conservation Service. <<http://www.statlab.iastate.edu/survey/SQI/range.html>>.

Information sheets on rangeland soil quality

Soil Biological Communities. United States Department of Agriculture Bureau of Land Management. Information sheets. <<http://www.blm.gov/nstc/soil/index.html>>.

Ingham, E. 1996. The soil foodweb: Its importance in ecosystem health. Accessed at <<http://rain.org:80/~sals/ingham.html>>.

The Soil Foodweb Incorporated. <<http://www.soilfoodweb.com/index.html>>.

Soil microbiology, soil ecology information and laboratory analyses of soil biology.

SoilFacts. Soil science related publications from North Carolina State University. Includes: Poultry Manure as a Fertilizer Source, Good Soil Management Helps Protect Groundwater, Nitrogen Management and Water Quality, and Soils and Water Quality <<http://ces.soil.ncsu.edu/soilscience/publications/Soilfacts/AG-439-05/>>.

United States Department of Agriculture – Agricultural Research Service. <<http://www.nps.ars.usda.gov/>>.

Research programs addressing soil and water quality, rangeland, pastures, and forests, and integrated agricultural systems.

Water Quality

Pellant, M., P. Shaver, D.A. Pyke, and J.E. Herrick. 2000. Interpreting Indicators of Rangeland Health. Version 3. Technical Reference 1734-6. National Science and Technology Center Information and Communications Group. Denver, CO. <<http://www.ftw.nrcs.usda.gov/glti/pubs.html>>.

SERA-17. Minimizing Phosphorus Losses from Agriculture. <<http://www.soil.ncsu.edu/sera17/publicat.htm>>.

National, multi-agency information on phosphorus fate and transport, including the development of the phosphorus index.

United States Environmental Protection Agency Department of Water. 1999. Laws and Regulations, Policy and Guidance Documents, and Legislation. Accessed at: <<http://www.epa.gov/OW/laws.html>>.

Concentrated Animal Feeding Operations (CAFOs) Effluent Guidelines for larger scale farms. <<http://www.epa.gov/ost/guide/cafo/index.html>>.

Focuses on confinement systems but many of the nutrient management planning guidelines may also be appropriate for grazing systems.

Animal Feeding Operations. US EPA Office of Water. <http://cfpub.epa.gov/npdes/home.cfm?program_id=7>.

EPA's National Agriculture Compliance Assistance Center. <<http://es.epa.gov/oeca/ag/>>.

Information on environmental laws affecting agricultural operations.

Riparian Grazing

Riparian Grazing Project - University of California Cooperative Extension <http://www.calcattlemen.org/riparian_grazing_project.htm>.

Effects of Cattle Grazing in Riparian Areas of the Southwestern United States <<http://www.earlham.edu/~biol/desert/riparian.htm>>.

Managed Grazing and Stream Ecosystems. Laura Paine and John Lyons. <<http://www.uwrf.edu/grazing/>>.

Driscoll, M. and B. Vondracek. 2001. An Annotated Bibliography of Riparian Grazing Publications. The Land Stewardship Project. <<http://www.landstewardshipproject.org/resources-main.html>>.

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HTML

<http://www.attra.ncat.org/attra-pub/nutrientcycling.html>

PDF

<http://www.attra.ncat.org/attra-pub/PDF/nutrientcycling.pdf>