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Chapter 1

Managing Fertilizer Nutrients to Protect the Environment and Human Health

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Nutrient management for production, profit, and environmental protection: Striking the balance

Strategies to manage nutrients in crop production were first designed to maximize crop yields, an objective that became increasingly possible with the development of inorganic fertilizers during the past century. Later, as economic analysis of farm profitability became more sophisticated, strategies shifted somewhat toward optimizing economic returns from the fertilizer nutrients applied.

Increased awareness of ecological principles during the past 50 years resulted in an improved understanding of the complex relationship between farming and ecosystems. Society, through government, increasingly recognized the danger of allowing agricultural practices that lead to deterioration of land and water resources. Various laws designed to protect water quality have targeted farming practices that result in excessive soil loss from erosion or excessive application of nutrients to soils. As the practical regulatory definition and enforcement of those laws evolves, the necessity of developing a consciousness of the ecological implication of farming practices takes on increasing economic significance to all farmers. Therefore, farmers not only must be concerned with balancing productivity and profit relative to fertilizer nutrients but they also must factor environmental concerns into their nutrient management strategies.

While adequate levels of plant nutrients are essential for healthy and productive crop growth, some nutrients, particularly nitrogen (N) and phosphorus (P), pose environmental risks when improperly managed. In much the same way that pesticides are regulated to ensure the safety of the applicator and the food and water supply, there is a growing trend toward regulating the use of fertilizer nutrients. Just as farmers are required to keep records of pesticide applications, they may soon be required to do the same for fertilizer nutrients. Just as farmers need to know their cost of production to ensure a financially efficient operation, they have to be aware of environmental costs resulting from their practices. And just as farms need a sound financial plan, they also need a nutrient management plan.

The goal of a nutrient management plan is to ensure the availability of adequate nutrients for crop production with minimal nutrient loss in runoff or leaching from the root zone. Such a plan should include

- evaluation of site environmental concerns
- evaluation of available soil nutrient status
- calculation of nutrient application amounts based on realistic crop yields and available soil nutrients
- appropriate nutrient application methods.

This chapter explains how fertilizer nutrients can be environmental pollutants and, in some cases, a danger to human health. It describes the evolution of regulations designed to protect society from this pollution, and it provides details about what goes into a nutrient management plan.

Assistance in developing nutrient management plans is available in all states from U.S. Department of Agriculture (USDA) agencies: the Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service), and the Cooperative Extension Service (CES, which in Hawaii is part of the College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa). Traditionally, involvement in conservation planning by NRCS was entirely voluntary for farmers. However, under the 1985,1990, and 1996 Farm Bills, federal program benefits to farmers are increasingly tied to developing approved conservation plans, and nutrient management planning is now required for conservation plans. In developing those plans, NRCS emphasizes assessment of the vulnerability of natural resources at the site and the risks associated with current land uses. Producers are referred to CES for specific fertilizer recommendations based on analysis of nutrients in the soil and in plant tissues; CES also can advise about appropriate fertilizer application methods.

In Hawaii, the need for better nutrient management planning has not been perceived as especially urgent by most farmers. Current regulations in other states, however, provide strong indications that nutrient management planning will become increasingly important in Hawaii.

Nutrient management regulations in other states

Most states have traditionally relied on voluntary and incentive-based programs to encourage good nutrient management. Recently, an increase in regulatory legislation requires farmers to develop nutrient management plans. Such legislation is made in recognition of the increasingly clear association between agricultural nutrient application and the impairment of the nation's waters by nutrient pollution, which has been established by state environmental monitoring agencies and the federal Environmental Protection Agency (EPA). The 1996 National Water Quality Inventory conducted by EPA cites nutrients (N and P) as leading causes of water quality impairment of the nation's rivers, lakes, and estuaries (see <http://www.epa.gov/305b/>). Nutrients have also been implicated in reduced oxygen levels in bodies of water (hypoxia) that have resulted in fish kills in the Gulf of Mexico and off the east coast of the USA. Similarly, Hawaii's Department of Health has identified streams and coastal waters around the state that exceed water quality standards for nutrients and require special attention.

Enforceable regulation of agricultural nutrients is quite variable in the USA. Many states have regulations on the disposal of wastes from concentrated animal feeding operations, which typically have facility and siting requirements imposed on them based on the number of animals kept (Environmental Law Institute 1997). Only a few states have provisions to limit misapplication of fertilizers or the resulting nutrient pollution. Most states have laws regulating fertilizers, but these are to protect the consumer of fertilizer products by ensuring nutrient content and efficacy. Several states, however, have recently passed legislation that indicates a trend toward increased regulation of the application of nutrients from all sources.

In 1993, Pennsylvania passed the Nutrient Management Act, which primarily targets animal waste nutrient sources and requires farmers to develop nutrient management plans (Penn State 1993). This legislation has been studied and copied by other states, especially in the Chesapeake Bay region. West Virginia requires permits for disposal of animal wastes and also authorizes the implementation of mandatory "best management practices" for the use of fertilizers and manures if there is evidence of groundwater pollution.

Several other states have laws designed to deal with nutrient pollution from both animal wastes and fertilizers that threaten groundwater or surface water quality (Environmental Law Institute 1997). In Nebraska, groundwater contamination occurring from nonpoint sources (diffuse sources, in contrast to point sources, which are discreet and identifiable) can result in adoption of a mandatory "action plan" enforceable by cease-and-desist orders and sanctions. Michigan's groundwater protection program also provides for protection against nitrate pollution and allows control of rates, locations, and methods of fertilizer and waste applications. Arizona has provided for the development of agricultural "general permits" for N fertilizer applications or concentrated animal facility operations.

Maryland passed one of the nation's most comprehensive nutrient management laws in 1998, requiring all farmers to develop and implement nutrient management plans for N and P by the year 2002 (see <http://www.mda.state.md.us/pocomoke/highligh.htm>). These plans apply to the use of commercial fertilizers as well as animal manure and sewage sludge, and they must be filed with the Maryland Department of Agriculture. Failure to file or to implement a plan results in fines and loss of government cost-sharing benefits. The legislation also provided tax incentives, new cost-sharing programs, and at least 110 new personnel to provide technical assistance in developing plans.

A federal influence on state nutrient management programs is the establishment of "total maximum daily loads" (TMDLs) as specified by the federal Clean Water Act. TMDLs are required for priority water bodies and associated watersheds that fail to meet state or federal water quality standards, including nutrient levels (see <http://www.epa.gov/owow/tmdl/>). A TMDL establishes the maximum allowable pollutant loading for a water body and allocates that load among pollutant contributors. Many states have developed or are developing TMDL standards that include controls on agricultural nutrient use to limit the total amounts of nutrient loading in watersheds. In addition, permits issued under the National Pollution Discharge Elimination System are used to control point-source discharges of pollutants, such as nutrient-rich effluents from food processing plants and confined animal facilities.

In Hawaii, the issuance of permits for Pollution Discharge Elimination Systems is well established, and the development of TMDL standards is under way. The Hawaii Department of Health and the federal EPA are working on this. Other types of regulation (such as permits, zoning, or civil penalties) and nonregulatory approaches (such as taxes, cost-sharing, and planning assistance) are being considered in conjunction with the development of a Coastal Nonpoint Source Pollution Control Program (see the section below on Hawaii's nutrient management regulations and policy).

How excess nutrients can damage the environment

Farmers should be aware of the importance of identifying plant nutrient deficiencies and excesses and of determining the amounts and types of nutrient additions needed. Other chapters in this book deal with these subjects. It is also important that farmers be aware of how nutrients in excessive amounts can be harmful not only to the crop to which they are applied but to the environment and its interdependent web of organisms, including humans. The following three sections focus on N and P, which if deficient severely limit plant growth and which in excess pose the greatest threats to the environment. Agricultural sources of N contamination are usually due to the high solubility of N applied in fertilizers and manure. Agricultural sources of P contamination are usually due to P carried in eroded soil.

Nutrient management in agriculture began with the simple objective of adding fertilizers to obtain a "yield response" (increased yield or crop quality). This was carried to the extreme and the objective became to obtain the "maximum yield," where additional fertilizer produced no further yield response, an approach advocated for many years by fertilizer manufacturers. This approach was later modified to maximize profitability, where the costs of inputs were considered in relation to profit rather than in their ability to result in an absolute, maximum yield.

During the past 15–20 years, another objective added to nutrient management strategies was the need to ensure that environmental impacts are considered and that negative effects of fertilizer applications are minimized. This trend requires an increasingly precise assessment of crop nutrient requirements. Nutrient management thus has become more complex as it seeks to satisfy the multiple agricultural goals of increasing productivity, being economically viable, and sustaining environmentally healthy soil and crop systems.

Negative impacts of excessive nitrogen levels

Excess N in the soil can reduce crop quality, increase the effects of weed competition, and increase the crop's susceptibility to attack by plant diseases and insects. Of even greater potential harm are the effects of excess levels of nitrate N (NO_3^-) on humans and ecosystems.

Effects on humans. The highly soluble nitrate form of N is the major concern in terms of impacts of excess N on the environment and humans. Nitrate contamination is particularly harmful to infants and young children in causing methemoglobinemia, a reduction in the blood hemoglobin level. Because of this health hazard, a national standard was established to declare nitrate a contaminant at a level above 10 mg NO_3^- N per liter (10 parts per million, or ppm).

Effects on water bodies. Water bodies such as rivers, lakes, and oceans are subject to nutrient enrichment, which stimulates excessive growth of many aquatic organisms, often with disastrous consequences. Algae usually are the first to respond to increased levels of N and P in water bodies, and their populations increase quickly, sometimes causing algal "blooms." When they grow and multiply rapidly, they exhaust the oxygen supply in the water and begin to die. Other organisms in the environment also suffer from this lack of oxygen. Occasionally, excessive amounts of nutrient N and P are only noticed after the eutrophication process has resulted in massive damage to lakes and streams causing severe kills of fish and other organisms.

Algal blooms and other increases in algae populations have occurred in Hawaii. West Maui, for example, has been affected with unusually large amounts of algae that have washed ashore and become unsightly and offensive. These unusually large quantities of algae have been attributed to increased levels of nutrients in the water.

Groundwater nitrate. As indicated above, nitrate N is the most common form of nutrient N and is highly soluble in the soil solution. Thus it moves with excessive water from rainfall or irrigation, and its fate is generally determined by the water relations and hydrology of the site. Nitrogen excess is important in island environments such as Hawaii, in part because of the vulnerable condition of our drinking water supplies. Most of our water comes from groundwater, fed by the high rainfall in the mountainous parts of the islands. Rainwater percolates into the island mass and collects in a lens-shaped aquifer (the Ghyben-Herzberg lens) perched above the saline ocean water that permeates the islands below sea level. These aquifers are confined to each land mass, not shared among the islands, and they are finite and subject to depletion. If the aquifer is contaminated, it is unsure what remedial action can be applied, or whether remediation is possible at all.

The Pearl Harbor recharge area is one example of a water resource in Hawaii that is susceptible to damage by nutrient N excess. Data from deep wells that provide drinking water to the City and County of Honolulu indicate that levels of N have been steadily increasing during the past 40 years and are currently only slightly less than the 10 mg/liter NO_3^- N contamination threshold. While the causes are difficult to identify at the watershed level, there appears to be an overall correlation between land use, N management, and the increases in nitrate levels in the aquifer.

Effects on crop yield and quality. Excess N can be detrimental to crop yield and quality. Overfertilizing with N can lead to increased susceptibility to plant diseases and insect attack. In root crops, excessive N can slow or arrest root or corm bulking, reducing yield. Too much N late in the sugarcane growth cycle reduces sugar production, and in taro it can result in a condition called *loliloli*, which severely affects corm quality. Taro farmers usually withhold N applications after the fifth or eighth month of growth, depending on location.

Negative impacts of excessive phosphorus levels

Unlike N, phosphorus does not pose a direct threat to human health, but it can be just as damaging to bodies of water. While N becomes a problem because of its high solubility and mobility, the nutrient phosphorus is of concern because it is sorbed (held, or "fixed") very tightly by many tropical soils.

In Hawaii, soil sorption of P varies widely. Recent organic soils that develop among the rocks of ʻaʻā lava on the island of Hawaii sorb almost no P, and a high percentage of fertilizer P added to those soils is available to plants. In sharp contrast, there are also highly weathered volcanic ash soils along the Hamakua Coast on the island of Hawaii that are among the strongest P-sorbing soils in the world. These soils hold P strongly against plant uptake. Such soils require large amounts of P fertilizer to reach the point at which P applied becomes available for plant uptake. In these cases, P is applied more as a soil amendment than a fertilizer, because it is initially applied to amend the soil's chemical properties to the point where further amounts can act as fertilizer.

While N, because of its solubility, often becomes a pollutant of groundwater, P is more often a pollutant of surface water bodies. Most of the P causing problems is dissolved in surface runoff or carried on soil particles eroded from fields and washed into rivers, lakes, and the ocean. The release of P to runoff can be one of the most serious sources of P impairment to water bodies. The transported P-rich sediments can also release P into solution, sustaining the growth of aquatic organisms and resulting in an explosion of their populations, which, as described above, can affect the aquatic environment and be harmful to other organisms.

Farmers should assess the level of P in their soil to determine the amount of P fertilizer they should apply. The CTAHR Agricultural Diagnostic Service Center records indicate that many commercial growers and home gardeners do not know the amount of P needed by their particular soil. The analysis log shows that a large number of soil samples are in the excessive or extremely excessive range for P. Excess P can cause nutrient imbalance in other organisms, including crops, lawns, and other vegetation, as well as pose a threat to nearby bodies of water. Because the nutrient requirements of soils vary, growers need to manage the soils within a field—rather than the field as a whole—when planning nutrient applications. Growers also must take steps to ensure that runoff is minimized and erosion is prevented.

Potential negative impacts of animal manure

There is presently a great deal of concern about the environmental fate of animal wastes generated at points where they are concentrated, such as pens and feedlots. One way of managing such materials is to spread them over large areas of land as fertilizer or soil amendment. When animal manure (feces and urine) is applied to the land, problems with overapplication of nutrients can be encountered. Both the N and P present in manure are of particular concern. Manure applications should be part of a crop nutrient management program to meet crop needs without resulting in environmental damage by nutrient overloading. Phosphorus in manure is of concern because it remains in the soil and can increase to high levels with continued manure or effluent application. This increases the potential of nutrient imbalances and P contamination of water bodies by erosion and runoff.

Another concern with the use of animal manure is the possible presence of pathogens hazardous to human health. Composting manure is an effective way of killing pathogenic microorganisms. The composting process must be well managed and monitored. For composting to be effective against pathogens, the entire mass of material being processed must be exposed to the critical temperature (greater than 131°F) for at least three days. (For more information, see CTAHR publication AWM-1, *Composted animal manures: precautions and processing*.)

Animal manure does not usually contain viruses that infect humans, and only a few fungal diseases of importance to humans are found in it. However, bacterial disease organisms are present in some animal manure, with the most important threat to humans coming from the salmonella types. Also, protozoan and helminth parasites may be present in animal manure and are a potential public health problem. During composting, care in ensuring that fresh manure is not mixed with the "finished" compost usually reduces human health risk to an acceptable level. A general recommendation is that feces of dogs, cats, and other carnivores not be included in animal manure composts.

The economics of fertilizer use

In the early years of agricultural research and extension, fertilizer management was considered to be the concern of soil and crop scientists, who assisted farmers in reaching the goal of "maximum yield." It was not until the 1940s that agricultural economists, notably Professor Earl Heady at Iowa State University, incorporated economics into input models and decision-making. Profit maximization replaced yield maximization as the presumed goal of farmers and society. The revolution in environmental consciousness that began in the 1960s raised awareness that excess fertilizer use could damage the environment, and that such off-farm costs to society were not adequately considered in profit-maximization models.

The model diagrammed in Figure 1-1 illustrates how the thinking about fertilizer recommendations has changed over time. This simple model assumes that a crop's response to increasing amounts of fertilizer (curve Y in Fig. 1a) is known. It peaks at maximum yield, Y_m. The marginal benefit (curve MB in Fig. 1b) is the change in yield resulting from one-unit increases in fertilizer multiplied by the price of the output. In other words, the marginal benefit is the additional income derived from increased fertilizer use. Maximum yield occurs when the marginal benefit of additional fertilizer declines to zero, which is at fertilizer-use level fm. However, maximum yields do not produce maximum profits because the cost of additional fertilizer use is not considered. Profits are maximized when MC_p, which is the cost of an additional unit of fertilizer, is equated with marginal benefit, MB. This occurs at fertilizer-use level f_p and is associated with a yield, Y_p, that is less than maximum yield.

If environmental damage from fertilizer use was considered, then the "social cost" of fertilizer would include both fertilizer costs and environmental costs. The social cost (curve MC_S in Fig. 1b) increases as more fertilizer is applied. The socially optimum fertilizer use occurs when MC_S is equated with MB, with the fertilizer application f_S and the resulting yield Y_S being less than that achieved in the profit-maximization model.

How much less fertilizer should be applied than that which produces maximum yield? The answer is site-specific and crop-specific. Generally, “rules of thumb” are offered to prevent overapplication of nutrients. For instance, a common recommendation is to use 5–10 percent less fertilizer than is required for maximum yield in order to maximize profits. The socially optimal rate will be even less, but by how much less is site-dependent.

Soil and climatic conditions that influence nutrient uptake and loss vary, making it difficult to predict the most profitable and environmentally and socially optimal levels of fertilizer use. As a result, growers often follow broad guidelines that lead to either insufficient or excessive fertilizer application. Studies of fertilizer recommendations in the USA revealed that some commercial soil testing services consistently have recommended the use of far more fertilizer than was needed.

It is likely that avoiding excessive fertilizer application can eliminate much of the environmental damage from fertilizers—without having to sacrifice profits. Because fertilizer is relatively cheap, growers may overapply in pursuit of maximum yield, even though the crop’s yield response function may be flat at the top, as shown in Fig. 1a. They may also overapply because they do not adequately know the soil’s fertility. A CTAHR Agricultural Diagnostic Service Center survey revealed high levels of P in many farm soils, yet the growers often continue to apply this fertilizer. CTAHR researchers and Cooperative Extension personnel working with growers commonly observe them applying N fertilizer far in excess of what is believed to be needed, in some cases two or three times the recommended rate. It is likely, therefore, that many growers can increase their profits by reducing fertilizer application amount or frequency. Economic analysis also can be a useful tool in searching for the appropriate level of fertilization when the true costs and benefits are quantified.

The need for fertilizer can be reduced through more efficient management of nutrient cycles and more precise application of fertilizers. Such practices may include application of organic waste residues from animals and crops, crop rotation with legumes, soil testing, and banded and split applications of fertilizers.

Site sensitivity

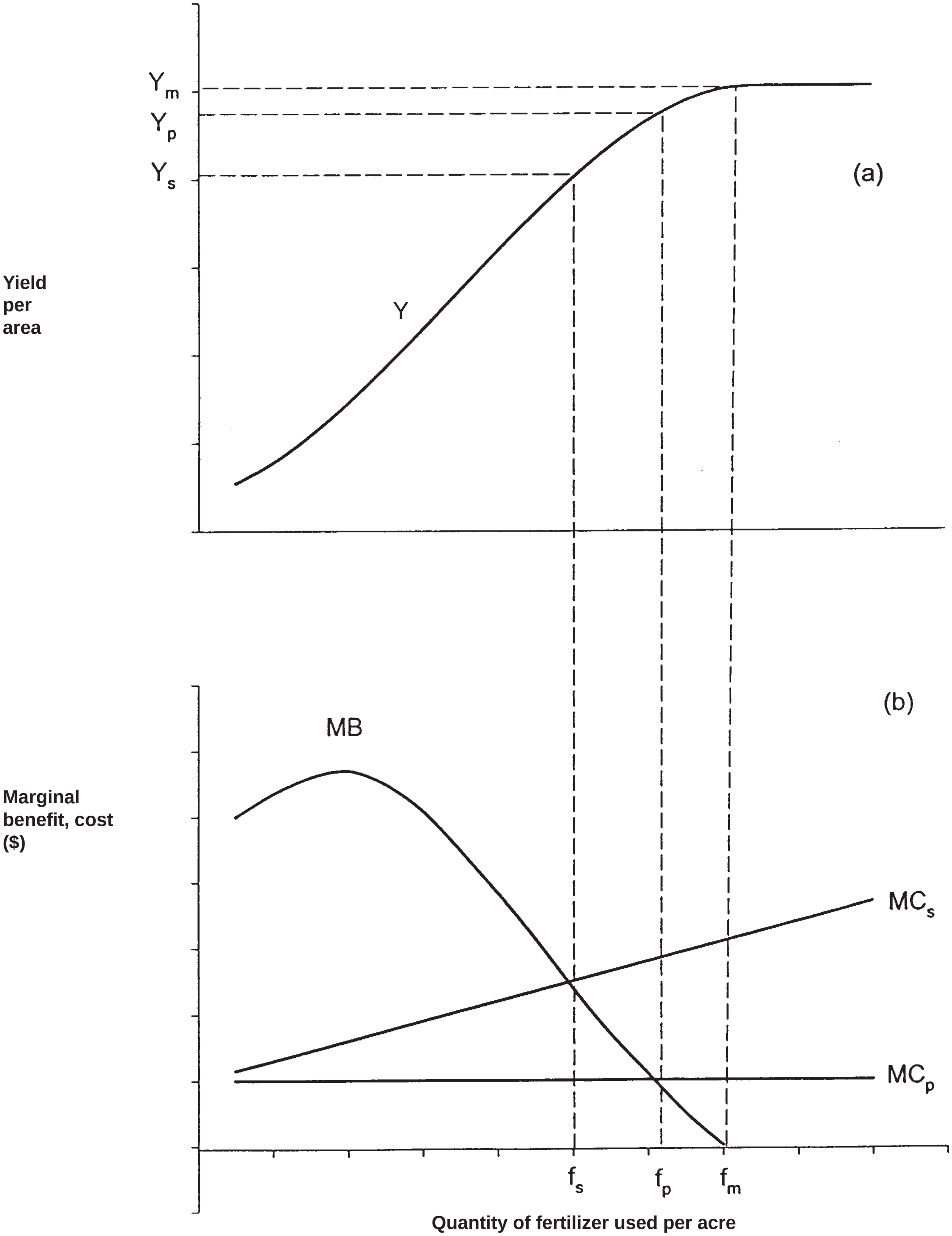
Site characteristics

In relation to nutrient management, it is important to consider not only the potential for loss of nutrients from a field but also the possible consequences of these losses on surrounding areas. The geographic location and situation of a site in the landscape can greatly affect both productivity and environmental protection. Management strategies for a site are influenced by the weather and the biophysical characteristics of the site (over which producers have little or no control). However, many farming practices can be adapted to minimize the risks of environmental damage. Also, if the site is in close proximity to an especially sensitive or valuable resource (such as a sole-source drinking water aquifer, endangered species habitat, or pristine coastal waters), special precautions may be necessary, such as improved soil conservation practices to reduce runoff losses, or planting of stream buffer vegetation. In some cases, reduced fertilizer application rates may be desirable if an especially valuable resource is in jeopardy. These special practices should be encouraged, as much as possible, on a voluntary basis.

The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture is the federal agency that works with growers to develop plans for protection of natural resources. Their conservation planning emphasizes environmental site sensitivity by assessing the vulnerability of soil, water, air, plant, and animal resources and then determining the risks associated with current land uses. Many of the physical characteristics of the land are recorded in the soils database maintained by NRCS. That information is readily available in published soil survey reports for the State of Hawaii (Foote et al. 1972, Sato et al. 1973) as well as in updated electronic formats. Aerial photographs in these reports allow one to precisely identify the geographic location of a site. The soil mapping units given on the photographs provide information on the steepness of slope and identify the class of soils in the area of the site. In most instances, the soil classification nomenclature in the soil survey report also provides information on mean annual temperature, water permeability, and soil depth, and makes inferences to rainfall distribution, all of which is useful information for land management decisions. Proximity of a site to streams can also be determined from the soil survey maps. These data are checked by NRCS planners through field measurements and observations as they develop a conservation plan with a cooperating grower.

The amount and distribution of rainfall has important implications on possible leaching and erosion at a

Figure 1-1. The relationship between yield, marginal benefit / cost, and fertilizer use.



site. Rainfall varies considerably with location in the Hawaiian Islands. Most of the rainfall in windward areas (northeast portions) of the islands results from the cooling of moisture-laden trade winds as they rise over the mountains. These rains often fall as light to moderately heavy showers. Rainfall on the leeward sides (southwest portions) of the islands is mostly from winter storms coming from the west-southwest (Hawaii Water Resources Regional Study, 1979). These rains are often intense and can cause flooding and erosion. Hawaii has a wet-dry seasonal pattern. In general, the dry season is from May through September and the wet season is from October through April. Soils on the windward sides of the islands are more prone to losses of nutrients by leaching, so heavy N applications should be avoided in these locations at any time and at all locations during the wet season. Frequent, small N applications are preferable to allow the nutrient to be more completely taken up by plants, leaving less to be subject to leaching. Soils on the leeward sides of the islands are more prone to movement of P by soil erosion losses during heavy winter storms. In these locations, practices that reduce erosion, such as terracing, cover crops, and contour planting, should be adopted in management of agricultural land.

NRCS planning procedures for control of nutrient contamination consider the soil properties at the farm site. Information on the potential for surface soil loss or leaching of agricultural nutrients and chemicals on various soil types is found in NRCS field office technical guides (unpublished documents available at each field office). This qualitative rating of soils provides a relative assessment of surface runoff and leaching loss potential. Seasonal water budgets are also considered, as well as the presence of unique biological or cultural resources at the site, the distance from fields to nearby surface waters, and the presence and designated use of groundwater aquifers. These data are compiled for the grower into a recommendation report, which lists any special conditions and cautions for fertilizer application at the site. Growers are referred to the Cooperative Extension Service for specific recommendations on nutrient application methods and rates.

Certain physical and chemical properties unique to many tropical soils can also be important to managing crop nutrients in ways that take environmental sensitivity into account. Many tropical soils have variable cation exchange capacity (CEC) that is affected by pH. The CEC is associated with the electrical surface charge on the clay particles in the soil. As pH increases in these soils, the amount of negative charge that holds nutrient cations such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) increases, but when pH decreases, the amount of positive charge that holds anions such as nitrate (NO_3^-) and sulfate (SO_4^{2-}) increases. In Hawaii, the Oxisols, Ultisols, and Andisols have this property of variable cation exchange capacity, as do soils with high amounts of organic matter, such as Histosols. This property allows these soils to hold more cations at higher pH and more anions at lower pH. Thus when the soil pH is low (acidic), these soils hold anions well but hold cations weakly. If the pH of these soils is increased by liming, the hold on anions is weakened, and they become susceptible to leaching, but more cations are held. Thus agricultural practices that raise pH in these soils can result in release of nitrate, with potentially negative effects on groundwater and other environmental consequences.

Another property, mentioned earlier, that is unique to many tropical soils is the ability to hold phosphate ions (PO_4^-) very tightly so that they do not leach and also are less available to plants. This makes it necessary to apply relatively large amounts of P fertilizer to these soils in order to supply plants with adequate P. It is important to know a site’s soil properties so proper fertilization and management practices can be followed.

Surface waters

The State of Hawaii classifies its surface waters as either inland or marine (Hawaii Administrative Rules, Title 11, Chapter 54, Water Quality Standards). Inland waters, consisting of streams and lakes, are few, and many of the streams are intermittent, flowing only during high-rainfall periods. Inland waters are classified by their use and the degree of protection required. Class 1 waters are of the highest social and ecological value and require the greatest protection, and Class 2 waters are mainly of recreational value. The Hawaii Stream Assessment (Smith 1990) lists perennial streams and outstanding aquatic, riparian, cultural, and recreational resources. Hawaii’s marine waters are further classified as embayments, open coastal, or oceanic waters. Class AA waters are intended to remain in a pristine natural state with an absolute minimum of pollution, while Class A waters are protected from harmful discharges or alteration of water quality and are to be used primarily for recreational purposes.

Pollution problems have been found in Hawaii in all classes of waters but especially in embayments and near-coastal waters. Hawaii's Assessment of Nonpoint Source Pollution (DOH 1990) identified 14 water bodies within the state that could not reasonably be expected to attain or maintain State Water Quality Standards. These water bodies were designated as Water Quality-Limited Segments. Subsequently, two additional coastal segments were added, both on the island of Maui, along with various streams around the state. State monitoring of many of these coastal areas continues to show significant violation of the water quality standards for suspended solids and nutrients (especially phosphate) that necessitates the designation of these segments as Water Quality-Limited. These segments and the land areas that drain into the impacted waters receive special attention in pollution control and remediation programs.

Potential contamination of groundwater and aquifers

Basal groundwater, existing as lens-shaped systems floating on underlying sea water, is the primary potable water source in Hawaii. Basal groundwater supplies about 85 percent of the state's domestic and commercial water (USGS 1987). This basal groundwater body, commonly called the Ghyben-Herzberg lens, is unique to island and coastal environments. Groundwater aquifers of each of the major islands in Hawaii have been well characterized in a series of reports (Mink and Lau 1990a, 1990b, 1992a, 1992b, 1993) in which aquifers are classified in terms of hydrology (basal, high level, confined, or unconfined), geology (flank, dike, perched, or sedimentary), designated use (current use, potential use, drinking, or ecologically important), and status (salinity, uniqueness, and vulnerability). It is clear that some aquifers, such as the highly vulnerable and irreplaceable aquifers that are used for drinking water, need special protection. It is important for farmers to know if their agricultural fields lie over such aquifers, so that they can take extra precautions to avoid contamination with agricultural chemicals.

Until a few years ago, Hawaii's groundwater contamination problems were few in number, and investigations were comparatively minor in scale (Lau and Mink 1987). The overall quality of Hawaii's groundwater is outstanding, and most of it can be consumed safely without prior treatment. Groundwater protection became an issue of public concern in Hawaii with the detection of pesticides used by the pineapple and sugar industries in the early 1980s. The discovery of volatile organic chemicals in a number of wells around the state was of great concern to the public as well as to the scientific and engineering community. The Hawaii Department of Health responded by initiating a groundwater protection strategy consistent with the goals of the U.S. Environmental Protection Agency.

Nitrate concentrations in groundwater are low in most areas of Hawaii and are generally close to the assumed natural background level of about 1 mg/liter NO_3^- N (USGS 1986). However nitrate concentration above this level has been found in some wells on the islands of Oahu and Maui (Hawaii Department of Health, Groundwater Program). The Honolulu Board of Water Supply detected increasing nitrate levels over the past 20 years in drinking water wells in the central part of Oahu (for example, in the Kunia area) that reached 8 ppm in some wells in 1993. Central Oahu is an area of particular concern because it overlies the important Pearl Harbor aquifer that supplies drinking water to most of Honolulu. The cause of these elevated nitrate levels in central Oahu is still uncertain, but agricultural sources are a strong possibility. In this as well as other vulnerable areas around the state, good agricultural nutrient management must be stressed to minimize agricultural nitrate as a source of contamination.

Nutrient management regulations and policy

Many growers feel targeted by environmental legislation and wonder why there is such a focus on agriculture. There is an increasing perception in the USA that agriculture is the main contributor to N and P pollution. The strong conservation and water-quality focus in the 1985 Farm Bill (and subsequent 1990 and 1996 Farm Bills) demonstrates the "clout" that national environmental groups have in influencing environmental protection policy for agriculture. It is clear that increased attention to environmental protection will be urged for all farming operations, including nutrient management. Some of the most important environmental laws at the federal, state, and local levels in Hawaii are summarized below. Although none of these laws currently contain strong nutrient management regulations, several provide the framework for developing such regulations, and precedents have been set in other states that have developed nutrient management regulations, as mentioned previously.

Federal pollution control legislation

Probably the most important environmental legislation is the Clean Water Act, which sets standards and provides direction for many of the control measures that have been enacted in the past 20 years. The Clean Water Act of 1972 (formally the Federal Water Pollution Control Amendments) set the objective of restoring and maintaining the nation's waters as a national mandate. The act identified two main categories of water pollution: point sources, which are discrete, identifiable discharges, and nonpoint sources, which are diffuse sources. In addition to maintaining the chemical, physical, and biological integrity of the nation's waters, the act was intended eventually to eliminate pollutants altogether.

The Clean Water Act functions to reduce point sources of pollution primarily by requiring permits from the Environmental Protection Agency for polluting activities. The act authorizes states to implement and enforce its provisions, which is done through each state's environmental regulatory agency. In Hawaii, the Department of Health serves this role and is authorized to issue permits under the National Pollutant Discharge Elimination System. This permit system is based on water quality standards developed by the EPA or by the state. Under the system, all water bodies are classified according to current or planned uses, and a water quality standard is developed to protect those uses from pollution. All permits issued must then contain limitations on discharges sufficient to protect the water quality standard for that water body. This system has been very successful in reducing point sources of pollution in Hawaii as well as nationwide.

In the 1987 amendment to the Clean Water Act, new emphasis was placed on nonpoint source pollution control. Under Section 319, states are required to develop nonpoint source management programs based on an assessment report of water quality pollution within the state. Hawaii's Assessment of Nonpoint Source Pollution was prepared in 1990 to identify categories of nonpoint sources and list "waters of the state" that cannot reasonably attain water quality standards. The pollutant categories considered to be significant nonpoint sources in Hawaii were sediment turbidity, nutrients/fertilizers, toxic substances, pathogens, and pH. Among these sources, sediments were identified as the most visible and prevalent nonpoint source pollutant in Hawaii, but nutrients (particularly N and P) are frequently indicated as causing coastal water quality impairment.

Another important federal law is the Safe Drinking Water Act (SDWA), which was initially passed in 1974 and which sets standards for drinking water quality and for protection of drinking water resources. The act provides for the upgrading of water delivery systems to meet minimum standards nationwide and also establishes "Wellhead Protection Areas" in conjunction with unique and vulnerable groundwater sources. Although Hawaii's groundwater is generally well below the SDWA standard of 10 ppm nitrate N, increasing N levels in groundwater in central Oahu have raised concerns and led to some calls for regulation of all nutrient applications in that area.

Hawaii state laws

Hawaii has effectively used land management as a strategy to protect groundwater quality. A good example of this is the establishment of Conservation Districts at higher elevations, which are kept in a condition that is as natural as possible to enhance groundwater recharge volume and to protect the purity of rainfall that percolates into the ground. Another example is the state regulation that controls underground injection of contaminated water. A "no pass" line sets off regions in which direct injection of wastewater is prohibited. Most of each island's land area falls in the zone between the top of the Conservation District and the injection line. The unregulated areas are largely underlain by unconfined aquifers that are potentially vulnerable to contamination. The dominant land use is agricultural; therefore, a strategy to prevent contamination by land use activities is essential.

Hawaii's groundwater antidegradation policy states that "degradation of groundwater resources that may compromise existing or future beneficial uses will not be allowed or permitted within the State of Hawaii. As a matter of priority, all existing underground sources of drinking water will be given the highest levels of protection. Groundwater in other areas will be protected as potential drinking water sources."

Specific state laws relating to nutrient management include Hawaii Revised Statute 342D on "Water Pollution," which was enacted in 1993 to "prevent, control, and abate" pollution. This statute is implemented through Hawaii Administrative Rule 11-54 (1992), which establishes "Water Quality Standards" for the state. There also is a general "Nonpoint Source Pollution Management and Control" statute, HRS 342E (1993), which is broad in scope but has no administrative rules and is fairly ineffective in controlling pollution.

County grading ordinances and Soil and Water Conservation District plans

The counties of Hawaii also have developed and administer grading ordinances to control erosion from urban areas, especially those areas temporarily bared before construction activities. Hawaii was one of the first states to enact a law to regulate erosion and sediment. Act 249, Hawaii Revised Statutes, enacted in 1974, required each of the four counties to develop their own ordinances to control erosion according to criteria established by the Department of Health. As a result, Maui County has developed a grading ordinance that requires a permit from their Public Works Department for any grading, grubbing, or stockpiling. To obtain the permit, the applicant must incorporate into the development plans certain procedures and possible construction improvements to prevent any soil erosion problems.

For agricultural land use, Act 249 and the county ordinances provide a waiver from having to apply for county grading permits each time lands are uncovered, as long as the land owner shows that a conservation plan approved by the directors of the Soil and Water Conservation District is being implemented. An approved conservation plan includes various "best management practices" that growers must implement. As with urban lands, the intent here is to keep the soils on site. Although these ordinances primarily relate to sediment and erosion control, new conservation plans being developed also require a nutrient management plan.

The goal of a nutrient management plan is to minimize movement of nutrients out of the field and leaching of nutrients from the root zone. A key element of the plan will be implementation of best management practices (BMPs), which are "a practice or combination of practices that are determined to be the most effective and practicable means of controlling pollution at levels compatible with environmental goals" (Soil Conservation Society of America). Therefore, nutrient management plans for particular farms would include practices that provide for efficient use of all nutrient sources to meet production goals without loss of excess nutrients to the environment.

Section 6217: the Coastal Nonpoint Source Pollution Control Program

The Coastal Nonpoint Source Pollution Control Program is a new federally mandated program currently under development in Hawaii and other coastal states and territories. This program was authorized by Congress under Section 6217 of the Coastal Zone Act Reauthorization Amendments of 1990. The Environmental Protection Agency and the National Oceanic and Atmospheric Administration developed the guidelines for the program (EPA 1993). The Hawaii Office of Planning is leading the program development locally. The goal of this legislation is to develop comprehensive state programs for controlling water pollution in lands affecting coastal areas, which in Hawaii includes the entire state.

The Coastal Nonpoint Source Pollution Control Program stands to have a far-reaching impact on pollution control measures in Hawaii and other coastal states and territories. This legislation is intended to address comprehensively the problem of polluted runoff and groundwater contamination, although its emphasis is on runoff. In this respect it attempts to further the pollution prevention goals outlined in the Clean Water Act. It requires all coastal states and territories with federally approved Coastal Zone Management Plans (there are 29 states and territories with such plans) to establish effective and enforceable pollution control programs. All land uses are covered by this program, including agriculture, forestry, urban use, marinas, hydromodifications (such as stream channelizations and dams), and wetlands. Although in this chapter we are concentrating mainly on the program developments related to agriculture, there are similar provisions for the other land uses.

Hawaii's program is designed to build upon, strengthen, and coordinate existing pollution control programs rather than initiate entirely new activities. For example, the program would coordinate technical services provided by the Natural Resources Conservation Service and the Cooperative Extension Service and regulatory actions by the State of Hawaii's Departments of Health and Agriculture. The program is considered to be "technology based" rather than "water quality based," in that program success is based on implementation of practices rather than on monitoring of water quality for compliance with standards. However, since the federal guidelines require that the program include "enforceable mechanisms" to ensure implementation of the pollution control measures, some new regulations and activities are likely to be required.

Under the "6217" program plan, there are requirements for nutrient management planning as well as for the related activity of Management of Wastewater and Runoff from Confined Animal Facilities. Under the Animal Waste Management measure, wastewater and runoff from facilities must be stored in facilities that would withstand a 24-hour "25-year" storm, and the stored runoff and solids must be managed through an appropriate waste utilization system. Also, under the Irrigation Management Measure, irrigation timing and amount should match crop needs, and chemicals should be applied carefully to minimize backflow (movement of injected materials back into the water source), leaching, and tailwater discharge (the discharge of water from the end of the irrigation line).

Hawaii's program plan emphasizes nonregulatory mechanisms as much as possible. To this end, the agricultural management measures are consolidated into a single pollution prevention plan ("P3 plan"), for which producers would only have to complete those components that apply to their operations. The P3 plans would be similar in design to but of greater scope than current conservation plans developed voluntarily by farmers with the Soil and Water Conservation Districts. The incentives for completion and implementation of this plan might include

- exemption from financial liability and other enforcement actions related to compliance with the management measures
- educational opportunities related to farm management for pollution prevention
- eligibility to participate in USDA cost-sharing programs
- maintenance of "dedicated agriculture" property tax status.

As a last resort, growers who fail to implement a pollution prevention plan and are found to cause pollution would be subject to "bad actor laws" that could result in civil penalties. The coordinating organization for plan development and approval has been suggested to be the Hawaii Association of Conservation Districts, with help from the Natural Resources Conservation Service, the Cooperative Extension Service, and, possibly, certified consultants.

Conditional approval for Hawaii's plan was received from the EPA in June 1998. It probably will be mainly voluntary in nature and developed from successful conservation planning and extension programs already in place. Such a program will require coordinated efforts on the part of government and private agencies and individuals, with sharing of resources and responsibilities. Under this program, growers would be strongly encouraged but not necessarily required to develop and implement nutrient management plans (as well as overall pollution prevention plans). Many details, such as the approval process for the plans and the agency responsible, have yet to be determined. However, the continuing development of the Coastal Nonpoint Source Pollution Control Program in Hawaii is indicative of the trend for increased government oversight and control over nutrient management.

Maximizing nutrient use efficiency

Optimal nutrient balance

Plants require not only an adequate supply of essential nutrients but also a balanced supply of these nutrients. If a nutrient is limiting, plant growth will be limited to that allowed by the limiting nutrient. Once that limitation has been corrected, growth will increase to the level allowed by the next most limiting nutrient. This is known as the "Law of the Minimum," which was first stated in 1862 by Justus von Liebig, recognized as the "father of agricultural chemistry." For example, if a soil has a low K level and only N and P fertilizers are applied, yields will be limited by the K deficiency. Only when K fertilizer is also applied will the full effects of the N and P fertilizers on yield be realized.

Therefore, agriculturists must determine which nutrients are limiting and supply them to the crop. Soil analysis is used to determine the supply of nutrients in the soil before the crop is planted. Fertilizer recommendations are developed based on the soil nutrient analysis data, other known characteristics of the soil, and the known requirements of the crop.

The relative quantities (the ratios, or "balances") of certain nutrients in the soil affect their availability to plants. This is particularly true for K, Ca, and Mg, which "compete" for absorption by plants. Availability

Table 1-1. Distribution of nitrogen in soil columns after applying 20 inches of water immediately following N fertilizer applications to the Helemano soil (Kanehiro et al. 1960).

	Form of nitrogen						
Depth (inches)	Ammonium chloride	Ammonium sulfate	Mono-ammonium phosphate	Di-ammonium phosphate	Aqua ammonia	Sodium nitrate	Urea
	Percent of added nitrogen found at various soil depths						
0–2	20	17	41	56	80	1	4
2–4	14	17	24	17	13	2	4
4–6	15	17	16	13	7	3	5
6–8	13	17	9	7	4	3	9
8–10	12	16	7	6	2	1	4
10+	29	15	4	0	0	84	76

of K is somewhat more dependent on its concentration relative to that of Ca and Mg than on the total quantity of K present. A soil that is high in Ca or Mg thus may require greater amounts of fertilizer K for adequate K nutrition of crops. When lime is applied to raise soil pH, the Ca level is often raised enough to decrease the availability of K and Mg to plants, and additional amounts of these nutrients may have to be applied.

Micronutrients are also subject to nutrient imbalances. Excess copper (Cu), manganese (Mn), zinc (Zn), and molybdenum (Mo) can interact with iron (Fe), causing Fe deficiency in plants. Zn uptake can be inhibited by high levels of Fe, Cu, and Mn, which probably compete for the same uptake sites on plant roots. High P availability can induce Zn deficiency in soils that are marginally Zn-deficient. Cu uptake can be inhibited by high levels of Zn, Fe, and P in the soil solution. Many micronutrients are less available to plants when the soil pH is above 7, either naturally or as a result of lime application. Growers must be aware of these possible problems when applying micronutrient fertilizers and lime to their crops.

Realistic crop yield goals

Setting realistic yield goals is critically important for accurate fertilizer recommendations. Growers generally base the amount of fertilizer to be applied to a crop on the yield they expect to obtain that year. This is known as the "yield goal" and is one of the most important factors affecting the amount of fertilizer used. A realistic yield goal should be based on the average yield for a particular field over the past five years, not on the highest yield obtained or hoped for. In a study of Nebraska corn farmers (Scheppers et al. 1991), yield goals averaged 9 percent higher than the actual yield averages. Such overly optimistic yield goals resulted in excess N fertilizer applications of approximately 20 lb N per acre, additional N that could contribute to environmental contamination.

N fertilizer management

Both the fertilizer form and the way that N fertilizer is applied influence the possibility of nitrate leaching through the soil profile. The three most commonly used forms of N are urea, ammonium, and nitrate. These differ in their mobility, transformation, and volatilization characteristics, and in the manner in which they are taken up by plants.

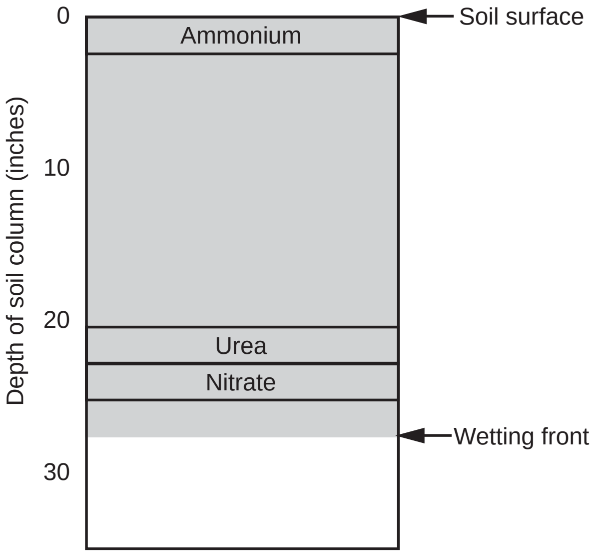
As Table 1-1 illustrates, ammoniacal forms are less prone to leaching. Aqua ammonia and diammonium phosphate were the least mobile, with 93 and 73 percent, respectively, being retained in the surface 4 inches of soil. The ammonium ion is held on the soil's cation exchange sites and thus is resistant to leaching. Urea and nitrate, on the other hand, are readily leached immediately after application because they are not held on cation exchange sites (Table 1-1 and Figure 1-2). Urea is converted to ammonium within one to four days after application by the enzyme urease, which is commonly found in soils, but in amounts that vary from soil to soil. This variability is illustrated in Figure 1-3, where the Lualualei and Paaloa soils converted urea in about a day, while the Wahiawa soil took about four days to convert most of the urea to ammonium. The high pH of the Lualualei soil caused loss of ammonia by volatilization. Ammonium ions held on cation exchange sites are eventually transformed to nitrate by soil microorganisms, and they then become subject to leaching. Conversion of ammonium to nitrate can be delayed by the use of a nitrification inhibitor.

Nitrogen fertilizers can be applied by hand, tractor, or airplane, or in irrigation water. Because ammonium fertilizers are not readily mobile in soil, they should be placed near the plant roots. Urea and nitrate fertilizers, on the other hand, move readily in soil, and there is less restriction on where they are applied as long as they are in proximity to the plants. When N fertilizers are applied in solution via drip irrigation systems, the fertilizer is deposited near the drip orifices. However, with urea and nitrate fertilizers, continued irrigation after fertilizer application can result in leaching the nutrients beyond the root zone. Therefore, these fertilizers should be injected into a drip system toward the end of an irrigation to minimize the possibility of leaching beyond the roots. Sufficient time should be allowed before the next irrigation to allow the urea to be converted to ammonium, which will resist leaching. Slow-release N fertilizers such as sulfur-coated urea also can minimize the possibility of nitrate leaching beyond the root zone.

In poorly drained soils anaerobic conditions prevail, and nitrogen applied in fertilizer or manure is lost to the atmosphere in gaseous forms. Nitrous oxide, for example, has been implicated as a minor contributor to the "greenhouse effect." While the impact of these N losses is less direct in its potential to damage the environment than nitrate leached into groundwater, it is nevertheless desirable to minimize such losses by maintaining well aerated soils.

Nitrogen applications should be made when crop demand is highest—early in the crop cycle when the crop is growing rapidly. As the crop starts to mature, growth is reduced and the demand for N decreases. Little if any N should be applied after maximum growth of the crop has been attained. The quantity of N applied at any one time should match the crop's requirement at that stage of growth. It is generally better to apply several small quantities of N than a few large doses of N. Application of quantities of N in excess of plant needs will result in loss by volatilization and leaching and can harm the environment.

Figure 1-2. The relative movement of ammonium, urea, and nitrate in soil when a broadcast application of each moves downward into a dry soil with irrigation water (Green 1981).



Water management

Water percolating through the soil is necessary for nitrate leaching. Infiltration of water from rainfall into the soil is inhibited by soil conditions that encourage runoff, which is also undesirable. Water from irrigation, however, can and should be managed to avoid N losses by leaching. In some cases this is difficult, as when crops are irrigated by furrow, and water is often overapplied at the head of the furrow to ensure that enough reaches the lower end.

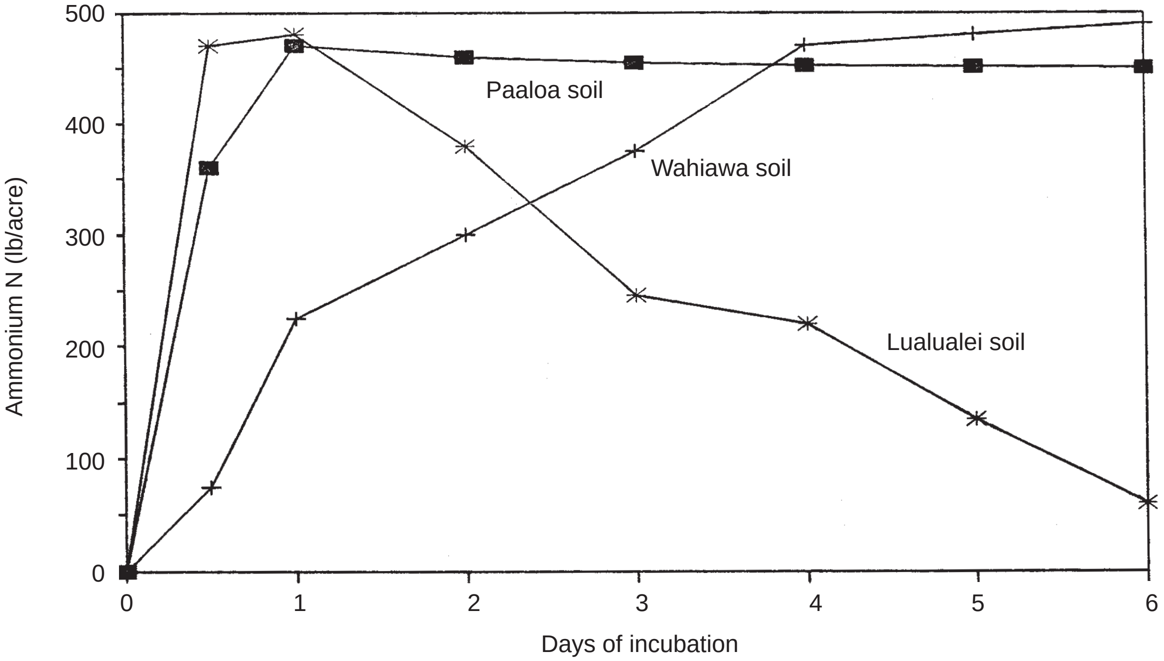
Most nitrate leaching from cropped fields occurs when no crop is present, except in the case of sandy soils, which are highly permeable (Power and Schepers 1989). An actively growing crop removes large quantities of water and nutrients from the soil and thus minimizes the amount of water and N moving below the root zone.

Nitrate is subject to greater losses during the wet season when heavy rains cause nitrate leaching. To limit this, N applications should be reduced, and nitrification inhibitors should be used.

Phosphorus management

The common forms of fertilizer P are simple superphosphate, triple (concentrated) superphosphate, rock

Figure 1-3. Soils vary in the rate at which applied urea fertilizer is converted to ammonium. This diagram shows how three soils converted urea to ammonium nitrogen following an application of 500 lb/acre (Tamimi and Kanehiro 1962).



phosphate, and various ammonium phosphates. Except for rock phosphate, these fertilizers are soluble, and the P they contain is readily available to crops in soils that do not sorb P strongly. Due to the P-sorbing ("P-fixing") character of many of Hawaii's soils, surface applications of P are often ineffective, because the P is held by the surface soil and does not move into the root zone. Also, P fertilizer applied to the soil surface is highly vulnerable to movement by erosion, and P in solution can be transported in runoff.

Incorporating P into the soil reduces its vulnerability to erosion loss, but mixing soluble P fertilizer into a soil with a strong P-sorption capacity results in much of the P being sorbed and made unavailable to plants. In these soils, "banded" placement of P concentrates the application in a zone about 2 inches below and 2 inches to the side of the seed row. Exposure of the fertilizer to the soil particles is minimized, and a P-rich zone is created in proximity to the developing plant.

Rock phosphate should be applied only to acidic (low pH) soils, because it must react with soil acids before the P it contains becomes available to plants. Rock phosphate should be mixed thoroughly into the root zone to maximize its contact with soil and promote the acidulation reaction.

Phosphorus pollution can be reduced by minimizing soil erosion and runoff and using subsurface placement (banding). Practices that reduce erosion and runoff include the use of cover crops, no-till cropping, contour planting, and terracing.

The amount of P applied should be determined by soil analysis so that fertilizer P is applied only to soils with inadequate soil P. Phosphorus application to soil with adequate soil P is a waste of money, can cause nutrient imbalance, and increases the potential for phosphorus pollution of the environment.

Animal manure management

Animal manure provides a broad spectrum of plant nutrients and also contributes to the soil organic matter, which benefits soil structure, permeability, and moisture retention. The nutrient content of animal manure is much lower than that of inorganic fertilizers. Chicken manure, for example, contains 2–4% N, compared to urea with 46% N. Therefore, large amounts of animal manure must be applied to supply a given amount of nutrient. For chicken manure containing 2.5% N, at least 8000 lb (4 tons) per acre must be applied to supply 200 lb of total N per acre, compared to the 435 lb of urea needed to supply the same amount.

Because the nutrients in animal manure are largely in organic form, they must be mineralized by microorganisms and converted to inorganic forms that can be taken up by plants. Mineralization requires adequate moisture and proper temperature for microorganisms, and the process of releasing the organic N to plants can continue for several years after the application.

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