Managing Nutrients Across Regions of the United States

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ABSTRACT

Nutrient balance in the ecosystem involves profitability of the agricultural enterprise and commitments to resource management to maintain quality of air, water, and land resources. Phosphorus and N are the two nutrients of major concern, and they behave differently in soils. Most P adheres strongly to soil particles and moves laterally with the soil during erosion processes, but with high concentrations more P remains in soluble forms and moves in the water fraction. Most N is soluble and moves laterally or downward with soil water. Soil scientists and agronomists have researched soil processes, plant nutrition, cropping systems, and water quality issues mainly on a field and farm level, but now the movement is to management and regulation of nonpoint problems on a watershed basis as proposed in the Clean Water Action Plan. The plan recognizes the vast diversity of soil parent materials and climates among geographic areas, even among and within watersheds, that determine crop adaptation and cropping systems, the role of states in regulatory processes, and the need for local citizens to have operational involvement. This process insures that nutrient management guidelines will be more site-specific and solutions can be focused on the direct problem. Directed efforts will be needed to educate local citizens, landowners, and caretakers of agricultural enterprises, and regulatory agencies. Several factors, including economic and social incentives for implementation must be considered along with the technologies available. The solutions are multidisciplinary, will require long-term research to accommodate climate variation, and should be associated with a strong commitment to education. Public funding will be needed to support the effort.

(**Key words**: nutrients, land-use, watershed, soil management)

Abbreviation key: **MLRA** = major land resource area, **AFO** = animal feeding operation, **CAFO** = concentrated animal feeding operation.

INTRODUCTION

The role of nutrient management in livestock systems takes on new meaning as producers and the public together consider economic and noneconomic issues. Until recently, landowners and land managers had relative freedom for application and redistribution of mineral elements. Similarly, the producer, who often was the landowner, had near total responsibility for proper land stewardship to minimize detrimental effects on soil and water resources. But as technologies improved and populations grew, fewer people were involved directly with agrarian society, pesticides and chemical fertilizers increased in use, and the public became more aware of the need to insure a quality environment. Today, there is increased accountability for stewardship of natural resources, i.e., sound land management, clean air, and high quality water.

For several years, point-source problems were the major concern, and effective policies and practices have been developed. But with advances in assessment technologies, increased concentrating of livestock, and increased public concern about safety in the food production process, nonpoint-source problems are also being addressed. As judicious users and vested guardians of much of the nation's public resources, the agriculturalist is accountable. Water and air quality are affected by agriculture and both require new technologies and the expertise to apply them. Thus, this symposium on nutrient management is well founded and timely. My goal is to review effects of geographic, climatic, and agronomic factors on nutrient balance. Within these constraints local approaches to solutions will need to be fitted. The solutions will differ, however, depending on the location of the watershed, nature of the individual agricultural enterprise, management alternatives available, and social and economic variables that affect local decision-making.

EVOLUTION OF THE PROBLEM

Geologic processes, climatic variables, and the degree of human intervention have led to different soils and landscapes that are occupied by natural and agricultural ecosystems, each with its own distinction. In addition, each mineral element has a unique chemistry in the soil and availability to plants, i.e., its own niche in the ecosystem. Although there can be some grouping for principles, the two nutrients of most concern are P, a major cause of eutrophication, and excess N, a major risk to human health. These two differ markedly in origin, use, and behavior in the environment. Many other minerals in the ecosystem, in addition to those required by plants and animals, can accumulate, cycle, and be transported in agricultural systems (32).

Figure 1 summarizes factors influencing nutrient balance. Agricultural practices have a large effect on nutrient balance in both positive and negative ways. For sustainability, nutrient losses to the environment and removal of crop and livestock products need to be offset by release of new soil minerals (inorganic) from the parent material, additions of nutrients through fertilizers and wastes, and retention or improvement of the organic matter content. Maintaining or improving the soil and minimizing losses to the environment are major goals. Agricultural and land use practices alter the routes and rates that nutrients pass through or are recycled in the system. Fertilizers and manures can be applied to supplement the balance, especially in managed ecosystems. Human and industrial waste also need to be considered in the total balance.

Over 30 years ago Cooke (6) reviewed nutrient balance on a country level and indicated a growing awareness of P accumulation in developed countries. More than a century ago, Johnston and Cameron (13) indicated P reserves were building up in the United Kingdom because P removal through cropping and pastures was only 85% of that added. Animal manures, but not recycling of human or industrial products, were included in the balance. In 1956 (again not considering recovery of human or industrial waste by crops and livestock) the United Kingdom showed an even greater annual rate of P buildup in the system, mainly in the soil (5). Nitrogen was also in a positive balance and was assumed to be accumulating as a major component of soil organic matter or lost to air and water. Potassium was not yet in a positive balance. Clearly, P was accumulating as a reserve.

In the United States, a much larger and more diverse country, Lipman and Conybeare (19) in 1936 added erosion and leaching losses to the crop and livestock removal and concluded nutrients returned annually to the soil replaced about 67% of the N and only 33% of the P that was removed or lost. By 1963, largely because of the rapid increase in fertilizer use, 70% of the N and 54% of the K loss and removal was supplied by fertilizer. Additions of P were 18% greater than loss and removal, indicating soil-P reserves were increasing. In the early 1960s Donald (9) recognized that P was accumulating in Australia's soils, even when losses caused by erosion and leaching were considered.

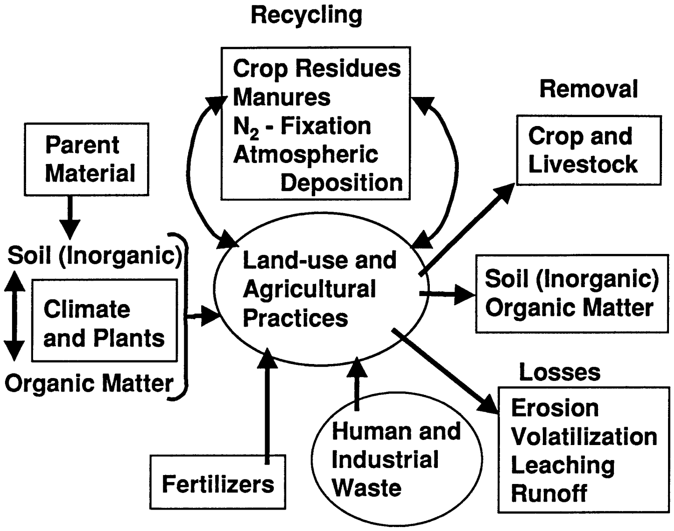

Figure 1. Effect of inputs, outputs, and agricultural practices on the nutrient balance in a field, watershed, or country.

During the past few decades the agricultural community and general public have became more aware of eutrophication, or overenrichment of nutrients, caused largely by P accumulation in lakes, reservoirs, and slower moving streams (18). Nitrogen enrichment contributes to eutrophication in saline waters of estuaries and bays and to other water quality problems resulting from leached N, largely as NO_3^- (11). Many industrialized nations have become acutely aware of the need to consider land, including cropland, as a disposal site for human and manufacturing waste. For example, Korea and Japan have imported vast quantities of N, P, K, and other mineral elements in food and feedstuffs, to the point that reserves of soil P from recycling waste materials in many agricultural soils are well beyond those needing supplemental fertilizers for crop production (Kwang Yong Jung, 1998, personal communication, Rural Development Administration, Suweon, Korea). In contrast, soil P levels are still deficient for crop production in many tropical soils (26).

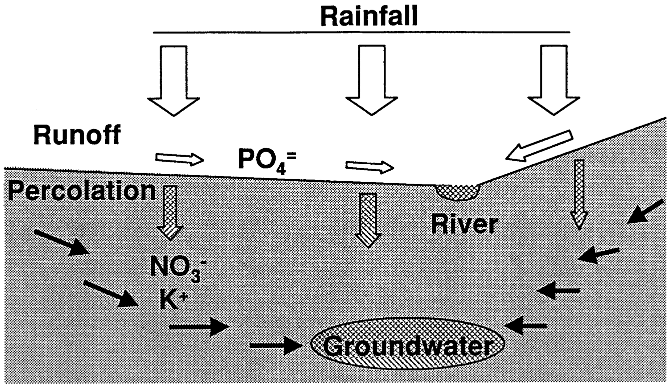

Figure 2. Effect of slope of the soil on the relative distribution of water to runoff and percolation. Runoff has major effects on quality of surface waters whereas leaching past the root zone has implications for quality of groundwater.

SOIL PROPERTIES AND NUTRIENT MANAGEMENT

Soil Water Management

Soil hydrology is a major factor affecting nutrient management, especially relative to water quality issues (25). The two major processes of dispensing with incident precipitation are percolation, or flow-through, and surface runoff (Figure 2). The proportional distribution of water movement depends on the slope of the land, rate of percolation in the soil, and the intensity and duration of the rainfall event. Percolation rate depends on physical properties of the soil, mainly texture and structure. In general, soils with high sand content have higher rates of percolation than do those with high clay content. Organic matter and the associated microflora contribute positively to development and maintenance of good soil structure that aids air and water movement within the soil.

Soils with an open, porous structure percolate faster. Earthworms and decaying roots form macropores or channels to facilitate water movement. Animal and vehicular traffic cause compaction in the upper soil layers to reduce porosity and reduce percolation rates. Some soils are characterized by hardpans or claypans below the tilled horizons, which severely restrict continued downward movement of water and growth of roots to lower levels of the profile. Water that percolates to an impervious layer can move laterally in the soil and can exit again downslope as subsurface runoff. Surface runoff carries soluble nutrients such as N, K, and some forms of P to streams and impoundments.

The slope of the soil and the nature and amount of vegetation cover determine the rate of lateral movement across the soil surface and, therefore, the energy for suspending and moving sediment, and the timespan a given unit of surface water has to percolate into the soil. Vegetation on and above the soil surface intercepts raindrops, reducing their force of impact, which helps retain soil structure and its ability to absorb water, and increases percolation by physically slowing lateral flow of surface water. Buffer strips and riparian areas are examples of methods used to decrease lateral flow before the water leaves a field or enters a stream.

Soil Fertility and Crop Production

Soil productivity refers to the capability of a soil to produce a crop and incorporates soil physical factors, the prevailing climate, natural fertility plus additional elements from manures or fertilizers, and management variables such as tillage and the cropping system (31). Nutrient management alters one component of the productivity index, the soil fertility status. Nitrogen is generally the yield-limiting nutrient in grasslands and extensively managed agricultural cropping systems and, when limiting, is efficiently recycled within the ecosystem and losses are minimal (11). Fertilizer or biological N is added to intensively managed systems. Once the N requirement is met, P is generally the limiting nutrient in more intensive cropping systems. The amount of soluble P in soils is generally small and losses are minimal unless erosion occurs. In natural systems, therefore, nature has built in checks and balances for regulating the loss of these two nutrients from the local system, either by efficient recycling among plants (N) or by having sufficient storage capacity in the soil (P).

Fertilizer requirement is the amount of a nutrient or nutrients that needs to be added to achieve the desired, but not necessarily maximum yield level (31). Manures have long been recognized as good sources of nutrients. Although concentrations of P and N often limit productivity, the need for repositories of vast quantities of manures and waste materials has expanded thinking about requirements. No longer is the question focused only on crop response. Now manure or nutrient management includes the times and processes to minimize early nutrient loss after application to the soil and to enhance the ability of the soil and cropping system to sequester the nutrient for a long time in an environmentally friendly way. Social factors such as sight and odor of manures now also need to be considered. Agricultural engineers and agronomists are developing new methods to meet nutritional needs for plant growth in environmentally benign ways.

Soil Fertility and the Environment

It is beyond the scope of this assessment to review details about N and P cycles except for a few general principles. The main natural sources of N input include fixation by *Rhizobia* and other symbiotic bacteria, fixation by free-living soil bacteria, and some fixation by electrical discharge in the atmosphere (31). Other sources are industrial waste and recapture of N that is emitted from the soil in gaseous forms. When large amounts of carbonaceous material are available in the soil, the mineral N is incorporated into organic matter and is lessened as an environmental threat (12). The method for estimating N in the soil available for crop growth is generally based on its relationship with organic matter and the expected rate of organic matter decomposition by which N is changed to available forms (31).

The abilities to measure soils for potential environmental problems began as a natural extension of methods for measuring the N or P that is available to support plant growth. This amount is less than the total and is dependent on the chemical nature of the element in the soil that allows it to be available to plants. Nitrogen applied to soils, regardless of the form, is usually rapidly changed to NO_3^-, a form that is readily taken up by plants, but is very soluble and moves vertically and laterally in the water fraction. The NO_3^- in the soil can be sampled at various depths, and the amount can be measured. But if it moves below the rooting zone, NO_3^- can easily escape into the groundwater (Figure 2). When N is applied on the surface it can also dissolve and be moved laterally into the surface water.

Because of its behavior in the soil, there is little storage capacity for N aside from accumulated organic matter in the soil (Figure 3). Thus, it is most desirable to apply N during or just prior to active uptake stages of the crop, and inject manure slurries below the soil surface or incorporate them into the soil to minimize lateral movement with surface water and loss of NH_3 by volatilization.

The situation is more complicated for P because soils can differ markedly among regions because of parent material, and plant-available P varies with soil properties, especially pH. Further, at low to moderate concentrations P binds tightly to clay particles such that it moves very little in the water phase for leaching or runoff. At high P concentrations, however, the soil approaches saturation and more P remains in soluble forms, which move with water. The P soil test value for environmental purposes is generally much higher than for yield responses and agricultural applications because there is a large storage capacity (Figure 4). Determining the safe limit of storage capacity has been difficult because erosion potential and management effects add complexity in determining tolerable losses of soil P. Nevertheless, regulatory agencies in many states have already established the upper limit for soil test P, usually with little research data, and often at levels only marginally above the crop response. Generally, when the soil already tests at or above the acceptable maximum for P, annual application is limited to that equal to crop removal.

The norm for testing soil for agricultural use is to extract plant-available P, but the P test for environmental purposes should extract all or a high proportion of the soil-P fraction that is susceptible to direct surface runoff, leaching, or dissolution from eroded sediments (21). This limitation suggests soil testing for environmental purposes requires new methodologies and interpretations (28). For example, the depth of soil sampling for environmental tests will vary (Figure 2); it will be shallower than for the agricultural test when surface runoff is the major problem

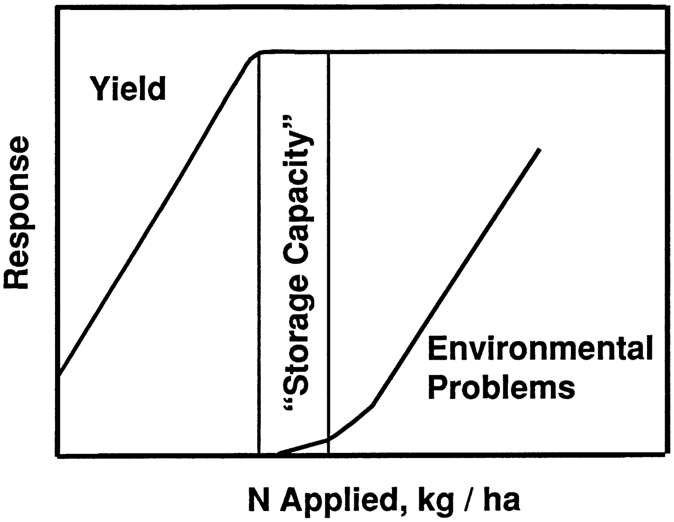

Figure 3. Effect of N application on crop yield and potential environmental problems, largely from leaching of NO_3^-. Adapted from (12). The storage capacity is very low indicating N should be applied just prior to active uptake by the plants.

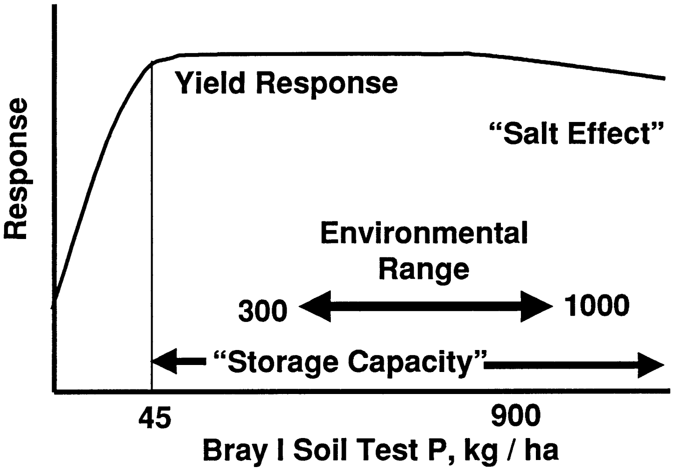

Figure 4. Effect of soil-test P on the crop yield response and the potential for environmental losses. Note that the soil has a large storage capacity because $PO_4^=$ adheres tightly to the soil particles. High rates of manure application can produce salt problems in some soils.

and deeper when leaching losses of soluble forms are the major problem (21).

Sims (27) proposed the Phosphorus Index, a system to guide P applications based on a weighting of eight soil and soil management characters. The potential for soil erosion, current soil-P test (upper 15 cm), and application rates of organic sources of P contribute most strongly to the index. The index uses coefficients that are based largely on the experience of scientists and not on multicomponent scientific data. But the index is relatively easy to learn, is relevant, and can be applied over a range of soil conditions. Scientific data support coefficients showing more P loss from surface runoff from soils that test high in P, especially in the upper 5 cm, than those testing low in P, and P loss from bare soil is greater than from the same soil covered by vegetation (1). With a high water table and very high concentrations of P in the soil, leaching and lateral subsurface flow can contribute dissolved P to surface waters.

Soil Characterization and Mapping

In an effort to bring organization to the natural diversity, early soil scientists developed maps delineating soil types based largely on the parent material, organic matter, and physical features of the soil and landscape. This classification system has proved to be very helpful for soil management and formed the national basis for decisions on crops and animal agriculture (14). With advances in technology, especially geographic information systems and global positioning systems, today's soil scientists have redirected the mapping process to be more detailed and to include multiple-use characteristics beyond agricultural production (2).

The USDA (33) embraced the changing paradigm and developed a more forward-looking soil classification system, which is based on 204 major land resource areas (MLRAs) in the United States. These areas are geographically associated land units of several thousand hectares and include a particular pattern of elevation and topography, soils, climate, water resources, and land uses. The large MLRAs are independent of state boundaries but are important for statewide planning efforts on usefulness for productivity, operation of resource conservation programs, and they have value for interstate, regional, and national planning efforts.

THE CLEAN WATER ACTION PLAN

The MLRAs developed by the Natural Resources Conservation Service and the environmental initiatives promoted by EPA were brought together with the joint USDA/EPA release of the Clean Water Action Plan (35). This landmark effort between two large federal agencies provides the opportunity to apply new technologies into a plan that targets polluted runoff, habitat degradation, and safety of water supplies. It uniquely brings together a partnership of federal, state, tribal, and local agencies to work with nonprofit organizations and private groups (20).

Operation of the Plan

The plan is based on two fundamentals; 1) that problem solving is a bottom-up process that needs to be watershed based and requires site-specific solutions, and 2) that state agencies need to be involved because they administer many of the environmental laws enacted by the federal government. Many states have already adopted the watershed basis because it is difficult to develop a comprehensive program for nonpoint-source problems based on regulatory standards formulated for point-source problems.

The state-federal partnership allows further state relations with local groups within a watershed to fine-tune, monitor, and administer the programs locally. This model places the oversight and procedural details at the local level, with the people within the watershed who are most fully aware of the potential for problems and the feasibility of solutions. The local effort also insures a broad base of public participation, which is critical because the problems and solutions are site specific. For example, in general, the combination of soil types and high precipitation in the southeastern United States leads to more challenges with surface runoff and associated P loss compared with much of the arid west and flatter Great Plains, where N may be a greater problem (29). Yet among watersheds within several of the geographic areas, the range among site-specific situations is nearly as diverse.

Concentrations of Animals

The action plan was accompanied by collective action by USDA and EPA to have a more unified national strategy (16) for an animal feeding operation (**AFO**) and a concentrated animal feeding operation (**CAFO**). An AFO is a facility in which animals are stabled or confined for a total of 45 or more days during a 12-mo period, such that normal vegetation or forage growth is not sustained in a normal growing season. These AFOs range from small facilities with a few animals to large facilities and land areas capable of dispersing several hundred animals that generate large amounts of waste. Most AFO issues are being addressed voluntarily by individual states, but the scope and nature of programs differ from state to state. The programs offer technical assistance, cost-share financial assistance, or other incentives.

In contrast with an AFO, a CAFO is categorized as a point source and must have a pollutant discharge permit for liquid and solid components of manure. A CAFO is defined as a facility with more than 1000 animal units, or one with 301 to 1000 animal units that discharges pollutants into waters governed by the United States. Containment is a major issue that requires managed lagoons, perimeter barriers, and strict record keeping (15). Operation of either an AFO or CAFO may be amenable to management as a ‘closed system’ of nutrient balance (17), which uses detailed accounting of all nutrient inputs and outputs in the farm system (Figure 5). Specific efforts are made to reduce runoff and volatilization from manures, recycle nutrients in cropping systems, and trap NH_3 release from structures and manure pits.

Closed systems have been considered in some areas in the United States and may serve societal needs if lateral movement of surface water can be controlled and losses through percolation and subsurface lateral movement of water are minimal. These systems may also be very useful for specific areas within a watershed. Some CAFOs may be amenable to use of constructed wetlands to process toxic and nontoxic contaminants before releasing the water into sensitive aquatic environments (22). Dealing with AFOs and CAFOs will be a major responsibility in planning and operation of the watershed.

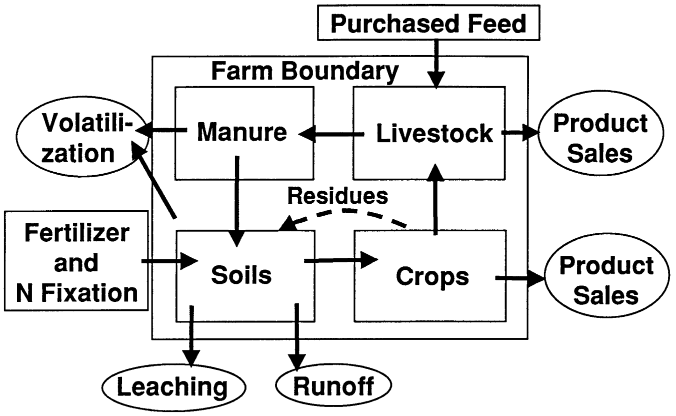

Figure 5. A closed system depends on the amount of nutrients that enters a farm and the amount leaving as products, leaching, and runoff. The input-output budget based on the total system should be zero or less than zero.

Implementing the Plan

As part of the Action Plan, the contiguous United States has been divided into 2111 watersheds, each consisting of several thousand hectares (Figure 6). Alaska and Hawaii are to be considered later. Further, each watershed has been classified, using 15 water resource indicators, into one of six categories according as to its current condition of water quality (better, less serious, and more serious) and as to its vulnerability (low or high) to a decrease in quality (34). There are still many watersheds with insufficient data to classify.

An upcoming step in the implementation of the Clean Water Plan is the development of nutrient budgets on a watershed basis that reflect relative contributions of nutrients from all sources in the outflow of water from the watershed. First, USDA will identify counties with excess nutrient losses from manure. Then EPA and USDA will combine data based on fertilizer sales, the Agricultural Census, and permit limits to establish a baseline of nutrient loads for the sensitive watersheds. Funding for education and outreach programs will likely be focused on problem watersheds, especially those with high risks from AFOs. The mechanisms for acquisition and scientific assessment of research data are less clear.

The implementation and decision making of the Action Plan brings together several operating principles and the underlying science of a watershed. It has

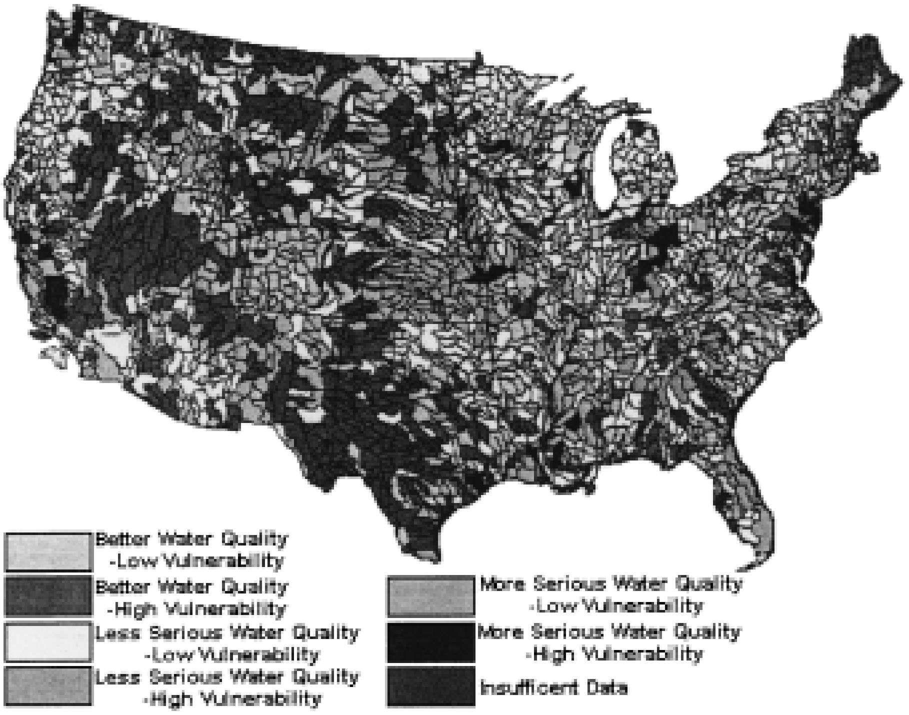

Figure 6. The 48 contiguous states have been divided into watersheds that are classified according to current quality of the water and vulnerability to a reduction in water quality.

been widely acknowledged that rates of runoff and sediment loss from a field plot or an entire field cannot be equated directly to a reduction in quality of water leaving a watershed, although it clearly contributes to the potential (8). Similarly, rates of percolation and leaching of nutrients from a plot or field nearly always overestimate the amount that will eventually reach the groundwater or receiving streams (7).

Implications of a Watershed Plan

The quality of water as precipitation and the deposition of particulate matter that contains nutrients will differ from watershed to watershed. Overall, each field, pasture, AFO, CAFO, woodland, road and right-of-way, fenceline, farmstead, riparian strip, golf course, town, and any other land surface within the watershed contributes to the nutrient balance of the watershed in its own way. The proximity of the erosion event to the receiving stream is critical. Further, the geographic distribution of specific agricultural or nonagricultural activities within the watershed will alter their effect. This again points out the need for a good database and sound scientific assessment of the watershed.

Most watersheds consist of a network of several third- and even fourth-order streams that collect the runoff and seepage from the landscape. This network allows for some pollutant disposition within the watershed itself, both in time and space (4). Contaminants such as fecal coliform bacteria have a natural attrition that is time dependent as the water flows from the loading area into the tributaries and eventually the main receiving stream. Thus, contaminant entry near the mouth contributes disproportionately higher amounts of these organisms to watershed outflow than do similar loading areas further upstream. Generally, there is also some reduction of nutrient load as it moves in the water, but the exact dynamics and long-term effects in the ecosystem food chain need further research.

The emphasis for each watershed should consider both the spatial distribution of the agricultural enterprises within the watershed and the practices used within each enterprise. For example, with similar managements, an AFO or CAFO at a less critical position or farther from the main receiving stream, in general, is less likely to be a major problem. Adding management practices to minimize soil erosion and nutrient losses due to runoff in cropping systems are also critical. Locating more intensive pasture management systems, where more fertilizer inputs are used, further from the receiving stream, and locating more extensive management systems nearer the receiving streams can improve water quality (7). Use of riparian zones with proper vegetation and excluding livestock from sensitive areas of receiving streams are also very effective for nutrient management in a watershed (10).

Grazing systems influence the distribution of nutrients in manure and urine because animals generally excrete nutrients at sites away from where they were ingested. Distribution patterns and high rates of urine and feces deposition in pastures and rangelands are often associated with spatial locations of water, shade, mineral supplements, and topographical features such as ridges and draws, areas where animals congregate and rest (23). Uniformity of manure deposition in the grazed areas is better when high stocking rates are used in rotational stocking systems compared with continuous stocking. Distance from potential grazing areas to water and the geometric shape of the allocated grazing area are also factors (24).

SCALING FROM FIELDS TO WATERSHEDS

Coupling global positioning technology with geographic information systems to determine slopes, soil types, and climatic factors adds a powerful approach to understanding the movement of water and the potential dissolution, transport, and fate of soil sediment. Often one field drains water onto another field within a farm. But soil types and drainage patterns do not fit farm boundaries, making it difficult to evaluate nutrient management on a farm basis in most areas of the United States. This is not the case at all locations, however, and several European countries have movements and policies to develop ‘closed’ farms (Figure 5), i.e., farms for which the movements of nutrients onto and off the farm are monitored and accounted for.

Each watershed has distinct features that must be considered in the nutrient management plan (4). Watersheds may culminate in a standing water system such as a lake or impoundment, or a moving water system such as a creek or river. In general, moving water allows the system to flush by moving the pollutant along or dilutes it by mixing with other sources of water. In contrast, the standing water accumulates the pollutant depending on the accumulation and breakdown rates. Few data are available at the landscape level, but it is clear that runoff and percolation data from small plots does not scale very well to predict or estimate the effect on the stream flowing from the watershed (7). This difficulty arises because surface runoff is intercepted by the vegetation in the next field, and contaminants in percolated water have a longer time to be altered or mitigated before they resurface as contributors.

The landform and soil type within a geographic location influence both the cropping systems and the potential for surface and subsurface delivery of pollutants from the watershed. Now the concept can be expanded to accommodate the crops that are adapted to the region, the distribution of locations within the watershed on which they are grown, and the management regulations needed to be in compliance. It has been established that nutrient delivery to a receiving watercourse is highly dependent on the proximity to the watercourse. Fields in close proximity are much more likely to contribute contaminants to the watercourse than those some distance away. Thus, a change in the geographic distribution of crops or manure distribution sites within a watershed will alter the water quality even though the total area occupied by each activity remains the same. Unique or special management systems may need to be developed for certain crops in sensitive areas.

The Role of Precision Farming

The scale for decision making about nutrient management involves the field, farm, and the watershed, each representing much different levels of management complexity in time and space. The land manager of a farming operation usually considers his decision on a field-by-field basis, a concept that is supported by technology that has led to precision agriculture or site-specific farming. Using electronic technology and satellites for global positioning, today’s agriculturalist can pinpoint soil fertility status, weed problems, and actual yields at specific locations in the field. The technology has brought a new dimension of understanding to soil-plant relationships and higher efficiency in crop production.

Early adopters of precision agriculture were seeking economic benefits through improved efficiencies of fertilizer and pesticide use, factors that have been brought to the fore, but major strides have also been made in understanding the principles regarding environmental quality. A major outcome is the recognition that soil tests for mineral nutrients need to be more precise and, especially, the role of soil hydrology is more important than previously envisioned. This importance is due to the dominant role of hydrology in water availability for plant growth and the need to minimize solute or sediment movement. Clearly new advancements in technology for precision farming and incorporation of soil hydrology data will help develop effective and efficient nutrient management programs and practices. Eventually, concepts such as geographic information systems on a watershed basis will allow even more integrated use of precision agriculture.

Whereas early attempts at precision agriculture are most often on crop fields, the potential is also great for hay fields, pastures, and range. Economic returns with forages are generally less because of the lower productivity of the soils and management systems. In addition, grazing animals have a marked influence on nutrient redistribution. It is well known that grazing animals tend to concentrate feces and urine near watering sites and shaded areas (24). In a few years, the fertility status of distant points can be reduced markedly as the nutrients consumed are transferred and deposited in areas of animal congregation. In addition, overgrazing near congregating sites reduces vegetation cover and increases soil compaction. This decrease in vegetation alters soil hydrology in the accumulated areas. The net effect is reduced infiltration during precipitation events and increased runoff that carries soluble nutrients and soil sediment, including P.

AGRONOMIC STRATEGIES WITHIN THE WATERSHED

Altering Water Movement

Agronomically, the goals are to optimize uptake of minerals by crop plants and to minimize the rate and amount of loss from the soil-plant system. The former is addressed by encouraging vigorous crop growth to assimilate available nutrients and by supplementing soil with fertilizer nutrients just preceding maximum demand. This is especially true for nutrients such as N (mainly NO_3^-) and, to a lesser extent, K and several micronutrients that also move in the soil water. For most situations, however, N is the major mobile element and of most concern. At the beginning of a rainfall event mobile elements dissolve and flow laterally if infiltration is not rapid enough. As the event continues and soil is dislodged and moved, the movement of immobile elements that, like P, are attached to clay particles become most significant.

Compared with conventional tillage, performing fewer or no tillage operations in cropping systems can alter infiltration and percolation. A major advantage of minimun tillage is the residue remaining on the soil surface that reduces impact of raindrops so less soil is dislodged, fewer pores are sealed over, and less water, sediment, and associated nutrients are carried laterally. This technology has been helpful in reducing P losses from a field. But with slow infiltration, runoff occurs and carries soluble nutrients and sediment from the soil surface. Grass buffer strips can be used to slow surface runoff to allow sediment to settle. For example, during a simulated rainfall on a plowed area a 2.5-m strip of Kentucky bluegrass sod reduced the clay content of runoff water to 18% that of a fallow area. The physical slowdown allows some suspended materials to precipitate while microbes associated with the vegetation can tie up or convert nutrients and other contaminants to less damaging forms.

TABLE 1. Concentrations (g/kg dry weight) of N, P, K, Mg, and S in several forage species. Adapted from Follett and Wilkinson (11).

	N	P	K	Mg	S
Legumes	27	18	2.6	0.25	0.25
Cool-season grasses	18	27	2.3	0.15	0.23
Warm-season grasses	17	23	1.7	0.22	0.26
Tropical grasses	13	21	1.7	0.32	0.22
Annual grass silages	15	26	1.8	0.26	0.16

Plant Factors

Plants can play a major role in the nutrient balance by their season of growth and ability to take up and sequester mineral elements. The use of double cropping systems and winter cover crops in rotation with annuals increases soil cover and nutrient use. There are characteristic differences among species and groups of species in mineral composition of grains or seeds. For example, soybeans are much higher in N, Ca, and P than is corn grain, whereas the content of other mineral nutrients is similar (3). Similar conclusions fit forage crops where the harvested biomass is sampled (11). Legume forages are generally higher in N, Ca, Mg, and S than are cool-season grasses, and are higher in K than tropical grasses and annual silages (Table 1). Most minerals are increased in concentration in crops grown on soils high in that nutrient (32). While ‘accumulator crops’ may be helpful in some situations, the major factor dictating the amount of nutrient uptake is yield, i.e., high yielding crops accumulate and sequester larger amounts of minerals than do low yielding crops.

These conditions have led to great interest in plants and cropping systems that provide phytoaccumulation, i.e., mining by plants for transfer of the nutrient to some other location, or support biodegradation and bioremediation processes that leave the nutrient there, but in a status of less hazard (30). The latter may not be the best solution in the long term, however, as the contaminant is still in the system and needs to be dealt with eventually. Plant breeders are also developing crops with lower phytate levels in the seed and with higher concentrations of P that is available to animals. These crops will likely not remove more or less P from the soil, but will reduce the amount of supplemental P required in the ration and reduce the amount of P in the manure that needs to be recycled.

RESEARCH AND EDUCATION NEEDS

The need for research is paramount, and new and expanded sources of funding will be needed. Most studies that have applications and can scale to watersheds will be large, integrated evaluations that are based on sound component science. Each watershed will be unique and will require careful evaluation of the component and systems data to obtain credible interpretations and sound decision-making. Nearly all the research will need to be long term, to sample annual variance and cumulative effects of climates and agricultural practices. Good examples are the large watershed projects that are part of the national initiative on water quality. These large projects have been funded for about 10 yr and have given valuable insight into the scope of studies required and how data from specific plot experiments can be scaled and applied to a watershed.

Adequate public funding is required for these efforts. Although the private sector will have a strong interest in the outcomes, industry will probably not be a major player in supporting research, except for special projects of proprietary interest. Without proper research, the scientific community will be forced to make ‘best estimates’ for solutions that will be subject to public scrutiny and a potential erosion of confidence in and respect for the agricultural sciences.

All of the above will require a massive education effort, probably led by extension personnel with linkages to federal and state agencies, and with some help from private industry. Landowners, land managers, businesses, public officials, and the general public will have to be made aware of the process, problems, and potential solutions for nutrient management so equitable and enforceable decisions are made. Very likely there will be a range of ‘certification programs’ developed, mainly by professional societies and other credible organizations, to certify individuals as educators, consultants, and officials to assist the agencies responsible for the regulations.

REFERENCES

1 Beegle, D., A. Sharpley, and D. Graetz. 1998. Interpreting soil test phosphorus for environmental purposes. Pages 31–40 *in* Soil Testing for Phosphorus, Environmental Uses and Implications. J. T. Sims ed. Bull. 389, Southern Coop. Series, Univ. Delaware, Newark.

2 Bouma, J., and M. R. Hoosbeck. 1996. The contribution and importance of soil scientists in interdisciplinary studies dealing with land. Pages 1–15 *in* The Role of Soil Science in Interdisciplinary Research. R. J. Wagenet and J. Bouma, ed. Soil Sci. Soc. Am. Spec. Pub. 45. Madison, WI.

3 Church, D. C., and W. G. Pond. 1982. Basic Animal Nutrition and Feeding. 2nd ed. John Wiley, New York.

4 Clark, E. A. 1998. Landscape variables affecting livestock impacts on water quality in the humid temperate zone. Can. J. Plant Sci. 78:181–190.

5 Cooke, G. W. 1958. The nation’s plant food larder. J. Sci. Food Agric. 9:761–772.

6 Cooke, G. W. 1967. The Control of Soil Fertility. Hafner Pub. Co., New York.

7 Correll, D. L. 1996. Environmental impact of pasture systems on surface water quality. Pages 231–243 *in* Nutrient Cycling in Forage Systems. R. E. Joost and C. A. Roberts, ed. Potash-Phosphate Inst., Manhattan, KS.

8 Correll, D. L., T. E. Jordan, and D. E. Weller. 1992. Nutrient flux in a landscape: Effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries 15:431–442.

9 Donald, C. M. 1965. Phosphorus in Australian agriculture. J. Aust. Inst. Agric. Sci. 30:75–105.

10 Fitch, L., and B. W. Adams. 1998. Can cows and fish co-exist? Can. J. Plant Sci. 78:191–198.

11 Follett, R. F., and S. R. Wilkinson. 1995. Nutrient management of forages. Pages 55–82 *in* Forages (Vol. 2) The Science of Grassland Agriculture. R. F. Barnes, D. A. Miller, and C. J. Nelson, ed. Iowa State Univ. Press, Ames, IA.

12 Johnson, G. V., and W. R. Raun. 1995. Nitrate leaching in continuous winter wheat: Use of a soil-plant buffering concept to account for fertilizer nitrogen. J. Prod. Agric. 8:486–491.

13 Johnston, J.F.W., and C. A. Cameron. 1877. Elements of Agricultural Chemistry and Geology. 10th ed., Blackwood, Edinburgh, United Kingdom.

14 Hutson, J. L. 1996. The soil scientists role in estimating the fate of introduced nutrients and biocides. Pages 75–85 *in* The Role of Soil Science in Interdisciplinary Research. R. J. Wagenet and J. Bouma, ed. Soil Sci. Soc. Am. Spec. Pub. 45. Madison, WI.

15 Kershen, D. L., and P. E. Dougherty. 1998. Law and policy for feedlots. A report on the ABA-special committee on agricultural land management roundtable on environmental issues in animal feedlots. NewsCAST Supp. 25(2):1–6. Coun. Agric. Sci. Tech., Ames, IA.

16 Kosco, J. 1998. USDA/EPA announce new joint strategy on animal feeding operations. Nonpoint Source News-notes. Issue 52 (July/August), Pages 4–5, US EPA, Washington, DC.

17 Kuipers, A., F. Mandersloot, and R.L.G. Zom. 1999. An approach to nutrient management on dairy farms. J. Dairy Sci. 82(Suppl. 2):84–89.

18 Lemunyon, J., and T. C. Daniel. 1998. Phosphorus management for water quality protection: A national effort. Pages 1–4 *in* Soil Testing for Phosphorus, Environmental Uses and Implications. J. T. Sims ed. Bull. 389, Southern Coop. Series, Univ. Delaware, Newark.

19 Lipman, J. G., and A. B. Conybeare. 1936. Preliminary note on the inventory and balance sheet of plant nutrients in the United States. Bull. 607, New Jersey Agric. Exp. Stn., New Brunswick.

20 Meagher, J. 1998. Commentary: Implementing the clean water act. Nonpoint Source News-notes, Issue 52 (July/August), Pages 1–2. US EPA, Washington, DC.

21 Moore, P. A., Jr., B. C. Joern, and T. L. Provin. 1998. Improvements needed in environmental soil testing for phosphorus. Pages 21–29 *in* Soil Testing for Phosphorus, Environmental Uses and Implications. J. T. Sims, ed. Bull. 389, Southern Coop. Series, Univ. Delaware, Newark.

22 Peterson, H. G. 1998. Use of constructed wetlands to process agricultural wastewater. Can. J. Plant Sci. 78:199–210.

23 Peterson, P. R., and J. R. Gerrish. 1995. Grazing management affects manure distribution by beef cattle. Pages 170–174 *in* Proc. Amer. Forage Grassld. Coun., Lexington, KY.

24 Peterson, P. R., and J. R. Gerrish. 1996. Grazing systems and spatial distribution of nutrients in pastures: Livestock management considerations. Pages 203–212 *in* Nutrient Cycling in Forage Systems. R. E. Joost and C. A. Roberts, ed. Potash Phosphate Inst., Manhattan, KS.

25 Pionke, H. B., R. R. Schnabel, and J. A. Shaffer. 1996. The role of the soil scientist in watershed research. Pages 67–73 *in* The Role of Soil Science in Interdisciplinary Research. R. J. Wagenet and J. Bouma, ed. Soil Sci. Soc. Amer. Spec. Pub. 45. Madison, WI.

26 Sanchez, P. A., and J. G. Salinas. 1981. Low-input technology for managing oxisols and ultisols in tropical America. Adv. Agron. 34:279–406.

27 Sims, J. T. 1996. The phosphorus index. A phosphorus management strategy for Delaware's agricultural soils. Fact Sheet ST-05, Univ. Delaware, Newark.

28 Sims, J. T., S. Hodges, and J. Davis. 1998. Soil testing for phosphorus: Current status and uses in nutrient management programs. Pages 13–20 *in* Soil Testing for Phosphorus, Environmental Uses and Implications. J. T. Sims ed. Bull. 389, Southern Coop. Series, Univ. Delaware, Newark.

29 Stewart, J.W.B., D. A. Woolhiser, W. H. Wischmeier, J. H. Caro, and M. H. Frere. 1976. Control of Water Pollution from Cropland. Rep. EPA-600/2-75-0266, U. S. Gov. Print. Off., Washington, DC.

30 Stroo, H. F. 1996. Biodegradation and bioremediation of contaminated sites: The role of soil science. Pages 37–55 *in* The Role of Soil Science in Interdisciplinary Research. R. J. Wagenet and J. Bouma, ed. Soil Sci. Soc. Amer. Spec. Pub. 45. Madison, WI.

31 Tisdale, S. L., and W. L. Nelson. 1975. Soil Fertility and Fertilizers. 3rd ed. Macmillan, New York.

32 Troeh, F. R., and L. M. Thompson. 1993. Soils and Soil Fertility. Fifth ed. Oxford Univ. Press, New York.

33 USDA. 1981. Land resource regions and major land resource areas of the United States. Agric. Handbook 296, USDA Soil Conservation Service, Washington, DC.

34 US EPA. 1997. The index of watershed indicators. EPA-841-R97-010. USEPA Office of Water, Washington, DC.

35 US EPA. 1998. Clean water action plan: Restoring and protecting America's waters. EPA-840-R-98-001. Nat. Ctr. Environ. Pub. Inf., Cincinnati, OH.