Soil Phosphorous, Potassium and Micronutrients

Introduction

Phosphorous is second only to N in importance for the productivity and health of ecosystems

- P is scarce in most ecosystems
- Excessive application of P fertilizers can lead to *eutrophication* of water supplies

Introduction

Potassium is abundant in most soils

- Most is tied up and unavailable to plants
- K is required by plants in large amounts

9 of the 18 elements essential for plant growth are required in very small amounts

- Called *micronutrients* or *trace elements*

Phosphorous in Soils

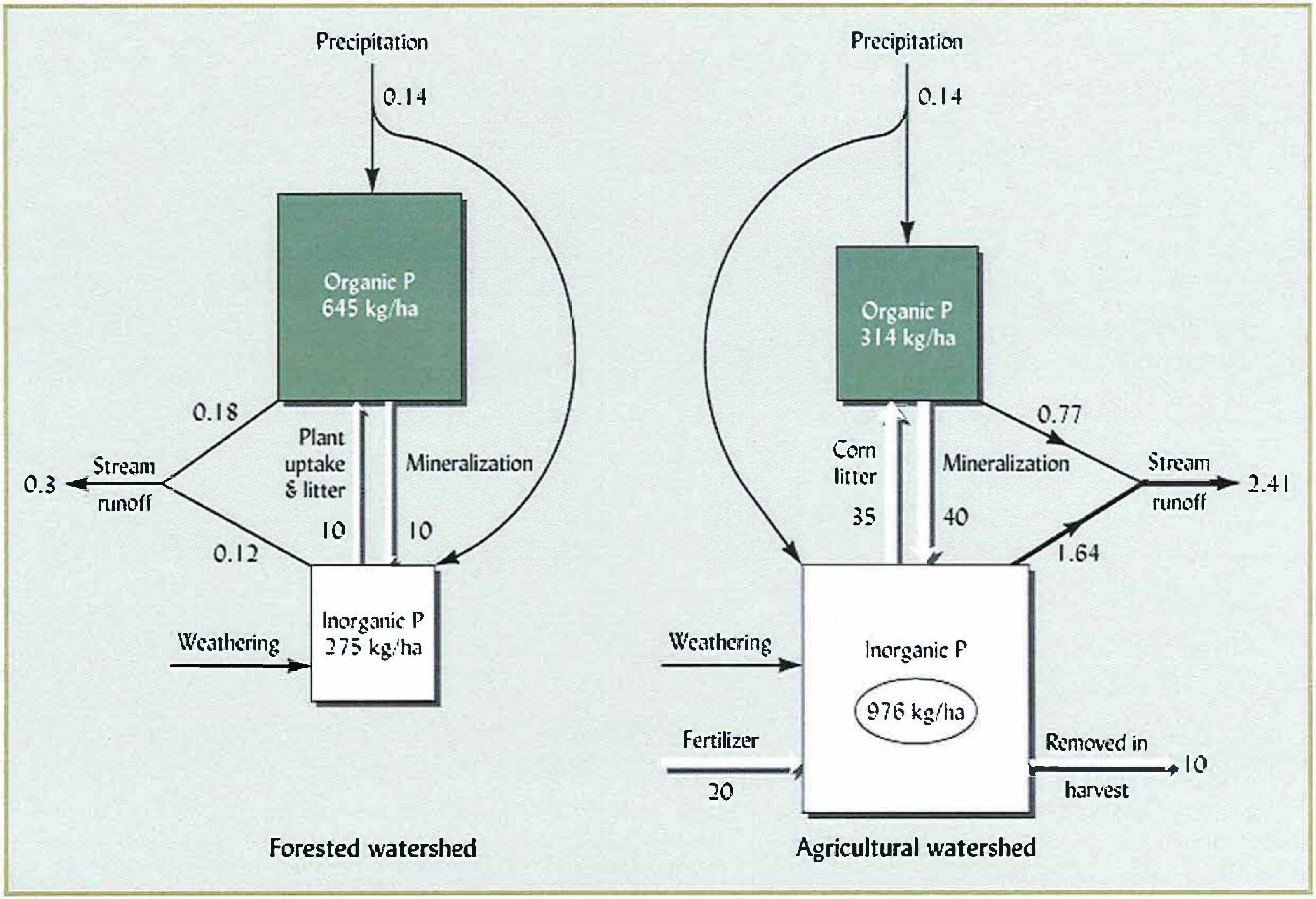
Phosphorous not abundant in natural ecosystems

- Amounts usually adequate for sustained plant growth as all P taken up by plant is returned to soil in residue

P in agricultural systems not sustainable for continued growth

- Plants are harvested, P not returned to soil in residue in sufficient quantities

Phosphorous Balance in Adjacent Watersheds



Phosphorous in Soils

In agricultural systems additional P is applied as manure, fertilizer etc.

- After fertilization, many soils have more P than can be used by the crop
- Runoff, leaching and erosion may move this excess P into waterbodies triggering eutrophication

Eutrophication

Accumulation of Phosphorous in bodies of water

- Stimulates algae and aquatic plant growth

- Decaying of plant matter uses up dissolved oxygen in the water
  - resulting in fish die off

Fish kill as a result of eutrophication—anoxic condition resulting from the decay of masses of algae whose growth was stimulated by excessive Phosphorous

Phosphorous in Soils

Where P is deficient land degradation may occur

- Common in parts of Africa where soils have been mined of P for years as result of subsistence farming
  - Plants grow sparsely and poorly, land becomes subject to erosion (wind and water) for lack of cover

- P deficiency indirectly causes N deficiency
  - low P inhibits effective nodulation of legumes

African Corn Field Showing Extreme Phosphorous Deficiency

Practical Management of P in Soils

1. Choose fertilizer to fit P status of soil
   - This can change over time, so as P availability increases, fertilizer should be reduced
2. Placement of P fertilizers
   - Localized placement in root zone reduces amount needed and reduces potential for P reactions and/or fixation
3. Use fertilizers containing ammonium and P
   - Increases uptake of P, especially in alkaline soils

Practical Management of P in Soils

4. Cycle organic matter
   - Increases plant available P as organic materials decompose

5. Control soil pH
   - P uptake optimized between pH 6 and 7

6. Enhance mycorrhizal symbiosis
   - May need to innoculate seedlings

7. Choose P-efficient plants

Practical Management of P in Soils

8. Reduce runoff and sediment losses
    - Use conservation practices, cover crops, residues etc.
    - Encourage water movement into soil rather than off it

9. Capture excess P before it enters waterbodies
    - Natural or constructed wetlands help tie up P

Potassium in Soils

Potassium (K) present in soil solution only as positively charged cation -- K^+

- Behavior in soil influenced primarily by
  - cation exchange properties
  - mineral weathering

Does not cause offsite environmental problems or toxicity to plants

Potassium in Soils

K found in high levels in most soils except those dominated by quartz sands

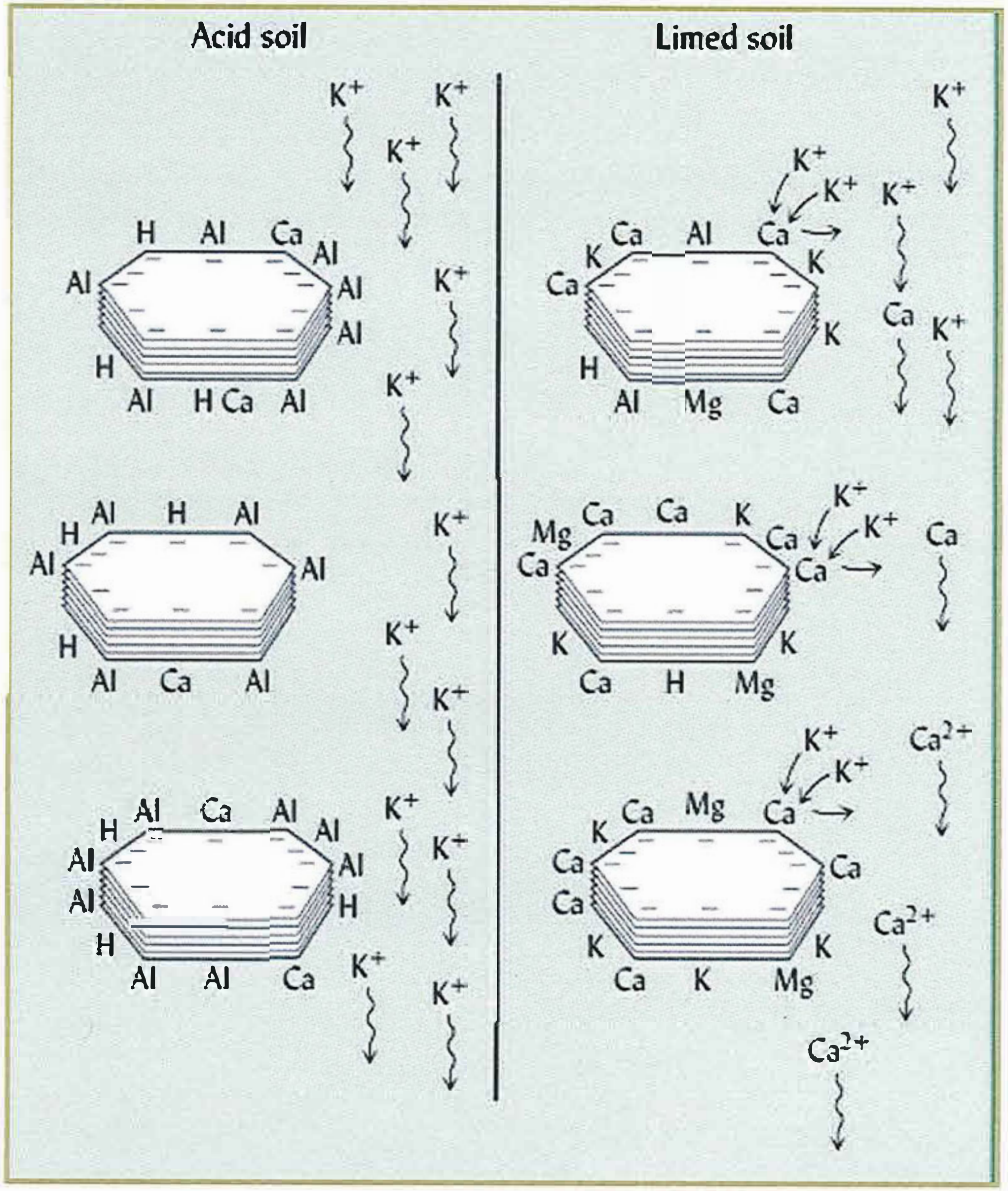
- Quantity held in exchangeable form at any time is small
  - Most K held as part of primary mineral structure or fixed in forms unavailable to plants

K is easily lost by leaching

- More readily leached in acid than limed soil
  - Attraction of K^+ to negatively charged colloids slows leaching in limed soils

How Liming an Acid Soil can Reduce Leaching Losses of Potassium

K^+ ions can more easily replace Ca^{2+} ions on the soil colloid in limed soil than they can Al^{3+} ions in an (unlimed) acid soil



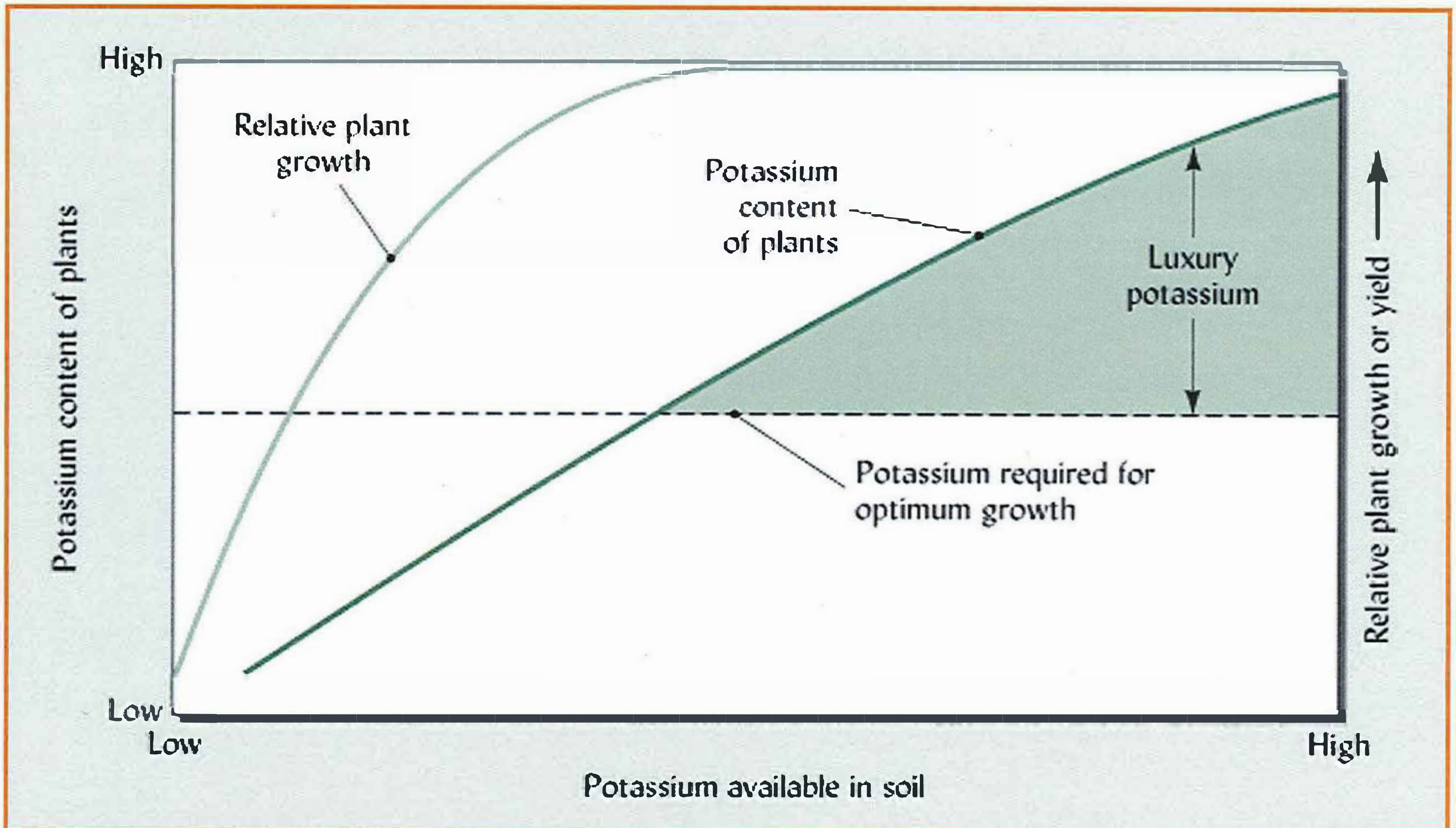
Potassium in Soils

Plants can take up very large amounts of K

- If K is present in sufficient quantities plants will take up more than they need
  - Termed luxury consumption

- If plant residues are not returned to the soil luxury consumption can reduce plant available K levels dramatically

Relationship Between Available Potassium Levels in Soils, Plant Growth and Plant Uptake of Potassium



Practical Potassium Management

1. Understand the sources of gains and losses of available potassium and of factors affecting them
    - Relative importance of each source will vary among soils
2. Realize that soils can supply most of the K required for a natural ecosystem
    - Must supplement where crops are removed

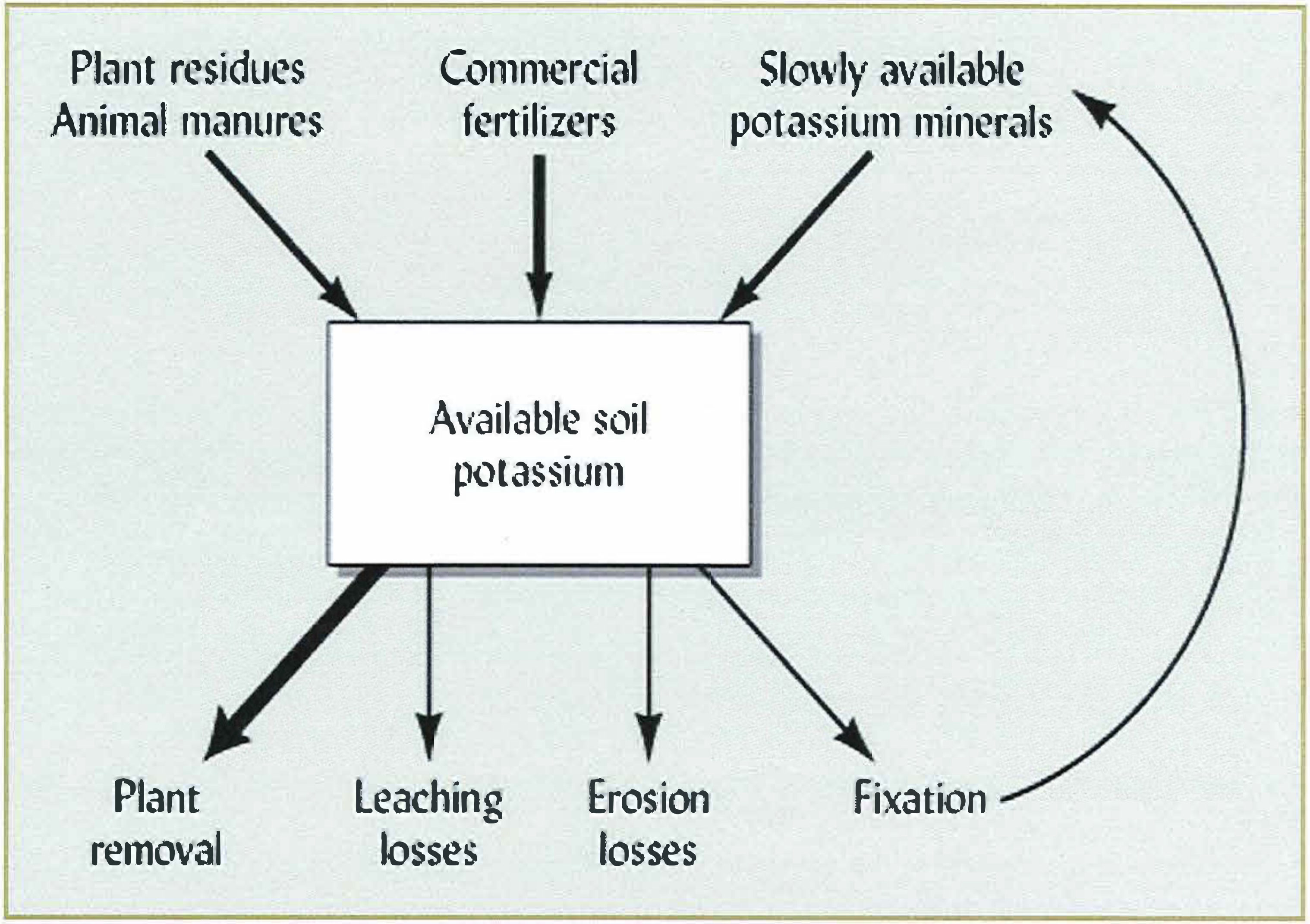
Practical Potassium Management

3. Avoid highly acid soils that permit extensive losses of potassium

4. Recycle as much plant absorbed K to soil as possible

5. When needed apply fertilizer in light applications
    - On an annual basis is best

Typical Gains and Losses of Available Soil Potassium in a Field System



Micronutrients

As important as macronutrients

- Required in much smaller amounts
- All can be found in igneous rocks
- Organic matter an important secondary source for many micronutrients
- Deficiencies likely to occur where total nutrient contents are low
  - Highly leached, acid soils and organic soils usually deficient

Micronutrients

Cation micronutrients include Iron, Zinc, Manganese, Copper, Cobalt, Nickel

- Most are soluble and plant available under acid conditions
  - Can be toxic in very acid soils

- Deficiencies more common in calcareous soils
  - pH of 6-7 allows sufficient solubility for plants without being toxic

Micronutrients

Anion micronutrients include Boron, Molybdenum, Chlorine

- Chlorine usually available in sufficient quantities
  - Can be present in toxic amounts in saline soils
- Boron commonly most deficient of micronutrients
  - Availability related to soil pH, most available in acid soils
- Molybdenum availability is increased with increasing pH
  - Liming acid soils will increase the availability

(P) commonly is one of the most limiting nutrients for crops and forage. The primary role of P in plants is storage and transfer of energy produced by photosynthesis for growth and reproductive processes. Phosphorus cycles in soil through various processes and in various forms. Some forms are readily available for plant use, and some are not (fig. 1). Adequate P levels promote fruit, flower, and seed production; increase crop yields; promote root growth and hardiness of plants in winter; stimulate tillering; and hasten crop maturity. Phosphate soil tests assist in determining the P cycling in soils, production potential, appropriate P levels for soil microbial processes, and potential crop response to P fertilizer. Moderate levels of P typically are adequate for productivity and soil microbial processes. High levels indicate excessive application of P fertilizer; a potential for loss of soluble P in surface runoff, drainage tile, and groundwater at a shallow depth; and a potential for leaching of P in sandy and organic soils.

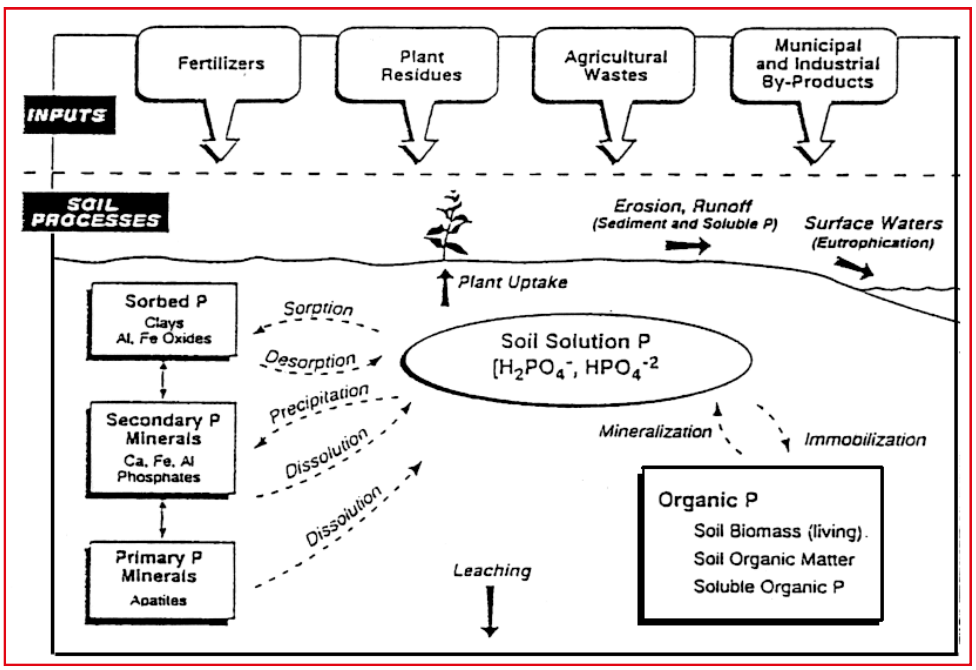


Figure 1.—Soil phosphorus cycle (Pierzinski and others, 1994).

Inherent Factors Affecting Soil Phosphorus

Inherent soil properties and climate affect the growth of crops and their response to applied P fertilizer and regulate the processes that can restrict the availability of P. Climatic conditions, such as rainfall and air temperature, and site conditions, such as soil moisture and aeration (oxygen level) and salinity (salt content/electrical conductivity) affect the rate of mineralization of P as a result of decomposition of organic matter. Organic matter decomposes, releasing P, more quickly in warm, humid climates than in cool, dry climates. Phosphorus is released faster from well-aerated soils (higher oxygen level) than from saturated soils (lower oxygen level).

Soil pH of 6 to 7.5 is ideal for the availability of P for plant use. Values of less than 5.5 and 7.5 to 8.5 limit availability of P as a result of fixation by aluminum, iron, or calcium (fig. 2), which commonly are associated with soil parent material.

Moderate levels of P do not readily leach out of the root zone in most soils. Potential for loss of P in these soils is associated mainly with erosion and runoff. Soils that have a high level of P are prone to loss of soluble P in surface runoff, drainage tile, and groundwater at a shallow depth, and sandy and organic soils are prone to loss of P through leaching. To minimize sedimentation and loss of soluble P, closely manage soils that have a high or very high level of P, are subject to erosion and runoff, or are in close proximity to streams, lakes, and other bodies of water.

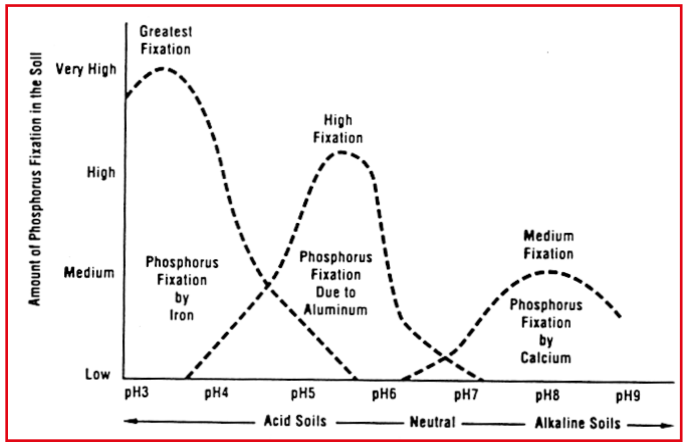


Figure 2.—Phosphorus availability across pH ranges (California Fertilizer Association, 1995).

Phosphorus Management

The availability of P can be increased by applying lime to acid soils, using practices that increase organic matter, and properly placing P fertilizer, which affects the efficiency of use by crops. Loss of P can be minimized by limiting erosion and runoff, injecting or incorporating P, and limiting or eliminating applications of P fertilizer if the level of P in the soil is high or very high.

Adequate P is essential for crop and forage production. It encourages vigorous root and shoot growth, promotes early maturity, promotes efficient use of water by plants, and increases grain yields. Phosphorus deficiency reduces yields by delaying maturity, stunting growth, and restricting energy use by plants.

Soil P is relatively stable; it moves very little as compared to nitrogen, unless it is present in excessive amounts. The lack of mobility and low solubility limit the availability of P applied in fertilizer because it is fixed by P compounds in the soil. Fixed P slowly becomes available to crops over several years, depending on the type of soil and P compounds (fig. 1). Phosphorus in eroded sediment in bodies of water is also released over several years.

Purple leaf tissue is symptomatic of P deficiency (fig. 3). It appears first on the tips of leaves and progresses until the entire leaf exhibits a purple color. Lower leaves die when phosphorus deficiency is severe, especially if hot, dry, windy conditions persist. Emerging leaves commonly are green because plants mobilize available P to the youngest leaves first.

Symptoms of P deficiency commonly occur as young plants are exposed to cool, wet conditions. Under these conditions, plant growth exceeds the ability of the roots to supply P. Young plants are especially vulnerable because their root systems are limited and P is immobile in the soil. Cultural or environmental factors that limit root growth contribute to the symptoms of P deficiency. These factors include cool temperatures, wet or dry conditions, compaction of the soil, damage from herbicide use, damage from insects, salinity, and root pruning from side-dressing knives or cultivators. Once growing conditions become favorable again and further root growth occurs, leaves normally regain their green color.

Figure 3.—Phosphorus-deficient corn characterized by purple color on lower leaves.

The availability of P is controlled by three primary factors—soil pH and mineralogy, content of organic matter, and placement of P fertilizer.

Lime should be applied to acid soils to achieve an ideal pH level (pH of 6 to 7). Low soil pH severely limits the availability of P for plant use. Soil pH of less than 5.5 typically limits the availability of P by 30 percent or more. Acidity also reduces root growth, which is critical for the uptake of P. High amounts of iron oxides, available aluminum, or calcium carbonates or sulfates in soil fix P, limiting its availability.

Maintaining the content of organic matter in the soil is important for controlling the availability of P. Mineralization of organic matter provides a significant portion of the P available for crop use.

Phosphorus fertilizer and manure or other organic amendments can be applied to remedy P deficiency, but careful management is needed to provide a form of P that is available for plant use. Roots must come in contact with available P for uptake to occur. It commonly is recommended to apply P in the rows as a starter fertilizer to increase early growth, even if the amount of P in the soil is sufficient for grain. Phosphorus can also be injected 2 inches below the seeds of row crops, which provides a ready source of P for young seedlings. Producers should carefully evaluate the value of applying P fertilizer early in the growing season. Seedlings may look better if starter P fertilizer is applied, but yields may not be increased.

Primary P management strategies:

1. Apply lime to acid soils to increase pH to between 6.5 and 7.0 (fig. 2).
2. Apply small amounts of P fertilizer frequently rather than large amounts all at one time.
3. Minimize the tie-up of P by banding or injecting P fertilizer or liquid manure.
4. Place P fertilizer near rows or in furrows, where roots are most active.

Measuring Soil Phosphate (PO_4)

Materials needed to measure phosphate:

____ Plastic container and probe for gathering and mixing soil samples

____ Phosphate test strips

____ 1/8-cup (29.5 mL) measuring scoop

____ Calibrated 120-mL vial with lid for shaking

____ Squirt bottle

____ Distilled water or rainwater

____ Pen, field notebook, permanent marker, and resealable plastic bags

Considerations:

Electrical conductivity (EC) should always be measured on a sample before measuring phosphate. Soil nitrate/nitrite and soil pH can also be measured on the sample using the steps in the following paragraphs.

Soil P tests, which help in determining potential crop growth and recommendations for fertilizer, are of value only if correlated and calibrated to the response of crops to applied P. Thus, soil P test results are an “index” of relative availability.

Quick in-field hand test:

1. Soil P levels in a field vary depending on location, past management, and time of year. Examples of variables include placement of P fertilizer (broadcast or banded; in rows or between rows), soil texture, organic matter content, and application of manure or other fertilizer. Using a soil probe, gather at least 10 small samples to a depth of 8 inches or less randomly from an area that represents a particular soil type and management history. Place samples in the small plastic container and mix. Samples gathered for no-till cropping, forage establishment, and environmental purposes can be taken to a shallower depth. Do not include large stones and plant residue. Repeat this step for each sampling area.
2. Neutralize hands by rubbing moist soil across palms. Discard soil. Place a scoop of the mixed soil in palm of hand and saturate with “clean” water (distilled water or rainwater).
3. Squeeze hand gently until a soil and water slurry forms.
4. Touch tip of phosphate test strip to the soil and water slurry. Leave until the liquid is drawn up at least 1/8 to 3/16 inch beyond the area covered by the soil (fig. 4).
5. After 1 to 2 minutes, compare color of wet test strip to color chart on the test strip container (fig. 5). The color on the chart that most closely matches the color on the test strip indicates the amount of phosphate in the saturated soil. Record value in table 1.

Figure 4.—Quick in-field hand test.

Figure 5.—Phosphate color chart.

1:1 soil to water phosphate test for classroom:

1. Soil sampling should be completed as instructed in step 1 under “Quick in-field hand test.”
2. Fill scoop (29.5 ml) with the mixed soil, tamping down during filling by carefully striking the scoop on a hard, level surface. Put soil in vial. Add one scoopful (29.5 ml) of water to the vial, resulting in a 1:1 ratio of soil to water, on a volume basis.
3. Tightly cap the vial and shake 25 times. Let settle for 1 minute. Remove cap, and carefully decant 1/16 inch of soil and water slurry into cap.
4. Allow to settle for 2 to 3 minutes. Touch end of phosphate test strip to soil and water slurry. Leave until the liquid is drawn up at least 1/8 to 3/16 inch beyond the area covered by the soil (fig. 6).
5. After 1 to 2 minutes, compare color of wet test strip to color chart on test strip container (fig. 5). The color on the chart that most closely matches the color on the test strip indicates the index value of phosphate in the water-saturated soil. Record value in table 1.

Figure 6.—1:1 soil to water test.

Interpretations

Compare water-soluble phosphate (PO_4) test results to other P test method results, PO_4 categories, and recommended fertilizer rates in table 1. Answer discussion questions.

Recommendations for fertilizer and PO_4 categories will vary with the type of crop grown and Land Grant University recommendations.

Table 1.—Phosphorus test results and agronomic recommendations for corn grown in Nebraska*
(Based on standard P tests and water-soluble PO_4 test for a 1:1 soil to water mixture.)

Site	Water-soluble PO_4 in 1:1 soil to water mixture		Soil P relational values by P test method (ppm)			Relative PO_4 level****	Recommended fertilizer for corn (lbs P_2O_5/acre and [P/ac**])	
	PO_4 (ppm)	Relative PO_4 level	Water-soluble PO_4***	Olsen P****	Bray 1-P****		Broadcast****	Band****
Ex.1	16	High	0-5	0-3	0-5	Very low	80 [35]	40 [17]
			5-10	4-10	6-15	Low	40 [17]	20 [9]
			10-15	11-16	16-24	Medium	---	20 [9]
			15-20	17-20	25-30	High	---	---
			>20	>20	>30	Very high	---	---

*If animal manure or compost has been applied, most soils generally have a medium to very high level of phosphorus and do not need supplemental fertilization. Land Grant University recommendations should be followed. Further guidance is provided in the NRCS Nutrient Management Standard 590 (http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046896.pdf)

**Recommendations are based on use of synthetic P fertilizer, but they can also be used for organic sources of P such as rock phosphate or soft phosphate that can supply equivalent levels of available P over time.

***Water-soluble P (PO_4) test (Hach trademark) for 1:1 soil to water mixture based on comparison with Bray 1-P and Olsen P tests for nineteen benchmark soils (Bray 1-P test for soils with pH <7.2; Olsen P test for soils with pH >7.2). Water-soluble Aquachek-based P recommendations agreed for twelve soils (63 percent) and were borderline for another three soils, for a total of 79 percent. Four 1:1 soil to water mixture/water-soluble PO_4 tests indicated higher available P than results of standard Bray 1-P and Olsen P tests.

****Based on “Fertilizer Suggestions for Corn,” University of Nebraska NebGuide G74-174-A, revised September, 2001. For soils that have a medium level of phosphorus, applying 10 to 20 pounds per acre of P_2O_5 may increase early growth and application is optional.

Are soil phosphate levels adequate? What are the relative P levels and recommended rate of application of P_2O_5 fertilizer according to table 1?

___

___

___

Do current management practices limit phosphorus losses from erosion and sedimentation? Do they prevent soluble P in runoff or drainage tiles from reaching streams or lakes?

___

___

___

Are proper management practices being used to maintain soil health (compaction, pH, salinity, and organic matter content)? Do they properly manage the placement and application rate of P fertilizer or manure? Why or why not?

___

___

___

Glossary

Immobilization.—Temporary "tying up" of water-soluble P as a result of soil micro-organisms decomposing plant residue. Immobilized P will eventually become available for plant use as decomposition progresses.

Mineralization.—Conversion of nutrients in soil organic matter (e.g., phosphorus, nitrogen, and sulfur) to inorganic forms that are available for crop use; occurs during respiration.

Orthophosphate.—Form of phosphorus absorbed by plants, generally H_2PO_4- or HPO_4^{2-}.

Phosphorus cycle.—Circulation of many different forms of P in soil. Some forms are available for plant use, and some are not, such as those fixed to iron, aluminum, and calcium minerals (fig. 1).

Phosphorus fixation.—Phosphate that is bound to iron, aluminum, and calcium minerals and sorbed on clay minerals. Fixation and availability of P vary with soil pH (fig. 2).

Soil phosphate.—Form of P that is available for plant use, expressed as PO_4.

Soil Quality Information Sheet

Soil Quality Concerns: Pesticides

USDA Natural Resources Conservation Service January 1998

What are pesticides?

Pesticides are synthetic organic chemicals used to control weeds in fields and lawns, and unwanted or harmful pests, such as insects and mites that feed on crops. Pesticides are divided into categories according to the target organisms they are designed to control (e.g., insecticides control insects).

Herbicides are by far the most commonly used pesticides in the United States. They range from non selective to highly selective for control of specific weeds in specific crops, with different products having postemergence, preplant, and preemergence uses. Insecticides are second in usage, and fungicides are third.

Effects of Pesticides on Soil Quality

The capacity of the soil to filter, buffer, degrade, immobilize, and detoxify pesticides is a function or quality of the soil. Soil quality also encompasses the impacts that soil use and management can have on water and air quality, and on human and animal health. The presence and bio-availability of pesticides in soil can adversely impact human and animal health, and beneficial plants and soil organisms. Pesticides can move off-site contaminating surface and groundwater and possibly causing adverse impacts on aquatic ecosystems.

What are pesticide formulations?

The formulation is the chemical and physical form in which the pesticide is sold for use. The active ingredient (a.i.) is the chemical in the formulation that has the specific effect on the target organism. The formulation improves the properties of the pesticides for storage, handling, application, effectiveness, or safety. Examples of formulated products are wettable powders and water-dispersible granules. A single pesticide is often sold in several different formulations, depending on use requirements and application needs.

Pesticide mode of action

Mode of action refers to the mechanism by which the pesticide kills or interacts with the target organism.

- Contact pesticides kill the target organism by weakening or disrupting the cellular membranes; death can be very rapid.
- Systemic pesticides must be absorbed or ingested by the target organism to disrupt its physiological or metabolic processes; generally they are slow acting.

How effective the pesticides are at killing the target organisms (efficacy) depends on the properties of the pesticide and the soil, formulation, application technique, agricultural management, characteristics of the crop, environmental or weather conditions, and the nature and behavior of the target organism.

Fate of pesticides in the environment

Ideally, a pesticide stays in the treated area long enough to produce the desired effect and then degrades into harmless materials. Three primary modes of degradation occur in soils:

- biological - breakdown by micro-organisms
- chemical - breakdown by chemical reactions, such as hydrolysis and redox reactions
- photochemical - breakdown by ultraviolet or visible light

The rate at which a chemical degrades is expressed as the half-life. The half-life is the amount of time it takes for half of the pesticide to be converted into something else, or its concentration is half of its initial level. The half-life of a pesticide depends on soil type, its formulation, and environmental conditions (e.g., temperature, moisture). Other processes that influence the fate of the chemical include plant uptake, soil sorption, leaching, and volatilization. If pesticides move off-site (e.g., wind drift, runoff, leaching), they are considered to be pollutants. The potential for pesticides to move off-site depends on the chemical properties and formulation of the pesticide, soil properties, rate and method of application, pesticide persistence, frequency and timing of rainfall or irrigation, and depth to ground water.

Retention of pesticides in the soil

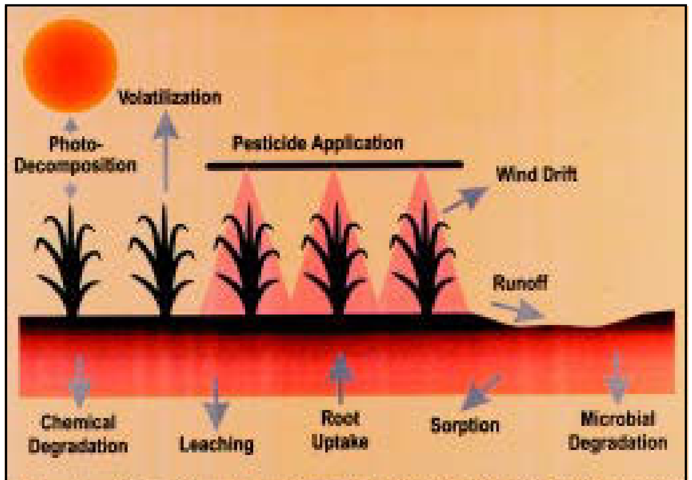
Retention refers to the ability of the soil to hold a pesticide in place and not allow it to be transported. Adsorption is the primary process of how the soil retains a pesticide and is defined as the accumulation of a pesticide on the soil particle surfaces. Pesticide adsorption to soil depends on both the chemical properties of the pesticide (i.e., water solubility, polarity) and properties of the soil (i.e., organic matter and clay contents, pH, surface charge characteristics, permeability). For most pesticides, organic matter is the most important soil property controlling the degree of adsorption.

For most pesticides, the degree of adsorption is described by an adsorption distribution coefficient (K_d), which is mathematically defined as the amount of pesticide in soil solution divided by the amount adsorbed to the soil.

Pesticide toxicity

The toxicity level of a pesticide depends on the deadliness of the chemical, the dose, the length of exposure, and the route of entry or absorption by the body. Pesticide degradation in soil generally results in a reduction in toxicity; however, some pesticides have breakdown products (metabolites) that are more toxic than the parent compound.

Pesticides are classified according to their potential toxicity to humans and other animals and organisms, as restricted-use (can only be purchased and applied by certified persons who have had training in pesticide application), and general use (may be purchased and applied by any person).



Fate of pesticides in the environment (after Aislabie and Lloyd-Jones).

Use and application considerations

- Apply pesticides at the lowest effective level.
- Avoid unnecessary pesticide treatments.
- Use Integrated Pest Management.
- Follow all label instructions.
- Apply proper rates and times as label indicates.
- Calibrate application equipment.
- Apply formulations that minimize drift.
- Use safety equipment when handling.
- Store and dispose of pesticide containers properly.
- Use biological controls when appropriate.
- Alter farming or cropping systems to control pests.
- Use disease and insect resistant crop varieties.

(Prepared by the National Soil Survey Center in cooperation with the Soil Quality Institute, NRCS, USDA, and the National Soil Tilth Laboratory, Agricultural Research Service, USDA).

Visit our Web site:
http://soils.usda.gov

Effect of Soil Quality on Nutrient Efficiency

USDA

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Soil Quality Institute
2150 Pammel Dr.
Ames, IA 50011
515-294-4592

Technical
Note No. 4

August, 1997

This is the fourth Agronomy fact sheet in a series on on soil quality. This fact sheet is general. For specific application, contact your NRCS State Agronomist.

Nutrient efficiency is a measure of how much crop is produced per unit of nutrient supplied. The higher the efficiency, the more product is produced per unit of nutrient. The quality of soil affects nutrient use efficiency. Soil quality is measured or evaluated by a number of indicators. This technical note will discuss how 13 indicators relates to nutrient efficiency.

1. Soil Quality definition with regards to nutrients

A healthy soil functioning at nearly full capacity stores and cycles nutrients and allows crops to grow and use nutrients efficiently. In a healthy soil, nutrients become available when the plants need them. There is little risk for crop nutrients to move below the root zone through leaching, off the edge of field by runoff and erosion, or above the crop canopy by volatilization. Crop nutrients that move beyond the crop's zone of uptake could potentially contaminate the environment.

2. Erosion

Erosion and runoff are both detrimental to nutrient management. Nutrients contained in the topsoil, along with soil organic matter, can be carried away by erosion or washed out with runoff water. The organic matter is the first to be transported by water or wind because of its lower specific gravity. Additional nutrients are required to maintain productivity lost when topsoil is carried away by erosion.

3. Deposition of Sediment

Sediment additions in the field can be good or bad. Some sediment, especially the finer clay particles and organic matter, bring in nutrients. The coarser sediments, like sands, do not have a high nutrient content and tend to cover the topsoil that is in place. Coarser textured soils also lack moisture-holding and pesticide-retention capacity.

4. Compaction

Compact soils restrict the movement of roots. Less root volume in the soil prevents nutrient uptake. Compaction also restricts the diffusion and flow of nutrients in the soil. Few roots and limited nutrient movement can result in stunted growth because the plant is unable to take up the nutrients in the soil. Compacted soils retard air movement and gas exchange in the root zone. This can lead to nutrient losses, like denitrification or toxic gas build-up near the roots.

5. Soil Aggregation at the Soil Surface

Good soil aggregation means better water and nutrient movement through the soil. More aggregation means more of the surface area of the soil particles have capacity for adsorbed nutrients. Surface aggregation allows pore space for water infiltration and gas exchanges. Good soil aggregation is closely tied to the amount of active organic matter and to biological activity. Thus soil aggregation is connected to nutrient cycling.

6. Infiltration

Plants require water. Nutrients move with the water through the soil pores and are absorbed into the plant. When nutrients are applied to the soil surface, as in no-till systems, water is required to move the nutrients down into the root zone. Good soil infiltration permits this to happen. Nutrients that are not carried into the root zone are susceptible to runoff. Percolating water carries the nutrients deeper into the root zone and also removes harmful salts that may accumulate there.

7. Soil Crusting

Crusting seals the soil surface and restricts water infiltration and gas exchange. If not allowed to infiltrate, surface applied nutrients on crusted soils are susceptible to runoff and wind transport. Crusting also reduces seed germination and seedling survival which directly has an effect on the plant population and the amount of nutrients necessary for the crop.

8. Nutrient Loss or Imbalance

Nutrients need to be applied according to the crop and soil requirements. Soil and plant analyses are a good way to determine the amount of nutrients needed. Over-application of nutrients can lead to plant toxicity, poor pH reaction, and excess nutrients susceptible to runoff, leaching, and volatilization. A deficiency in nutrients will not sustain optimum plant growth.

9. Pesticide Carryover

Pesticides with residual soil activity can stunt growth of subsequent crops. If roots are affected, their ability to absorb nutrients will be lessened. Any effect on plant photosynthesis will reduce nutrient uptake and metabolism. Without pesticide or weed control, weeds can utilize nutrients in competition of the crop. The weed residue may not decompose and recycle plant nutrients for the subsequent crops.

10. Organic Matter

Soil organic matter is a very valuable component of the topsoil. Organic matter stores nutrients, feeds soil organisms that decompose organic material, and return the basic nutrients to the soil. Organic matter holds soil moisture for plant use. Soil organic matter is developed by combining of carbon, oxygen, and nitrogen plus other nutrients in the soil. Nitrogen and other nutrients must be available to soil microorganisms for development of organic matter.

11. Biological Activity

A healthy soil has a diverse set of macro and micro organisms that assure a well functioning soil food web. Microorganisms decompose organic material, store nutrients in their bodies, and as they decay or become food for other organisms, they release nutrients. Some small animals like insects and crustacea carry organic material and related nutrients into the soil and aid in its decomposition. Some microorganisms have a symbiotic relationship with plants such as mycorrhiza. Mycorrhiza live in plant roots and help the plants assimilate water and nutrients.

12. Weeds and Pathogens

Nutrients can be used by crops or by weeds. Weeds utilize nutrients, but fail to produce a marketable commodity. So, the nutrients are not efficiently used to grow crops. The same is true for crops that are attacked by disease and insects. Efficient utilization means nutrients are converted to a harvestable product.

13. Extreme Soil Moisture Conditions

The amount of soil moisture impacts nutrient cycling. A dry soil does not promote root extension in the root zone. And, since nutrients are carried by water, plants are unable to obtain adequate nutrition. Waterlogged soils affect the transformation of nutrients. Phosphorus becomes more mobile and less attached to minerals in waterlogged conditions. Nitrate nitrogen is denitrified by changing form from a liquid to a gas which can be lost to the atmosphere. Roots consume oxygen and respire carbon dioxide. Because gases are transported much more slowly through water (about one ten thousanth slower) than air, some gases such as carbon dioxide can accumulate in the soil and be toxic to roots.

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Soil Quality Institute
2150 Pammel Dr.
Ames, IA 50011
515-294-4592

Technical
Note No. 4

August, 1997

Soil Enzymes

Soil enzymes increase the reaction rate at which plant residues decompose and release plant available nutrients. The substance acted upon by a soil enzyme is called the substrate. For example, glucosidase (soil enzyme) cleaves glucose from glucoside (substrate), a compound common in plants. Enzymes are specific to a substrate and have active sites that bind with the substrate to form a temporary complex. The enzymatic reaction releases a product, which can be a nutrient contained in the substrate.

Sources of soil enzymes include living and dead microbes, plant roots and residues, and soil animals. Enzymes stabilized in the soil matrix accumulate or form complexes with organic matter (humus), clay, and humus-clay complexes, but are no longer associated with viable cells. It is thought that 40 to 60% of enzyme activity can come from stabilized enzymes, so activity does not necessarily correlate highly with microbial biomass or respiration. Therefore, enzyme activity is the cumulative effect of long term microbial activity and activity of the viable population at sampling. However, an example of an enzyme that only reflects activity of viable cells is dehydrogenase, which in theory can only occur in viable cells and not in stabilized soil complexes.

Factors Affecting

Inherent - Soil enzymes have varying optimum pH and temperature values at which they function most effectively. For example, the activity of phosphatase, aryl sulfatase, and amidase involved in phosphorus, sulfur, and nitrogen cycling, respectively, is strongly correlated to variations in soil pH. Since enzyme structure and substrate binding can be altered by heat and extreme cold temperature, enzyme activity decreases above and below the optimum temperature. The activity of many enzymes often correlates with soil moisture content, as well. Drought may suppress enzyme activity. Soil texture influences enzyme activity, and normally enzyme activities are significantly and positively correlated with clay content. Clayey soils have greater ability to store organic matter that promotes microbial communities, and clay forms clay-enzyme complexes. In contrast, sandy soils tend to exhibit low rates of enzyme activity because they are naturally low in organic matter and have poor water holding capacity which results in lower microbial biomass and therefore lower enzyme activity.

Dynamic - Addition of organic amendments and adoption of management practices that increase soil organic matter lead to increased enzyme activity (figs 1 and 2). Plant roots stimulate enzyme activity because of their positive effect on microbial activity and production of exudates rich in substrates acted on by enzymes.

Elevated soil concentrations of chemical compounds that are end products of enzymatic reactions can inhibit enzyme activity by feedback inhibition. For example, phosphatase activity increases in phosphorus deficient soil, but its activity decreases in soil with high phosphorus concentration. Similarly, urease activity may be suppressed by ammonia-based nitrogen fertilizer because ammonium is the product of urease activity (fig 2).

Compaction may limit the activity of enzymes involved in nutrient mineralization because of decreased oxygen in the soil for those reactions or organisms requiring an aerobic environment. Conversely, anaerobic conditions from compaction or water saturation increase enzymatic reaction rates related to denitrification. Application of materials containing heavy metals can reduce enzyme activity (e.g., amidase) due to their toxic effect on soil organisms and roots or direct inhibition of enzyme reactions.

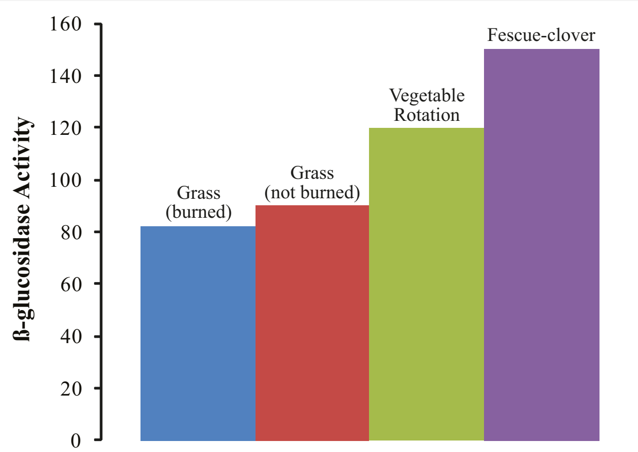


Figure 1. Effects of cropping systems on ß-glucosidase (adapted from Dick 1994).

Relationship to Soil Function

Enzymes respond to soil management changes long before other soil quality indicator changes are detectable. Soil enzymes play an important role in organic matter decomposition and nutrient cycling (table 1). Some enzymes only facilitate the breakdown of organic matter (e.g., hydrolase, glucosidase), while others are involved in nutrient mineralization (e.g., amidase, urease, phosphatase, sulfates). With the exception of phosphatase activity, there is no strong evidence that directly relates enzyme activity to nutrient availability or crop production. The relationship may be indirect considering nutrient mineralization to plant available forms is accomplished with the contribution of enzyme activity.

Problems with Poor Activity

Absence or suppression of soil enzymes prevents or reduces processes that can affect plant nutrition. Poor enzyme activity (e.g., pesticide degrading enzymes) can result in an accumulation of chemicals that are harmful to the environment; some of these chemicals may further inhibit soil enzyme activity.

Improving Enzyme Activity

Organic amendment applications, crop rotation, and cover crops have been shown to enhance enzyme activity (figs 1 and 2). The positive effect of pasture (fig 2) is associated with the input of animal manure and less soil disturbance. Agricultural methods that modify soil pH (e.g., liming) can also change enzyme activity.

Measuring Enzyme Activity

Enzymes are measured indirectly by determining their activity in the laboratory using biochemical assays. Enzyme assays reflect potential activity and do not represent true in situ activity levels and must be viewed as an index.

Interpretation and Assessment

When possible, compare the site of interest to samples taken from an adjacent, undisturbed site on the same soil type. Alternatively, for a newly implemented land management system, track changes from time zero to five or more years with annual sampling to detect temporal changes in activity of soil enzymes.

Specialized equipment, shortcuts, tips:

A spectrophotometer, and in some cases a fume hood, centrifuge, and/or shaker. For better results, use the enzyme optimum temperature and pH.

Time needed: variable, 30 to 60 minutes

References:

Bandick AK and Dick RP. 1999. Field management effects on enzyme activities. Soil Biology and Biochemistry 31:1471-1479.

Dick RP. 1994. Soil Enzyme Activity as an Indicator of Soil Quality. In: Doran JW et al., editors. Defining soil quality for a sustainable environment.. Madison, WI. p107-124.

Tabatabai MA. 1994. Soil Enzymes. In: Weaver RW et al., editors. Methods of soil analysis. Part 2. Microbiological and Biochemical Properties. p 775-833.

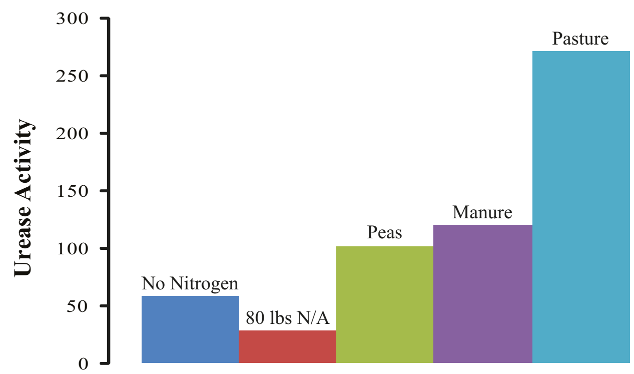


Figure 2. Effects of management on urease activity (adapted from Bandick and Dick 1999).

Table 1. Role of soil enzymes

Enzyme	Organic Matter Substances Acted On	End Product	Significance	Predictor of Soil Function
Beta glucosidase	carbon compounds	glucose (sugar)	energy for microorganisms	organic matter decomposition
FDA hydrolysis	organic matter	carbon and various nutrients	energy and nutrients for microorganisms, measure microbial biomass	organic matter decomposition nutrient cycling
Amidase	carbon and nitrogen compounds	ammonium (NH_4)	plant available NH_4	nutrient cycling
Urease	nitrogen (urea)	ammonia (NH_3) and carbon dioxide (CO_2)	plant available NH_4	nutrient cycling
Phosphatase	phosphorus	phosphate (PO_4)	plant available P	nutrient cycling
Sulfatase	sulfur	sulfate (SO_4)	plant available S	nutrient cycling

Heavy Metal Soil Contamination

United States
Department of
Agriculture

Natural
Resources
Conservation
Service

Soil Quality Institute
411 S. Donahue Dr.
Auburn, AL 36832
334-844-4741
X-177
Urban Technical
Note No. 3

September, 2000

This is the third note in a series of Soil Quality-Urban technical notes on the effects of land management on soil quality.

Introduction

Soil is a crucial component of rural and urban environments, and in both places land management is the key to soil quality. This series of technical notes examines the urban activities that cause soil degradation, and the management practices that protect the functions urban societies demand from soil. This technical note focuses on heavy metal soil contamination.

Metals in Soil

Mining, manufacturing, and the use of synthetic products (e.g. pesticides, paints, batteries, industrial waste, and land application of industrial or domestic sludge) can result in heavy metal contamination of urban and agricultural soils. Heavy metals also occur naturally, but rarely at toxic levels. Potentially contaminated soils may occur at old landfill sites (particularly those that accepted industrial wastes), old orchards that used insecticides containing arsenic as an active ingredient, fields that had past applications of waste water or municipal sludge, areas in or around mining waste piles and tailings, industrial areas where chemicals may have been dumped on the ground, or in areas downwind from industrial sites.

Excess heavy metal accumulation in soils is toxic to humans and other animals. Exposure to heavy metals is normally chronic (exposure over a longer period of time), due to food chain transfer. Acute (immediate) poisoning from heavy metals is rare through ingestion or dermal contact, but is possible. Chronic problems associated with long-term heavy metal exposures are:

- Lead – mental lapse.
- Cadmium – affects kidney, liver, and GI tract.
- Arsenic – skin poisoning, affects kidneys and central nervous system.

The most common problem causing *cationic* metals (metallic elements whose forms in soil are positively charged cations e.g., Pb^{2+}) are mercury, cadmium, lead, nickel, copper, zinc, chromium, and manganese. The most common anionic compounds (elements whose forms in soil are combined with oxygen and are negatively charged e.g., MoO_4^{2-}) are arsenic, molybdenum, selenium, and boron.

Prevention of Heavy Metal Contamination

Preventing heavy metal pollution is critical because cleaning contaminated soils is extremely expensive and difficult. Applicators of industrial waste or sludge must abide by the regulatory limits set by the U.S. Environmental Protection Agency (EPA) in Table 1.

Table 1. Regulatory limits on heavy metals applied to soils (Adapted from U.S. EPA, 1993).

Heavy metal	Maximum concentration in sludge (mg/kg or ppm)	Annual pollutant loading rates		Cumulative pollutant loading rates	
		(kg/ha/yr)	(lb/A/yr)	(kg/ha)	(lb/A)
Arsenic	75	2	1.8	41	36.6
Cadmium	85	1.9	1.7	39	34.8
Chromium	3000	150	134	3000	2,679
Copper	4300	75	67	1500	1,340
Lead	420	21	14	420	375
Mercury	840	15	13.4	300	268
Molybdenum	57	0.85	0.80	17	15
Nickel	75	0.90	0.80	18	16
Selenium	100	5	4	100	89
Zinc	7500	140	125	2800	2500

Prevention is the best method to protect the environment from contamination by heavy metals. With the above table, a simple equation is used to show the maximum amount of sludge that can be applied. For example, suppose city officials want to apply the maximum amount of sludge (kg/ha) on some agricultural land. The annual pollutant-loading rate for zinc is 140 kg/ha/yr (from Table 1). The lab analysis of the sludge shows a zinc concentration of 7500 mg/kg (mg/kg is the same as parts per million). How much can the applicator apply (tons/A) without exceeding the 140 kg/ha/yr?

Solution:

(1) Convert mg to kg (1,000,000 mg = 1kg) so all units are the same:
7500 mg X (1 kg/1,000,000 mg) = 0.0075 kg

(2) Divide the amount of zinc that can be applied by the concentration of zinc in the sludge:
(140 kg Zn/ha) / (0.0075 kg Zn/kg sludge) =18,667 kg sludge/ha

(3) Convert to lb/A: 18,667 kg/ha X 0.893 = 16,669 lbs/A
Convert lbs to tons: 16,669 lb/A / 2,000 lb/T = 8.3 T sludge per acre

Traditional Remediation of Contaminated Soil

Once metals are introduced and contaminate the environment, they will remain. Metals do not degrade like carbon-based (organic) molecules. The only exceptions are mercury and selenium, which can be transformed and volatilized by microorganisms. However, in general it is very difficult to eliminate metals from the environment.

Traditional treatments for metal contamination in soils are expensive and cost prohibitive when large areas of soil are contaminated. Treatments can be done *in situ* (on-site), or *ex situ* (removed and treated off-site). Both are extremely expensive. Some treatments that are available include:

1. High temperature treatments (produce a vitrified, granular, non-leachable material).
2. Solidifying agents (produce cement-like material).
3. Washing process (leaches out contaminants).

Management of Contaminated Soil

Soil and crop management methods can help prevent uptake of pollutants by plants, leaving them in the soil. The soil becomes the sink, breaking the soil-plant-animal or human cycle through which the toxin exerts its toxic effects (Brady and Weil, 1999).

The following management practices will not remove the heavy metal contaminants, but will help to immobilize them in the soil and reduce the potential for adverse effects from the metals – Note that the kind of metal (cation or anion) must be considered:

1. Increasing the soil pH to 6.5 or higher.

   Cationic metals are more soluble at lower pH levels, so increasing the pH makes them less available to plants and therefore less likely to be incorporated in their tissues and ingested by humans. Raising pH has the opposite effect on anionic elements.

2. Draining wet soils.

   Drainage improves soil aeration and will allow metals to oxidize, making them less soluble. Therefore when aerated, these metals are less available. The opposite is true for chromium, which is more available in oxidized forms. Active organic matter is effective in reducing the availability of chromium.

3. Applying phosphate.

   Heavy phosphate applications reduce the availability of cationic metals, but have the opposite effect on anionic compounds like arsenic. Care should be taken with phosphorus applications because high levels of phosphorus in the soil can result in water pollution.

4. Carefully selecting plants for use on metal-contaminated soils

   Plants translocate larger quantities of metals to their leaves than to their fruits or seeds. The greatest risk of food chain contamination is in leafy vegetables like lettuce or spinach. Another hazard is forage eaten by livestock.

Plants for Environmental Cleanup

Research has demonstrated that plants are effective in cleaning up contaminated soil (Wenzel et al., 1999). Phytoremediation is a general term for using plants to remove, degrade, or contain soil pollutants such as heavy metals, pesticides, solvents, crude oil, polyaromatic hydrocarbons, and landfill leacheates For example, prairie grasses can stimulate breakdown of petroleum products. Wildflowers were recently used to degrade hydrocarbons from an oil spill in Kuwait. Hybrid poplars can remove ammunition compounds such as TNT as well as high nitrates and pesticides (Brady and Weil, 1999).

Plants for Treating Metal Contaminated Soils

Plants have been used to stabilize or remove metals from soil and water. The three mechanisms used are *phytoextraction*, *rhizofiltration*, and *phytostabilization*. This technical note will define rhizofiltration and phytostabilization but will focus on phytoextraction.

Rhizofiltration is the adsorption onto plant roots or absorption into plant roots of contaminants that are in solution surrounding the root zone (rhizosphere). Rhizofiltration is used to decontaminate groundwater. Plants are grown in greenhouses in water instead of soil. Contaminated water from the site is used to acclimate the plants to the environment. The plants are then planted on the site of contaminated ground water where the roots take up the water and contaminants. Once the roots are saturated with the contaminant, the plants are harvested including the roots. In Chernobyl, Ukraine, sunflowers were used in this way to remove radioactive contaminants from groundwater (EPA, 1998).

Phytostabilization is the use of perennial, non-harvested plants to stabilize or immobilize contaminants in the soil and groundwater. Metals are absorbed and accumulated by roots, adsorbed onto roots, or precipitated within the rhizosphere. Metal-tolerant plants can be used to restore vegetation where natural vegetation is lacking, thus reducing the risk of water and wind erosion and leaching. Phytostabilization reduces the mobility of the contaminant and prevents further movement of the contaminant into groundwater or the air and reduces the bioavailability for entry into the food chain.

Phytoextraction

Phytoextraction is the process of growing plants in metal contaminated soil . Plant roots then translocate the metals into aboveground portions of the plant. After plants have grown for some time, they are harvested and incinerated or composted to recycle the metals. Several crop growth cycles may be needed to decrease contaminant levels to allowable limits. If the plants are incinerated, the ash must be disposed of in a hazardous waste landfill, but the volume of the ash is much smaller than the volume of contaminated soil if dug out and removed for treatment. (See box.)

Example of Disposal

Excavating and landfilling a 10-acre contaminated site to a depth of 1 foot requires handling roughly 20,000 tons of soil. Phytoextraction of the same site would result in the need to handle about 500 tons of biomass, which is about 1/40 of the mass of the contaminated soil. In this example, if we assume the soil was contaminated with a lead concentration of 400 ppm, six to eight crops would be needed, growing four crops per season (Phytotech, 2000).

Phytoextraction is done with plants called hyperaccumulators, which absorb unusually large amounts of metals in comparison to other plants. Hyperaccumulators contain more than 1,000 milligrams per kilogram of cobalt, copper, chromium, lead, or nickel; or 10,000 milligrams per kilogram (1 %) of manganese or zinc in dry matter (Baker and Brooks, 1989). One or more of these plant types are planted at a particular site based on the kinds of metals present and site conditions. Tables 2 and 3 demonstrate the importance of using hyperaccumulators.

Table 2. Percentage decrease in water-extractable zinc and cadmium in three soils after growth of Alpine pennycress (*Thlaspi caerulescens)* (McGrath, 1998).

Site Sampled	Zn	Cd
Farm	28	10
Garden	17	22
Mountain	64	70

Table 3. Removal of zinc in a hypothetical 4.5 T/A (dry matter) crop growing in soil contaminated with 1000 (ppm) zinc with a target of 50 ppm, showing the importance of hyperaccumulation (>10,000 ppm zinc) (McGrath, 1998).

ppm Zn in plant	Lbs. of Zn removed	% of soil total in one crop	years to target
100	0.9	0.04	2470.0
1000	9	0.38	247.0
10,000	90	3.85	24.7
20,000	179	7.69	12.4
30,000	268	11.54	8.2

Phytoextraction is easiest with metals such as nickel, zinc, and copper because these metals are preferred by a majority of the 400 hyperaccumlator plants. Several plants in the genus *Thlaspi* (pennycress) have been known to take up more than 30,000 ppm (3%)of zinc in their tissues. These plants can be used as ore because of the high metal concentration (Brady and Weil, 1999).

Of all the metals, lead is the most common soil contaminant (EPA, 1993). Unfortunately, plants do not accumulate lead under natural conditions. A chelator such as EDTA (ethylenediaminetetraacetic acid) has to be added to the soil as an amendment. The EDTA makes the lead available to the plant. The most common plant used for lead extraction is Indian mustard (*Brassisa juncea*). Phytotech (a private research company) has reported that they have cleaned up lead-contaminated sites in New Jersey to below the industrial standards in 1 to 2 summers using Indian mustard (Wantanabe, 1997).

Plants are available to remove zinc, cadmium, lead, selenium, and nickel from soils at rates that are medium to long-term, but rapid enough to be useful. Many of the plants that hyperaccumulate metals produce low biomass, and need to be bred for much higher biomass production.

Current genetic engineering efforts at USDA in Beltsville, MD, are aimed toward developing pennycress (*Thlaspi*) that is extremely zinc tolerant. These taller-than-normal plants would have more biomass, thereby taking up larger quantities of contaminating metals (Watanabe, 1997).

Traditional cleanup *in situ* may cost between $10.00 and $100.00 per cubic meter ($m^3$), whereas removal of contaminated material (*ex situ*) may cost as high $30.00 to $300/ m^3. In comparison, phytoremediation may only cost $0.05/ m^3 (Watanabe, 1997).

Future Prospects

Phytoremediation has been studied extensively in research and small-scale demonstrations, but in only a few full-scale applications. Phytoremediation is moving into the realm of commercialization (Watanabe, 1997). It is predicted that the phytoremediation market will reach $214 to $370 million by the year 2005 (Environmental Science & Technology, 1998).

Given the current effectiveness, phytoremediation is best suited for cleanup over a wide area in which contaminants are present at low to medium concentrations. Before phytoremediation is fully commercialized, further research is needed to assure that tissues of plants used for phytoremediation do not have adverse environmental effects if eaten by wildlife or used by humans for things such as mulch or firewood (EPA, 1998). Research is also needed to find more efficient bioaccumulators, hyperaccumulators that produce more biomass, and to further monitor current field trials to ensure a thorough understanding. There is the need for a commercialized smelting method to extract the metals from plant biomass so they can be recycled.

Phytoremediation is slower than traditional methods of removing heavy metals from soil but much less costly. Prevention of soil contamination is far less expensive than any kind of remediation and much better for the environment.

References

Baker, A.J.M., and R.R. Brooks. 1989. Terrestrial plants which hyperaccumulate metallic elements – a review of their distribution, ecology, and phytochemistry. Biorecovery 1:81:126.

Brady, N.C., and R.R. Weil. 1999. The nature and properties of soils. 12th ed. Prentice Hall. Upper Saddle River, NJ.

Environmental Science & Technology. 1998. Phytoremediation; forecasting. Environmental Science & Technology. Vol. 32, issue 17, p.399A.

McGrath, S.P. 1998. Phytoextraction for soil remediation. p. 261-287. *In* R. Brooks (ed.) Plants that hyperaccumulate heavy metals their role in phytoremediation, microbiology, archaeology, mineral exploration and phytomining. CAB International, New York, NY.

Phytotech. 2000. Phytoremediation technology. http://clu-in.org/PRODUCTS/SITE/ongoing/demoong/phytotec.htm

U.S. EPA. 1993. Clean Water Act, sec. 503, vol. 58, no. 32. (U.S. Environmental Protection Agency Washington, D.C.).

U.S. EPA. 1998. A citizen's guide to phytoremediation. http://clu-in.org/PRODUCTS/CITGUIDE/Phyto2.htm

Watanabe, M.E. 1997. Phytoremediation on the brink of commercialization. Environmental Science & Technology/News. 31:182-186.

Wenzel, W.W., Adriano, D.C., Salt, D., and Smith, R. 1999. Phytoremediation: A plant-microbe based remediation system. p. 457-508. *In* D.C. Adriano et al. (ed.) Bioremediation of contaminated soils. American Society of Agronomy, Madison, WI.

Animal Manures for Increasing Organic Matter and Supplying Nutrients

The quickest way to rebuild a poor soil is to practice dairy farming, growing forage crops, buying . . .grain rich in protein, handling the manure properly, and returning it to the soil promptly.

—J. L. HILLS, C. H. JONES, AND C. CUTLER, 1908

Once cheap fertilizers became widely available after World War II, many farmers, extension agents, and scientists looked down their noses at manure. People thought more about how to get rid of manure than how to put it to good use. In fact, some scientists tried to find out the absolute maximum amount of manure that could be applied to an acre without reducing crop yields. Some farmers who didn't want to spread manure actually piled it next to a stream and hoped that next spring's flood waters would wash it away. We now know that manure, like money, is better spread around than concentrated in a few places. The economic contribution of farm manures can be considerable. On a national basis, the manure from 100 million cattle, 60 million hogs, and 9 billion chickens contains about 23 million tons of nitrogen. At a value of 50 cents per pound, that works out to a value of about $25 billion for just the N contained in animal manures. The value of the nutrients in manure from a 100-cow dairy farm may exceed $20,000 per year; manure from a 100-sow farrow-to-finish operation is worth about $16,000; and manure from a 20,000bird broiler operation is worth about $6,000. The other benefits to soil organic matter buildup, such as enhanced soil structure and better diversity and activity of soil organisms, may double the value of the manure. If you're not getting the full fertility benefit from manures on your farm, you may be wasting money.

Animal manures can have very different properties, depending on the animal species, feed, bedding, handling, and manure-storage practices. The amounts of nutrients in the manure that become available to crops also depend on what time of year the manure is applied and how quickly it is worked into the soil. In addition, the influence of manure on soil organic matter and plant growth is influenced by soil type. In other words, it's impossible to give blanket manure application recommendations. They need to be tailored for every situation.

We'll start the discussion with dairy cow manure but will also offer information about the handling, characteristics, and uses of some other animal manures.

Manure Handling Systems

Solid versus Liquid

The type of barn on the farmstead frequently determines how manure is handled on a dairy farm. Dairy-cow manure containing a fair amount of bedding, usually around 20% dry matter or higher, is spread as a solid. This is most common on farms where cows are kept in individual stanchions or tie-stalls. Liquid manure-handling systems are common where animals are kept in a "free stall" barn and minimal bedding is added to the manure. Liquid manure is usually in the range of from 2% to 12% dry matter (88% or more water), with the lower dry matter if water is flushed from alleys and passed through a liquid-solid separator or large amounts of runoff enter the storage lagoon. Manures with characteristics between solid and liquid, with dry matter between 12% and 20%, are usually referred to as semisolid.

Composting manures is becoming an increasingly popular option for farmers. By composting manure, you help stabilize nutrients (although considerable ammonium is usually lost in the process), have a smaller amount of material to spread, and have a more pleasant material to spread—a big plus if neighbors have complained about manure odors. Although it’s easier to compost manure that has been handled as a solid, it does take a lot of bedding to get fresh manure to a 20% solid level. Some farmers are separating the solids from liquid manure and then irrigating with the liquid and composting the solids. Some are separating solids following digestion for methane production and burning the gas to produce electricity or heat. Separating the liquid allows for direct composting of the solids without any added materials. It also allows for easier transport of the solid portion of the manure for sale or to apply to remote fields. For a more detailed discussion of composting, see chapter 13.

Some dairy farmers have built what are called “compost barns.” No, the barns don’t compost, but they are set up similar to a free-stall barn, where bedding and manure just build up over the winter and the pack is cleaned out in the fall or spring. However, with composting barns, the manure is stirred or turned twice daily with a modified cultivator on a skid steer loader or small tractor to a depth of 8 to 10 inches; sometimes ceiling fans are used to help aerate and dry the pack during each milking. Some farmers add a little new bedding each day, some do it weekly, and others do it every two to five weeks. In the spring and fall some or all of the bedding can be removed and spread directly or built into a traditional compost pile for finishing. Although farmers using this system tend to be satisfied with it, there is a concern about the continued availability of wood shavings and sawdust for bedding. More recently, vermicomposting has been introduced as a way to process dairy manure. In this case, worms digest the manure, and the castings provide a high-quality soil amendment.

Manure from hogs can also be handled in different ways. Farmers raising hogs on a relatively small scale sometimes use hoop houses, frequently placed in fields, with bedding on the floor. The manure mixed with bedding can be spread as a solid manure or composted first. The larger, more industrial-scale farmers mainly use little to no bedding with slatted floors over the manure pit and keep the animals clean by frequently washing the floors. The liquid manure is held in ponds for spreading, mostly in the spring before crops are planted and in the fall after crops have been harvested. Poultry manure is handled with bedding (especially for broiler production) or little to no bedding (industrial-scale egg production).

Storage of Manure

Researchers have been investigating how best to handle, store, and treat manure to reduce the problems that come with year-round manure spreading. Storage allows the farmer the opportunity to apply manure when it’s best for the crop and during appropriate weather conditions. This reduces nutrient loss from the manure, caused by water runoff from the field. However, significant losses of nutrients from stored manure also may occur. One study found that during the year dairy manure stored in uncovered piles lost 3% of the solids, 10% of the nitrogen, 3% of the phosphorus, and 20% of the potassium. Covered piles or well-contained bottom-loading liquid systems, which tend to form a crust on the surface, do a better job of conserving the nutrients and solids than unprotected piles. Poultry manure, with its high amount of ammonium, may lose 50% of its nitrogen during storage as ammonia gas volatilizes, unless precautions are taken to conserve nitrogen. Regardless of storage method, it is important to understand how potential losses occur in order to select a storage method and location that minimize environmental impact.

Chemical Characteristics of Manures

A high percentage of the nutrients in feeds passes right through animals and ends up in their manure. Depending on the ration and animal type, over 70% of the nitrogen, 60% of the phosphorus, and 80% of the potassium fed may pass through the animal as manure. These nutrients are available for recycling on cropland. In addition to the nitrogen, phosphorus, and potassium contributions given in table 12.1, manures contain significant amounts of other nutrients, such as calcium, magnesium, and sulfur. For example, in regions that tend to lack the micronutrient zinc, there is rarely any crop deficiency found on soils receiving regular manure applications.

TABLE 12.1: Typical Manure Characteristics

	Dairy Cow	Beef Cow	Chicken	Hog
Dry Matter Content (%)				
Solid	26	23	55	9
Liquid (fresh, diluted)	7	8	17	6
Total Nutrient Content (Approximate)				
Nitrogen				
pounds/ton	10	14	25	10
pounds/1,000 gallons	25	39	70	28
Phosphate, as P_2O_5				
pounds/ton	6	9	25	6
pounds/1,000 gallons	9	25	70	9
Potash, as K_20				
pounds/ton	7	11	12	9
pounds/1,000 gallons	20	31	33	34
Approximate amounts of solid and liquid manure to supply 100 pounds N for a given species of animal*				
solid manure (tons)	10	7	4	10
liquid manure (gallons)	4000	2500	1500	3600

*Provides similar amounts of nutrients.

Source: Modified from various sources.

The values given in table 12.1 must be viewed with some caution, because the characteristics of manures from even the same type of animal may vary considerably from one farm to another. Differences in feeds, mineral supplements, bedding materials, and storage systems make manure analyses quite variable. Yet as long as feeding, bedding, and storage practices remain relatively stable on a given farm, manure nutrient characteristics will tend to be similar from year to year. However, year-to-year differences in rainfall can affect stored manure through more or less dilution.

The major difference among all the manures is that poultry manure is significantly higher in nitrogen and phosphorus than the other manure types. This is partly due to the difference in feeds given poultry versus other farm animals. The relatively high percentage of dry matter in poultry manure is also partly responsible for the higher analyses of certain nutrients when expressed on a wet ton basis.

It is possible to take the guesswork out of estimating manure characteristics; most soil-testing laboratories will also analyze manure. Manure analysis should become a routine part of the soil fertility management program on animal-based farms. This is of critical importance for routine manure use. For example, while the average liquid dairy manure is around 25 pounds of N per 1,000 gallons, there are manures that might be 10 pounds N or less OR 40 pounds N or more per 1,000 gallons. Recent research efforts have focused on more efficient use of nutrients in dairy cows, and N and P intake can often be reduced by up to 25% without losses in productivity. This helps reduce nutrient surpluses on farms using only needed P.

FORMS OF NITROGEN IN MANURES

Nitrogen in manure occurs in three main forms: ammonium (NH_4^+), urea (a soluble organic form, easily converted to ammonium), and solid, organic N. Ammonium is readily available to plants, and urea is quickly converted to ammonium in soils. However, while readily available when incorporated in soil, both ammonium and urea are subject to loss as ammonia gas when left on the surface under drying conditions— with significant losses occurring within hours of applying to the soil surface. Some manures may have half or three-quarters of their N in readily available forms, while others may have 20% or less in these forms. Manure analysis reports usually contain both ammonium and total N (the difference is mainly organic N), thus indicating how much of the N is readily available—but also subject to loss if not handled carefully.

Effects of Manuring on Soils

Effects on Organic Matter

When considering the influence of any residue or organic material on soil organic matter, the key question is how much solids are returned to the soil. Equal amounts of different types of manures will have different effects on soil organic matter levels. Dairy and beef manures contain undigested parts of forages and may have significant quantities of bedding. They therefore have a high amount of complex substances, such as lignin, that do not decompose readily in soils. Using this type of manure results in a much greater long-term influence on soil organic matter than does a poultry or swine manure without bedding. More solids are commonly applied to soil with solid-manure-handling systems than with liquid systems, because greater amounts of bedding are usually included. A number of trends in dairy farming mean that manures may have less organic material than in the past. One is the use of sand as bedding material in free-stall barns, much of which is recovered and reused. The other is the separation of solids and liquids with the sale of solids or the use of digested solids as bedding. Under both situations much less organic solids are returned to fields. On the other hand, the bedded pack (or compost barn) does produce a manure that is high in organic solid content.

When conventional tillage is used to grow a crop such as corn silage, whose entire aboveground portion is harvested, research indicates that an annual application of 20 to 30 tons of the solid type of dairy manure per acre is needed to maintain soil organic matter (table 12.2). As discussed above, a nitrogen-demanding crop, such as corn, may be able to use all of the nitrogen in 20 to 30 tons of manure. If more residues are returned to the soil by just harvesting grain, lower rates of manure application will be sufficient to maintain or build up soil organic matter.

The Influence of Manure on Many Soil Properties

The application of manures causes many soil changes—biological, chemical, and physical. A few of these types of changes are indicated in table 12.2, which contains the results of a long-term experiment in Vermont with continuous corn silage on a clay soil. Manure counteracted many of the negative effects of a monoculture cropping system in which few residues are returned to the soil. Soil receiving 20 tons of dairy manure annually (wet weight, including bedding—equivalent to approximately 8,000 pounds of solids) maintained organic matter and CEC levels and close to the original pH (although acid-forming nitrogen fertilizers also were used). Manures, such as from dairy and poultry, have liming effects and actually counteract acidification. (Note: If instead of the solid manure, liquid had been used to supply N and other nutrients for the crop, there would not have been anywhere near as large a beneficial effect on soil organic matter, CEC, and pore space.)

High rates of manure addition caused a buildup of both phosphorus and potassium to high levels. Soil in plots receiving manures were better aggregated and less dense and, therefore, had greater amounts of pore space than fields receiving no manure.

Table 12.2: Effects of 11 Years of Manure Additions on Soil Properties

	Application Rate (tons/acre/year)				
	Original Level	**none**	**10 tons**	**20 tons**	**30 tons**
Organic matter	5.2	4.3	4.8	5.2	5.5
CEC (mg/100g)	19.8	15.8	17.0	17.8	18.9
pH	6.4	6.0	6.2	6.3	6.4
P (ppm)*	4.0	6.0	7.0	14.0	17.0
K (ppm)*	129.0	121.0	159.0	191.0	232.0
Total pore space (%)	ND	44.0	45.0	47.0	50.0

* P and K levels with 20 and 30 tons of manure applied annually are much higher than crop needs (see **table 21.3A**).

Note: ND = not determined.

Sources: Magdoff and Amadon (1980); Magdoff and Villamil (1977).

An example of how a manure addition might balance annual loss is given in figure 12.1. One Holstein "cow year" worth of manure is about 20 tons. Although 20 tons of anything is a lot, when considering dairy manure, it translates into a much smaller amount of solids. If the approximately 5,200 pounds of solid material in the 20 tons is applied over the surface of one acre and mixed with the 2 million pounds of soil present to a 6-inch depth, it would raise the soil organic matter by about 0.3%. However, much of the manure will decompose during the year, so the net effect on soil organic matter will be even less. Let's assume that 75% of the solid matter decomposes during the first year, and the carbon ends up as atmospheric CO_2. At the beginning of the following year, only 25% of the original 5,200 pounds, or 1,300 pounds of organic matter, is added to the soil. The net effect is an increase in soil organic matter of 0.065% (the calculation is [1,300/2,000,000] x 100). Although this does not seem like much added organic matter, if a soil had 2.17% organic matter and 3% of that was decomposed annually during cropping, the loss would be 0.065% per year, and the manure addition would just balance that loss. Manures with lower amounts of bedding, although helping maintain organic matter and adding to the active ("dead") portion, will not have as great an effect as manures containing a lot of bedding material.

Using Manures

Manures, like other organic residues that decompose easily and rapidly release nutrients, are usually applied to soils in quantities judged to supply sufficient nitrogen for the crop being grown in the current year. It might be better for building and maintaining soil organic matter to apply manure at higher rates, but doing so may cause undesirable nitrate accumulation in leafy crops and excess nitrate leaching to groundwater. High nitrate levels in leafy vegetable crops are undesirable in terms of human health, and the leaves of many plants with high N seem more attractive to insects. In addition, salt damage to crop plants can occur from high manure application rates, especially when there is insufficient leaching by rainfall or irrigation. Very high amounts of added manures, over a period of years, also lead to high soil phosphorus levels (table 12.2). It is a waste of money and resources to add unneeded nutrients to the soil, nutrients that will only be lost by leaching or runoff instead of contributing to crop nutrition.

Application Rates

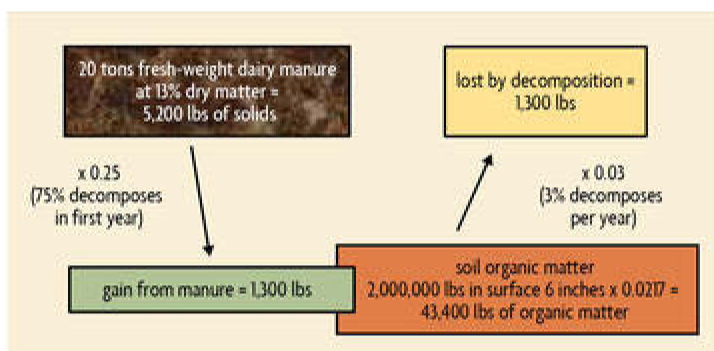


Figure 12.1. Example of dairy manure addition just balancing soil organic matter losses.

A common per-acre rate of dairy-manure application is 10 to 30 tons fresh weight of solid, or 4,000 to 11,000 gallons of liquid, manure. These rates will supply approximately 50 to 150 pounds of available nitrogen (not total) per acre, assuming that the solid manure is not too high in straw or sawdust and actually ties up soil nitrogen for a while. If you are growing crops that don't need that much nitrogen, such as small grains, 10 to 15 tons (around 4,000 to 6,000 gallons) of solid manure should supply sufficient nitrogen per acre. For a crop that needs a lot of nitrogen, such as corn, 20 to 30 tons (around 8,000 to 12,000 gallons) per acre may be necessary to supply its nitrogen needs. Low rates of about 10 tons (around 4,000 gallons) per acre are also suggested for each of the multiple applications used on a grass hay crop. In total, grass hay crops need at least as much total nitrogen applied as does a corn crop. There has been some discussion about applying manures to legumes. This practice has been discouraged because the legume uses the nitrogen from the manure, and much less nitrogen is fixed from the atmosphere. However, the practice makes sense on intensive animal farms where there can be excess nitrogen—although grasses may then be a better choice for manure application.

For the most nitrogen benefit to crops, manures should be incorporated into the soil in the spring immediately after spreading on the surface. About half of the total nitrogen in dairy manure comes from the urea in urine that quickly converts to ammonium (NH_4^+). This ammonium represents almost all of the readily available nitrogen present in dairy manure. As materials containing urea or ammonium dry on the soil surface, the ammonium is converted to ammonia gas (NH_3) and lost to the atmosphere. If dairy manure stays on the soil surface, about 25% of the nitrogen is lost after one day, and 45% is lost after four days—but that 45% of the total represents around 70% of the readily available nitrogen. This problem is significantly lessened if about half an inch of rainfall occurs shortly after manure application, leaching ammonium from the manure into the soil. Leaving manure on the soil surface is also a problem, because runoff waters may carry significant amounts of nutrients from the field. When this happens, crops don't benefit as much from the manure application, and surface waters become polluted. Some liquid manures—those with low solids content—penetrate the soil more deeply. When applied at normal rates, these manures will not be as prone to lose ammonia by surface drying. However, in humid regions, much of the ammonia-N from manure may be lost if it is incorporated in the fall when no crops are growing.

Figure 12.2. Injection of liquid manure into shallow frozen soils, which eliminates compaction concerns and reduces spring application volumes.
Photo by Eleanor Jacobs.

Other nutrients contained in manures, in addition to nitrogen, make important contributions to soil fertility. The availability of phosphorus and potassium in manures should be similar to that in commercial fertilizers. (However, some recommendation systems assume that only around 50% of the phosphorus and 90% of the potassium is available.) The phosphorus and potassium contributions contained in 20 tons of dairy manure are approximately equivalent to about 30 to 50 pounds of phosphate and 180 to 200 pounds of potash from fertilizers. The sulfur content as well as trace elements in manure, such as the zinc previously mentioned, also add to the fertility value of this resource.

Because one-half of the nitrogen and almost all of the phosphorus is in the solids, a higher proportion of these nutrients remain in sediments at the bottom when a liquid system is emptied without properly agitating the manure. Uniform agitation is recommended if the goal is to apply similar levels of solids and nutrients across target fields. A manure system that allows significant amounts of surface water penetration and then drainage, such as a manure stack of well-bedded dairy or beef cow manure, may lose a lot of potassium because it is so soluble. The 20% leaching loss of potassium from stacked dairy manure mentioned above occurred because potassium was mostly found in the liquid portion of the manure.

Timing of Applications

Manures are best applied to annual crops, such as corn, small grains, and vegetables, in one dose just before soil tillage (unless a high amount of bedding is used, which might tie up nitrogen for a while—see the discussion of C:N ratios in chapter 9). This allows for rapid incorporation by plow, chisel, harrow, disk, or aerator. Even with reduced tillage systems, application close to planting time is best, because the possibility of loss by runoff and erosion is reduced. It also is possible to inject liquid manures either just before the growing season starts or as a side-dressing to row crops. Fall manure applications on annual row crops, such as corn, may result in considerable nitrogen loss, even if manure is incorporated. Losses of nitrogen from fall-applied manure in humid climates may be as much as 25% to 50%—resulting from conversion of ammonium to nitrate and then leaching and denitrification before nitrogen is available to next year's crop. It was determined in modeling studies that fall applications of liquid manure posed the greatest risk for nitrate leaching in a dairy system in New York.

Without any added nitrogen, perennial grass hay crops are constantly nitrogen deficient. Application of a moderate rate of manure—about 50–75 pounds worth of available nitrogen—in early spring and following each harvest is the best way to apply manure. Spring applications may be at higher rates, but wet soils in early spring may not allow manure application without causing significant compaction.

Although the best use of manure is to apply it near the time when the crop needs the nutrients, sometimes time and labor management or insufficient storage capacity causes farmers to apply it at other times. In the fall, manure can be applied to grasslands that don't flood or to tilled fields that will either be fall-plowed or planted to a winter cover crop. Although legal in most states, it is not a good practice to apply manures when the ground is frozen or covered with snow. The nutrient losses that can occur with runoff from winter-applied manure are both an economic loss to the farm and an environmental concern. Ideally, winter surface applications of manure would be done only on an emergency basis. However, research on frost tillage has shown that there are windows of opportunity for incorporating and injecting winter-applied manure during periods when the soil has a shallow frozen layer, 2 to 4 inches thick (see chapter 16). Farmers in cold climates may use those time periods to inject manure during the winter (figure 12.2), although the windows of opportunity may be limited.

Potential Problems

As we all know, too much of a good thing is not necessarily good. Excessive manure applications may cause plant-growth problems. It is especially important not to apply excess poultry manure, because the high soluble salt content can harm plants.

Plant growth is sometimes retarded when high rates of fresh manure are applied to soil immediately before planting. This problem usually doesn't occur if the fresh manure decomposes for a few weeks in the soil and can be avoided by using a solid manure that has been stored for a year or more. Injection of liquid manure sometimes causes problems when used on poorly drained soils in wet years. The extra water applied and the extra use of oxygen by microorganisms may mean less aeration for plant roots, and loss of readily plant-available nitrate by denitrification may also be occurring.

When manures are applied regularly to a field to provide enough nitrogen for a crop like corn, phosphorus and potassium may build up to levels way in excess of crop needs (see table 12.2). When ammonium is properly conserved, the manure rate necessary to meet crop nitrogen requirement is substantially reduced. Correspondingly, phosphorus and potassium applications are moderated, reducing or eliminating the accumulation of these nutrients in soil.

When manure is applied based upon needed or allowed P additions, as required by some nutrient management plans, N-conserving management means that less fertilizer N will be needed. Erosion of phosphorus-rich topsoils contributes sediments and phosphorus to streams and lakes, polluting surface waters. When very high phosphorus buildup occurs from the continual application of manure at rates to satisfy crop nitrogen needs, it may be wise to switch the application to other fields or to use strict soil conservation practices to trap sediments before they enter a stream. Including rotation crops, such as alfalfa—that do not need manure for N—allows a "draw-down" of phosphorus that accumulates from manure application to grains. (However, this may mean finding another location to apply manure. For a more detailed discussion of nitrogen and phosphorus management, see chapter 19.)

E. COLI 0157:H7

The bacteria strain known as E. coli 0157: H7 has caused numerous outbreaks of severe illness in people who ate contaminated meat and a few known outbreaks from eating vegetables—once when water used to wash lettuce was contaminated with animal manure and once from spinach grown near a cattle farm. This particular bacteria is a resident of cows' digestive systems. It does no harm to the cow, but—probably because of the customary practice of feeding low levels of antibiotics when raising cattle—it is resistant to a number of commonly used antibiotics for humans. This problem only reinforces the commonsense approach to manure use. When using manure that has not been thoroughly composted to grow crops for direct human consumption—especially leafy crops like lettuce that grow low to the ground and root crops such as carrots and potatoes— special care should be taken. Before planting your crop, avoid problems by planning a three-month period between incorporation and harvest. For short-season crops, this means that the manure should be incorporated long before planting. Although there has never been a confirmed instance of contamination of vegetables by E. coli 0157: H7 or other disease organisms from manure incorporated into the soil as a fertility amendment, being cautious and erring on the side of safety is well justified.

Farmers that purchase much of their animal feed may have too much manure to safely use all the nutrients on their own land. Although they don't usually realize it, they are importing large quantities of nutrients in the feed that remain on the farm as manures. If they apply all these nutrients on a small area of land, nitrogen and phosphorus pollution of groundwater and surface water is much more likely. It is a good idea to make arrangements with neighbors for use of the excess manure. Another option, if local outlets are available, is to compost the manure (see chapter 13) and sell the product to vegetable farmers, garden centers, landscapers, and directly to home gardeners.

Poultry and hogs are routinely fed metals such as copper and arsenic that appear to stimulate animal growth. However, most of the metals end up in the manure. In addition, dairy farmers using liquid manure systems commonly dump the used copper sulfate solutions that animals walk through to protect foot health into the manure pit. The copper content of average liquid dairy manures in Vermont increased about fivefold between 1992 and the early 2000s—from about 60 to over 300 ppm on a dry matter basis—as more farmers used copper sulfate footbaths for their animals and disposed of the waste in the liquid manure. Although there are few reports of metal toxicity to either plants or animals from the use of animal manures, if large quantities of high-metal-content manure are applied over the years, soil testing should be used to track the buildup.

Another potential issue is the finding that plants can take up antibiotics from manure applied to soil. About 70% of the antibiotics used in animal agriculture ends up in the manure. Although the amounts of antibiotics taken up by plants are small, this is an issue that may be of concern when using manures from concentrated animal production facilities that use considerable amounts of these substances.

Summary and Sources

Summary

Animal manures can be very useful sources of amendments for building healthy soils. They are high in nutrients needed by plants and, depending on the species and the amount of bedding used, may help build and maintain soil organic matter levels. Because of the wide variability of the characteristics of manures, even from the same species—depending on feeding, bedding, and manure handling practices—it is important to analyze manures to more accurately judge the needed application rates. When using manures, it is important to keep in mind the potential limitations—pathogen contamination of crops for direct human consumption; accumulations of potentially toxic metals from high application of certain manures; and overloading the soil with N or P by applying rates that are in excess of needs, as demonstrated by soil test and known crop uptake.

Sources

Cimitile, M. 2009. Crops absorb livestock antibiotics, science shows. *Environmental Health News*. http://www.environmentalhealthnews.org/ehs/news/antibiotics-in-crops.

Elliott, L.F., and F.J. Stevenson, eds. 1977. *Soils for Management of Organic Wastes and Waste-waters.* Madison, WI: Soil Science Society of America.

Endres, M.I., and K.A. Janni. Undated. *Compost Bedded Pack Barns for Dairy Cows. http://www.extension.umn.edu/agriculture/dairy/facilities/compost-bedded-pack-barns/.*

Harrison, E., J. Bonhotal, and M. Schwarz. 2008. *Using Manure Solids as Bedding.* Report prepared by the Cornell Waste Management Institute (Ithaca, NY) for the New York State Energy Research and Development Authority.

Madison, F., K. Kelling, J. Peterson, T. Daniel, G. Jackson, and L. Massie. 1986. *Guidelines for Applying Manure to Pasture and Cropland in Wisconsin*. Agricultural Bulletin A3392. Madison, WI.

Magdoff, F.R., and J.F. Amadon. 1980. Yield trends and soil chemical changes resulting from N and manure application to continuous corn. *Agronomy Journal* 72: 161–164. See this reference for dairy manure needed to maintain or increase organic matter and soil chemical changes under continuous cropping for silage corn.

Magdoff, F.R., J.F. Amadon, S.P. Goldberg, and G.D. Wells. 1977. Runoff from a low-cost manure storage facility. *Transactions of the American Society of Agricultural Engineers* 20: 658–660, 665. This is the reference for the nutrient loss that can occur from uncovered manure stacks.

Magdoff, F.R., and R.J. Villamil, Jr. 1977. *The Potential of Champlain Valley Clay Soils for Waste Disposal.* Proceedings of the Lake Champlain Environmental Conference, Chazy, NY, July 15, 1976.

Maryland State Soil Conservation Committee. Undated. *Manure Management Handbook: A Producer's Guide.* College Park, MD: Author.

Ontario Ministry of Agriculture and Food. 1994. *Livestock and Poultry Waste Management.* Best Management Practices Series. Available from the Ontario Federation of Agriculture, Toronto, Ontario, Canada.

Ontario Ministry of Agriculture and Food. 1997. *Nutrient Management.* Best Management Practices Series. Available from the Ontario Federation of Agriculture, Toronto, Ontario, Canada.

Pimentel, D., S. Williamson, C.E. Alexander, O. Gonzalez-Pagan, C. Kontak, and S.E. Mulkey. 2008. Reducing energy inputs in the US food system. *Human Ecology* 36: 459–471.

Soil Conservation Society of America. 1976. *Land Application of Waste Materials.* Ankeny, IA: Author.

van Es, H.M., A.T. DeGaetano, and D.S. Wilks. 1998. Space-time upscaling of plot-based research information: Frost tillage. *Nutrient Cycling in Agroecosystems* 50: 85–90.

A Case Study: Darrell Parks

Manhattan, Kansas

Even if Darrell Parks didn't like working with hogs, he would still raise them on his 600-acre farm in the Flint Hills of Kansas, if only for the manure that makes up a key part of his soil fertility program. Each year, Parks's farm produces forty-five sows plus corn, milo, wheat, soybeans, and alfalfa.

Parks spot-treats his land with hog manure to help areas needing extra fertility. He likes how targeting problem areas with thicker applications of manure corrects soil micronutrient deficiencies. "I've been working to better utilize farm-produced manure and cover crops as well as a crop rotation and management system that will allow me to eliminate purchased fertilizer, herbicides, and insecticides," says Parks, who received a grant from USDA's Sustainable Agriculture Research and Education (SARE) program to hone his use of manure on cropland. He was successful in that endeavor, and his cropland has been certified organic since 1996.

Parks's crops are raised mainly in two rotations. In one rotation, alfalfa is grown for three years, followed by a year each of corn and soybeans before returning to alfalfa. In the other, he plants Austrian winter peas in the late fall following wheat harvest. The peas, incorporated in the spring, are followed with a cash crop of milo or soybeans prior to a fallor spring-planted wheat crop.

To ensure a sufficient nutrient supply for his wheat crops, Parks typically treats his wheat fields with liquid manure at a rate of approximately 660 gallons per acre. He collects this manure in a concrete pit adjacent to a building where sows are housed for brief periods during breeding or when being sold. The liquid manure, for which he does not typically obtain a nutrient analysis, “catches a lot of rainfall and is fairly dilute—[essentially] high-powered water,” he says. “I avoid wet conditions when spreading and try to hit the wheat in March or April during a dry period on a still day, before [the wheat] is too big.”

Parks sometimes lets older sows out to pasture on some of his fields, where they spread their own manure. He cautions, however, against pasturing young pigs on alfalfa. “You’d think they’d balance their ration better,” he says, “but they don’t—they overeat.”

For most of their lives, Parks’s hogs are raised on half of a 10-acre field. He plants the remaining 5 acres to corn. Once the corn is harvested, he moves the hogs and their pens over to the “clean ground” of corn stubble. “Going back and forth like this seems to work well in keeping the worms down,” he says. And he says that the 50–60 pounds of N per acre put down with the hogs’ manure helps grow “some pretty good corn” in that field each year.

Parks notes that his tillage regime, on which he is dependent for weed control in his organic system, makes maintaining and improving his soil organic matter content especially challenging. That’s why he remains committed to integrating the use of both animal and “green” manures on his farm.

In response to organic grain and fuel price spikes, he decided recently to reduce the number of hogs he raises from sixty to forty-five. Striving for economic sustainability, he is constantly weighing the pros and cons of becoming more selfsufficient by raising his own feed for the hogs versus taking advantage of the price premiums for organic grains.

“It’s a hard decision,” he says. “Right now, if I cut down on hogs, maybe it would be better economically. But if I get out [of raising hogs entirely], it’s not easy to get back in.”

For now, he is betting that over the longer term, he’s better off keeping his hogs. “A lot of people don’t like the idea of how pigs are raised” within a conventional operation, he says. “We’re meeting [the demand of] a niche market in its infancy that is sure to grow.”

—UPDATED BY AMY KREMEN

Soil Test Interpretations and Recommendation Guide Commercial Fruits, Vegetables and Turf

Manjula Nathan
Director, MU Soil and Plant Testing Lab

John Stecker
MU Soil and Plant Testing Lab

Other Contributors

Erik Erwin
John Dunn
Michele Warmund
David Trinklein
Ray Rothenberger
Peter Schraf
Teresa Lee

College of Agriculture, Food, and Natural Resources
University of Missouri Extension

October 1999

Introduction

This bulletin presents nutrient management information for commercial fruit and vegetable growers, and an explanation of fertilizer recommendations that accompany soil test results that are analyzed by the University of Missouri Soil and Plant Testing Laboratory. On the last two pages of this bulletin are copies of the Soil Sample Information Form for Commercial Fruits, Vegetable and Turf (MP 727) used by the Soil Testing Laboratory. Those growers who wish to have soils analyzed for commercial fruits, vegetables and turf should submit samples with these forms. The forms can be obtained from County Extension Offices or the Soil Testing Laboratories in Columbia or Portageville. Proper submission of samples of the requested information will result in a better fertilizer recommendation and interpretation of the soil test results.

The nutrition of fruits and vegetables is a very important aspect of their production. Adequate nutrition is required not only for optimum yield, but also for optimum quality. In general, production practices that lead to the greatest yield are associated with the best quality. Proper fertilization for many fruit crops requires a balance between vegetative and fruit growth. Proper fertilization also promotes uniform crop growth and maturity, which are important at harvest.

With the exception of carbon, hydrogen and oxygen, plant nutrients are primarily supplied to plants by the soil. Fertilizers, manure and amendments are often applied to soils to supplement nutrients supplied by the soil. Responsible nutrient management considers first a soil's ability to supply plants with essential nutrients. Soil testing is a nutrient management strategy grounded in research that measures essential plant nutrients in the soil and relates the amounts to crop needs. Fertilizer and amendment recommendations are based on soil tests, soil type, crop yield, crop age (for some perennial crops) and past crop management. By eliminating the guesswork of providing nutrients, the efficiency of supplying nutrients to crops can be increased. Thus growers may benefit from lesser costs and better yields. Also lesser amounts of nutrients are less likely to contribute to non-point source pollution such as phosphorus contamination of surface water or nitrates leaching into groundwater.

Soil Sampling

Collecting a soil sample is a very important part of soil testing. The soil sample must be representative of the area or field to be sampled. Otherwise, interpretations and recommendations based on the results could be misleading, inaccurate and potentially counterproductive. Errors in collecting a representative sample may be made in choosing the area to sample or in the collection of the sample itself.

Individual samples should be taken from areas that will be managed the same and have similar properties which could affect soil test values. Topography, slope, soil texture, drainage, topsoil color, previous fertilizer, lime and manure applications, and cropping history all are factors to consider when selecting an area to sample. A soil survey map may be helpful for determining areas with similar soil properties. Twenty acres may be represented by one sample for uniform or level fields, but for non-uniform areas one sample should represent only 5 acres. When specific crops are grown on small acreages, an even smaller area may be sampled.

Because soils are inherently variable in their distribution of plant nutrients, an individual soil sample should be a composite of several subsamples. Thus the composite sample becomes an "average" of the soil in the area to be represented. Each composite sample should consist of 15-30 subsamples. The more variable the soil, the more subsamples should be collected. Avoid sampling near dead furrows, old fence rows, previous locations of manure or brush piles or any other unusual area. Sample at least 300 feet from crushed limestone or gravel roads, as the road dust can affect soil pH. The collection of subsamples should be mixed, and cores or chunks of soil broken apart. From this mixed soil, a pint of soil should be sent to the Soil Testing Laboratory, preferably in a soil sample bag or box. Soil boxes are available from either of the University of Missouri Soil Testing Laboratories in Columbia or Portageville, or from county extension centers.

The proper depth for collecting soil samples is 6-8 inches for annual crops and 3-4 inches for turf. For established trees or perennial crops, collect soil to a 6 inch depth. At establishment it is preferable to take another sample at 6 to 12 inches for perennial crops, provided there exists the means to fertilize the deeper volume of soil. A soil tube, soil auger or a spade are all appropriate tools for collecting samples. To avoid contamination of the sample, a clean plastic pail is a preferred container into which to collect the sample.

Soil samples may be taken any time of the year, although if results are to be compared across years, it is best to collect the samples at the same time of the year. When obtaining soil test information for specific nutrients, differing sampling frequencies may be necessary. These will be covered more completely later in the bulletin.

Soil Testing

Once soil samples arrive at a soil testing laboratory, soil testing procedures are used to determine nutrient amounts in the soil that may be available to crops. Most soil tests are only an **index** of the total amount of nutrients available to a crop. Through research the index are correlated to crop response in the field. Soil test values within a range are grouped (given ratings) according to the probability of crop response to supplemental fertilizer or amendment applications. Table 1 shows an example of the ratings that might be used to describe the probability of a response to fertilizer.

Table 1. General relationship between soil test rating, crop yield and the probability of response to fertilizer.

Soil Test Rating	Average relative yield without fertilizer (%)	Probability of response to fertilizer	Fertilizer Recommendation
Very low	<50	greater than 90%	Large applications for soil building purposes
Low	50 - 75	75 - 90	Annual applications to maximize crop response and increase soil fertility
Medium	75 100	30 - 75	Annual applications to maximize yields
High	100	less than 30%	Small annual applications to maintain soil level. Amounts may be doubled and applied in alternate years.
Very high	100	unlikely	None until level drops back into the high range.

Several soil test nutrient values are reported in lb/acre. Unfortunately, this sometimes results in the incorrect interpretation that soil test values can be directly related to recommended amounts of fertilizer in lb/acre. For example it would be incorrect to conclude that a soil with a soil test value of 10 lb P/acre would require 35 lb P/acre to bring the soil "up to test" to a high rating of 45 lb P/acre.

A listing of the soil test procedures used by the Soil Testing Laboratories is provided below. The first eight listed are provided with a regular soil test analysis.

1. Soil pH_s (1:1 solution:soil suspension). Solution is 0.01M $CaCl_2$
2. Lime requirement (Neutralizable Acidity) Uses the Woodruff Buffer Solution
3. Organic Matter (%) Loss on ignition
4. Extractable Phosphorus (Bray-1 P)
5. Exchangeable Potassium (Ammonium Acetate (NH_4OAc) extraction)
6. Exchangeable Calcium (NH_4OAc extraction)
7. Exchangeable Magnesium (NH_4OAc extraction)
8. Cation Exchange Capacity (estimated from Exchangeable K, Ca, Mg, and Neutralizable Acidity)
9. Extractable Zinc (DPTA extraction)
10. Extractable Sulfur (calcium phosphate in acetic acid extraction)
11. Extractable iron, manganese and copper (DPTA extraction)
12. Exchangeable Sodium (NH_4OAc extraction)
13. Hot water extractable Boron (0.1% $CaCl_2 \cdot H_20$)
14. Nitrate-nitrogen and Ammonium-nitrogen (2 M KCl extraction)
15. Soluble salts (electrical conductivity in a 1:1 soil:water saturation extraction)
16. Particle size analysis (Hydrometer method)

Basis for Recommendations

Field studies correlate the fertilizer nutrient amounts required by crops to the level of nutrients measured by soil test. When field data are insufficient or a soil test does not reliably measure a nutrient for crop availability, fertilizer recommendations are based on the total amount of a nutrient needed by a crop and an estimated supply by the soil. Because different nutrients vary in the types of reactions with the soil, strategies vary to provide efficient and economical recommendations. For example, a nutrient like nitrogen tends not to accumulate in the soil in plant available forms. Whereas, other nutrients can be accumulated through several growing seasons that remain in plant available forms.

Phosphorus and potassium are both nutrients that are used in large amounts by crops and tend to be held well by the soil. This allows them to be reliably increased in the soil. Thus recommendations are based on supplying the current year's crop needs (maintenance) and future crop need (buildup). A maintenance amount is that amount of the nutrient removed by the crop in a single season. A buildup amount is the amount of nutrient needed to gradually increase the soil test value through several growing seasons. An eight year nutrient buildup period provides an economical amortization of fertilizer costs and results in efficient fertilizer use by minimizing rapid fixation of a large amount of a nutrient with the soil.

When soil test values are low, phosphorus and potassium recommendations include both maintenance and buildup amounts. As values approach high levels, the recommended amount is increasingly based on maintenance. At very high levels, the soil is considered to contain an excessive nutrient amount, and a gradual decline in the soil nutrient level is desired. So not even a maintenance amount is recommended. Otherwise without an expected increase in yield, additional fertilization would increase the potential for environmental pollution. In addition to being environmentally hazardous and economically wasteful, excessive fertilization can lead to legislated fertilizer management or a ban of agricultural production altogether in specific areas.

Fertilizer nutrient recommendations provided in this publication are not varied by yield goal, but rather are varied by nutrient soil test values. Recommended amounts of fertilizer are decreased by increasing amounts of the nutrient measured in a soil test. Higher yields are not to be expected by greater fertilization, but by better management. Such management changes may include row width, water supply, plant population, etc. When improved management results in greater yields, then greater amounts of phosphorus and potassium may be applied to replace the greater amounts of nutrients removed by the harvested portion of the crop.

Fertilizers

All commercially sold fertilizers report the percent of primary nutrients (nitrogen, phosphorus and potassium) that are contained within the fertilizer. These three nutrient percentages are referred to as the fertilizer grade. It is shown on the label of the fertilizer and is guaranteed by the manufacturer. Nitrogen is expressed on an elemental basis (N), while phosphorus and potassium are reported on an oxide basis, P_2O_5 and K_2O. This method of reporting should not be confused with the chemical forms in which the nutrients are present in the fertilizer. For instance a commonly used fertilizer, diammonium phosphate, has a grade of 18-46-0. The fertilizer has 18% nitrogen and 46% phosphorus (as P_2O_5). However, the nitrogen in this fertilizer is in the ammonium form (NH_4^+) and the phosphorus is in the phosphate form ($HP0_4^{-2}$). To accommodate fertilizer grades, fertilizer recommendations are also based on amounts of N, P_2O_5 and K_2O per area (usually per acre or per 1000 ft^2).

For each primary nutrient, many different fertilizer sources are available. Some fertilizers are sold as complete fertilizers, i.e., they contain all three primary nutrients. Single nutrient fertilizers are also widely available. Urea (46-0-0) and potassium chloride (0-0-60) are examples of single nutrient fertilizers for nitrogen and potassium, respectively. Complete fertilizers are often a blend of single nutrient fertilizers. Many different fertilizer sources exist. Aside from fertilizer grade, each has different properties which influence their management and the situations in which they are best used.

Soil pH

Soil pH is a measurement of a soil's reaction, i.e., its acidity or alkalinity. Most Missouri soils have a pH less than 7.0 and thus have varying degrees of acidity. Alkaline soils (those with a pH greater than 7.0) are typically not native to Missouri, but usually result from or repeated lime applications or circumstances of location (e.g. lime dust from roads). As an important chemical property, a soil's acidity level affects nutrient availability, the activity of soil microbes and the growth of plants

The University of Missouri Soil Testing Laboratory measures soil acidity in a very dilute salt solution, and it is reported as a salt pH (pH_s). Commercial laboratories typically measure soil pH in water. Although both methods accurately measure soil acidity, salt pH is usually 0.5 pH unit less than pH measured in water.

The acidity measured in either water or a dilute salt solution is a measure of the soil's active acidity. On soils that are strong to very strongly acid, a much larger reserve acidity exists. A laboratory procedure different from pH measures this acidity, which is called neutralizable acidity (NA). From this value lime recommendations are determined. As with pH, commercial laboratories typically use a different laboratory measurement to determine reserve acidity. Their measurement of reserve acidity is reported as a buffer pH. While both measurements are proper methods of reserve acidity, there is not a good means for comparing the two. The method used for calculating a lime recommendation from a value of neutralizable acidity cannot be used with a buffer pH value.

Fruit and Vegetable and Turf pH_s Preferences and Limestone Recommendations

Horticulture crops vary in preferable soil pH_s. Most prefer a pH_s between 5.5 and 6.5. Where the pH_s is much greater or lesser than the preferred range, some corrective measure is recommended. Table 2 shows preferred pH_s ranges, and the pH_s values at which an amendment should be applied to correct the pH_s.

Some crops benefit from either high or low pH_s. Blueberries prefer acidic soil and on most Missouri soils, lowering the pH_s is necessary for economical blueberry production. Other crops grow better at high or low pH_s in response to disease suppression. Scab (*Streptomyces scabies*) is a soil inhabiting fungus of potatoes that is suppressed by low pH_s (< 4.7). The optimum pH_s range for scab resistant potatoes is 5.1 – 5.7. When potatoes are grown in rotation with other crops that do not prefer a low pH_s, lime should be applied after the potato harvest and before planting the rotation crop. Alternatively, the soil fungus that causes Clubroot of cole crops is increasingly suppressed as pH_s becomes greater than 6.5. Yet the preferred pH_s range is no more than 6.5-7.0, as crop growth is decreased for other reasons at greater pH_s.

Table 2. Preferred pH_s ranges and recommended correction.

	Preferable pH_s range	High pH correction	Low pH correction
Most fruits and vegetables	5.5-6.5	pH_s > 7.0, apply sulfur	pH_s < 5.5, apply limestone
Blueberries Potatoes	4.3 - 5.0	pH_s > 5.5, apply sulfur	pH_s < 3.5, apply limestone
Asparagus Beets Cabbage	5.5 - 7.5	pH_s > 7.5, apply sulfur	pH_s < 5.5, apply limestone
Turf	5.5 - 7.2	pH_s > 7.2, apply sulfur	pH_s < 5.5, apply limestone

Soil test reports provide a rating of the measured pH_s (Table 3). Soils with a pH_s rating of very low to low have a definite need for limestone. The low pH_s is likely limiting yield potential. A medium pH_s indicates that soil acidity is near a yield limiting point, and limestone may be needed in coming seasons, as the soil acidifies naturally or through the application of manure and/or ammonium based fertilizers. A high pH_s rating indicates that the soil acidity is optimum for crop growth. A very high rating indicates that the pH_s is above the preferred range, and nutrient availability may be reduced. A very high pH_s may also be an indicator of other soil problems that could be limiting to growth such as salinity or excessive sodium.

Table 3. pH_s rating for Vegetables, Turf and Fruit Crops

	Vegetables, Fruits, Turf	Blueberries, Potatoes
Rating	pH range	
Very low	< 4.5	< 3.5
Low	4.5 – 5.3	3.5 – 4.3
Medium	5.3 – 6.0	4.3 – 5.0
High	6.0 – 7.5	5.0 – 6.0
Very high	> 7.5	> 6.0

Guidelines for increasing pH_s.

Recommendations for increasing pH_s are based upon a single application of lime with the objective of increasing the pH_s to the optimum range, 6.1 – 6.5, to a depth of six inches. Limestone is recommended by amounts of lb ENM/acre. Effective neutalizable material (ENM) is used as a means for standardizing limestone. Limestone originating from different quarries can vary in effectiveness because of purity and particle size. Both of these variables are used to calculate an ENM value for limestone. Purity is defined by the calcium carbonate equivalent. It represents how much acidity is neutralized by a given amount of limestone. Fineness of grind or particle size affects how rapidly and thoroughly limestone reacts with soil. Small or finely ground particles react with a larger soil volume and thus neutralize acidity in a lesser amount of time than larger particles. All limestone sold in Missouri must have an ENM rating. Although limestone is the most commonly applied amendment to increase soil pH, any liming material can be used with ENM recommendations.

The equation used to calculate ENM is given below:

$$ENM = 400 * \left[N.Acid - \frac{N.Acid}{41.425 - 10.3078\,pH_s + 0.629 * pH_s^2} \right]$$

Suppose a recommendation suggests a need of 1500 ENM (lb/ton), and limestone available at the local quarry has an ENM rating of 500 (lb/ton). The proper amount of limestone to apply would be three tons/acre. For a more complete discussion of ENM see UMC Ext. Pub. G09107, “Missouri Limestone Quality-What is ENM.”

Because it is undesirable to increase pH_s for blueberries and potatoes to the pH_s targeted in the above equation, an ENM of 500 is recommended when the pH_s is less than 3.5. Soil sample again in a year to determine if the limestone application increased pH_s to the desired range.

Guidelines for Lowering pH_s.

Acidifying soils (lowering pH) for better crop growth is likely to be economical for acid loving blueberries. Blueberries require acid soils for growth and respond well to amendments that decrease pH. For other crops, higher than desired pH may not sufficiently reduce growth to warrant the cost of applying acidifying amendments to large acreages. Few soils in Missouri have excessively high pH for horticultural crops.

Recommendations for lowering pH_s are based on the application of finely ground elemental sulfur. Application rates to decrease the pH_s by one pH_s unit in the surface six inches are shown in Table 4. Rates vary by the soil's cation exchange capacity (CEC), which can be related to soil texture. Sulfur's effect on soil pH_s is slow and typically takes several months to react with the soil. It should be incorporated and for perennial plants applied a year before planting.

Table 4. Soil texture and CEC effects on sulfur recommendation to lower pH_s.

Soil Texture	CEC	Ground Sulfur*
	(meq/100 g)	(lb/acre)
Sand, Sandy loam	< 10	350
Silt loam, Loam	10 - 18	600
Clay loam, Clay	> 18	1000

*Amount necessary to reduce the soil pH_s by one unit.

Other materials can be used to lower soil pH_s. or maintain a low soil pH_s. Iron sulfate reacts faster than elemental sulfur (within 3 to 4 weeks), yet it requires 4 to 5 times more material. Single applications should not exceed 2 tons/acre. Greater amounts will cause salt injury. Ammonium sulfate and urea when used as nitrogen sources will maintain low soil pH_s. Although higher rates could decrease pH_s, they are not recommended because of salt injury.

Soluble Salts

Soluble salts refer to electrolyte compounds in the soil that dissolve in the soil water. Soluble salt level is also referred to as the salinity level. At high levels soluble salts can reduce water uptake in the plant, restrict root growth, cause root tip burn and in general reduce plant growth and fruit or vegetable yield. Soluble salts compete with plants for soil water. Plant symptoms of excessive salts are similar to those from water stress. Seed germination and seedling growth are the most sensitive growth stages to high salinity levels. Plant species and cultivars vary in their sensitivity to soil salts.

The soil test to measure soluble salts is electrical conductivity. It is determined from a saturated paste extract and is reported in units of mmhos/cm. The sensitivity of plants to soluble salt levels is shown in Table 5. The salt tolerances of specific horticultural crops is given in Table 6.

Most Missouri soils are sufficiently leached by precipitation such that very low salinity levels exist. Human activities are usually the cause of high salinity levels in Missouri. Over fertilization, fertilizer spills or placing fertilizer too close to roots can create soluble salt problems for plants.

Table 5. Soluble salt levels and relative plant sensitivity.

Electrical Conductivity	Salinity Level	Effect on plant growth
mmhos/cm		
0 to 2	non-saline	none
2.1 to 4	very slightly saline	sensitive plants are inhibited
4.1 to 8	moderately saline	many plants are inhibited
8.1 to 16	strongly saline	most cultivated plants inhibited
> 16	very strongly saline	few plants are tolerant

Table 6. Salt tolerances of horticultural crops.

Non-tolerant	Slightly tolerant	Moderately tolerant	Tolerant
0 to 2 mmhos	2 to 4 mmhos	4 to 8mmhos	8 to 16mmhos
Blueberry	Apple	Beet	Asparagus
Carrot	Cabbage	Broccoli	
Beans	Cucumber	Musk Melon	
Onion	Grape	Spinach	
Pea	Lettuce	Squash	
Radish	Peach	Tomato	
Raspberry	Pear		
Strawberry	Pepper		
	Plum		
	Potato		
	Sweet Corn		
	Sweet Potato		

Primary Nutrients

Nitrogen, phosphorus and potassium are referred to as primary nutrients because plants use these nutrients in greater amounts than other nutrients. Soils typically contain these nutrients in amounts sufficient to supply many years of crops. However, the annual supply of these nutrients may be deficient for optimum plant growth.

Nitrogen Recommendations

Nitrogen is the nutrient most often limiting for crop growth. Soils generally contain large amounts of nitrogen in soil organic matter, which releases it to plant available forms. However, the release rate is usually too slow to adequately supply a growing crop. Within crops' rooting zone, these forms are ephemeral because of plant uptake and soil reactions. Consequently, a reliable soil test for determining nitrogen availability has not been developed.

Nitrogen supply to crops is estimated from variables that directly and indirectly affect nitrogen release from organic matter. Soil organic matter content and CEC are two variables measured in the soil test that are used for calculating available nitrogen. If a legume crop has preceded the crop to be grown, the nitrogen recommendation is reduced by an amount called the nitrogen credit. Another variable is an individual crop's requirement for nitrogen. Crops vary in the amount of nitrogen needed to produce a marketable product and also in their ability to obtain nitrogen from the soil.

Fruit Crops

Nitrogen recommendations for fruit crops vary only by organic matter content and whether plantings are new or established (Table 7). Less nitrogen is recommended for high organic matter soils as they mineralize more nitrogen than soils with lower organic matter levels. Newly planted fruit trees require little nitrogen, as at this time roots must become established. Excess nitrogen at this time encourages top growth at the expense of root growth. In Table 7 the Newly Established category for fruit trees refers to young non-fruiting trees. At this growth stage higher nitrogen rates encourage rapid shoot growth. Once established and trees mature to become fruit bearing, a decreased nitrogen rate for fruit crops maintains a balance between vegetative growth and fruit development. Under fertilizing crops decreases yield and quality, while over-fertilization can result in poor fruit color, delayed maturity and irregular ripening, decreased winter-hardiness and increased disposition for disease.

Table 7. Nitrogen recommendations for fruit crops.

	Organic Matter Level/Rating			
	< 2.5 %	2.5–4.5%	> 4.5 %	
	Low	Medium	High	Application Time
Newly Established	-------------- lb/acre ------------			
Apples/Pears	60	45	30	½ at planting, ½ sidedress in June
Grapes	60	45	30	½ at planting, ½ sidedress in June
Blueberries	40	30	20	Sidedress when 2nd flush of growth starts
Brambles†	60	50	40	½ at planting, ½ sidedress in June
Stone Fruits‡	60	45	30	½ at planting, ½ sidedress in June
Strawberries	80	70	60	½ at planting, ½ sidedress in August
Established				
Apples	30	20	10	Sidedress in spring
Grapes	30	20	10	Sidedress in spring
Pears	30	20	10	Sidedress in spring
Brambles	60	50	40	Sidedress in spring
Stone Fruits	60	40	20	Sidedress in spring
Strawberries	80	70	60	Topdress after renovation
Age				
Blueberries 1-2 year		60		
3 year		80		Sidedress in spring
4 year		100		

† Raspberries, Blackberries, Gooseberries,
‡ Peaches, Plums, Apricots, Cherries, Nectarines

Vegetable Crops

The calculation of nitrogen recommendations for vegetable crops is diagrammed below.

Recommended nitrogen (lb/acre) = Maximum N amount (Table 8) – Organic Matter Adjustment (Table 9) – Legume Credit (Table 10)

The first part of the equation determines the maximum amount of nitrogen needed by a crop (Table 8). This amount is based on a yield goal, which is listed beside the required nitrogen amount. The other two parts of the equation reduce the amount of nitrogen recommended. The Organic Matter Adjustment is an estimate of the amount of nitrogen released from organic matter during a growing season. It is dependent on CEC and the percent organic matter in the soil (Table 9). Greater amounts of nitrogen are released from soils which have greater organic matter levels and CEC. The Legume Credit estimates the amount of nitrogen that is supplied from the breakdown of a legume crop residue from the previous year (Table 10).

Table 8. Nitrogen needs for vegetable crops and application methods.

Crop	Yield Goal	Maximum Required N.*	Suggested application times
	cwt/acre	lb N/acre	
Asparagus (New)	-		½ at planting, 2/3 sidedress during cultivation
Asparagus (Est.)	40	80	Topdress before cutting starts or after harvest
Beans/Peas	80	30	Broadcast
Beets	200	100	½ at planting, ½ sidedress 3-5 wks after planting
Broccoli	120	180	1/3 at planting,1/3 sidedress 2 wks after 1/3 sidedress 5 wks after planting
Brussels Sprout	175	140	1/3 at planting,1/3 sidedress 2 wks after 1/3 sidedress 5 wks after planting
Cabbage	400	180	1/3 at planting,1/3 sidedress 2 wks after 1/3 sidedress 5 wks after planting
Carrots	400	120	½ at planting, ½ sidedress when plants are established
Cauliflower	150	180	½ at planting, ½ sidedress when plants are established
Cucumbers	250	100	½ at planting, ½ sidedress when vines begin to run
Lettuce	300	120	½ at planting, ½ sidedress 3-5 wks after planting
Melons	200	100	½ at planting, ½ sidedress when vines begin to run
Onions, dry	500	130	¼ banded at planting, ¾ sidedress 4-5 wks after emergence
Onions, green	150	80	¼ at planting, ½ sidedress 4-5 wks after emergence, ¼ sidedress 4 wks before harvest
Peppers	200	140	½ at planting, ½ sidedress when fruit appear
Potatoes		180	1/5 at planting, 2/5 at emergence, 2.5 at hilling
Pumpkins/Squash	400	70	½ at planting, ½ sidedress when vines begin to run
Radishes	70	60	At planting
Spinach	150	100	½ at planting, ½ sidedress 4-5 weeks after planting
Sweet corn	180	140	1/5 in starter, 2/5 at 4-6 leaf stage, 2/5 at 10-12 leaf stage
Sweet potatoes		60	1/5 at planting, 2/5 at emergence, 2/5 at hilling
Tomatoes	270	130	¼ at planting, ¼ 2 wks after planting, ¼ 4 wks after planting, ¼ 6 wks after planting

*Maximum amount to apply

Plant available nitrogen primarily exists in two forms, ammonium and nitrate. Whether derived from manufactured fertilizer, organic fertilizer, soil organic matter, manure or legume crop residue, nitrogen is eventually converted into ammonium and then nitrate by soil microbes. In the nitrate form, nitrogen may be “lost” from a crop’s rooting zone through volatilization or leaching. Both processes can drastically reduce fertilizer efficiency and deprive a crop of adequate nitrogen for optimum growth and yield. Application time of nitrogen fertilizer then becomes important. By coinciding the conversion of nitrate to ammonium with active crop growth, more of the applied nitrogen is available to crops.

Table 9. Organic matter adjustment by CEC and percent soil organic matter.

CEC	Soil Organic Matter	Organic Matter Adjustment
meq/100 g	(%)	(lb/acre)
≤ 10	≤ 0.5	10
≤ 10	0.5 – 1.5	20*OM*
≤ 10	≥ 1.5	30
10 - 18	≤ 2.0	20
10 - 18	2.0 – 4.0	10*OM
10 - 18	≥ 4.0	40
> 18	≤ 2.0	10
> 18	2.0 – 5.0	5.0*OM
> 18	≥ 5.0	25

*OM – percent organic mater

Table 10. Nitrogen credit for previous legume crop.

Crop	Nitrogen Credit (lb/acre)
Alfalfa (good stand)	50
Alfalfa (poor stand)	40
Birdsfoot Trefoil	40
Grass-Legume Hay	40
Grass-Legume Pasture	40
Red Clover	40
Beans/Peas	30

The suggested application times and methods in Table 8 are intended to optimize availability to the crop during the growing season to produce the best quality product. Because nitrogen has such a profound effect on plant growth, ripening, and fruit development, specific application times can greatly affect crop development, for the benefit of the crop (e.g. greater yield or better color) or also to the detriment of the crop value (e.g. splitting of fruit or rank vegetative growth).

Phosphorus Recommendations

Phosphorus exists in the soil as rather insoluble compounds with iron and aluminum at low pH and with calcium at high pH. Upon contact with the soil, phosphorus fertilizer is rapidly converted into these compounds. Plants take up phosphorus in the form of the orthophosphate anion ($H_2PO_4^-$). Soil phosphorus compounds supply the soil solution with orthophosphate in relatively small amounts. The Bray-1 P soil test provides an estimate of phosphorus released from soil compounds that are available to plants. The Bray-2 P soil test is a variation of the Bray-1 P test. It is best used when a field has a history of rock phosphate fertilization.

The insoluble nature of soil phosphorus compounds limits movement of phosphorus in the soil to very short distances, usually less than an inch from the point of application. Consequently for best fertilizer effectiveness, phosphorus fertilizer should be incorporated into the surface soil or banded near the crop rather than topdressed. Banding all or a portion of phosphorus fertilizer near the seed or vegetable transplants is most beneficial in the spring when soils are cool. In such conditions, a readily available supply of phosphorus enhances root growth and uptake of phosphorus.

Soil test phosphorus ratings are the same for both fruit crops and vegetable crops (Table 11).

Table 11. Phosphorus ratings by soil test phosphorus

Soil Test Rating	Soil Test Phosphorus
	lb P_2O_5/acre
Very low	< 20
Low	20 – 40
Medium	40 – 80
High	80 – 200
Very High	> 200

Fruit Crops

Phosphorus fertilizer recommendations for fruit crops are given in Table 12. Recommended amounts for blueberries and brambles are 25 lb P_2O_5/acre less than for the other fruit crops. New plantings receive a 25 percent greater recommendation than established plantings. When the calculated recommendation is less than 20 lb P_20_5/acre but greater than zero, the recommendation is rounded up to 20 lb P_20_5/acre.

Table 12. Phosphorus recommendations for fruit crops.

Crop	Recommendation equation	Maximum amount
		P_2O_5 (lb/acre)
New Plantings	P_2O_5=Established Rec.*1.25	-
Established		
Blueberries	P_2O_5=95 - 1.25*PTest	75
Brambles†	P_2O_5=95 - 1.25*PTest	75
Apples/Pears	P_2O_5=120 - 1.25*PTest	100
Grapes	P_2O_5=120 - 1.25*PTest	100
Stone Fruits‡	P_2O_5=120 - 1.25*PTest	100
Strawberries	P_2O_5=120 - 1.25*PTest	100

† Raspberries, Blackberries, Gooseberries,
‡ Peaches, Plums, Apricots, Cherries, Nectarines

Vegetable Crops

Ratings for soil test phosphorus for vegetables are the same as that of fruit crops. Recommendations for fertilizer phosphorus are based on four equations, which are provided in Table 13. These recommendations provide for a buildup when soil tests are low, maintain nutrient levels when soil tests are medium to high and allow for gradual drawdown when soil tests are very high.

Table 13. Phosphorus recommendations for vegetable crops.

Crop	Yield Goal	Soil Test Phosphorus in lb P_2O_5/acre										Equation
		10	30	50	70	90	110	130	150	170	190	
	ton/acre	Phosphorus recommendation, lb P_2O_5/acre										
Asparagus (Est.)	2	140	110	90	60	40	10	0	0	0	0	P_2O_5 = 150 – 1.25*PTest
Asparagus (New)	-	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Beans, Lima	2	140	110	90	60	40	10	0	0	0	0	P_2O_5 = 150 – 1.25*PTest
Beans, Snap	4	140	110	90	60	40	10	0	0	0	0	P_2O_5 = 150 – 1.25*PTest
Beets	13	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Broccoli	4	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Brussels Sprout	5	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Cabbage	20	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Cantaloupes	9	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Carrots	15	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Cauliflower	8	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Cucumbers	15	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Lettuce	20	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Onions, dry	20	250	225	200	175	150	125	100	75	50	25	P_2O_5 = 263 – 1.25*PTest
Onions, green	8	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Peas	3	140	110	90	60	40	10	0	0	0	0	P_2O_5 = 150 – 1.25*PTest
Peppers	10	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest
Potatoes		250	225	200	175	150	125	100	75	50	25	P_2O_5 = 263 – 1.25*PTest
Pumpkins	20	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Radishes	4	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Spinach	6	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Squash	15	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest

Sweet corn	10	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Sweet potatoes	10	175	150	125	100	75	50	25	0	0	0	P_2O_5 = 188 – 1.25*PTest
Tomatoes	30	250	225	200	175	150	125	100	75	50	25	P_2O_5 = 263 – 1.25*PTest
Watermelons	11	215	190	165	140	115	90	65	40	20*	0	P_2O_5 = 225 – 1.25*PTest

*When the calculated recommendation is less than 20 lb P_2O_5/acre, the recommendation is rounded up to 20 lb P_2O_5/acre.

Potassium Recommendations

Available potassium exists in the soil as the K^+ ion. Because potassium attaches to clay minerals in the soil, movement and supply of potassium in the soil is dependent on soil texture. In soils with loam, silt loam or heavier textures, potassium movement is greatly restricted. Thus potassium fertilizer can be applied to buildup soil potassium levels. Also incorporation is preferred to topdressing. On sandy soils with lesser amounts of clay, potassium moves more freely such that it can actually leach from the root zone. Fall application of potassium on these soils is not recommended, since the potassium may leach from the root zone during the winter months.

Potassium chloride, which contains 60 percent K_20, is the cheapest and most common potassium fertilizer. Potassium, like phosphorus, can be beneficial when banded near the seed at planting. Due to the potential for salt injury, potassium should not be applied directly with the seed, but rather 2-3 inches from the seed. On low potassium testing soils, the bulk (at least half) of recommended potassium should be applied broadcast and the rest in a band. No more than 50 lb K_20 should be applied as a banded starter near the seed.

Potassium ratings are the same for fruit and vegetable crops (Table 14).

Table 14. Potassium ratings by soil test potassium level

Soil Test Rating	Soil Test Potassium
	lb P_2O_5/acre
Very low	< 65
Low	65 – 110
Medium	110 – 220
High	220 – 330
Very High	> 330

Fruit Crops

Potassium fertilizer recommendations for established fruit crops are generated using three different equations (Table 15). For some crops a set value is used at the higher soil test potassium levels. However the range of soil test potassium at which recommendations change are not consistent across crops. So the crops are grouped below according to their potassium recommendations. For all crops fertilizer recommendation for new plantings 1.25 times the established recommendation.

Table 15. Potassium recommendations for fruit crops.

Crop	Recommendation equations	Recommended Potassium (lb K_2O/acre)			
	Soil Test Potassium Ranges (lb K_2O)	# 230	> 230		
Blueberries	K_2O=230 - 1.0*Ktest – 150 lb K_20 maximum	Use Equation	0		
	Soil Test Potassium Ranges (lb K_2O)	<180	180-220	220-260	>260
Brambles[†]	K_2O=210 - 1.0*KTest – 100 lb K_20 maximum	Use Equation	30	20	0
	Soil Test Potassium Ranges (lb K_2O)		< 200	220-330	>330
Other Fruits[‡]	K_2O=250 - 1.0*KTest – 200 lb K_20 maximum		Use Equation	30	0

[†] Raspberries, Blackberries, Gooseberries

[‡] Apples, Pears, Grapes, Strawberries, Peaches, Plums, Apricots, Cherries, Nectarines

Vegetable Crops

Potassium recommendations for vegetable crops are varied according to soil texture. For sands and loamy sands, recommendations are given in Table 16. For all heavier textured soils, recommendations are given in Table 17. Within both recommendation tables, four equations are used for individual vegetable crops. Similar to phosphorus, the recommended amounts provide for a buildup with low soil test values plus a maintenance amount and only maintenance amounts at high soil test levels

Table 16. Potassium recommendations for vegetable crops on soils with CEC less than.

Crop	Yield Goal	Soil Test Potassium Level (lb K_2O/acre) 50	75	100	125	150	175	200	225	250	275	300	325	Equation
	ton/acre	Potassium recommendation, lb K_2O/acre												
Asparagus (Est.)	2	205	185	160	140	115	95	70	50	25	20*	0	0	K_2O = 250 – 0.9*KTest
Asparagus (New)	-	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Beans, Lima	2	205	185	160	140	115	95	70	50	25	20*	0	0	K_2O = 250 – 0.9*KTest
Beans, Snap	4	205	185	160	140	115	95	70	50	25	20*	0	0	K_2O = 250 – 0.9*KTest
Beets	13	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Broccoli	4	330	310	285	265	240	220	195	175	150	130	105	85	K_2O = 375 – 0.9*KTest
Brussels Sprouts	5	330	310	285	265	240	220	195	175	150	130	105	85	K_2O = 375 – 0.9*KTest
Cabbage	20	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Cantaloupes	9	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Carrots	15	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Cauliflower	8	330	310	285	265	240	220	195	175	150	130	105	85	K_2O = 375 – 0.9*KTest
Cucumbers	15	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Lettuce	20	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Onions, dry	20	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Onions, green	8	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest

Peas	3	205	185	160	140	115	95	70	50	25	20*	0	0	K_2O = 250 – 0.9*KTest
Peppers	10	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Potatoes		330	310	285	265	240	220	195	175	150	130	105	85	K_2O = 375 – 0.9*KTest
Pumpkins	20	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Radishes	4	205	185	160	140	115	95	70	50	25	20*	0	0	K_2O = 250 – 0.9*KTest
Spinach	10	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Squash	15	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Sweet corn	10	230	210	185	165	140	120	95	75	50	30	20*	0	K_2O = 275 – 0.9*KTest
Sweet potatoes		280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest
Tomatoes	30	330	310	285	265	240	220	195	175	150	130	105	85	K_2O = 375 – 0.9*KTest
Watermelons	11	280	160	135	215	190	170	145	125	100	80	55	35	K_2O = 325 – 0.9*KTest

*When the calculated recommendation is less than 20 lb K_2O/acre, the recommendation is rounded up to 20 lb K_2O/acre.

Table 17. Potassium recommendations for vegetable crops on with CEC greater than.

Crop	Yield Goal	Soil Test Potassium Level (lb K_2O/acre)												Equation
		50	75	100	125	150	175	200	225	250	275	300	325	
	ton/acre	Potassium recommendation, lb K_2O/acre												
Asparagus (Est.)	2	200	175	150	125	100	75	50	25	0	0	0	0	K_2O = 250 – 1.0*KTest
Asparagus (New)	-	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Beans, Lima	2	200	175	150	125	100	75	50	25	0	0	0	0	K_2O = 250 – 1.0*KTest
Beans, Snap	4	200	175	150	125	100	75	50	25	0	0	0	0	K_2O = 250 – 1.0*KTest
Beets	13	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Broccoli	4	325	300	275	250	225	200	175	150	125	100	75	50	K_2O = 375 – 1.0*KTest
Brussels Sprouts	5	325	300	275	250	225	200	175	150	125	100	75	50	K_2O = 375 – 1.0*KTest
Cabbage	20	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Cantaloupes	9	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Carrots	15	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Cauliflower	8	325	300	275	250	225	200	175	150	125	100	75	50	K_2O = 375 – 1.0*KTest
Cucumbers	15	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Lettuce	20	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Onions, dry	20	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Onions, green	8	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Peas	3	200	175	150	125	100	75	50	25	0	0	0	0	K_2O = 250 – 1.0*KTest
Peppers	10	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Potatoes		325	300	275	250	225	200	175	150	125	100	75	50	K_2O = 375 – 1.0*KTest

Pumpkins	20	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Radishes	4	200	175	150	125	100	75	50	25	0	0	0	0	K_2O = 250 – 1.0*KTest
Spinach	10	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Squash	15	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Sweet corn	10	225	200	175	150	125	100	75	50	25	0	0	0	K_2O = 275 – 1.0*KTest
Sweet potatoes		275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest
Tomatoes	30	325	300	275	250	225	200	175	150	125	100	75	50	K_2O = 375 – 1.0*KTest
Watermelons	11	275	250	225	200	175	150	125	100	75	50	25	0	K_2O = 325 – 1.0*KTest

Secondary Nutrients

The secondary nutrients – calcium, magnesium, and sulfur - are used by plants at amounts almost similar to some of the primary nutrients, but they are less likely to be in deficient supply to a crop.

Calcium Recommendations for Fruits and Vegetables

Available calcium exists in the soil as the Ca^+ ion. It attaches to clay minerals in the soil, so the amount and supply of calcium is dependent on soil texture. Calcium deficiency in field soils is relatively rare, but it may occur on acid sandy soils. For most crops calcium needs can be met by liming the soil to increase soil pH. However for blueberries and potatoes, the maintenance of a low pH can result in low calcium levels, which may require corrective measures. For potatoes grown in rotation, a small amount of lime (1000 lb/acre) can be applied during the cropping year out of potatoes to meet calcium needs and yet not adversely affect soil pH for the potatoes.

The calcium rating assigned to a soil is dependent on CEC and soil test calcium (Table 18). With less clay to hold calcium on low CEC, sandy soils, less soil test calcium is necessary to obtain a high calcium rating. No corrective Ca applications are recommended for soils with a high Ca rating.

Table 18. Calcium rating by soil test calcium and the soil CEC.

	Soil CEC		
Rating	< 10	10 - 20	> 20
Low	Ca ≤ 1000	Ca ≤ 3000	Ca ≤ 5000
Medium	1000 ≥ Ca ≥ 1600	3000 ≥ Ca ≥ 5000	5000 ≥ Ca ≥ 8000
High	Ca > 1600	Ca > 5000	Ca > 8000

Gypsum (calcium sulfate) is an amendment that supplies calcium. Yet unlike lime it does not have a large effect on soil pH_s. Thus it can be used to supply calcium for acid loving crops. The pH_s ranges for which gypsum is recommended are given in Table 19.

Table 19. Soil pH_s range for which gypsum is recommended for different crops.

Crop	pH_s range to recommend gypsum
Blueberries, potatoes	4.3 – 5.0

Asparagus, Beets, Cabbage	5.5 – 7.0
All other fruits and vegetables	5.5 – 6.5

The recommended amount of gypsum to supply calcium is dependent on the soil CEC and soil test Ca. The formula to calculate a gypsum recommendation is given below.

$$Gypsum\ (lb/acre) = \left\{ \frac{\left[\left(CEC * 300 \right) - CaTest \right] * 30}{400} \right\} * 43.56$$

Calcium deficiencies can occur with some crops despite the presence of adequate calcium in the soil. These deficiencies are related to physiological disorders and include blossom end rot in tomatoes and peppers, tipburn in lettuce, cabbage or cauliflower, black heart in celery, or bitter pit in apples. In soils in which the soil pH has been corrected to 6.0 or above, soil applied calcium will not correct these disorders. Foliar sprays of calcium chloride at a rate of 5 to 10 lb per acre or calcium nitrate at 10 to 15 lb per acre can help overcome these disorders. Solutions of these calcium sources should be applied at a rate of 100 gallons per acre directly to the crop's foliage.

Magnesium Recommendations for Fruits and Vegetables

Magnesium is available to plants as the Mg^{+} ion. Similar to calcium it is primarily held in the soil by clay particles, Its deficiency typically occurs on acid, low CEC or sandy soils. On soils with marginal magnesium levels, deficiencies can be induced by high application rates of potassium or a heavy application of calcitic limestone.

Soil magnesium ratings are based on the percent magnesium saturation which is calculated using soil test magnesium and CEC (see equation below). Magnesium ratings are given in Table 20.

$$\%\ Magnesium\ Saturation = \frac{MgTest / 240}{CEC} * 100$$

Table 20. Magnesium rating by soil test magnesium and the soil CEC.

Rating	% Magnesium Saturation
Very low	< 2
Low	2 – 5
Medium	5 – 10
High	10 – 32.5
Very high	32.5 – 55
Extremely high	55

Magnesium recommendations are based on soil test magnesium and CEC and are calculated using the equation below.

$$Mg(lb/acre) = \frac{CEC * (240 - MgTest)}{20}$$

If CEC is less than 6, assume 6, or if greater than 20 assume 20.

Magnesium can be supplied from dolomitic limestone, which can also correct low soil pH that may be coincident with low soil magnesium levels. Other sources of magnesium include potassium magnesium sulfate (trade names of K-Mag or Sul-Po-Mag; 11% magnesium), magnesium sulfate (Epsom salts, 10% magnesium) and magnesium oxides.

Sulfur Recommendations for Fruits and Vegetables

Plant available sulfur exists in the soil as the sulfate ion (SO_4^{2-}). Similar to nitrate-nitrogen, it is susceptible to leaching. Sulfur is supplied to crops by the breakdown of organic matter and by atmospheric deposition of sulfur, which primarily originates from the burning of coal. Sulfur deficiencies are usually found on sandy, low organic matter soils, i.e., soils on which sulfur supply is likely to be small and on which sulfur has a greater potential to leach beyond the root zone. Soil test sulfur ratings are given in Table 21. Fertilizer sulfur is recommended (30 lb/acre) only for soils that test low.

Table 21. Sulfur rating by soil test value.

Sulfur Rating	Sulfur Soil Test Value
	(ppm)
Low	≤ 6
Medium	6 – 12
High	>12

Micronutrients

Micronutrients are used by crops in only small amounts. Yet when micronutrients are deficient, yield reductions can be as severe as those incurred by deficiencies of the primary nutrients. Micronutrients discussed here include: boron, copper, iron, manganese and zinc. Most soils typically supply micronutrients in sufficient amounts for crop needs. However, some soils have a greater proclivity for micronutrient deficiencies. Crops also vary in their demand for micronutrients and their response to applied micronutrients when deficiencies exist (Table 22).

Table 22. Relative response of fruit and vegetable crops to applied micronutrients when soil conditions favor a deficiency.

Crop	Boron	Copper	Iron	Manganese	Zinc

Apples	high	medium	-	high	high
Asparagus	low	low	medium	low	low
Beans, Snap	low	low	high	high	high
Beets	high	high	high	high	medium
Blueberries	low	medium	high	low	-
Broccoli	high	medium	high	medium	-
Cabbage	medium	medium	medium	medium	medium
Carrots	medium	high	-	medium	low
Cauliflower	high	medium	high	medium	-
Cucumbers	low	medium	-	high	-
Grapes	medium	low	high	high	medium
Lettuce	medium	high	-	high	medium
Onions, dry	low	high	-	high	high
Peaches	medium	medium	-	high	high
Pears	medium	medium	-	-	medium
Peas	low	low	-	high	low
Peppers	low	low	-	medium	-
Potatoes	low	low	-	high	medium
Radishes	medium	medium	-	high	-
Raspberries	medium	-	high	high	-
Spinach	medium	high	high	high	-
Strawberries	medium	medium	high	high	-
Sweet corn	low	medium	medium	medium	high
Tomatoes	high	medium	-	medium	-

Because micronutrients are required in such small amounts, they can be combined with primary nutrient fertilizers and applied in the same fertilizer application. For dry fertilizers the micronutrients may be incorporated at the time of granulation or impregneated onto the surface of granules. With liquid fertilizers, micronutrients are well suited to be added to suspension fertilizers or to ammonium polyphosphate (10-34-0).

Boron Recommendations

Boron is available to plants as H_3BO_3. It is mobile in the soil and is subject to leaching, especially on sandy soils. It also does not accumulate in the soil, so boron responsive crops may need annual applications. Boron availability may be reduced on neutral to alkaline soils. A deficiency should be identified by soil test or plant analysis before a boron fertilizer application is made, because excessive boron is very toxic to plants. Soil test ratings for boron are given in Table 23.

Table 23. Boron rating by soil test value.

Boron Rating	Boron Soil Test Value (ppm)
Low	≤ 0.4
Medium	0.4 – 0.9
High	> 0.9

Even when deficient, boron recommendations are small. Boron recommendations are given for fruit crops in Table 24 and for vegetable crops in Table 25. Fertilizer sources of boron include Borax (11% B), Boric acid (17% B) and Solubor (28% B).

Table 24. Boron recommendations for fruit crops.

Crop	Soil Boron Rating Low	Medium	High
	lb Boron/acre recommended		
Apples/Pears	2	1	0
Blueberries	1	0	0
Brambles	2	1	0
Grapes	2	1	0
Stone Fruits	2	1	0
Strawberries	2	1	0

Table 25. Boron recommendations for vegetable crops.

Crop	Soil Boron Rating Low	Medium	High
	lb Boron/acre recommended		
Asparagus (Est.)	1	0	0
Asparagus (New)	1	0	0
Beans, Snap	0	0	0
Beets	4	2	0
Broccoli	4	2	0
Brussels Sprouts	4	2	0
Cabbage	2	1	0
Cantaloupes	1	0	0
Carrots	2	1	0
Cauliflower	4	2	0
Cucumbers	0	0	0
Lettuce	1	0	0
Onion, dry	2	1	0
Onions, green	1	0	0
Peas	0	0	0
Potatoes	1	0	0
Pumpkins	1	0	0
Radishes	2	1	0
Spinach	2	1	0
Squash	1	0	0
Sweet corn	1	0	0
Sweet potatoes	1	0	0
Tomatoes	2	1	0
Watermelons	1	0	0

Copper Recommendations

The copper ion Cu^{+2} readily binds with organic matter in the soil. Copper may be available to plants as the Cu^{+2} ion or as a chelated ion with organic matter. Deficiencies are most likely to occur on organic soils, rather than the mineral soils of Missouri. No fertilizer recommendations are given for copper, but a soil test rating is given in Table 26.

Table 26. Copper rating by soil test value.

Copper Rating	Copper Soil Test Value (ppm)
Low	≤ 0.2
High	> 0.2

Manganese Recommendations

Manganese exists in the soil as various oxides and hydroxides, but is available to plants in the Mn^{+2} form. This form represents only a small fraction of the total amount of manganese in the soil. Soil pH, organic matter levels and aeration all affect manganese availability. Neutral to alkaline soil pH and high organic matter levels decrease manganese availability. Alternatively, very acid soils may have manganese toxicity.

As indicated in Table 22, fruit and vegetable crops are most responsive to manganese deficiency. Soil test ratings for manganese are given in Table 27. If a manganese deficiency occurs, apply 1-2 pounds of manganese per acre. Fertilizer sources of manganese include manganese sulfate (27% Mn) and manganese chelate (12% Mn).

Table 27. Manganese rating by soil test value.

Manganese Rating	Manganese Soil Test Value
Low	≤ 1.0 (ppm)
High	> 1.0 (ppm)

Iron Recommendations

Iron is an abundant element in the soil; however, it exists in relatively small amounts in a plant available form, Fe^{+2}. Iron deficiency symptoms (an interveinal chlorosis) on plants occurs frequently on high pH_s soils ($pH_s > 7.2$) in which soil iron is unavailable to plant roots. Because of the chemical reactions associated with soil iron, soil application of iron, particularly inorganic fertilizer salts, is ineffective. Soil application of iron chelates can be economically effective for some vegetable crops. Deficiencies are best treated by a foliar application of an iron fertilizer solution at a rate of 0.5 to 3.0 lb/acre. Application of farmyard manure can provide a long term correction to iron deficiency by keeping iron in an available chelate form. Ratings of soil iron are given in Table 28.

Table 28. Iron rating by soil test value.

Iron Rating	Iron Soil Test Value (ppm)
Low	≤ 2.1

Medium	2.1 – 4.5
High	> 4.5

Zinc Recommendations

Zinc is available to plants as the ion Zn^{+2}. Zinc deficiencies in Missouri have been noted on sandy or low organic matter soils. Eroded or graded soils that have had the subsoil exposed or alkaline soils may also have zinc deficiencies. Soil application of zinc sulfate can be used to correct a zinc deficiency. These rates are shown in Table 29. If a zinc chelate is used, the amount applied should be reduced to 1/5 that of the inorganic rate. Zinc is relatively non-mobile in the soil, so incorporation or placement in a band is suggested. When banded zinc fertilizer should not come in contact with the seed. A single zinc application may be effective for three to five years. In season deficiencies can be corrected by foliar applications of chelated zinc at a rate of 2 oz of zinc per acre.

Table 29. Zinc rating by soil test value.

Zinc Rating	Zinc Soil Test Value (ppm)	Zinc to apply (lb/acre)
Low	≤ 0.5	10
Medium	0.5 – 1.0	5
High	> 1.0	0

Fertilizer Recommendations For Turf

Soil pH_s

Turf prefers a soil pH_s of 5.5 to 7.2. An acid soil is detrimental to turf growth from several perspectives. First, an acid soil is more likely to be impervious to water. Second, microbial activity is reduced which decreases decay of dead roots and clippings. Consequently, turf becomes root-bound. Third, acid soil can develop toxic amounts of aluminum, iron, and manganese or drastically reduced amounts of available phosphorus. Forth, turf prefers a supply of both ammonium and nitrate, and an acid soil decreases the microbial conversion of ammonium to nitrate.

Lime recommendations are calculated as indicated earlier. For new seedings, lime should be mixed with the surface 6 inches of soil, and precede seeding by several months to allow the lime's reaction with the soil. Do not use more than 100 lb/1000 ft^2 on high cut turf and 50 lb/1000 ft^2 on low cut turf. Burnt lime (CaO or MgO) or hydrated lime ($Ca(OH)_2$ or $Mg(OH)_2$) are not recommended for application directly to turf. These products can burn the turf and stick to the shoes of people walking on the turf.

Nitrogen Recommendations

Turf typically requires fertilizer nitrogen to enhance turf color; promote tillering which thickens turf, and maintain plant vigor. Nitrogen requirements for turf vary according to establishment, species, and management. As turf is often stressed through use, weather, and disease, proper nitrogen management helps turf endure stresses and heal damaged areas. Nitrogen rate, source and fertilizer application time are all important management factors.

Establishing Turf

Less nitrogen is needed to establish turf than to maintain it. Recommended fertilizer amounts are intended to supplement nitrogen released by the soil organic matter. Less nitrogen is released as soil organic matter levels decrease, and in lower CEC soils, the rate of release is decreased. Two equations are used for determining nitrogen recommendations: one for soils with a CEC < 11 and another for soils with a CEC > 11.

When the CEC is <11, the following equation applies:

$$Nitrogen(lb/1000\,ft^2 = \left\{\frac{\left[2+\left(CEC-6\right)*0.2\right]-\%OM}{43.56}\right\}*25$$

When the CEC is >11, the following equation applies:

$$Nitrogen(lb/1000\,ft^2) = \left\{\frac{\left[3+(CEC-11)*0.1\right]-\%OM}{43.56}\right\}*25$$

To obtain nitrogen recommendations in lb/acre, multiply either equation by 43.56. When the calculated recommendation is less than 0.5 and greater than 0, then the recommendation will be 0.5 lb/1000 ft^2.

<u>Maintenance Turf Nitrogen Recommendations</u>

Turf is maintained for several different purposes. Nitrogen recommendations for the various management objectives are based not on a prediction of nitrogen supplied by the soil, but rather on the specific nitrogen needs of turf in relation to its management (Table 30). Fertilizer application times and amounts are coordinated primarily to mollify effects of stress incurred through use and season.

Grass species are classified according to the season in which they grow best. Cool season grasses grow well in the spring and fall. They are fertilized to optimize growth during these times and minimize stress during the warm summer months. Fall fertilization is particularly important. Turf fertilized in the fall will stay green later into the fall, build root reserves to overwinter in a healthier condition and begin growth earlier in the spring. Cool season grasses include: bluegrass, fescue, ryegrass and bentgrass. Warm season grasses grow best and are best fertilized during the warm summer months, and include bermudagrass, zoysiagrass and buffalograss.

Table 30. Nitrogen recommendations for turf according to application month, use and grass species.

Turf Use	Grass Species	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
		----------	----------	----------	----------	lb/1000 ft^2	----------	----------	----------	----------
Athletic Fields	Cool Season			1		1^+		1		1
	Warm Season			2		2				
Commercial Sod	Cool Season			1				1^+		1
	Warm Season			2		2				
Low maintenance	Cool Season			1				1^+		

	Warm Season						1^-			
Golf Courses										
Putting Greens	Bentgrass (soil)	½	½	½	½	½	½	½	½	½
	Bentgrass (sand)*	¼ - ½*	¼ - ½*	¼ - ½*	¼ - ½*	¼ - ½*	¼ - ½*	¼ - ½*	½	½
Fairways	Cool Season	½ - 1	½ - 1			½ - 1		½ - 2		
	Warm Season			1	1		1^+			
Tees	Cool Season	½ - 1	½ - 1		1	½	½ - 1	½ - 2		
	Warm Season			1	1		1^+			

+ designates an application in the early part of the month
- designates an application in the late part of the month
*Applied at biweekly intervals

A variety of nitrogen sources are formulated specifically for turf. They vary in the rate at which nitrogen is released and the potential for burning grass blades when applied. Slow release products are important to avoid over stimulation of the turf. In any one application, half of the nitrogen should be in a slow release form. Table 31 lists some typical nitrogen sources used for turf. Most contain urea or derivatives of urea, which are generically called ureaform. Ureaform is the product resulting from the reaction of urea and formaldehyde in which urea is formed into chains of different length. In general, the longer the chain the slower the release. Release rates are also described by the solubility in water (WIN) or hot water (HWIN).

Table 31. Nitrogen sources typically used for turf.

Nitrogen Source	Percent Total Nitrogen	Percent Ammonium Nitrate	Percent Urea	Percent SRN†	Percent WIN‡	Percent HWIN#	Speed of N release	Burn potential
UAN	28	50	50				Fast	High
Urea	46	100					Release	Burn
Methylol urea	30		50	50				
Suspended Methylene Urea	18		35	40	25	5		
Methylene urea	41		35	30	36	13		
Methylene urea polymers	38		11	17	72	40	Slow Release	Low Burn

† Short chain soluble nitrogen, soluble reacted urea
‡ Water soluble nitrogen
# Hot water soluble nitrogen

Phosphorus Recommendations For Turf

Phosphorus recommendations for establishing turf are calculated using the equation below. Recommended maintenance amounts are half that of establishment.

$$P_2O_5(lb/1000\,ft^2) = \frac{110*\left(\sqrt{85} - \sqrt{Ptest}\right)}{4*43.56}$$

Potassium Recommendations For Turf

Potassium recommendations for establishing turf are varied by soil potassium level and CEC, and are calculated using the equations below. Recommended maintenance amounts are half that of establishment. If the CEC is less than 6, then assume 6, and if greater than 20 then assume 20.

$$K_2O(lb/1000\,ft^2) = \frac{75.5\left(\sqrt{100 + 10*CEC} - \sqrt{Ktest}\right)}{4*43.56}$$

Secondary and Micronutrients

Secondary and micronutrient recommendations for turf are the same as those detailed for fruit and vegetable crops. The one exception is that of boron. For turf boron is rated the same as other horticulture crops. However, no boron recommendation is given for turf.

Soil Sample Information Form

On the following page is a copy of the soil sample information form that is used with the submission of commercial horticultural crops and turf. Proper entry of grower and county information is necessary for correct billing of the soil tests. As many as six soil samples can be submitted per form. With each sample information is requested regarding irrigation, topography, last liming date, soil region and prior crop. This information although not necessary for obtaining a recommendation is useful toward providing a better recommendation. Also requested is the cropping option for which a recommendation is desired. Crop codes are chosen from the gray box above the cropping options box. Crop age applies only when blueberries are chosen as a cropping option.