Chapter 4

Technologies To Improve Nutrient and Pest Management

CHAPTER HIGHLIGHTS

- U.S. agriculture has become highly specialized and is unevenly distributed across the country. Potential for agrichemical contamination of groundwater probably is strongly associated with certain farming systems, and with intensity of use in those systems.
- A variety of technological opportunities exist for reducing agrichemical contamination of groundwater within the general categories of: 1) improved point source controls, 2) improved agrichemical efficacy and application, 3) agrichemical use reduction, and 4) nonchemical alternatives. Farming systems designed to reduce the potential for agrichemical contamination of groundwater are likely to use a combination of technologies within these categories.
- Nutrients must be added to any cropping system intended to remain productive; however, the source and amount of nitrogen (the plant nutrient of concern to groundwater contamination) added may vary widely. Because nitrogen is part of a natural cycle, reducing loss of nitrogen as nitrate from soil systems through careful management is the primary means of reducing nitrate contamination of groundwater.
- Control of agricultural pests may be accomplished through chemical or nonchemical (biological and cultural) means, with varying and largely uncertain effects on productivity of farming systems. However, these technologies generally are not mutually exclusive such that, while chemical controls will likely continue to be an important element of pest control systems, managing whole farming systems to reduce potential for infestations and implementing of least potentially hazardous techniques can aid in pest control without unacceptable loss of yield or income.
- Although technologies related to use and management of nutrients and pesticides clearly are relevant to reducing the potential for agrichemical contamination of groundwater, these elements of a farming system cannot be separated from consideration of crop, soil, and water management components of farming. All interact, and thus in combination have potential to reduce potential agrichemical contamination of groundwater.
- Ultimately, the quality of and attention to management of a farming system is the most important factor in enhancing the efficacy of external inputs, and reducing waste in agricultural production. “Integrated farm management” decisionmaking will form the basis of successful systems.

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Technologies To Improve Nutrient and Pest Management

INTRODUCTION

The agricultural sector has provided food, clothing, and shelter for the increasing U.S. population as well as contributed to global food security. This increased productivity has resulted from significant scientific research and application of improved technology ranging from the development and use of agrichemicals to current trends in biotechnology research and development. Advances in plant breeding using germplasm from native and exotic species have contributed to yield enhancement and stress tolerance of major crop plants, Similarly, research on pest-control methods and irrigation developments have made significant contributions. However, increasing concern exists that the costs of these advances may be greater than expected, particularly with respect to potential adverse effects on the environment and thus on future productivity of the land (8).

Many agricultural production approaches seem to have been developed without consideration of the fundamental linkages among components of the agroecosystem (73), often neglecting potential interactions or transformations within the agroecosystem. It is difficult, if not impossible, to account for all of the natural site characteristics and agricultural practices (agrichemical application rates and methods, tillage and surface shaping, cropping arrangements) that interact to determine groundwater vulnerability at a given site. However, certain patterns have emerged in groundwater contamination, which suggest that packages of agricultural and site-specific parameters strongly influence groundwater vulnerability. For example, atrazine, a nonvolatile and widely used herbicide, has been shown to leach at variable rates depending on the soil, geology, and agricultural practices of different regions. Leaching was less prevalent in silty clay and clay loam (nonirrigated) soils in Pennsylvania than in irrigated permeable soils in Nebraska (87).

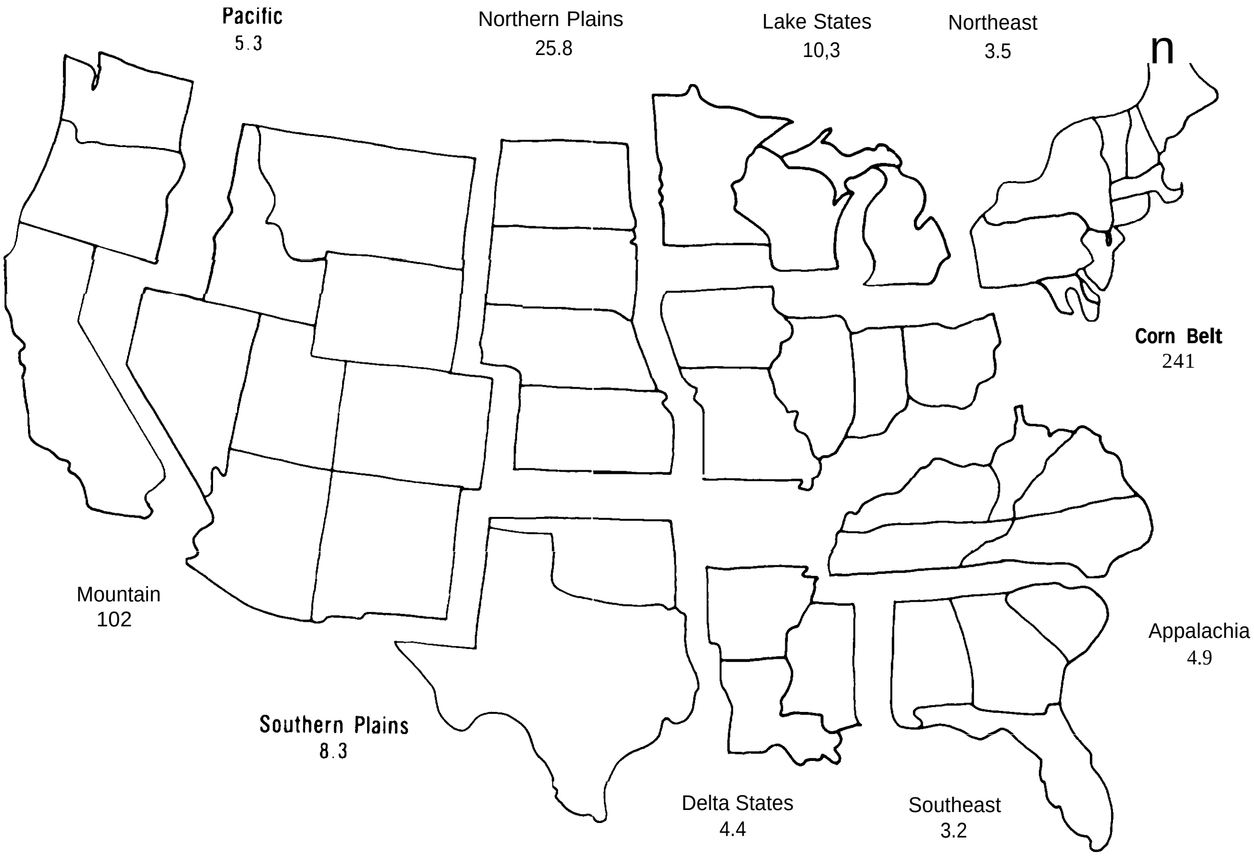
Ultimately, the quality of management maybe the factor of greatest importance in reducing the potential for agrichemical contamination of groundwater from agricultural production practices. Irrespective of the nutrient source, overapplication may occur in the absence of proper soil-testing and application methods. Similarly, inappropriate timing of application or unsuitable application methods may easily offset any environmental benefits that might be realized from reducing pesticide applications.

Agricultural production often depends on manipulation of numerous agroecosystem components and application of a broad variety of technologies. An agroecosystem refers to the blend of biological and physiochemical features (e.g., soil, water, nutrients) as they are modified by agronomic practices (e.g., tillage and cropping systems, and agrichemical inputs). The interactions of these local features give rise to highly diverse site conditions such that no two agroecosystems are identical. Similarly, farming systems are diverse in terms of crops, cropping patterns, and management systems (figure 4-1; box 4-A). Given the variability of agroecosystems and farming systems, effective approaches to reduce groundwater contamination from agricultural practices will need to be flexible and equally diverse. For example, cover crops may offer a mechanism for uptake of residual soil nitrate in humid regions; however, in dry regions where nitrate leaching potential is less, this practice may only create a soil moisture deficit for subsequent crops.

In addition to nutrient and pest management practices, potential for agrichemical contamination of groundwater may also be influenced by crop, water, and soil management practices. Cropping pattern and cultivar choice may directly affect the need for agrichemical use. For example, legume-based crop rotation systems may provide nitrogen for subsequent or interplanted crops as well as interrupting development of pest populations. Irrigation scheduling designed to reduce deep percolation may concurrently reduce chemical movement. Tillage systems (e.g., no-till v. conventional) may have a profound effect on agrichemical needs, and on the rate, timing, and method of agrichemical application.

The suite of farm management decisions are not made in isolation, rather they interrelate to such an extent that whole farm management becomes an integrated approach to managing the agroecosystem. Opportunities to reduce the potential for agrichemi-

Figure 4-l—Percentages of Cropland Used for Crops by Region, 1989



SOURCE: Adapted from U.S. Department of Agriculture, Economic Research Service, "Cropland," *Agricultural Resources: Cropland, Water, and Conservation Situation and Outlook Report,* AR-16, September 1989.

cal contamin ation of groundwater arising from agronomic practices center largely on:

- improved point-source controls (e.g., mixing, loading, storage, and disposal practices);
- improved agrichemical efficacy and application (e.g., selective chemicals, enhanced efficiency in application equipment);
- agrichemical use reduction; and
- use of nonchemical practices (e.g., biological pest control, crop rotation, cultivation).

Improved point-source controls focus on management practices and physical facilities for agrichemical storage, mixing, loading, and residue disposal, and on livestock-waste management. Agrichemical spills and leaks at commercial facilities have been responsible for numerous detections of chemicals in groundwater (74). Certain on-farm agrichemical handling practices present similar, if smaller scale, threats to groundwater. Frequent handling of large **volumes** of chemicals at mixing and loading sites increases the risk of groundwater contamination at these points. Point-source contamination also may involve direct conduits of agrichemical entry into groundwater, such as abandoned wells, sinkholes in karst areas, or back-siphoning during mixing.

Improved agrichemical efficacy and application may involve using more selective chemicals, improving rate and timing of agrichemical applications, and using improved application methods or equipment. Agrichemical efficacy has increased over the last several decades, allowing significant reduction in the amount of active ingredient applied per acre. However, little advantage is gained in using more effective products if they do not arrive at the target. Recent trends toward lower application rates of pesticides and plant nutrients require more application precision than was necessary even a decade ago (73,60).

Box 4-A—Regional Diversity of U.S. Agriculture and Agrichemical Use

Approximately **50** percent of all cropland under cultivation in **1989** ***was*** located in the Corn Belt and Northern Plains States. These States encompass a large land area devoted to crop production and include Iowa and Illinois, the two States ranked highest in volumes of fertilizer and pesticides used (62). The Corn Belt also is the only area to expand its regional share of the nation's cropland during the 1980s (227), probably due to uneven distribution of land idled under Federal conservation programs.

Certain characteristics of agricultural production regions have implications for the degree of agrichemical use. Areas with longer growing seasons, and areas that do not experience significant cold winter seasons or other conditions conducive to pest eradication are more likely to maintain pest populations, For example, crop production in the warm, humid Southeast tends to require relatively larger amounts of pesticides than crop production in the Northern United States (62).

The relative amounts and locations of land devoted to different types of crops also influence overall agrichemical use. Corn, for example, requires comparatively larger amounts of agrichemical inputs per acre than other field crops; thus corn acreage accounts for the greatest percentage of fertilizer and pesticide use (228,62). Most U.S. cropland acreage is used for production of wheat, corn, soybeans, cotton, rice, and feed grains such as sorghum, barley, and oats. In 1989, these crops were grown on 75 percent of the 342 million acres of U.S. cropland under cultivation (227,228). (See tables 4-1 and 4-2.)

Each year, USDA estimates the proportion of acreage treated with commercial fertilizers for corn, cotton, soybeans, wheat, rice, and potatoes. Average nutrient application rates also are estimated. Overall, an estimated 20,5 million tons of plant nutrients were applied in the 1988-89 crop year (228). U.S. agricultural producers use an estimated 661 million pounds of pesticide active ingredient annually (62).

Table 4-1—U.S. Fertilizer Application Rates (pounds per acre)

Year	Corn			Wheat			Soybeans			Cotton		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
1965	75	50	48	31	30	35	10	32	39	81	55	57
1970	112	71	72	39	30	36	14	37	51	75	55	57
1975	105	58	67	46	35	35	15	40	53	78	50	55
1980	130	66	86	58	39	40	17	46	70	72	46	46
1985	140	60	84	60	35	36	15	43	72	80	46	52
1988	137	63	85	64	37	52	22	48	79	78	42	39

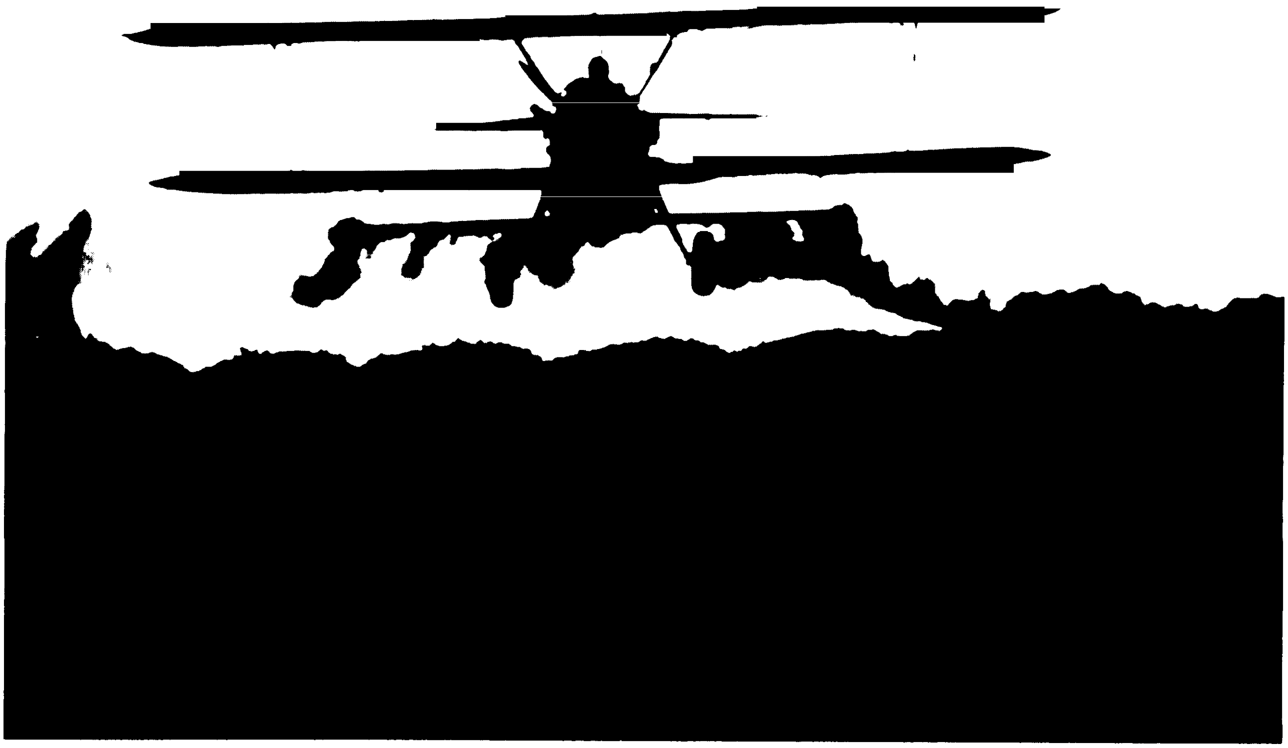
SOURCE: U.S. Department of Agriculture, Economic Research Service, ***Agricultural Resources: Inputs, Situation and Outlook***, AR-15 (Washington, DC: U.S. Government Printing Office, August 1989),

Table 4-2—Projected Pesticide Use on Major U.S. Field Crops, 1989

Crops	June 1 Acres	Herbicides	Insecticides	Fungicides
	Million	Million pounds		
Row:				
Corn	72.8	219	27.1	0.06
Cotton	10.5	16	15.6	0.16
Grain/sorghum	11.9	11	1.9	0.0
Peanuts	1.7	6	1.3	6.19
Soybeans	61.3	108	9.5	0.06
Tobacco	0.7	1	2.7	0.35
Subtotal	158.9	361	58.1	6.82
Small grains:				
Barley & oats	21.4	5	0.2	0.0
Rice	2.8	12	0.5	0.07
Wheat	76.7	16	2.2	0.88
Subtotal	100.9	33	2.9	0.95
Total	259.8	394	61.0	7.77
1988 total	243.4	372	59.7	7.56

NOTE: June 1 planted acreage for the 10 major field crops increased from 243 million acres in 1988 to 260 million. The area planted to corn, grain sorghum, soybeans, tobacco, and wheat went up whilecotton, barley, oats, and rice declined. Peanuts remained constant,

SOURCE: U.S. Departmentof Agriculture, Economic ResearchService, ***Agricultural Resources: Inputs, Situation and Outlook***, AR-15 (Washington, DC: U.S. Government Printing Office, August 1989).



credit: vironmental tec ency—Charles 'Rea

Only 1 to *2* percent of pesticides used in agriculture are estimated to reach the target pest; the remainder of the volume applied is lost to the environment, and represents a financial loss to the farmer. These losses can be reduced by improving the efficacy of chemicals and of application equipment and methods.

Appropriate timing and placement of agrichemical applications may facilitate their uptake and use by plants or affect their effectiveness against pests and, thus, reduce potential for loss via leaching, volatilization, or other environmental pathways. Similarly, improvements in application methods may allow achievement of a desired yield response with fewer agrichemical inputs. For example, rather than applying an insecticide to an entire field or farm, pheromone baits may be used to lure insects into a few insecticide-treated areas.

Agrichemical use reduction may involve using a variety of techniques, including more efficacious agrichemicals and application methods, cropping patterns that break pest cycles, crop cultivars with greater resistance to pest infestations, and improved management of agrichemical inputs. In addition to these approaches, establishing and understanding of pest tolerance levels (i.e., pest-free fields may not be economically optimal) may contribute to reduced agrichemical use. Adaptive research to establish agrichemical application rates and procedures for site-specific use might identify reduced agrichemical doses under certain conditions while maintaining economic yields.

Nonchemical practices to control pests and supply plant nutrients may be used exclusively (e.g., organic farming[1]), in preference to agrichemical use

[1]Organic farming was defined by USDA as a production system that avoids or largely excludes the use of synthetic fertilizers, pesticides, and other farm chemicals. Organic systems tend to rely on such inputs as crop residues, green- and livestock manures, legumes, crop rotations, mechanical cultivation and biological pest control to supply plant nutrients and control pest populations (218).

(e.g., low chemical input farming), or in combination with agrichemical use (e.g., integrated pest management). Farming practices that do not rely on agrichemical inputs can be productive; however comparative economic analysis is lacking (136). These production systems commonly depend on crop rotations, biological pest control, nutrients from livestock waste or green manures, and greater management attention.

Management practices within each of these categories can be implemented as individual Best Management Practices, or as components of integrated farming systems. Development of comprehensive agrichemical management systems or whole farming systems" could provide the basis for addressing pest and nutrient management in a coordinated fashion that minimizes adverse environmental impacts. Systems approaches designed to operate in concert with existing natural processes are likely to result in decreased agrichemical needs.

Current on-farm management activities that are linked to agrichemical use and thus affect the potential for agrichemical contamination of groundwater fall into four general categories: nutrient management, pest management, crop management, and soil and water management. Opportunities to reduce agrichemical losses to groundwater exist within each of these categories, and while singly their contributions to resource protection may be small, collectively they may offer significant benefits.

Agricultural researchers have provided U.S. farmers with a wide array of technologies that, when implemented properly, can help minimize groundwater contamination by agrichemicals. Some of these technologies are in operation on farms today; some familiar ones from the past are being readopted. Others need modernization or are undergoing research and testing, and still others remain conceptual. What their combined impacts may be is not yet known. What is known today, though, is that "old' and ''new" technologies are less likely to be viewed separately in the environmental setting of the farm than in the past. The view today increasingly is one that recognizes farming activities as part of the overall environment: the agroecosystem.

This view recognizes the importance of working within the framework of the hydrologic and other natural cycles if groundwater contamination from agrichemicals is to be prevented. This systems approach is evidenced by current efforts such as *Integrated* Pest Management, *Integrated* Farm Management Systems, *Integrated* Crop Management, and the Farmstead Assessment program. It is within these systematic approaches that new technologies will find their role. It is unlikely that one particular technological "black box" will be found to solve the agrichemical/groundwater contamination problem.

"Good housekeeping, " involving careful storage, handling, and use of agrichemicals, can play an important role today, and already is doing so on many farms. Farmers are conscious of the large role economics plays in their survival and, therefore, minimizing waste of important agrichemicals makes good sense. Additional opportunities exist to find new uses for old ''wastes,' like manure and sludge, which can turn these from wastes to resources.

Central to the successful application of technologies is the understanding that the physical situation changes from one farm site to another, e.g., soils, geology, and topography. Because of this, technologies, packages of technologies, or systems involving technologies have to be adapted to the local conditions at the farm site. Finally, whatever approach is used ultimately rests with the farmer.

NUTRIENT MANAGEMENT

Addition of nutrients to a cropping system is an accepted axiom of agricultural production. Agricultural products, whether plant or animal, remove nutrients from the land on which they are produced. For example, corn production in the United States is estimated to remove nearly 5.7 billion pounds of nitrogen annually. Hawaii exports 2,200 tons of potassium each year in its pineapple crop alone (212), Even well-maintained organic farms that carefully collect and return crop residues and livestock wastes to the soil do not replace all of the soil nutrients without external inputs or through rapid weathering of soil minerals.

Nutrients also are removed through a number of other natural processes, including erosion, leaching, and volatilization. If the nutrient supply is not replenished, soil fertility decreases. Management practices attempt to avoid limiting crop growth by ensuring that sufficient nutrients exist in the soil, or are applied, and that excessive nutrient losses to other media do not result.

Box 4-B—Phosphorus and Potassium: Potential for Movement to Groundwater

Unlike nitrogen, which has a relatively short residual activity in soils, phosphorus tends to accumulate in soils in relatively insoluble inorganic forms. Thus, phosphorus fertilization leads to increased soil phosphorus levels over time. In many intensively managed soils, particularly where high-value crops such as vegetables are grown, phosphorus levels have become quite high.

Phosphorus buildup is of practical significance. Only a very small amount of fertilizer phosphorus is lost from soils if erosion is controlled. Even these small amounts, however, can be significant and can accelerate surface water eutrophication. This avenue of loss can be minimized through proper erosion control.

Although some phosphorus may be lost by movement into groundwater through leaching, the amounts generally are insignificant from both agronomic and waterquality standpoints. However, significant phosphorus may enter groundwater where the water table is high or approaches the plow layer. Similarly, flooding may provide anaerobic conditions in soils, and in such cases phosphorus concentrations can be fairly large in effluent from tile drains and can be a groundwater pollutant.

Like phosphorus, potassium from fertilizers can accumulate in soils over time. Soils in humid areas of the United States are inherently low in potassium, so yields can be enhanced by potassium application. Many soils in the more arid regions contain adequate potassium levels (72). Thus, as with any input, care is needed to ensure that potassium is applied only on soils with low natural potassium levels. Potassium fertilizer does not appear to be a source of pollution for surface or groundwater.

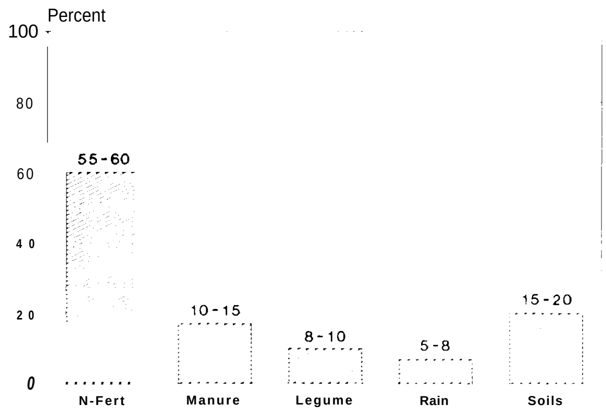
Plants require carbon, oxygen, hydrogen, nitrogen, phosphorous, potassium, calcium, magnesium, chlorine, ‘and sulfur in relatively large quantities (and another six elements—iron, manganese, boron, zinc, copper, and molybdenum-in small amounts). The frost three elements are freely available in the atmosphere and the latter four are common in temperate soils; thus, nitrogen, potassium, and phosphorus are the most commonly added nutrients. Although plants may take up ammonium (NH_4, the predominant nitrogen uptake form is nitrate (NO_3), which is relatively mobile in the soil environment. Because of this mobility, nitrogen (N) availability is most often the limiting nutrient factor for plant growth and the most common agrichemical contaminant found in groundwater. The chemical properties of phosphorus (P) and potassium (K) generally restrict their movement through the soil profile (box 4-B), although phosphorous loading of surficial waters can be a significant problem in certain areas (110).

Whether soil nutrient replacement is accomplished by addition of organic (e.g., manures) or commercial fertilizers is an individual’s choice, but agriculture has to replace what it has taken from the soil in order to maintain long-term crop production. Early agriculture depended on soil- and atmosphere-derived nutrients and plant and animal residues to maintain soil fertility. Legume-based systems were introduced to increase available nitrogen in cropping systems. Natural weathering produces new soil and releases additional nutrients, but the process is slow and does not keep pace with modern agricultural needs. Today, genetically improved, high-yielding crop varieties require much higher nutrient levels than are naturally available in the soil, and most U.S. croplands are managed to sustain high yields, normally requiring frequent nutrient inputs (208).

Nutrient sources have gradually become more sophisticated, shifting from livestock manures to concentrated single-element particulate formulations and to complete fertilizer combinations. Commercial fertilizers are the main source of resupply of the soil nutrients needed for continued agricultural production (figure 4-2). A broad variety of commercial fertilizer formulations exist, including granules, liquids, and gaseous forms, each requiring a specific application technology. Most forms either are applied on the soil surface or are subsurface injected, although some liquid nutrient formulations have been developed for foliar application and *chemigation* systems. The cost of fertilizing is increasing because production is highly energy-intensive, especially for nitrogen fertilizers (figure 4-3).

Limestone, gypsum, dolomite, greensand (glauconite), rock phosphate, and granite are common rocks that, when ground to a fine particle size, also can be added to cropland soils to provide calcium, magnesium, potassium, and phosphorus. These freely ground, less soluble natural materials were the basic inorganic soil nutrient inputs prior to industrial

Figure 4-2--Sources of Nitrogen in the Environment



Nitrogen for crop production may be derived from a variety of sources, however, commercial fertilizers comprise the main source of resupply of the soil nutrients.

SOURCE: Environmental Protection Commission, Iowa Department of Natural Resources, *Iowa Groundwater Protection* Strategy, 1987.

synthesis of commercial fertilizers and usually are not included in the category "commercial fertilizers.

Nitrogen Cycle

Nitrogen in the soil and available for plant growth is derived from atmospheric dinitrogen (N_2). This chemically unreactive nitrogen is circulated from the atmosphere through the soil and living organisms through various processes that comprise the nitrogen cycle (figure 4-4).

Nitrogen additions to the soil maybe the result of several processes, biological or industrial dinitrogen fixation, lightning fixation, and ammonification. *Biological dinitrogen fixation,* conversion of atmospheric nitrogen to ammonia (NH_3), is carried out by microorganisms, either free-living or in symbiotic associations with other organisms. *Industrial nitrogen fixation,* which produces ammonia through a natural gas and petroleum-based process, is currently the major source of nitrogen fertilizers. A small amount of nitrogen may be freed into the soil through the process of *lightning fixation. Ammonification is the* decomposition of soil organic matter (i.e., dead animals, plants, microbes, and manures) by soil microbes to ammonium ions (NH_4).

Soil transformations of ammonium yield nitrite[2] and nitrate. Oxidation of ammonium to nitrite and **nitrate** is carried out by several bacterial species in the process of *nitrification.* Although nitrate is the primary nitrogen form taken up by plants, under acidic soil conditions with low populations of vitrifying bacteria, plants may take up nitrogen in the ammonium form.

Nitrogen is returned to the atmosphere from the soil through the activities of denitrifying bacteria. *Denitrification* is the anaerobic conversion of soil nitrate to the volatile forms of nitrogen. Plants may release small amounts of these nitrogenous forms to the atmosphere as well, particularly under high fertilizer application regimes (18 1).

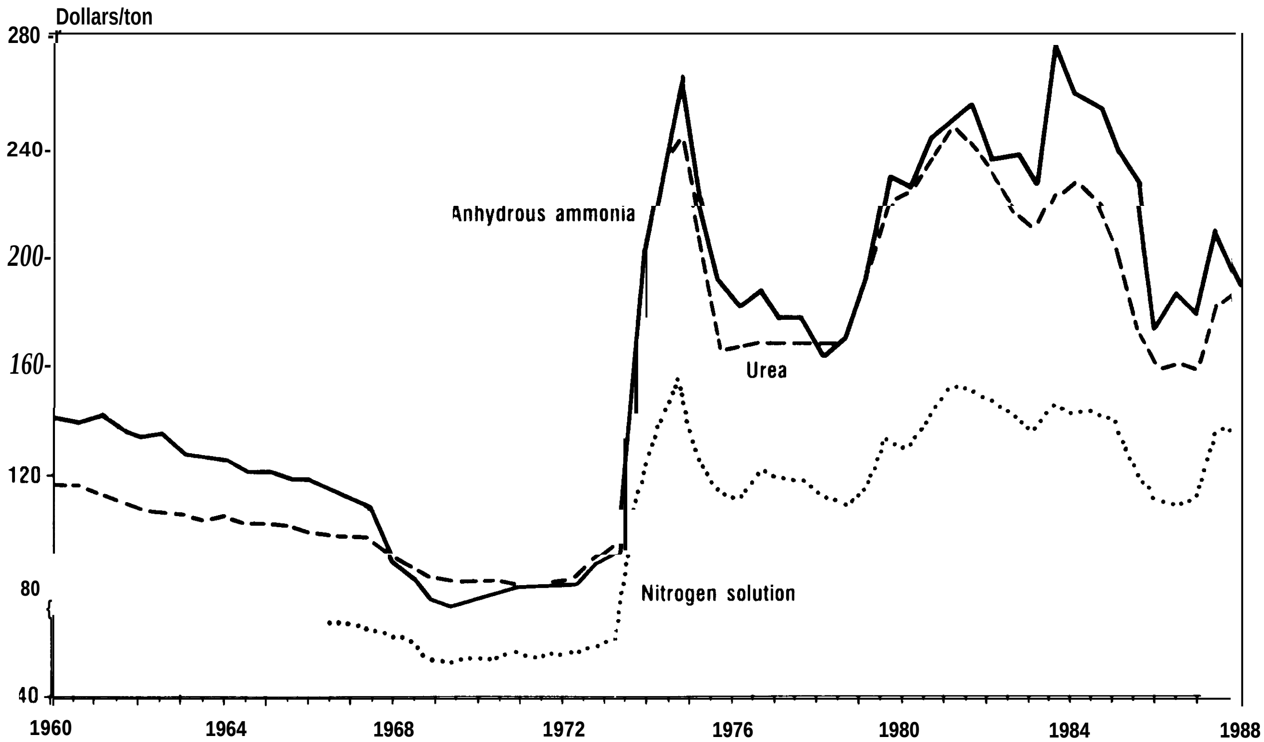
The nitrogen cycle processes of greatest importance to agriculture are those that yield inorganic forms of nitrogen. The processes by which organic nitrogen is converted to inorganic forms is referred to as *mineralization* (ammonification and nitrification). *Immobilization is the* sequestering of applied or extant plant-available nitrogen in organic matter. Uncertainties regarding rates of immobilization and mineralization complicate estimation of the amount of nitrogen that will become available to plants during a cropping season.

Three categories of processes control nitrogen availability to a growing crop: 1) direct physical or chemical effects (e.g., nitrate leaching and ammonia volatilization); 2) direct biological effects (e.g., dinitrogen fixation, mineralization); and 3) indirect biological effects (e.g., immobilization) (42). These processes are highly dependent on specific agroecosystem traits such as microbial populations, soil organic matter content, and soil moisture, and on the agronomic practices that affect these traits. The first category is of primary concern relative to the potential for nitrate contamination of groundwater, while the latter two categories are indirectly linked to nitrate leaching potential since they mediate soil nitrate levels.

Leaching is a natural pathway within the nitrogen cycle and nitrate is a naturally occurring form of nitrogen in water bodies. Nitrate, mineralized from soil organic matter and dissolved in water, leaches from the root zone of even unfertilized lands. Nitrate concentrations in groundwater vary with amount and timing of rainfall; soil composition, permeability, and porosity; time of year; vegetation management; and other site-specific factors. Measurements of

[2]The nitrite form of nitrogen is highly toxic to plants and is rapidly converted by bacterial action to the nitrate form.

Figure 4-3-Average Farm Prices of Selected Nitrogen Fertilizers



SOURCE: H. Vroomen, U.S. Department of Agriculture, Economic Research Service, ***Fertilizer Use and PriceStatistics, 1960-1988,*** Statistical Bulletin No. ***780*** (Washington, DC: U.S. Government Printing Office, 1989).

nitrate concentration in water may provide little understanding of the nitrate loss from a specific field (86).

The concentration of nitrate in groundwater is controlled by either the rate of nitrate addition to a constant flow of water or the rate of water flow through a region where nitrate is steadily becoming available. The nitrate concentration in the soil water of unfertilized grasslands and fields commonly is negligible, but may reach 3 ppm. It varies with the rate of nitrate mineralization from soil organic matter and with the rate of water percolation through the soil.

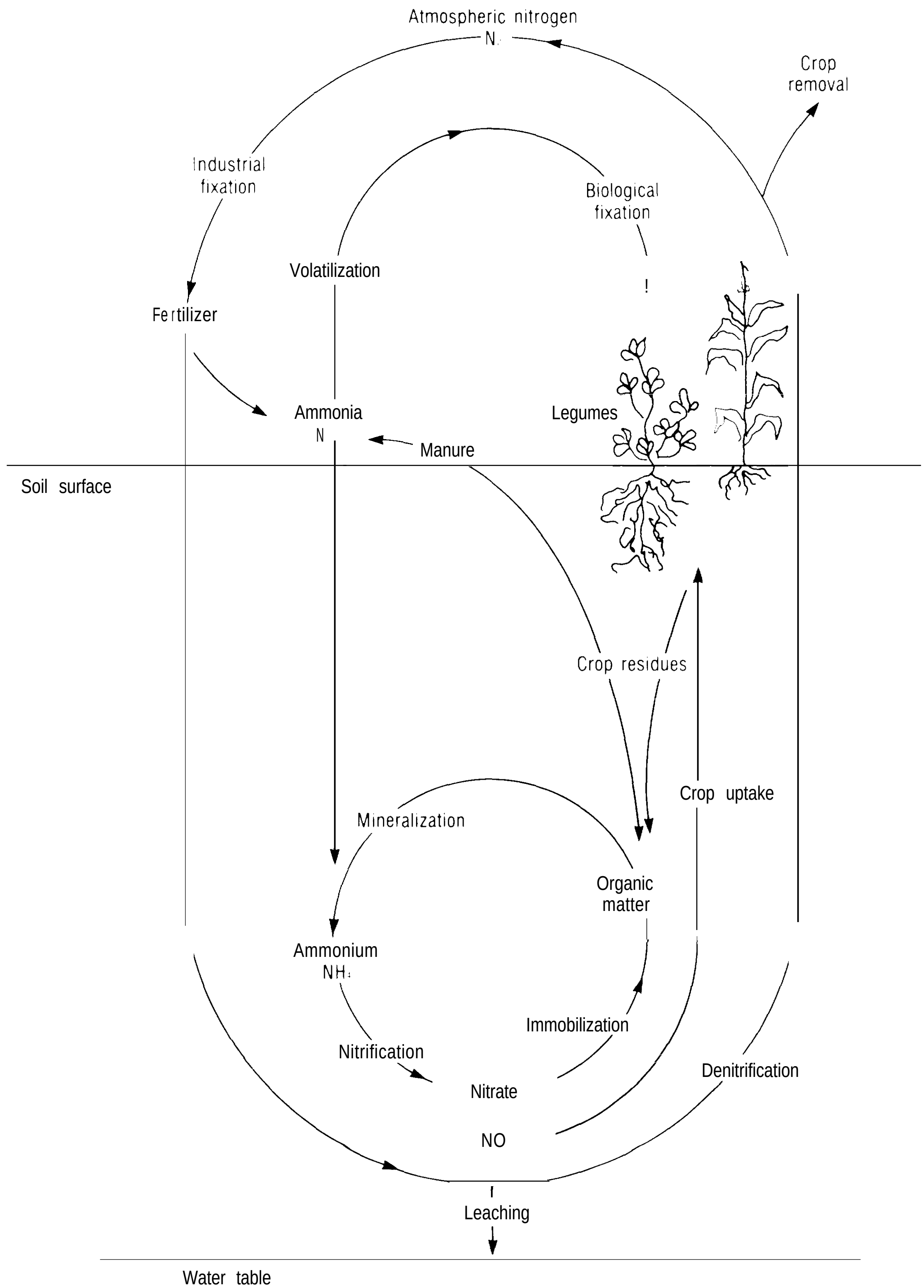
Thus, nitrate losses from cropland maybe visualized as integrated fluxes, i.e., rate of nitrate movement from the root zone per land area per unit of time. Viewed in this manner, in temperate lands, unfertilized native grasslands and agricultural fields lose about 20 lbs N/acre/year on average (range 5 to 40) as nitrate (86). How closely nitrate fluxes through cropland approach this value depends on a number of factors. Fertilized cropping systems lose on average from 22 lbs N/acre/year (rainfed systems) to **50** lbs N/acre/year (irrigated systems). These rates of loss are in part intrinsic to the nitrogen cycle and cannot foreseeable be eliminated. Given the natural flux, as well as the propensity for nitrate to arrive in groundwater from numerous sources, it seems likely that farmers will have difficulty meeting **a** strict groundwaterquality standard of 10 mg/1 in all areas (120).

Nitrogen Sources and Formulations

A variety of amendments are applied to Us. cropland annually to provide nutrients for crop production, including commercial fertilizers, manures, and sewage sludge, slurry, and wastewater. Commercial fertilizers comprise the greatest part of these additions with an estimated 20.5 million tons applied in the crop year 1988-89 (228).

Commercial fertilizers generally are synthesized or manufactured through various industrial processes and contain one or more of the essential plant nutrients (54). These include important soluble compounds of nitrogen, phosphorus, and potassium. Because commercial fertilizers are highly soluble

Figure 4-4—Nitrogen Cycle



SOURCE: Pennsylvania State University, College of Agriculture, "**Groundwater** and Agriculture In Pennsylvania," Circular 341 (College Station, PA: Pennsylvania State University, 1998).

Box 4-C—Summary of Best Management Practices for Controlling Potential Contamination of Surface and Groundwater From Fertilizers

- *soil* testing to determine soil nutrient content and appropriate fertilization and liming regimes;
- spring fertilizer applications in regions with wet soils, humid climates, and high infiltration;
- split applications may reduce potential losses by up to 30 percent compared to single applications;
- level terraces as a mechanism to reduce nitrate losses in runoff in areas with low vulnerability to nitrate leaching, contour farming is recommended in humid regions with high vulnerability to contamination;
- drainage control to reduce nitrate losses in wet and irrigated areas; to include wise irrigation management to prevent leaching losses;
- slow release nitrogen fertilizers;
- crop rotations, no-till, and conservation tillage to reduce surface losses of nitrogen;
- soil incorporation of broadcast fertilize
- level terraces as a phosphorus control measure;
- rotation grazing, crop rotation, cover crops, and conservation tillage to reduce phosphorus losses as compared to continuous grazing or conventional tillage; and
- sedimentation basins and flow control in irrigation systems to reduce phosphorus losses.

SOURCE: North Carolina State University, Agricultural Extension Service, Biological and Agricultural Engineering Department, *Best Management Practices for Agricultural Nonpoint Source Control, II: Commercial Fertilizer* (Raleigh, NC: North Carolina State University, n.d.).

and concentrated, concern exists that they may have certain long-term adverse impacts on soils, soil biota, water supplies, and other parts of the natural resource base (box 4-C).

Commercial Nitrogen Fertilizer

A variety of nitrogen-containing fertilizer compounds exist; however, only a few are used widely—the “conventional nitrogen fertilizers.” These include anhydrous ammonia, urea, ammonium nitrate, urea-ammonium nitrate solution, ammonium sulfate, monoammonium phosphate, and diammonium phosphate (152). Anhydrous ammonia, nitrogen solutions, and urea account for 40, 20, and 15 percent of U.S. fertilizer use, respectively (77). Formulations vary from gaseous (anhydrous ammonia) to granule to liquid, with each formulation requiring a specific application technology.

The rate of application of nitrogen to croplands can influence the amount of nitrate leaving fields via subsurface waters or drain tiles. As progressive increments of nitrogen become less efficient in increasing crop growth, the amount available for runoff or leaching increases.

Most nitrogen removed by surface runoff is organic nitrogen associated with sediment. Even though it is possible to lose significant amounts of fertilizer nitrogen in surface runoff, this accounts for only a small proportion of nitrogen lost from soils or applied fertilizer nitrogen (127).

The amounts of fertilizer nitrogen either lost to, or found in transit to, groundwater are quite variable. The partitioning[3] of nitrogen in the environment is highly dependent on climatic and soil factors as well as amendment type and application method. For example, under anaerobic soil conditions (e.g, waterlogged soils) denitrification is favored and gaseous losses of nitrogen to the atmosphere are likely to occur. The problem of nitrate leaching to groundwater is greater in humid or irrigated areas as compared to dryland cultivation systems. Nitrogen fertilizer use on irrigated sandy soils shows a high correlation with nitrate-contaminated aquifers (192, 170).

***Slow-Release* Fertilizers**-Slow-release fertilizers provide nitrogen to crops in a time-release fashion in contrast to the more rapid release action of conventional fertilizers. They operate in one of four general ways: 1) employing a physical barrier to control the escape of water-soluble materials containing ammonia or nitrate into soil; 2) possessing reduced water-solubility properties and containing plant-usable nitrogen (e.g., metal ammonium phosphates); 3) possessing low water-volubility and releasing plant-available nitrogen during chemical

[3] Partitioning refers t. the apportionment of nitrogen within the nitrogen cycle. Of greatest agronomic interest is what part of the applied nitrogen remains within the soil in a form usable by plants or in organic forms that may be released as nitrate through mineralization.

or biological decomposition (e.g., ureaforms and oxamides); and 4) having high water-volubility but a chemical structure that allows materials to decompose gradually and release plant available nitrogen (e.g., guanylurea salts). The nitrogen release rates and nitrogen transformations in the soil may be further modified by the addition of a nitrification or urease inhibitor.

Coatings, encapsulations, and matrixes are used as physical barriers to slow nitrogen release. Coatings may be impermeable or semipermeable. Impermeable coatings either may have tiny holes to allow release or may depend on abrasion or chemical or biological action to release nitrogen. Semipermeable coatings depend on an influx of water to rupture or distend the coating sufficiently to release the nitrogen. Most commercially important coatings are waxes, polymers, and sulfur. Most uncoated varieties have low volubility and only decompose to release plant-available nitrogen after going into solution. This dissolution rate is affected by size of particle, particle hardness, and degree of water volubility.

Slow-release materials may generate a more desirable apportionment of nitrogen among plant parts than faster acting nitrogen sources (82). Yield response seems to be comparable between the two nitrogen sources, although less nitrogen is accumulated by the plant when slow-release materials are used. This effect may be beneficial if the nitrogen remains available for subsequent crops; however, it also may represent a potential source of nitrate available for movement to groundwater.

Numerous advantages have been claimed for slow-release fertilizers, including: reduced seed, seedling, and leaf burn damage from heavy concentrations of fertilizer salts; improved crop quality; reduced disease infestation; reduced stalk breakage, improved seasonal nitrogen distribution; increased residual value of applied nitrogen; improved economy of use (e.g., single as opposed to multiple applications); and improved storage and handling properties (81).

Agronomic constraints to using slow-release fertilizers arise largely from their high cost and varying rates of nutrient release. For example, while a certain slow-release fertilizer may be appropriate to the nitrogen accumulation pattern of one specific crop it may not confer similar benefits to another crop or a cultivar with a different accumulation pattern. However, for high-value crops, or crops where split applications are problematic, slow-release fertilizers may offer sufficient advantage to offset certain of these constraints. Use of slow-release materials is growing for high-value crops or those grown under special conditions that hinder conventional fertilization techniques (e.g., crops grown using mulch in highly permeable soils and high rainfall, such as strawberries; and under conditions where vitrification/denitrification is highly likely, such as in rice paddies) (81). Increased understanding of nitrogen uptake and use by plants may aid in identification of specific crops and cropping situations where slow-release nitrogen sources may be valuable.

The environmental effects of slow-release fertilizers, however, have not been assessed. For example, these materials may continue to release their nitrogen to soil in the absence of plant growth (e.g., after harvest), This could result in the production and leaching of nitrate during winter and early spring (83).

Nitrification Inhibitors—When applied nitrogen is converted to nitrate more rapidly than plants can accumulate it, nitrate leaching potential is increased. Nitrification inhibitors retard this bacterial oxidation of ammonium to nitrate. Additionally, in order to be agronomically desirable, vitrification inhibitors should be as mobile as ammonium in the soil, remain effective over 1 to 2 weeks, be compatible with fertilizers, and lack toxicity to higher plants, soil microorganisms, and humans (82).

Vitrification inhibitors are effective at reducing nitrate losses and thus could have a large potential market. Identification of cropping systems in which nitrification inhibitors would be valuable could promote adoption of vitrification inhibitors as a nitrogen management tool. Similarly, increased fertilizer costs relative to the economic benefit derived from their use could improve the cost-effectiveness of nitrification inhibitors (82).

It may be desirable to reduce nitrification in soils for environmental reasons as well. Products of nitrification (nitrite and nitrate) may create a variety of undesirable effects, including: 1) seedling damage from nitrite accumulation in soil, 2) nitrate leaching out of plant root zone, and 3) increase in subsoil acidity. Research efforts that correlate nitrate loss rates with nitrification-inhibitor use under various climatic conditions and cropping systems are needed.

Use of a nitrification inhibitor to maintain midseason applications of ammonium nitrogen in the plant root system may be beneficial. On the other hand, such research may reveal that the short-term benefits derived by reducing nitrogen loss during the growing season may be offset in part by increased loss of nitrogen during the fall and winter. This is because vitrification inhibitor use often results in temporary storage of nitrogen in microbial tissue; this nitrogen may be released to the soil after crop harvest (83).

It is difficult to predict where use of a vitrification inhibitor will be beneficial. However, positive yield responses to vitrification inhibitors have been demonstrated in the field, generally under conditions where formation of nitrate would have promoted nitrogen loss via leaching or denitrification (e.g., in warm, high-rainfall areas with permeable soils; soils abnormally wet in the spring; irrigated, aerobic soils; and paddies). The utility of nitrification inhibitors seems highly likely under certain cropping situations, for example, in direct-seeded rice systems where starter fertilizer is added with seed and conditions are conducive to nitrification (81,82).

Manure

Manure is a mixture of feed residues, microorganisms, and metabolic products. Generally 40 to 60 percent of manure nitrogen is in an organic form that is rapidly decomposed. During this decomposition process, ammonium salts are formed and ammonium is emitted until the process ceases (81).

Although the nutrient content of manures maybe substantial (table 4-3), nitrogen content and nitrogen release rates may be highly variable. Under certain conditions an estimated 50 percent of the nitrogen is volatilized prior to field application, and 50 percent of that applied is not recovered by plants during the season of application, although estimates on the amounts lost to the atmosphere vary widely (81). Nitrogen and phosphorus accumulate in the root zone if manure applications greatly exceed crop nutrient requirements (135,122,168) and may **be** subject to leaching. The fraction of nutrients in the soil that actually leach, volatilize, denitrify, or are taken up by crops for typical livestock and crop production systems needs to be determined through further research.

Under proper manure application rates, crop yields that equal or exceed those from commercial fertilizers have usually been observed (table 4-4) (124). Yields with manure are often sustained for several more years after manure application than after commercial fertilizer application due to the slower release of residual nutrients from manures (1 14,1 13). This effect may lead to nitrogen remaining in the soil after harvest and thus increase potential for nitrate leaching to groundwater under humid conditions.

A method to determine proper manure application rates based on nitrogen content was developed by the U.S. Department of Agriculture, Agricultural Research Service (63). Technical guides to proper manure application and accurate soil analyses can be obtained from the Extension Service in most States or from commercial laboratories. These technical guides take into account the slow release rates of organic nitrogen in manure. Recommended manure application rates per 100 pounds of available nitrogen are shown in table 4-5. Application rates are highest in the first year and then drop in future years as mineralization releases nitrogen from the extant soil organic matter.

With proper management, manure application results in increased yields. However, excessive application rates generally do not increase yields appreciably, may increase soil nitrate levels (167, 124,247), and may even reduce the proportion of applied nutrients accumulated by the crop. For example, Bermuda grass took up 74 percent of the nitrogen in manure when applied at rates meeting plant nitrogen needs. However at application rates four times the recommended rate, plant uptake was only 33 percent of the nitrogen applied (197).

Clearly, manure represents a potentially significant nitrogen source for agricultural production. However, numerous constraints exist to improved and more widespread use of manure as a nutrient source. The energy and labor costs associated with improved collection and storage practices may be prohibitive particularly for large confinement operations. Distance to potential markets and high transportation costs create additional economic constraints to such recycling. Although this problem may be partially overcome in livestock operations that also produce feed, excessive manure production relative to nearby soil-loading capacity may pose constraints to on-farm recycling.

Opportunities have been examined for developing regional livestock waste processing facilities to reduce the potential for nonpoint source pollution

Table 4-3-Estimated U.S. Livestock and Poultry Manure Voided and Nutrient (N,P,K) Content[a]

Species	No. animals 1,000 head	Manure dry weight	Nutrients N	P	K
		Million tons/year			
Cattle inventory (January 1989)					
Beef cows and heifers	33,669	44.917	1.776	0.476	1.097
Cattle on feed	9,408	11.813	0.467	0.125	0.288
Stock on pasture	46,190	39.872	1.576	0.422	0.974
Dairy cows and heifers	10,217	29.088	1,091	0.228	0.703
Hogs and pigs inventory (December 1988)	55,299	15.542	0.734	0.456	0.734
Sheep inventory (January 1989)	10,802	1.762	0.065	0.013	0.052
Poultry inventory					
Laying hens (December 1986)	280,500	3.276	0.174	0.061	0.063
Turkeys (1988)	138,300	4.543	0.235	0.087	0.091
Broilers (1988)	951,900	7.644	0.382	0.104	0.139

[a]This information was developed using the 1988 American Society of Agricultural Engineers Manure Production data and characteristics.
[b]Includes sheep and lambs on range/pasture and on feed.

SOURCE: J.M. Sweeten, "Improving Livestock Management Practices To Reduce Nutrient Contamination of Groundwater," OTA commissioned paper, 1989.

Table 4-4--Crop Yields From Feedlot Manure Application Bushland, Texas, 1969-80

	Number of years		Average yields, lbs/acre/year		
Manure treatment	Applied	Recovery	Sorghum grain 1969-73	Corn 1975, 1977,1979	Wheat 1976, 1978,1980
0	11	0	4,490	8,350	1,400
0 (id.;..:.-.-:::;.'::::	11	0	6,440	13,390	4,050
0 (N,P,K)	11	0	6,410	13,560	4,290
10	11	0	6,640	13,920	3,430
30	11	0	6,490	13,400	4,530
60	5	6	6,360	14,340	4,000
120	5	6	5,120	13,950	4,260
240	3	8	900	15,260	4,330
240	1	10	330	12,100	2,810

SOURCE: J.M. Sweeten, "Improving Livestock Management Practices To Reduce Nutrient Contamination of Groundwater," OTA commissioned paper, 1989.

from storage or inappropriate disposal of animal wastes. Marketable products that might be generated from anaerobic digestion of livestock wastes include: energy from methane production, liquid slurry to be used as a fertilizer, and livestock bedding materials (46),

Sludge and Wastewater

Sludge is an accumulation of the solids generated from wastewater treatment. Septage is a sludge produced from the individual home on-site treatment system using a septic tank and drainfield. Forty-one percent of sewage sludge now goes to municipal landfills and 21 percent to incinerators with no recovery of the nutrient components. Growing levels of sludge production in the United States (4 million tons in 1970 to 7 million tons in 1987) coupled with declining availability of disposal sites clearly indicate that alternative disposal methods are needed (80). Increasing application of wastewater treatment products on agricultural land has been suggested as a major alternative to other disposal methods (215).

Sludge application to agricultural and forest land has received increased research attention; studies indicate the potential for nutrient recycling in these systems. While land application allows for recycling of nutrients contained in sludge, it also provides the opportunity for introducing undesirable components into an agricultural system (table 4-6). Further, the

Table 4-5-Dry Tons of Manure Needed To Supply 100 Pounds of Available Nitrogen of the Cropping Year

	Nitrogen content of manure, percent dry basis					
	1.0	1.5	2.0	2.5	3.0	4.0
Years manure is applied	Tons of dry manure/100 lb nitrogen					
1	22.2	11.6	7.0	4.6	3.1	1.4
2	15.6	9.0	5.8	3.9	2.8	1.4
3	12.7	7.7	5.1	3.6	2.6	1.4
4	11.0	6.9	4.7	3.4	2.5	1.3
5	9.8	6.3	4.4	3.2	2.4	1.3
10	6.9	4.9	3.7	2.8	2.2	1.3
15	5.6	4.2	3.3	2.6	2.0	1.2

SOURCE: C.B. Gilbertson, F.A. Norstadt, A.C. Mathers, R.F. Holt, A.P. Barnett, T.M. McCalla, C.A. Onstad, R.A. Young, L.A. Christensen, and D.L. VanDyne, U.S. Department of Agriculture, Agricultural Research Service, *Animal Waste Utilization on Cropland and Pastureland: A Manual for Evaluating Agronomic and Environmental Effects*, URR 6 (Washington, DC: U.S. Government Printing Office, 1979), *In:* Sweeten, J. M., 1989.

Table 4-6-Average Concentrations of Heavy Metals in Grain From Six Wheat Cultivars Grown With Three Fertilizer Treatments at Mesa, Arizona in 1983

	Cadmium	Zinc	Copper	Lead	Nickel
Fertilizer treatment	mg kg-1				
Suggested N, P, K from commercial fertilizer	0.4	31.6	10.6	1.4	10.5
Sewage sludge to provide suggested N with no additional fertilizer	0.6	45.3	12.0	4.5	22.4
N, P, K from commercial fertilizer equal to sewage sludge	0.5	34.8	11.5	1.6	14.9

SOURCE: A.D. Day and R.K. Thompson, "Fertilizing Wheat With Dried Sludge," *BioCycle*, pp. 30-32, September 1986, *In: Moore,* J.A., 1989.

nutrient content of waste byproducts can be quite variable depending on factors such as the type of raw material and treatment process (191) (table 4-7).

Land spreading of sludge on agricultural lands now accounts for only 15 percent of the total produced, but this method is growing rapidly. Maryland now land applies at least 90 percent of the sludge generated in the State. Concerns over negative aspects of land application (i.e., odors, toxic heavy metals, disease vectors, surficial and groundwater contamination) have caused some communities to delay or cease land application operations. Pathogen reduction processes are required in sludge treatment before land application to protect public health. Lag times between spreading and harvest, and access limitations, also are required for certain crops to protect the food chain. Additional support to evaluate and monitor receiver systems and provide expanded educational programs could foster improved use of sludge in agriculture.

While research on the fate, availability, and pathways of sludge constituents in the soil-plant system is still expanding, a procedure has been developed to determine agronomic loading rates. Calculation of the annual and total loading rates (site life) of a heavy metal to a site can be determined knowing the application rate and characteristics of the sludge.

Studies of the potential of forest ecosystems to assimilate nutrients from liquid-sludge applications have been very promising. Overall positive aspects of silvicultural sludge application include:

- low risk of food chain contamination since forest crops are generally nonedible,
- positive vegetative growth response to applications resulting in improved wildlife habitat and nutritional quality of forage plants,
- sequestering and removal of undesirable elements such as heavy metals,
- reduced likelihood of surface runoff due to high permeability of forest soils, and
- reduced potential for human contact with sludge applications due to the distance of application sites from population centers (80).

Studies indicate sludge application to forestlands to be economically and technologically feasible. However, the variability of nutrient cycling among

Table 4-7—Total N, P, and K Concentrations in Selected Waste Materials

Waste material	N	P	K
Solid or semisolid: [a]			
Composted/shredded refuse	0.57-1 .30	0.08-0.26	0.27-0.98
Waste food fiber	2.00	0.01	0.36
Paper mill sludge	0.15-2.33	0.16-0.50	0.44-0.85
Citric acid production wastes	0.51 -4.13	0.06-0.29	0.01-0.19
Tomato processing wastes	2.33	0.29	0.28
Municipal sewage sludge	‹0.1 -17.6	‹0.10-14.30	0.02-2.64
Liquids: [b]			
Municipal wastewater	16-37	7-13	14-22
Whey	1500	500	1820
Vegetable and fruit processing wastes	19-318	4-91	—

[a]Expressed on adry-weight basis.
[b]Expressed on a wet-weight basis (commonly called suspended solids).

SOURCE: L.F. Sommers and P.M. Giordano, "Use of Nitrogen From Agricultural, Industrial, and Municipal Wastes," ***Nitrogen in Crop Production*** (Madison, WI: ASA-CSSA-SSSA, 1984), pp. 207-220.

different forest ecosystems requires that site-specific application rates be determined to generate forest growth benefits in an environmentally sound manner (80).

Comporting is a popular pretreatment process that uses sewage sludge and produces an acceptable product. Several examples exist of large comporting operations producing and marketing the product to lawn and garden and agricultural markets. Comporting sludge with an organic material yields a nearly odorless humuslike material that is free of enteric pathogens. This product can be used as a soil amendment and is a minor source of plant nutrients (table 4-8) (217). Composted materials have a variety of uses, including applications for agronomic crops, land reclamation efforts, nursery operations, and turf grass production. These materials applied at equivalent fertilizer nutrient rates may generate higher yields due to the associated improvements in soil physical properties.

Irrigation with wastewater offers another recycling mechanism. Field experiments show that nearly 67 percent of applied nitrogen is assimilated by corn under a wastewater irrigation regime as compared to 58 percent of applied N from ammonium nitrate. This implies that greater efficiency is achieved under the wastewater regime. However, another study on nitrogen assimilation by grasses showed no appreciable difference between wastewater or conventional fertilizer application regimes (191).

Table 4-8-Composition of Nutrients and Heavy Metals in a Washington, DC, Area Composted Sewage Sludge

Nutrient components as percent of total:	
Nitrogen	<1.50/0
Phosphorus	<2.0%
Potassium	4.2%
iron	<4.0%
Heavy metal concentration in parts per million:	
Zinc	1,250.0
Copper	500.0
Cadmium	12.5
Nickel	200.0
Lead	500.0
Mercury	5.0

SOURCE: U.S. Department of Agriculture, Use of Sewage ***Sludge Compost for Soil Improvement and Plant Growth,*** Agricultural Reviews and Manuals, ARM-NE-6, 1979, *In*: Moore, J.A., 1989.

Opportunities exist to increase the use of wastewater treatment products in an agricultural setting. However, concerns over the addition of undesirable sludge components (i,e., heavy metals, pathogens, etc.) to agricultural systems require consideration. In addition, further information is needed on the fate of organic and inorganic nitrogen after field application of wastes to improve management practices and determination of appropriate application rates of wastewater treatment products.

Fertilizer Application Rates

Fertilizer application-rate information commonly is obtained from local agriculture agency offices and field personnel. Land-grant universities in each state have developed "Official Fertilizer Recommendations" that are made available to the public through the Cooperative Extension Service and maybe used by all segments of agriculture. These recommendations are used by private soil-testing laboratories and producers in developing fertilizer application rates. Recommendations are in a continuing state of review and may be revised as new information becomes available.

Fertilizer application rates are determined based on crop nitrogen requirements and nitrogen-use efficiencies, yield goal, level of available soil nitrogen, fertilizer replacement values for nutrients in manure, legume or irrigation water inputs, cultural practices, and other variables. Plant-available soil nitrogen is composed of newly applied sources, residual nitrate in the profile, and that mineralized from soil organic matter. Rational fertilizer application regimes incorporate this information to arrive at appropriate application rates.

Soil- and tissue-testing methods exist to quantify residual soil nitrate, nitrogen derived from soil organic matter, and nitrogen levels in plant tissues. This information can be used to help determine fertilizer needs. Complex interactions among the variables governing the availability of soil nitrogen to plants make accurate determination of efficient application rates difficult.

Numerous factors affect the accuracy and use of soil testing in determiningg fertilizer need. The lack of a generally accepted index for mineralization means that an accurate picture of the quantity and release rate of nitrogen during the cropping season may not be obtained through soil testing.

The currently used residual nitrate test identifies how much nitrate is contained in the soil. However, it measures only nitrate present at the time of sampling, and thus is less useful in areas where nitrate may be removed before plant uptake as a result of leaching or denitrification (19). The spring nitrate test currently under evaluation may be applicable for humid regions; evidence is now available to support use of the late spring soil nitrogen test in Iowa (101). This test measures residual nitrate and also estimates nitrate that may be released during the growing season.

Failure to account for all of the various sources of' nitrogen as fertilizer application rates are determined can lead to overapplication and increased potential for nitrogen loss from the cropping system (161). Computer modeling may become a valuable tool in determining fertilization schemes. To obtain maximum economic yield and optimum fertilizer-use efficiency, and to minimize potential impacts on the environment, a practitioner must be able to accurately manipulate a broad array of data in making fertilizer application rate decisions. The capability of computers in such a setting could facilitate this process (box 4-D) (194, 183).

Nitrogen Use Efficiency

Nitrogen use efficiency describes the extent to which nitrogen is taken up by crops relative to the amount remaining in the soil or lost to the environment. Thus, improving nitrogen-use efficiency has potential to reduce amounts available for leaching and loss to groundwater. One approach to improving nitrogen use efficiency is to control vitrification. Nitrification of ammonium-producing substances (e.g., fertilizers, animal manures, crop residues) converts the relatively immobile ammonia to the mobile form of nitrate. Further action by denitrifying bacteria may convert nitrate to gaseous forms that are lost to the atmosphere. Vitrification may be controlled by:

- slowing the rate at which fertilizer materials dissolve in the soil environment,
- slowing the rate at which fertilizer releases N to the soil solution,
- timing applications to match plant uptake patterns and thus compete more effectively with the nitrifying bacteria, and
- using nitrification inhibitors (81).

Recovery of fertilizer nitrogen in the above-ground portions of grain crops seldom exceeds 50 percent at recommended application rates and is often lower (19,152) (table 4-9); these figures vary however, based on site characteristics. The remaining nitrogen may be volatilized (denitriffied), immobilized in microbial tissue and nitrogenous constituents of soil organic matter, stored as nitrate in the soil profile, or lost via erosion or leaching to groundwater. The partitioning of fertilizer N among these fates varies with soil, cultural, and management conditions. Nitrogen use efficiency also may be affected by nitrogen application practices, primarily application rate, timing, and placement (77).

Realistic Yield Goals

Yield goals should be based on the productive capacity of the agroecosystem and the crop nitrogen need. However, yield goals commonly contain a subjective value that is incorporated into the fertilizer application decision—an individual's desire to achieve maximum yield. Overapplication of nutrients commonly is attributed to an overestimation of the productive capacity of the cropped area.

Fertilizer application rates based on highest yield year(s) may in fact be inappropriate given the numerous variables responsible for crop growth (152). Realistic yield goals are developed by averaging production over past cropping years (generally 5 years) with the addition of no more than five percent to that value (191). Further, this value should be calculated on a field-by-field basis to account for the inherent heterogeneity of the agroecosystem.

Box 4-D—Modeling as a Tool for Predicting Nitrogen Contamination Potential From Agricultural Practices

Manipulation of a broad range of data is necessary in order to identify the potential for nitrate movement to groundwater from agricultural activities. Computer modeling has been instrumental in illustrating agrichemical movement through the soil profile and current effort is substantial in this field of diagnostic modeling. The following examples describe a number of models that are helping identify the groundwater vulnerability and the fate of agrichemicals in the soil environment.

AGNPS-Agricultural NonPoint Source-single event, cell-based model that simulates sediment and nutrient transport from agricultural watersheds.

DRASTIC---empirical standardized system for evaluating groundwater pollution potential by using hydrogeologic settings; the seven parameters estimated by the NWWA to be most significant in controlling pollution potential are: 1) Depth to water table, 2) net Recharge, 3) Aquifer material, 4) Soil, 5) Topography, 6) Impact of the vadose zone, and 7) Conductivity of the aquifer.

EPIC—Erosion Productivity Impact Calculator-a model to determine the relation between soil erosion and soil productivity; capable of simulating periods greater than 50 years; incorporates hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, economics, and plant environment control.

GLEAMS-Groundwater Loading Effects of Agricultural Management Systems-developed to evalute the effects of agricultural management systems on the movement of agricultural chemicals in and through the root zone for field-size areas.

LEACHMN-Leaching Estimates and Chemistry Model Nitrogen-process-based model of water and N movement, transformations, plant uptake, and N reactions in the unsaturated zone,

NITWAT-Nitrogen and Water Management-developed especially for corn on sandy soils; evaluates N transformations and transport in relation to crop growth under certain weather and irrigation conditions.

NLEAP-Nitrate Leaching and Economic Analysis Package-computer application package developed to estimate potential nitrate leaching from agricultural areas and project impacts on associate aquifers.

NTRM-Nitrogen Tillage and Residue Management—model with emphasis on management of nitrogen sources at the soil surface in conventional and reduced till systems. N transformations and transport are detailed using the NCSOIL submodel with active and passive N pools.

RZWQM-Root Zone Water Quality Management—in development; will compare alternative management practices and their potential for groundwater contamination; comprehensive model includes macropore flow and N cycle description; expert systems approach.

SOURCE: J.W.B. Stewart, R.F. Follett, and C.V. Cole, "Lntegrationof Organic Matter and Soil Fertility Concepts Into Management Decisions,' Soil *Fertility and Organic Matter as Critical Components of Production Systems* (Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 1987).

Soil Testing

Soil testing is used to diagnose the soil nutrient content prior to planting to determine fertilizer need. Plant available nitrogen may be derived from two soil pools: 1) mineral nitrogen, and 2) nitrogen mineralized from soil organic matter. While characterization of mineral nitrogen is a relatively simple procedure, quantification of mineralizable nitrogen is more difficult (152). Tests that measure phosphorus, potassium, and mineral nitrogen (i.e., nitrate) levels in soils are well-established laboratory procedures. Testing to assess potential mineralizable nitrogen may require laboratory or field incubation and chemical extraction and thus are more costly and time consuming. Many laboratories use previous farm management records to account for mineralizable nitrogen in making nitrogen application rate recommendations (152).

Most laboratories conduct chemical extraction of soils and correlate the results with various soil types to provide a basis for determiningg fertilizer application rates to provide optimum nutrient availability to the crop. These studies correlate soil nitrogen content, application rate, and plant yield to establish the validity of soil tests in the area where they are used (194).

The correlative approach is time consuming and expensive and depends on an assessment of actual and potentially available nutrients prior to planting. Further, it is so specific to crop, soil type, and cultivation technique that transferring recommendations to other settings is inappropriate. An alterna-

Table 4-9-Recovery of Fertilizer Nitrogen by Corn in the Application Year and Following Year

N rate lb N/acre	Percent recovered Plant	soil	Total	Recovery in soil in following year percent
Goodhue Co.:				
67	51	32	83	5
134	40	34	74	7
Waseca co.:				
89	42	37	81	1
178	35	44	79	1

SOURCE: G.W. Randall, "Who's Responsible for Nitrates in Groundwater," presented at 1986 Soils, Fertilizer, and Agricultural Pesticides Short Course, Dec. 9, 1986, Minneapolis, MN.

tive to the correlative approach is the maintenance concept, whereby fertilizer recommendations are based on the amount expected to be taken up by the crop and exported by harvest.

Periodic in-field soil tests would allow farmers to account for seasonal changes in the amounts of available plant nutrients-for example, nitrate levels are highly variable throughout the year as a result of mineralization, immobilization, denitrification, leaching processes, and changes in soil moisture, temperature, and organic matter level. Thus, depending on the timing of soil tests, an accurate picture of the soil's maeronutrient content may or may not be obtained. Proper testing techniques such as sampling at appropriate soil depth, accurate delineation of the management unit to be sampled (i.e., field), and determining the number of samples to be taken per management unit are critical to obtaining accurate soil test results (152).

As management changes affect the timing of cultivation and organic matter incorporation, it will be necessary to reevaluate existing soil tests for applicability under the new management system—requiring costly field experimentation to provide correlation data. This makes it all the more compelling to understand the processes involved in nitrogen transformations in soil (194). EPA has suggested that a joint USDA/EPA soil-testing program be undertaken in an effort to reduce the volume of nitrogen applied to U.S. cropland (69).

Tissue testing of crops for overall nitrogen and nitrate content offers another technique that may be used to determine nitrogen deficiency or sufficiency. Indices exist that identfy sufficiency, deficiency, and excessive nitrogen content for specific plant parts of numerous crops. Comparison of tissue test results with these values then provides information as to crop nitrogen need.

Correct timing of tissue tests and testing of correct plant part axe critical to obtaining a representative sample and thus accurate test results. Although tissue sampling techniques have not been examined as widely as those for soil tests, the number of samples should account for heterogeneity of soils and plant biology to obtain a representative sample for the management unit tested (152).

Fertilizer Replacement Value

Fertilizer replacement value (nitrogen credits or FRV) is a method to assess the N-supplying capability of a legume preceding growth of a nonlegume. Values represent the amount of manufactured nitrogen fertilizer that would be required to produce a corn yield equivalent to that following a legume under otherwise comparable test conditions (57,91). Legumes so evaluated are interpreted as replacing various amounts of fertilizer nitrogen for the frost nonlegume cropping season after legume plowdown. FRVs vary among and within cropping regions due to site-specific factors, crop species, and management methods. In many tests, the FRV for perennial legumes (e.g., alfalfa) is similar to the nitrogen fertilizer rates recommended for corn.

The FRV approach may be used to estimate the minimum amount of fertilizer nitrogen required by a nonlegume following a legume. One shortcoming of the approach is that the magnitude of the FRV estimated in a specific experiment depends strongly on the fertilizer-use efficiency of the nonlegume. Thus, this approach may not provide accurate assessment of the contribution of legume N to a succeeding crop. Recent studies involving radiolabeled N_{15} indicate that the FRV may in fact overestimate the ability of a legume to provide N to succeeding crops (86).

Timing of Fertilizer Application

Nutrient accumulation patterns vary among crops and even among cultivars, thus, timing nutrient application to coincide with greatest crop need provides an opportunity to reduce nutrient loss to the environment. Varying rates of nitrogen release from nutrient sources may complicate efforts to match nitrogen availability with maximum crop need. However, reduction in the time interval between application of fertilizers and time of maximum crop uptake may reduce the potential for leaching and denitrification losses (165,77).

A variety of fertilizer application regimes are practiced including fall, spring preplant, and split. Each regime generates slightly different benefits and all have differing potentials for nutrient contamination of groundwater. Multiple, small applications of fertilizer generally promote better plant uptake and thus reduce the potential for nitrate loss via leaching as compared to a single, large application. Fertigation (i.e., fertilizer application in irrigation water) may be particularly advantageous for multiple applications under certain irrigation regimes such as sprinkler systems that allow uniform water distribution (19).

In many regions it is common to apply fertilizers in the fall for subsequent spring crops. While this practice reduces the demands on a grower's time during spring planting season, it may create potential for denitrification and in some cases leaching losses. However, in dryer regions where leaching is unlikely this practice may not pose a potential hazard. Application techniques that may improve the efficacy of fall applications include use of a nitrification inhibitor and application after the soil reaches a critical temperature (i.e., 45° F) that inhibits nitrification of applied nitrogen.

Preplant applications, weeks before maximum uptake, are common for tall-growing crops like corn that can be damaged by application of fertilizers later in their growing season. Such practices clearly expose nitrate to the leaching potential of rainfall and irrigation prior to nutrient uptake by a crop (208).

Split applications generally entail a starter application of fertilizer with a subsequent application later in the growing season. This method is designed to reduce the amount of nitrogen remaining in the soil and available for nitrification and potential losses from the cropping system as well as to match nitrogen availability to the time of the crops' maximum nitrogen uptake requirements.

Application Technology

Fertilizers may be distributed before primary tillage, at planting time, and supplementally during the growing season. By far the majority of plant nutrients are applied to the soil for uptake by plant roots and are incorporated into root zone by tillage, direct injection, or leaching with rainfall or irrigation water (208). Dry or solid forms of urea and ammonium nitrate may be broadcast and high--pressure anhydrous ammonia is injected or "knifed" in to the soil. These forms comprise the greatest market share of applied fertilizer materials in the United States. Liquid fertilizer forms are also broadcast or dribbled on soil or plant surfaces. Spray applications are widespread in custom applications since they allow relatively rapid coverage over large areas (164).

A variety of methods exist for fertilizer application, including broadcast, injection, banding, in-row, side-dress, top-dress, and foliar. *Broadcast* applications entail distribution of fertilizer across an entire field surface. The fertilizer then may be mixed into the soil or left on the surface and allowed to move into the soil with moisture (rainfall or irrigation). Use of nonhomogeneous particles, however, may result in nonuniform distribution and thus over- or under-fertilization in parts of the field (152).

Injection application methods may be used with gaseous, liquid, or solid fertilizer materials. Gaseous and liquid forms generally are knifed into the soil, while solid forms may be placed in slots or furrows created by shanks or chisels. *Banding* of fertilizers may be done either at planting or after the crop has emerged. Solid fertilizer may be placed on the soil surface in strips between crops rows and liquid forms may be injected below and to either side of the seed. Fertilizer is applied during planting and directly next to the seed in *in-row* application. In-row application generally is used for starter fertilizers.

Side-dress applications are used to apply fertilizer to an established row crop, generally in a band beside the row. Either surface or injection application methods may be used in side-dressing of fertilizers. *Top-dress* fertilizer applications are liquid or solid forms broadcast over an established crop. *Foliar* applications of fertilizers involve spraying of liquid forms onto plant foliage or application through a sprinkler irrigation system (i.e., fertigation). Sprayed applications generally are taken up by plant leaves while uptake under irrigation applications may largely be through the plant roots.

An important consideration in fertilizer application is the placement of the fertilizer to avoid positional unavailability of the nutrient for the growing crop. Depth and location of fertilizer placement relative to the crop rhizosphere is critical in assuring maximum nutrient uptake. In areas where the soil surface dries out and retards root activity, placement must be deep enough to allow extraction by the roots (164).

Point injection of liquid fertilizers has the potential to reduce certain avenues of nitrogen loss and is useful in conventional and conservation tillage systems. Developed by Iowa State University, the spoked wheel applicator injects fertilizer solution about 4 to 5 inches below the soil surface and at about 8-inch intervals. This method of introducing nutrients nearly eliminates runoff potential, requires less horsepower than conventional equipment, and reduces disturbance to residue layer. This technology is compatible with postemergence application to crop, thus allowing improvement in timing of application to greatest crop nitrogen uptake. Further, it allows positioning of nitrogen in ridges for ridge-till systems, reducing problems of positional unavailability of nutrients. Although testing has demonstrated significant yield increases with this technology, additional work is needed to bring the applicator to market (55,183).

Precision application methods offer some potential for reducing overapplication of fertilizer materials to U.S. cropland. Soil nutrient content may be highly variable across a single field, thus fertilization schemes that seek to ensure adequate amounts to the least fertile segment of a given field easily may overfertilize other parts. Application methods that take into account the heterogeneity of soil nutrient content can reduce overfertilization. For example, a precision fertilizer application system is capable of taking 3,000 soil-nitrate tests per acre and adjusting application rates based on these tests (29). The user determines desired soil nitrate content and the applicator system tests the in-soil nitrate level and then applies the amount needed to meet the predetermined level. The number of nitrate tests the system is capable of performing can account for the heterogeneity of soil nitrogen level in a field.

PEST MANAGEMENT

Pesticide use has changed dramatically over the years, in terms of compounds used and amount of cropland treated. Some of these changes seem linked to environmental concerns (e.g., decline in organochlorine insecticides), while others may be the result of certain agricultural programs. Prior to World War II, agricultural pest control methods relied largely on tillage, crop rotation, and hand removal of pests. Available pest control chemicals were expensive and contained inorganic, highly toxic components (e.g., copper, lead, antimony, arsenic). Development of new pest control chemicals during World War II, and improvements in application technology, fostered a pest control approach that replaced older, more labor-intensive practices (254).

Phenoxy herbicides and organochlorine insecticides became popular pest control chemicals after World War II. However, in the mid- 1960s their use declined in favor of triazine and amide herbicides and carbamate and organophosphate insecticides. The 1970s witnessed an increase in herbicide use on major field crops, while insecticide use declined largely in response to lower doses associated with newly introduced pyrethroids. Pesticide use seemed to stabilize or even decline in some cases during the 1980s, perhaps as a response to acreage diversion programs (148).

Pesticides are applied to agricultural crops to reduce yield losses due to insects, diseases, and weeds that even today destroy almost one-third of all food crops (73). Pesticide use has risen roughly 1,900 percent in the 50-year period between 1930 and 1980 (73). The percentage of herbicide-treated cropland planted to corn, cotton, and wheat climbed from about 10 percent in 1952 to nearly 95 percent by 1980 (148).

Generally, pesticide applications are considered *effective if they* **achieve the** desired degree of pest control, and *economical if the* crop yield and quality response is above and beyond the cost of chemicals and their application. Opportunities may exist to reduce volumes of applied agrichemicals; develop safer effective compounds (box 4-E); and develop improved application methods that might address concerns over the potential adverse environmental effects of pesticide use (93).

Pesticides are broadly classified on the basis of the kinds of pests they control (e.g., insecticides, herbicides, fungicides, nematicides, rodenticides, and miticides). Chemicals used for defoliation, desiccation, soil fumigation, and plant-growth regulation also are classified as pesticides (79)(box 4-F). Most pesticides are organic chemicals; some are synthetic, others are of natural origin. Many contain chlorine, nitrogen, sulfur, or phosphorus that determine the toxicological impacts of the compounds,

Box 4-E—Biological Pesticides

Biopesticides are naturally occurring toxins and microorganisms that tend to be highly specific for a particular pest *(206),* Attributes of biopesticides include target specificity, low production costs, and biodegradability (22). Currently biopesticides comprise a small part of the overall market ($35 million); however, it is estimated that growth will increase rapidly (22).

Persistence of biopesticides is low; generally they are proteins that degrade quickly when exposed to the environment. This may be percieved as a drawback since multiple applications of biopesticides may be needed to control pest infestations relative to conventional chemicals. However, new techniques in packaging might address this feature (22).

Most biopesticides tend to be pest specific, which means that more than one agent maybe needed for multiple infestations. However, potential exists to combine agents into one delivery vector (22). Certain biopesticides are effective against more than one pest species. One such pesticide, an extract of the seeds of a tropical evergreen, the neem tree *(Azadirachta indica),* shows promise as an insecticide with little or no toxic effects to mammals and effectiveness against a number of pests that have resistance to other commercial chemical pesticides (97,89).

Biological herbicides have been developed that use soil bacteria and fungi to retard weed growth. A strain of ***Pseudomonas is*** being tested by Iowa State and Texas A&M Universities as a potential bioherbicide for downy brome (cheatgrass) in wheat. Applying the bacterium prior to planting may increase yields as much as 35 percent. The soil fungus *Gliocladium virens* may have some potential as a broad spectrum herbicide. The fungus was effective on 15 of the 16 weed species on which it was tested in University of California-Berkeley studies (1 37).

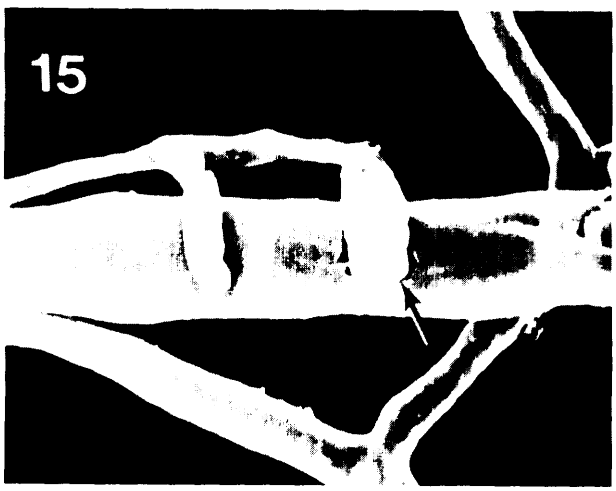


Photo credit: Colorado State University—Ralph Baker

Other biological control agents include fungal parasites prey on other soil fungi that are pathogenic to plants. Here, a photograph taken through a scanning electron microscope shows how the parasite penetrates its host.

Nearly 50,000 pesticide products are now registered with the U.S. Environmental Protection Agency (EPA) (62), although only a few are used extensively. The agricultural sector accounted for at least 75 percent of all pesticides applied in the United States in 1988 (236). Pesticide use on major crops has grown from 225 million pounds of active ingredient in 1964 to 558 million pounds in 1982, with greater herbicide use accounting for a significant part of this increase (148). Projected pesticide use for 1989 was 463 million pounds of active ingredient (228). This decrease from previous years may reflect a reduction in treated acres generated by acreage reduction programs (148) or a reduction in total amount applied as a result of the lower application rates allowed by newer pesticides (229).

Some 1,800 weed species cause an estimated 10 percent annual production loss in U.S. agriculture (valued at nearly $12 billion) (7), and farmers spend at least $8 billion annually for weed control. Herbicides comprise the greatest part of the pesticide market and account for most pesticide detections in groundwater to date.

Pest control practices may be initiated based on pest scouting—monitoring to determine existence of a pest problem. Depending on the type of pest identified, the organization of the production system, and the extent of infestation, various control approaches may be used. Additional monitoring of the pest population may be initiated if the extent of infestation is deemed to be below an economic threshhold.[4] If infestation is significant, pesticides

[4]Economic threshold is defined as the level at which the costs of control are equivalent to the benefits to be derived from control measures. This term also includes a subjective value-risk aversion of the producer-that makes the definition somewhat variable based on the individual.

Box 4-F—Plant Growth Regulators

Plant growth regulators (PGRs) are organic compounds that are applied to promote, inhibit, or otherwise modify plant physiological processes (21). Such compounds have been used on horticultural crops since the 1940s and have been applied to agronomic crops during the last 20 years (31). Their use on agronomic crops largely is limited to antilodging for cereals, maturation and yield enhancements in cotton, and enhancing sugar content of sugarcane (31). Major categories of effects of PGRs include:

- yield enhancement—inhibition of certain growth patterns may stimulate greater fruit set (e.g., mepiquat chloride used on cotton has been shown to increase cotton yields by 6 to 8 percent),
- conservation of energy or labor requirements-stimulation of uniform maturation allowing harvest in fewer passes,
- quality control—stimulation of ripening promoting uniform maturation, also applications postharvest to enhance product appearance,
- morphological control—through inhibition of certain growth patterns, application of PGRs may stimulate a preferred growth pattern (e.g., inhibition of flowering may stimulate increased vegetative growth giving rise to denser foliage, particularly important in ornamentals) (31).

At least 75 percent of the cotton grown in the United States is defoliated or dessicated annually using plant growth regulators. Other crops that commonly recieve dessication treatments to facilitate harvest include: soybeans, rice, potatoes, grain sorghum, sunflower, lentils, trefoil, dry beans, guar, and sugarcane. Many of these defoliants have been placed on EPA's Rebuttable Presumption Against Registration lists (31).

PGRs commonly are applied as foliar sprays. They must be retained on the plant surfaces in order to be effective, since the desired response depends on absorption of PGRs through the plant tissue and translocation to the appropriate reaction site (21). However, performance of these chemicals maybe affected by numerous factors internal and external to the plant. Lack of performance consistency has been noted in certain PGRs (31) and may be a symptom of such effects.

Research directions in PGRs are focused on increasing plant protein content, enhancing plant stress tolerance, promoting development of vegetative tissue, and mediating plant flowering (31). Disadvantages of some defoliants and dessicants include expense, unpleasant odors, explosive or flammable properties, and high mammalian toxicity. An increasingly important research area is the search for herbicide resistance. Protestants or safeners may be applied to a crop (usually seed) so that when herbicides are applied to the crop row only the non-protected plants are killed (214). Concern exists over this trend and the potential for accelerating herbicide use or promoting indiscriminate use.

may be used, requiring decisions on application method, timing, and rate of application. Alternative control measures (e.g., cultural or biological controls) may be used in lieu of or in conjunction with pesticides. All of these strategies are combined in the development of integrated pest management (lPM) programs (210,254).

Pest Scouting

A number of pest-scouting techniques exist, including visual inspection, pheromone traps, and other highly technical counting and collection methods. Once pest populations reach an economic threshhold level, pest control methods may be undertaken. In this way scouting can diminish the need for certain pesticide ''insurance" applications (73), however, some pests (e.g., diseases, nematodes) may not be easily scouted. Scouting also may identify pest problems that may otherwise have been unnoticed and thus result in increased pesticide use.

Scouting can help determine pest pressure and "hot spots," allowing selective application of a specific pesticide based on need (73). Farm scouts or pest consultants recommend correct pesticide application time to farmers based on accurate identification of a pest problem, stage of crop growth, weather forecasts, and other factors (73).

Pesticides

Although pesticides are credited with a high rate of food and fiber production at relatively low cost, increasing concern has been expressed since the 1960s over the potential hazards and long-term environmental impacts associated with their use. Despite these concerns, however, overall pesticide use has not decreased significantly.

Photo credit: U.S. Department of Agriculture, Agricultureal Research Service

Insect **traps loaded with pheromone are** used to estimate pest populations for integrated pest management. Here, a research entomologist observes the night flight pattern of a moth through infrared glasses.

The potential for groundwater contamination by pesticides depends on pesticidal properties (e.g., half-life, mobility), application method, physical and chemical soil properties, depth to groundwater, and amount of irrigation and precipitation (159). Impacts of pesticide use on the environment are determined by the transport of the chemicals; their persistence, degradation, and dissipation in the environment; and the hazards associated with pesticides and their metabolizes (figure 4-5). Pesticide use practices developed with these factors considered, thus, offer an opportunity to protect groundwater resources (254).

Improved efficacy of the newer pesticides has allowed reductions in total active ingredient applied per acre (figure 4-6); lower doses generally are achieved through increased pesticide toxicity. The capability for accurate delivery of such small amounts to the target pest, however, is questioned. For example, numerous researchers have estimated that only 1 to 2 percent of foliar-applied insecticides arrive at the target pest (71,156). However, the efficiency of any pesticide application will depend on a variety of factors, including: the method of application, weather conditions during application, equipment operating condition, time of year, crop type, volume of liquid used, pesticide formulation, and pest location and density. Further, the avenues for loss from the time of application to the point of contact with the active site in the target pest are numerous (figure 4-7). Additional improvements in intrinsic activity of pesticides may, in fact, be offset by inefficiencies in delivery mechanisms. Thus, despite complicating factors, it seems clear that improvement in delivery systems, then, may offer additional opportunities to enhance the intrinsic activity of pesticides (73).

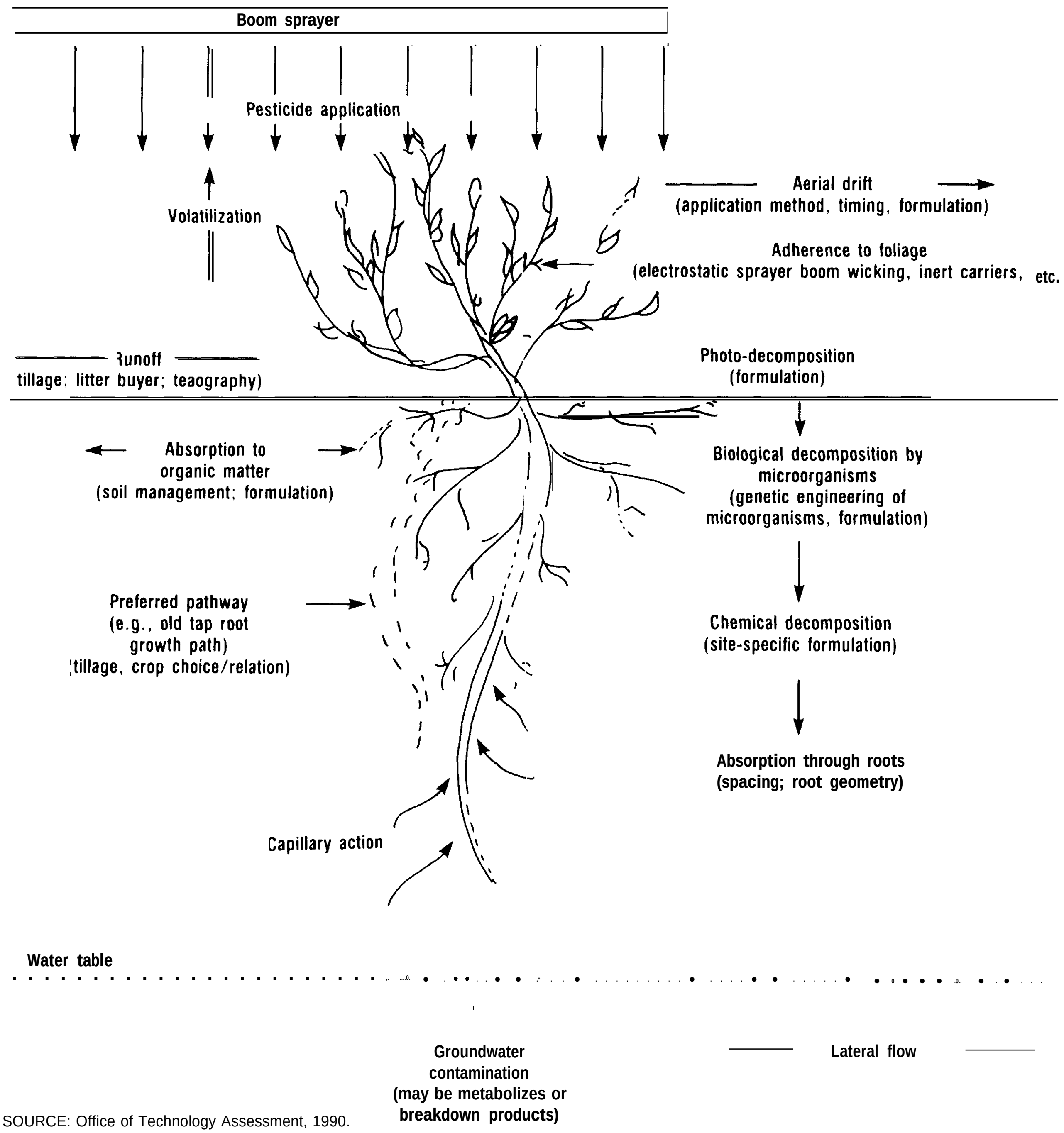
Concerns over the identified and potential harmful effects of pesticide chemicals in the environment has promulgated efforts to improve current use practices and identify alternative pest control approaches. Major research and development foci include:

- use reduction (e.g., fewer applications, lower levels of active ingredient);
- improved delivery systems (e.g., electrostatic sprayers, pheromone baits);
- environmentally more acceptable chemicals (e.g., biopesticides); and
- nonchemical approaches (e.g., cultural, genetic, or biological controls).

In addition to the current broad concern over environmental hazards of pesticide use, several other issues are associated with chemical pest control, including: 1) human exposure to pesticides (from the application process or where humans enter recently treated areas), 2) pest resistance, and 3) secondary pest outbreaks.

Pest Resistance—Resistance to a chemical may develop rapidly as pest life cycles may be short—some passing three or more generations in a single growing season. Within pest populations some individuals with genetic resistance to a chemical exist. As these individuals survive and reproduce, resistance is passed on to succeeding generations. Ultimately, a pesticide-resistant population devel-

Figure 4-5-Environmental Fate Pathways for Pesticides

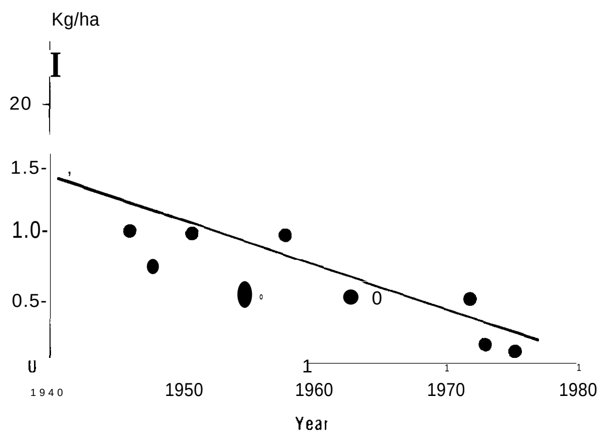


SOURCE: Office of Technology Assessment, 1990.

ops. For this reason, most pesticides have a finite effective life. For example, as of 1986, resistance had been reported in at least 447 species of ‘insects and mites, 100 species of plant pathogens, 48 weed species, 5 species of rodents, and 2 nematode species (61).

Effect on Nontarget Organisms and Secondary Pest Outbreaks—Pesticides generally are effective against a broad spectrum of plant-associated organisms of which only a fraction are considered pests. Thus, while a pesticide maybe applied to control a specific pest, it may also cause declines in beneficial

Figure 4-6-Evolution in Rate of Application of Insecticides



SOURCE: H. Geissbuhler, "Advances in Pesticide Science," International IUPAC Congress of Pesticide Chemistry (New York, NY: Pergamon Press, 1981).

populations. Such adverse effects on beneficial populations may create the conditions for secondary pest outbreaks. For example, continued use of a single herbicide or herbicide group may lead to prevalence of weed species not affected by the herbicide group (7). Also, natural control agents can be adversely affected by chemical applications directed toward the bona fide pest species. Secondary pest populations may then emerge as natural predator populations decline.

The effects of pesticides on soil fauna are highly complex, making generalizations difficult. Controlling variables include:

1. the abundance of biocidal compounds from various chemical families,
2. differences in persistence of pesticide compounds in the environment,
3. the diversity of invertebrate organisms in different soil communities,
4. metabolic products of different organisms that ingest pesticides,
5. chemical and physical heterogeneity of agroecosystems, and
6. the agricultural practices of pesticide users **(39).**

Where effects of pesticides in the soil environment have been observed and analyzed, the biotic responses are variable. Pesticides may affect soil fauna directly or indirectly; however, only certain organisms are adversely affected and some populations actually may increase. Certain pesticide residues may accumulate in the tissues of some soil organisms with no apparent ill effects, while certain sensitive species are killed from acute or chronic exposure. In almost all cases, the structures and functions of soil communities are modified by pesticide use (39),

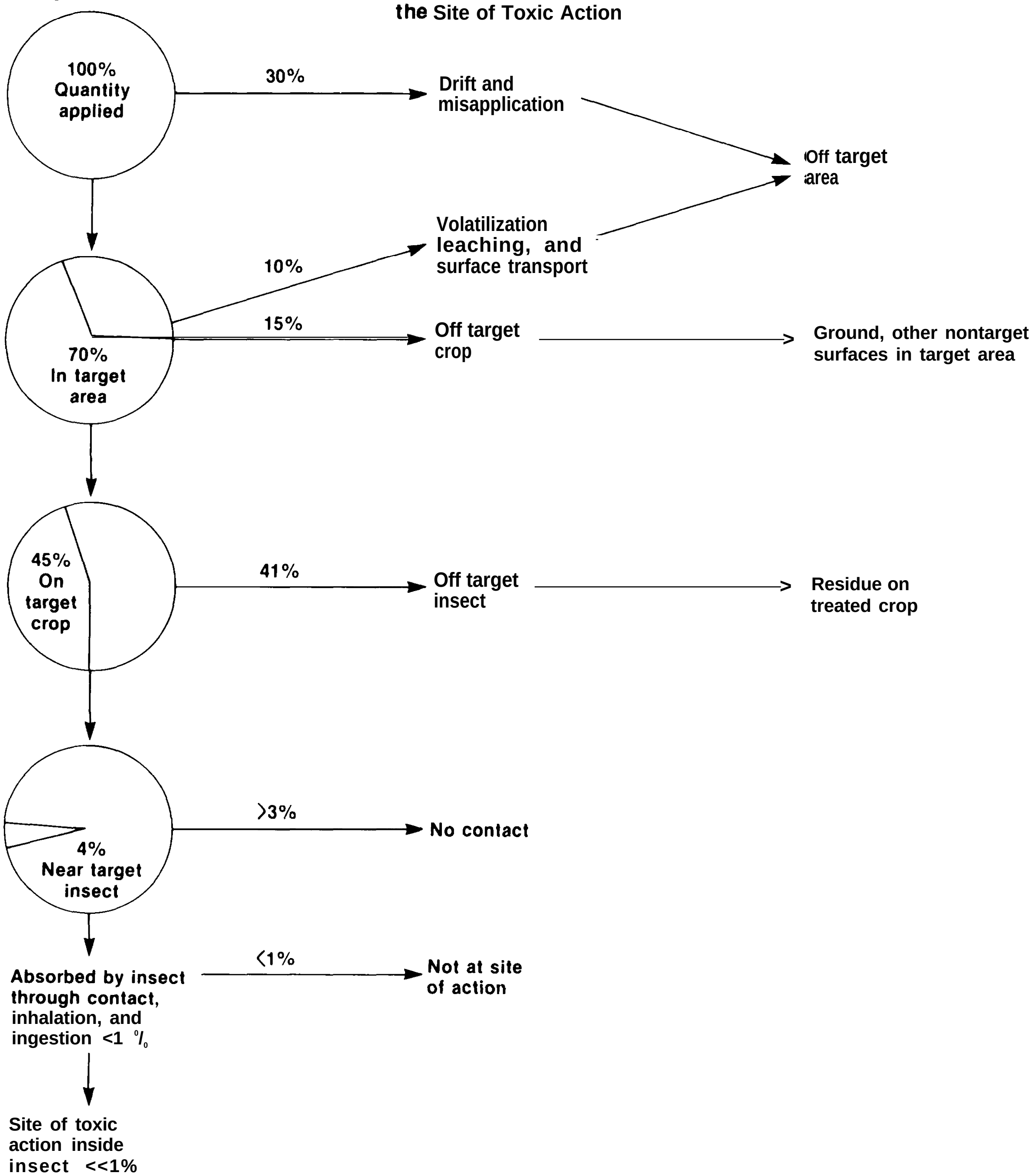
Inhibitions of microbial activity are most pronounced from fungicides and fumigants and suppression may remain for long periods. The impact may be so great that the natural balance among the resident soil microbial populations is upset and new organisms may become prominent. Moreover, certain nutrient cycles regulated by microorganisms are inhibited by fungicides and fumigants in such a way that significant adverse effects on plant growth and nutrition become evident. The lack of widespread concern for these antimicrobial agents is explained by the fact that they are not as widely used as insecticides and herbicides—the two major classes of pesticides (2).

Insecticides have received most attention in the past and are often acutely toxic as compared to other pesticides. These compounds may be applied directly to the soil for the control of soil-borne insects, or they may reach the soil from aerial drift or when previously treated plant residues are incorporated into the soil during cultivation.

While some soil microbial processes or populations may be inhibited by the presence of insecticides, the beneficial effects of insecticides in controlling insect pests argue for their use. Few instances of major suppressions of microbial activities in the field have been noted (2); however, further investigation of the links between pesticide use and modification of soil microbe populations seems warranted.

Herbicides are designed to control weed growth. Generally, small amounts of herbicide are used per unit of land area and the compounds are relatively selective for target plants, so little or no inhibition of other soil processes has been noted. In some instances, herbicides alter microbial activities, possibly because the suppression of target plant species may limit the availability of organic nutrients needed by microorganisms. These effects seem slight and have not raised questions over the use of particular chemicals (2). Herbicide use in no-till agriculture, however, is a matter of increasing

Figure 4-7-Typical Losses of Aerial Foliar Insecticide Application Between the Spray Nozzle and the Site of Toxic Action



SOURCE: R. Von Rumker, E.W. Lawless, and A.F. Meiners, "Production, Distribution, Use, and Environmental Impact Potential of Selected Pesticides," Environmental Protection Agency, Office of Pesticide programs, and Council on Environmental Quality, 1974.

concern because of the higher level of application associated with these cultivation systems (7). However, under certain reduced-tillage systems, these increases may be short-term; evidence exists showing that applications may drop significantly after 5 years (11 1).

Despite demonstrated problems with chemical pest-control approaches, numerous factors constrain use reduction (e.g., efficacy of alternative control methods, economic viability, practitioner risk perceptions). The demand for perfect cosmetic appearances of food by an affluent buying public may

Box 4-G—Pesticide Best Management Practices

Pesticide management practices that may reduce the amount of agrichemicals lost to the environment and potentially to groundwater include:

- following label instructions/documenting application practice and use patterns;
- application at the correct time per recommendations from scout/consultant;
- use of optimized approach rather than maximum label rate at the fill site; monitoring application so that tank is empty at end of the field to minimize waste being disposed of at fill-up site;
- use of small nurse tanks to dilute spray mixes remaining in pump and booms-spraying of this dilute mixture on way back to spray pads;
- tank rinsing with greatly diluted mixture to eliminate major point source contamination;
- calibration of application equipment (tagging yearly with calibration date);
- adjustment of spray volume and application rate by field, based on scouting information;
- following proper procedures for pesticide container disposal (on-farm demos by extension personnel);
- use of sound on-farm economic models to explore production/cost/crop loss relationships, thus diminishing tendency to insure, i.e., put it in the tank just to be sure;
- proper use of irrigation and better timing of sprays based on weather predictions to minimize movement through soil; and
- judicious management of pesticides based on selection, timing, dosage, and placement (ecological selectivity).

SOURCE: F.R. Hall, "Improving Pesticide Management Practices," contractor report prepared for the Office of Technology Assessment (Springfield, VA: National Technical Information Service, August 1989).

contribute to continued pesticide use despite growing evidence of pest resistance, groundwater contamination, or adverse health impacts on farmworkers (73). Premium prices received for cosmetically appealing fruits and vegetables make it difficult to produce and market these foods profitably without chemicals (73).

It seems likely that despite intensified and accelerated research on nonchemical pest control methods, there probably will be continued need for some chemical pesticides in agricultural production. Analysts have suggested that agricultural pesticide use has modified agroecosystems sufficiently such that significant losses to pests occur when chemical use is discontinued (43). Despite this, potential exists to reduce some of the adverse impacts associated with pesticide use through improving agrichemical application methods, rate and timing, and developing of safer pest control compounds (box 4-G).

Formulation

The pesticide formulation provides for dispersion of the product in application media (e.g., water), product integrity/stability in storage, and ability of the pure pesticide to move through lipid barriers to the biological site of activity. Formulation may affect the release rate of the active ingredient, reduce volubility and leaching potential, and optimize dose transfer to target pests (73). Most of these properties affect the efficacy of foliar-applied pesticides. Increased attention is now being given to formulation chemistry with emphasis on increasing ability of product to move through waxy layers of leaf surfaces, thus increasing efficacy and pesticide retention on plant surfaces (60). Formulation chemistry has an overwhelming effect on pesticide efficacy relative to application technologies and physical properties of spray materials (60). While chemistry of a product may not change for years, formulation often changes.

Pesticides are formulated in several physical types: liquids (aqueous, oil, emulsifiable concentrates); solids (dust, wettable powders, granules, encapsulated products); and gases (fumigants). Progress has been made toward new formulations that enable additional products to be applied as liquid sprays (60). For example, active ingredients that are not easily diluted in water require specific formulation to allow mixing with water (60). The type of formulation depends on the chemical nature of the pesticide, target pest, and other pesticidal properties (60,208).

The density of granular products significantly affects pesticide performance and deposition, While granules have less drift potential, they require moisture to release the active ingredient to the soil.

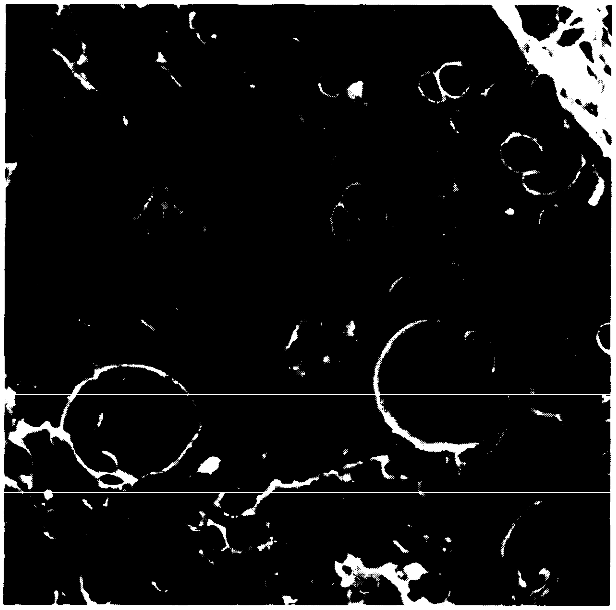


Photo credit: U.S. Department of Agriculture, Agricultural Research Service

Highly magnified granule of a starch-encapsulated herbicide shows pores through which herbicide is slowly released. Use of slow-release agrichemical formulations can reduce potential for high concentrations to **leach to** groundwater.

Thus, the release pattern is unlikely to be uniform because of variability in the carrier and soil. Opportunities also exist for improving application processes with existing equipment by improving formulations. For example, products that improve droplet size distribution of sprays may reduce the potential for pesticide drift from the application area (60). Liquid formulations, with a uniform state and higher quality control in manufacture, may increase uniformity of application (73). Controlled-release formulations (e.g., starch-encapsulated herbicides, ethylene vinyl acetate copolymers incorporated with pesticides) may reduce leaching potential in certain soils (73).

Formulation directly affects the physical properties of the final spray material and is an important factor in achieving accurate flow-rate measurements over a wide range of sprayer application rates (60). Similarly, if formulation fails to exploit the physical properties of a soil insecticide, delivery efficiency may be improved by application technology (72) and careful determin ation of application rates.

Pesticide Application Rates

Significant effort in terms of exhaustive field trials under varied climatic conditions goes into setting the recommended use rate for a pesticide-the level at which application is effective and meets environmental acceptability standards. Setting the application rate too low generates risk of product failure while setting it too high risks denial of approval by regulatory agencies (60), increases product cost, and lowers the flexibility in meeting food tolerance standards.

The trend toward reduction in active ingredient applied per acre has resulted in steadily declining application rates of insecticides from nearly 4.5 lb/acre (with carbaryl) to as low as 0.2 oz/acre with the new synthetic pyrethroids (73). However, these lower application rates generally indicate powerful active ingredients that may damage the crop if improperly applied. Small amounts of pesticides used per acre suggests that intrusion rates into surrounding environment would also be low. This suggestion, however, is complicated by the fact that off-target movement can vary widely depending on numerous variables, including crop type, soil factors, application system, rate and frequency of chemical application, and time of year. The capability to deliver small pesticide amounts effectively is questioned (71), suggesting that improvement in delivery systems should accompany efforts to enhance the intrinsic activity of pesticides.

Identification of pest tolerance levels for specific crops and cropping systems may offer another opportunity to reduce pesticide use. Weed-free fields, for example, may not be economically optimal. In a weed tolerance experiment conducted by ARS and Colorado State University, a one-sixth reduction in herbicide use had no effect on corn yields (cf: 103,137). These results suggest that reduction in chemical use may not necessarily result in depressed yields. Label-recommended application rates are developed on a nationwide basis; however, further work that identities what level of application produces economic yield could assist in revision of recommended application rates for specific sites and cropping situations.

Improved methods of delivering a pesticide to a selected target may affect application rates as well. Recently, the conventional practice of intermittently banding aldicarb granules along a row of trees (citrus) was replaced by a system based on sensing the trees with infrared photocells and then metering out the needed quantity of granules. Thus, the same pest control effect was achieved using significantly less material (73).

Pesticide Application Technology

The goal of pesticide application technology is to allow deposition of a precise amount of a formulated product on a specific target without exposing nontarget organisms to the pesticide (60). However, basic understanding of the complexities of agrichemical application technology has not kept pace with advancements in chemicals themselves or with public concerns for the environment (73). Chemicals that decompose readily and rapidly in the soil are of lesser concern than more persistent compounds that may be distributed broadly in the environment.

In general, costs of herbicides and insecticides have increased over the past 3 years, Pesticide manufacturing prices and dealer costs (e.g., liability insurance) have increased as well during this time period (table 4-10). This trend may create some incentive for producers to focus on more cost-effective applications of pesticides.

Since the early 1980s there have been numerous meetings and conferences focusing on agrichemical application technology and its role in determining the environmental fate of chemicals. The first national conference on the subject in 1985 concentrated on the hardware aspects of application technology and a following conference in 1988 focused on operator training and technology for improved operation of application equipment. However, few of the recommendations that emerged from these meetings have been followed (60).

While the efficiency of many application techniques is known to be low, the inherent variation of biological systems and a lack of significant research and development efforts hinder improvement. Lack of calibrated equipment is the number one problem for effective pesticide management-current equipment cannot easily deliver consistently lower pesticide rates with the necessary accuracy (73). Opportunities for improvement in application technology lie in permitting variable amounts of pesticide to be applied within a field (60) and in improving application accuracy. This may be done by improved calibration, mixing calculations, and monitoring equipment; equipment for incorporating pesticides that need to be mixed with the soil to proper soil depth; and education in the use of such equipment (60).

Table 4-10-U.S. Average Farm Retail Pesticide Prices

Pesticide[a]	1987	1988	1989
	Dollars per pound (active ingredient)		
Herbicides:			
Alachlor	4.84	5.10	5.40
Atrazine	2.20	2.28	2.7
Butylate	3.04	3.10	3.10
Cyanazine	4.63	4.78	5.03
Metolachlor	6.03	6.21	6.61
Trifluralin	6.3	6.45	6.60
2,4-D	2.44	2.53	2.60
Composite[b]	4.05	4.2	4.43
Insecticides:			
Carbaryl	3.9	4.06	4.07
Carbofuran	9.57	9.36	9.51
Chlorpyrifos	8.25	8.5	9.05
Fonofos	8.70	8.83	8.96
Methyl parathion	2.82	2.94	3.85
Phorate	6.59	6.68	6.85
Pyrethroids[d]	48.8	50.00	53.20
Terbufos	9.79	9.88	10.13
Composite[b]	10.25	10.57	10.88

[a]Derived from the April survey of farm supply dealers conducted by the NASS. USDA.
[b]Includes above materials and other major materials, not products registered in the last 2 to 3 years.
[c]Supplied by Fred Cooke, MS Agricultural Experiment station.
[d]Average of fenvalerate and permethrin prices based on 2.6 pounds of active ingredient per gallon.

SOURCE: U.S. Department of Agriculture, Economic Research Service, *Agricultural Resources: Inputs, Situation* and Outlook AR-15 (Washington, DC: U.S. Government Printing Office, August 1989), p. 26.

Pesticides commonly are only as effective as the application method (60). Changes in product packaging and formulation pose one of the greatest challenges to development of pesticide application equipment. Such formulation changes can affect the physical properties of the final pesticide material and thus affect the efficacy of the delivery mechanism. Pesticides used selectively to control specific pests without adversely affecting beneficial organisms may require highly precise application technology capable of delivering the compound at a rate small enough to avoid affecting beneficial organisms, yet large enough to control the pest.

Recent trends toward foliar-applied pesticides and lower application rates will require increased precision in application technology than was needed a decade ago. While these new trends have potential to decrease over application and to reduce contact of pesticides with the soil and thus soil water, the requirements for increased application precision

may exceed current application technology capability (60).

Simultaneous application of several pesticides (tank mixes) has increased dramatically, placing added requirements on pesticide application technology. This trend is particularly significant for injection sprayer systems because up to three different pesticides may be injected into the sprayer boom during application. Still other requirements are arising with the trend toward faster, lighter weight applicators that apply pesticides at low or ultra-low sprayer application rates and with less diluent (water) (60).

Pesticide application technology research and development started to increase in the 1960s and peaked in the 1970s. However, Federal and State research efforts have diminished significantly since that time with herbicide application technology effort alone decreasing from 11.1 scientist years to 2.5 between the years 1972 and 1982 (table 4-11). Similar trends are found in equipment development for insect and disease control (60).

Resources invested in development of application equipment are small relative to those invested in pesticide product development, which may range from $20 to $40 billion over 7 to 10 years (60). Advances in chemical technology have and continue to outdistance research and development of application technology. Causes for this condition include depressed equipment sales; lack of financial incentives for fundamental research by the application equipment industry; lack of basic information about the application process; and inadequate communication among users, manufacturers, and researchers (73). Only recently have some of the larger chemical companies tried to coordinate formulation development with application technology; much more effort is needed, however (60).

Currently ARS has the largest investment in application research effort. This is concentrated primarily in Texas, the Southwest, and Ohio. Development of agrichemical application equipment also is significant in the United Kingdom and some eastern European countries. Improved granule distribution equipment has been developed in France (60).

A few small companies, specialized to serve different market segments, are the major developers of pesticide application technology in the United States. Most large machinery manufacturers do not consider application equipment to be an important profit segment of the market but rather an essential complement to other product lines. For example, there are only two U.S. manufacturers of nozzles, valves, screens, and other hydraulic sprayer components (60). Herbicide application technology has lagged ever further behind that of insecticide and fungicide application technology, even though herbicides account for most pesticide use (71).

Table 4-n-Agricultural Engineering Research for Weed Control Equipment Development

Year	ARS	State	Total
	(SY)	(SY)	(SY)
1972			
1974	4.3	2.0	6.2
1977	2.9	1.5	4.4
1979	2.8	0.7	3.5
1982	1.7	0.8	2.5

SOURCE: C.G. McWhorter and M.R. Gebhardt (eds.), *Herbicide Application Technology* (Champaign, IL: Weed Science Society of America, 1988), p iii.

Despite relatively small investments in development of application technology, improvement has been made in overall accuracy of application equipment. Equipment designed to apply pesticides within plus or minus five percent of the recommended rate now exists. This constitutes a vast improvement over equipment used 40 years ago. Various pesticide applicator designs have been developed to increase uniformity of spray coverage, reduce drift, increase deposition at desired locations, and reduce volume of diluent-i.e., hydraulic sprayers, pneumatic sprayers, airblast devices, propeller-driven applicators, spinning cages, and spinning disks.

Certain application equipment development efforts are focusing on increasing the application accuracy by improving existing sprayer components. Although basic sprayer components have not changed, they are manufactured more accurately and have improved hydraulic components. Further, several new components designed to improve application efficiency are now available, many of them using modern electronics to control the application rate and to measure the amount applied per field or unit area. Most sprayers are now equipped with devices to agitate the spray mixture to ensure that the formulated pesticide stays in suspension (60).

Improved maintenance and calibration technology is the most significant short-range improvement that can be made to agrichemical application equipment, requiring no great amount of research but time for development. Some companies now offer kits to aid in calibration.

Technology and engineering concepts from other sciences and industries might be applicable to pesticide application technology; however, such interchange has been insufficient (71). Technology existing within the military and industrial manufacturing complex could be adapted for agricultural applications. For example, developing automatic guidance of sprayers and other equipment could improve efficacy of many products by eliminating skips and overlap. Improved flow rate measurements could also improve agrichemical application accuracy. Many small improvements, when aggregated, overall could have a significant beneficial effect on reducing agrichemical waste. Such an effort, however, may be quite difficult given the current state of the farm equipment industry (60).

Currently, three basic techniques exist for agrichemical application: ground-based, aerial, and chemigation (208). Ground-based and aerial pesticide applications generally are accomplished by spraying or wiping liquid formulations on plant surfaces or broadcasting pelletized forms. The majority of pesticides are applied as sprays with ground-based equipment using a hydraulic spray nozzle (208,60), although aerial application of agrichemicals is substantial (35 percent of all chemicals (73)).

Wicks, rollers, and other wiping devices offer the best available method for effectively eliminating application of herbicides onto the soil, but these application methods require sufficient weed growth to provide contact of foliage and stems with the topical application. Since weed growth is variable, several trips around the field may be necessary for control. However, this technology needs further development, especially if soil-applied (preemergence) herbicides are banned (60).

Electrostatic sprayer technology has been very successful in the commercial painting industry, but this technology has yet to show significant promise for agriculture—its greatest potential is for application of insecticides to plant foliage where coverage is very important for insect control. It may also be important technology as postemergence herbicide use increases (60).

The injection sprayer mixes formulated pesticides in the boom of the sprayer on the go during field

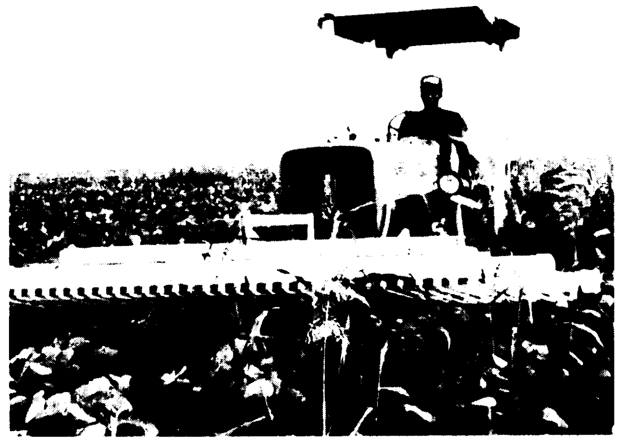


Photo credit: USDA Agricultural Research Service, Southern Weed Science Laboratory, Stoneville, Mississippi

Herbicide application with rope-wick applicator.

Photo credit: USDA Agricultural Research Service, Southern Weed Science Laboratory, Stoneville, Mississippi

Close-up of rope-wick applicator.

application, thus avoiding premixing and handling; the diluent is stored in a large tank on the sprayer. Only the pesticide actually applied is mixed into the spraying system-no residual material is left except what is contained in the boom. Direct injection of pesticides on the go should be evaluated for adoption by sprayer manufacturers. The technology is now commercially available (138,173) and offers an opportunity to reduce point source contamination from disposal of rinsate and mix-disposal problems.

Losses of agrichemicals during ground-based spraying operations may be reduced by shrouds or shields that reduce the effect of wind and other environmental conditions that may affect drift or evaporation. Such approaches may most directly affect air quality and ultimately water quality from atmospheric deposition.

In response to concern over environmental contamination from aerial application, the National Agricultural Aviation Association developed Operation SAFE (Self-regulating Application and Flight Efficiency). However, procedures for drift containment, waste disposal, rinsing, packaging, and container transfer/handling are needed to hold drift and environmental contamination to minimum under SAFE (73). Efficiency of aerial application could be increased by controlling the range of droplet size and developing pest-target-specific delivery devices (73).

Chemigation is the application of agrichemicals to crops through an irrigation system. The pesticide is mixed and distributed with water flowing through the irrigation system (208). It is a relatively new agrichemical application technology and is primarily used in conjunction with sprinkler irrigation systems. The concept of applying plant nutrients in irrigation water by dumping animal manure into irrigation canals likely arose hundreds of years ago; however, the basic concept of applying commercial fertilizer through sprinkler irrigation emerged only about 30 years ago. Now advances in irrigation system design and chemical injection equipment have produced technology for expanding chemigation to include all types of crop inputs (i.e., fertilizers and pesticides) (208).

Advances in chemigation technology may offer significant promise for reducing potential groundwater contamination by agrichemicals (223). Some examples include:

- wider use of advanced irrigation scheduling techniques,
- development and use of irrigation techniques that improve uniformity of distribution,
- development of agrichemical formulations particularly suited to chemigation,
- performance standards and reliability testing procedures for chemigation,
- backflow prevention systems (required by EPA), and
- exploitation of agrichemical application scheduling diversity offered by chemigation (208).

By controlling the amount of water applied and selecting a proper formulation, a chemical can be deposited either on foliage or the soil surface or distributed to a desired soil depth (208). However, chemigation techniques have been shown to promote leaching of chemicals under certain conditions such as wet years when heavy precipitation follows chemigation (223).

Application of agrichemicals via chemigation is subject to local, State, and Federal laws and regulations, labeling mandates, and guidelines by several professional societies. The American Society of Agricultural Engineers (ASAE) has described system components and presented an arrangement of these components comprising a functional system for minimizing potential environmental contamination and maximizing operator safety (ASAE Engineering Practice EP409). Combination of these efforts has resulted in broad consensus on appropriate, commercially available chemigation system components to achieve maximum practical prevention of chemical backflow into water sources (208).

Sprinkler irrigation systems, particularly center pivot and linear move systems, are ideal for chemigation because chemicals can be applied to foliage and soil-most insecticides and fungicides, many herbicides, and most growth regulators need to be applied to foliage. Chemigation via surface irrigation seems less desirable due to inherent difficulties in uniform water distribution. It is impractical and uneconomical with subirrigation systems (208).

Microirrigation systems with emitters or porous pipes are effective for chemigation of soluble nutrients and pesticides needing distribution through the soil; such systems with miniature sprinklers can chemigate soluble foliar-applied chemicals. However, small openings are a constraint for chemigation with microirrigation systems, limiting utility to soluble chemicals (208).

Advantages of chemigation relative to other agrichemical application approaches include:

1. increased uniformity of chemical application,
2. prescription application (timing and quantity),
3. easy chemical incorporation/activation,
4. reduced operator hazards, and
5. cost-effectiveness.

Under highly efficient chemigation systems potential exists to reduce agrichemical requirements for crop production, which could have a beneficial effect on groundwater quality. However, such systems also require a greater degree of management attention and further potential exists for backflow of chemicals into the water supply (208).

Timing of Pesticide Applications

Timing of pesticide applications is critical to the overall efficacy of use, Application during inappropriate weather or premature applications can release chemicals into the environment and yet not accomplish the desired pest control effect. Such circumstances may lead to the need for several applications to achieve pest control.

Timing, however, is problematic given the often narrow windows of opportunity for pesticide applications, particularly when such timing must also fit a custom applicator's schedule. Application equipment is costly and the trend toward purchasing the service of the custom applicator as opposed to owning and operating personal agrichemical application equipment may increase difficulties in timely agrichemical applications.

Use of economic injury levels and pheromone traps as decision aids to improve the timing of pesticide applications is a feature of improved management (95). Pest-prediction models (e.g., prognosis models, economic injury models, crop-1oss models, prediction of pathogen or aphid intensities) may improve practitioners' ability to match timing of crop-protection measures with pest infestations.

Alternative Control Methods

Nonchemical pest control methods such as crop rotations, crop monitoring, use of resistant varieties, timing of planting and harvest, and biological controls were prevalent prior to World War II.

Photo credit: U.S. Department of Agriculture, Agricultural Research Service

Insect parasites that colonize and develop within other insects are one type of biological control. Here, a parasitic wasp lays eggs in a tobacco budworm host.

Low-chemical-input producers use a number of these practices to control insect and weed populations today.

Cultural controls include a broad range of production practices that render the crop environment less favorable for the pest. Although widely used in the past, the more labor-intensive cultural controls were practiced less with the advent of the chemical era. Tillage and water management are effective cultural controls in the management of weeds. Tillage may also bury weed seeds. Further, increases in mortality in many insects that overwinter in the soil are likely to result from tillage practices. The destruction of crop residues may be important in the management of many pests, such as navel orangeworm in almond, late blight of potato, stem rot of rice, and pink bollworm and boll weevil in cotton. For these, compulsory plowdown dates exist in several regions as part of regional pest control programs.

Manipulation of planting and harvesting dates permit breaks in the development of pest populations in regions where pests develop throughout the year. Crop rotation can also be used to break the life cycles of many pest species. Applying fertilizer with the seed of annual crops or through drip-irrigation systems may also provide a measure of weed control, especially in contrast to broadcast applications.

Genetic controls include the traditional breeding of plant varieties resistant to pests and biotechnological approaches to conferring pest resistance in crop plants (see section on cultivar improvement). This second approach involves the introduction of genetic material that governs resistance characteristics such as toxin production. Genetic control may also be applied to the insect pest directly, for example, to create sterile organisms that will interrupt the natural pest population lifecycle. This method has been used to control screwworm in cattle, pink bollworm in cotton, and the Mediterranean fruit fly.

Mechanical control methods, common before the development of modern pesticides, are still used. Many crops require cultivation several times during the growing season. For example, soybeans in the Midwest receive more cultivation than corn largely due to the availability of long-lasting residual herbicides suitable for corn and not for soybeans, and to later planting time for soybeans (60,203).

Pheromones, viruses, bacteria, fungi, and bioengineered organisms have been touted as alternatives to conventional pesticides; however, their use is not widespread in part due to lengthy testing and registration procedures required under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (254).

Biological control is commonly considered the cornerstone of any integrated pest management (IPM) program. Often referred to as biocontrol, it is a biological approach to pest control that employs the use of natural enemies-predators, parasites, and disease-to reduce a pest population. This may involve the introduction of a natural enemy (classical biocontrol), rearing and periodic release of natural enemies (augmentative biocontrol), or conservation of a natural enemy extant in the agroecosystem (conservative biocontrol).

Augmentative and conservatory approaches to biological control often will require behavioral changes on the part of the practitioner. Because these methods rely on the acquisition and release of natural predators or conservation of those extant in the agroecosystem, respectively, such methods require an understanding of pest cycles, predator/prey relationships, and the biotic factors responsible for maintaining populations of beneficial organisms. Thus, to promote adoption of these techniques it is necessary to understand the factors that influence practitioner choice of pest-control methods, such as: 1) what the long-range goals are and what external factors affect how pest control methods are selected, and 2) what level and type of technical assistance will be needed and accepted by the practitioner.

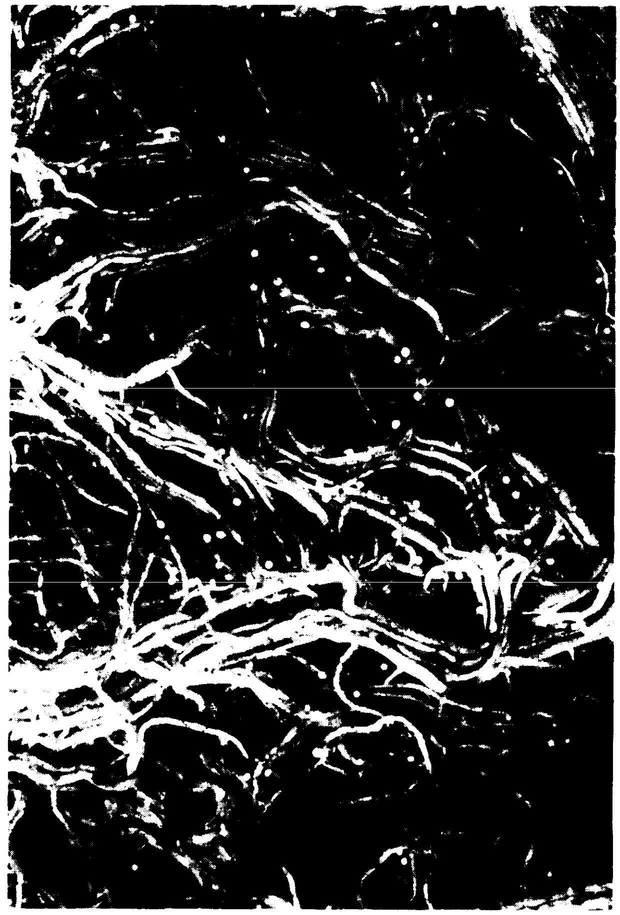


Photo credit: U.S. Department of Agruculture, Agricultural Research Service

Although commonly an agricultural pest, certain nematode species also are useful as commercial biological control agents. Augmenting or maintaining populations of beneficial nematodes has been shown to be an effective control measure for certain root weevils. Shown here are nematode cysts on plant roots.

Control of cottony-cushion scale on citrus in California was achieved by importation of the Vedalia lady beetle in 1888. Biological agents, primarily insects and plant pathogens, currently are applied to control as many as 100 weed species. Substantial control has been achieved for numerous weed species (e.g., klamath weed, prickly pear, lantana) (151). Additional examples of successful development and marketing of weed biocontrol agents include the use of *Collectotrichum gloeosporioides* on northern joint vetch and *Phytophthora* on stranglevine of citrus. Lack of funds for commercial development of biological control agents and biological pesticides, including bacteria, fungi, and viruses, has limited their availability and increased their price (96). Currently, 68 U.S. suppliers participate in a $25 million market in the global distribution of biological pest-control agents (92).

The narrow foundation of basic research may pose an obstacle to expeditious development of technologies to reduce environmental contamination b y agrichemicals. The agricultural research foundation could be expanded to emphasize the biological, ecological, and systems sciences to a much greater extent. These research areas, however, have received comparatively little attention and funding in public-sector programs. Research funding for Integrated Pest Management (IPM) programs, for example, has declined in the last ten years (254).

Another obstacle to the development of alternative pest control products is the high cost of commercializing new biological products, which discourages firms from expanding technologies available to farmers. Although the development costs of one of the frost commercial mycoherbicide (biological controls designed to combat fungal pathogens) was approximately $2 million as compared to nearly $30 million for development of a chemical herbicide (7), the marketing potential, stability, shelf life, and potential for mass production are issues of particular concern in commercializing a biological control agent, Costs of meeting regulatory requirements for registering new products and uncertainties as to whether or not products will be allowed to go on the market also may provide a disincentive to investment in new-product research. Even when products are placed on the market, uncertainty exists as to whether regulations will change, causing a product to be restricted or banned.

Specialized registration procedures for alternative pest control products (e.g., biological controls, fungi, viruses, and bacteria) might facilitate more rapid development and marketing of these products. Some allowances exempting certain aspects of registration for these products have already been made. For example, recently a nematicide developed from processed crustacean sheik received unconditional EPA approval (50). Although currently a small part of the market, such ''pesticides' present an alternative to certain traditional compounds (254). The specificity of such compounds means that the potential market is small in comparison to that of traditional compounds. Grants or tax incentives might promote development. Additional incentives for private development and marketing of innovative pest controls could promote this sector of the agrichemical industry. Additional research will likely be necessary to assess the potential for adverse impacts generated by use of nonchemical pest controls to the U.S. environment.

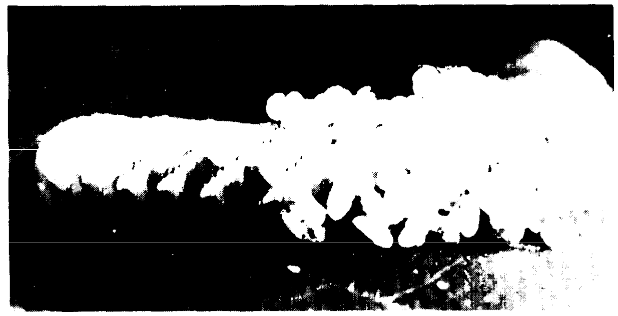


Photo credit: University of California-Riverside+Vancy E. Beckage

Parasitic wasp larvae have hatched and are feeding on this tobacco hornworm host. Use of natural predators may help control insect pests that cause billions of dollars of damage.

Integrated Pest Management

Integrated Pest Management (IPM) is a systems approach to pest control that is designed to provide benefits (economical, environmental) to the user and society. Where possible, IPM programs attempt to restructure an ecosystem to minimize the likelihood of pest damage. Programs are meant to be adaptive with a goal of improving program efficacy overtime. The broad goal is to maintain pest populations at near-harmless levels by reducing population fluctuation and to improve the predictability of control measures. IPM programs commonly are composed of a number of the pest control tactics discussed above.

The key concepts behind IPM are that:

- a threshhold population level exists, below which pest control is not economically practical;
- integration of chemical and natural methods of pest control is possible; and

- a sound understanding of the agroecosystem being managed is needed (including host, pests, natural enemies, competitors, alternate hosts, etc.) as pest populations interact with other ecosystem members.

The development of an IPM program requires thorough knowledge of the ecosystem being managed, the social and economic goals or reasons for its management, and the incentives and constraints imposed by social, economic, political, and regulatory rules and values. This knowledge comprises the framework within which an effective IPM program can be built. Thus, the system being managed and its specific needs are analyzed prior to design of the pest management strategy.

A common perception of IPM programs is that they represent a return to past, labor-intensive practices. While it is true that strategies may employ cultivation or crop-rotation practices that served to control pest populations in early U.S. agriculture, new techniques also are integral to modern-day IPM programs. Further, IPM does not mean the absence of chemical controls. Indeed, in certain instances chemical use may even increase under IPM. This effect sometimes may be attributed to recognition of a theretofore unnoticed pest population.

However, IPM programs have resulted in a significant decrease of pesticide use in several crops. These reductions in pesticide use occur because practitioners are trained to pay careful attention to the actual need for the pesticide, as well as its timing and application (254). For example, in an IPM program implemented in Egypt to control cotton leafworm, corn aphid, and three species of corn borers, the area that had to be treated with chemicals dropped from 692,000 to 22,000 acres within 5 years (43). IPM programs frequently are characterized by a combination of tactics designed to keep pest populations at a level below which economic injury would occur.

Growers may adopt IPM for a number of reasons. The most influential factor seems to be the potential for financial gain due to reduced inputs, increased production, or reduced pest damage (cf: 68,248). Recently, in response to public concern over pesticide residues in or on food, certain retailers have begun to advertise ''no detectable residues, ' with IPM being one of the marketing tools. The potential for entering new or premium-price marketing channels is causing some growers to reconsider their pesticide-use practices. For example, the New York State regulatory agency, at the request of growers and following guidelines being developed by the IPM program of Cornell University, is initiating a certification program for growers who produce crops using IPM practices (204). It seems likely that financial incentives or disincentives provided through government programs would have an impact on adoption of IPM and other low-input agricultural methods (254).

Photo credit: U.S. Department of Agriculture, Agricultural Research Service

A Mexican bean beetle-a major pest of snap- and soybeans-becomes a meal for the spined soldier-bug. Introducing, attracting, or maintaining populations of such natural predators in fields is one possible component of Integrated Pest Management systems. Increased understanding of plant-pest-predator-farming system interactions will allow for more efficient use of such biological controls in the future.

A crisis in pest control such as resistance to pesticides (cf: 33,66,96), loss of key pest control materials due to regulation (253), or severe secondary pest outbreaks may stimulate some producers to adopt IPM tactics. Environmental and on-farm health concerns were an important stimulus to IPM research, but they have typically contributed to adoption only because of some obvious problem or because of regulation resulting from a concern or problem (201). Growers rated protection of personal and public health and reduced environmental damage as the two least important incentives for adopting IPM in the national evaluation of extension IPM programs (163).

A number of constraints to IPM use have been identified in various studies (32,68). Obstacles fall into the following categories: technical, financial, educational, institutional, and social (246).

Technical Constraints-Insufficient development of IPM strategies and techniques such as monitoring guidelines, control action thresholds, biological controls, cultural controls, and host plant resistance for a wide variety of cropping systems comprise the primary technical obstacles. However, the technical constraints are regarded to be less important than other constraints (cf: 70,151). Simplification of IPM methodology may foster adoption of monitoring and sampling guidelines and control-action thresholds (5,33,65,96).

Financial Constraints-While IPM implementation commonly increases profits for adopters, there remains a perception that it does not offer the short-term economic advantages equal to those generated by conventional control, largely because of the additional labor costs from sampling and monitoring (157). The concept of purchasing the advice of private pest consultants and others providing IPM services still may be difficult to accept, particularly since costs are incurred in advance of pest problems, and even if no pest problem occurs (254).

Financial risk may be the most important obstacle to IPM adoption. Growers value pesticides for reducing production risk as well as contributing to profit. However, the more producers learn about pests in their fields and the likelihood of resultant damage, the more likely they are to make wise pesticide-application decisions. The value of IPM in terms of risk reduction may actually increase in relation to the grower's level of risk aversion (4).

Lack of funds for extension programs has been cited as a constraint to IPM adoption in numerous studies (cf: 58,202,248). Where such projects as the Federal extension pilot projects of the 1970s and State-supported IPM projects (e.g., California, Texas, and New York) have been initiated, enhanced IPM adoption can be documented. At present, most extension IPM activity occurs at the State level with a combination of State support and Federal formula funds. However, Federal funds have not increased during this decade, and the areas where major extension efforts are occurring are those with significant State contributions (254).

Educational Constraints-Implementation of IPM requires a complex set of methods, technologies, behaviors, and decisionmaking processes requiring intensive education of uses. However, it has been suggested that lack of education of IPM developers about the perceptions and needs of growers also comprises a significant obstacle (cf: 65,174). Such lack of understanding can lead to development of an inappropriate technology that is unlikely to be adopted (254).

Institutional Constraints-The structure and codes of regulatory, educational, and corporate or industrial institutions can influence the implementation and expansion of IPM programs. Lack of coordination, especially among organizations, personnel, and disciplines, may be particularly problematic (105,15 1).

Efforts to mandate or regulate IPM specifically have not been highly successful. For example, adoption of a mandated IPM program for lessees on State-owned land in California declined rapidly with the lack of enforcement (67). The cause was assessed as a lack of experience on the part of the State agency involved in addressing producer concern for risk (254),

Lack of interdisciplinary collaboration in IPM research, extension, and education has been suggested as a major constraint to more widespread use of IPM strategies (cf: 12,17,130). A tendency for research and education activities to be conducted within strongly discipline-oriented departmental units in land-grant universities has evolved in response to institutional pressures. Individual achievements rather than team accomplishments typically are rewarded (155), leading to the predominance of such efforts at the expense of multidisciplinary work. Programs leading to interdisciplinary, professional degrees rather than research degrees in plant health and pest management are few, and not well supported within higher education institutions (102).

Other organizational obstacles also exist, most notably cosmetic standards imposed by such agencies as the Federal Food and Drug Administration, USDA, and State departments of agriculture; corporations including processors, packers, and retailers; and commodity associations such as cooperatives and marketing orders (32,53). These quality standards have largely been imposed because of consumer demands, but also may be used as market regulating tools (254).

Social Constraints-The rate at which adoption occurs and the ultimate level of adoption may be affected by many social factors including demographic attributes of the agricultural population, communication channels used by growers or managers, and growers' perceptions of the technology. Growers receive pest management information from a variety of sources and in this regard chemical controls may have a competitive advantage over IPM. A well-established infrastructure exists for pesticide supply and use and a high ratio of commercial representatives exists relative to private pest management consultants or extension IPM personnel (237,189).

Agrichemicals are seen as easy to use despite regulations on their use and application and associated increased costs. In addition, pesticides give nearly immediate reinforcement in terms of pest control. Thus, most growers have developed confidence in their use (32,96,245). Alternatively, IPM often requires additional labor or specific knowledge, and may take longer to realize benefits. Further, the concept of economic thresholds is perceived as risky by many growers (155). However, experience with IPM may change this risk perception (68).

Photo credit: ***United Nations-M.*** Tzovaras

Past plant breeding efforts have been highly successful in increasing productivity of crops such as wheat. Current efforts are now being directed towards developing crop varieties that are more suited to specific cropping situations or are able to withstand a number of environmental stresses (e.g., drought tolerance, pest tolerance). Such efforts may reduce agrichemical inputs that are needed to compensate for agricultural production in unfavorable environments.

CROP, SOIL, AND WATER MANAGEMENT

Management of the soil and water environment for crop production requires an understanding of the interaction of these cropping-system components, and of the suitability of the chosen crop(s) for the agroecosystem. Production of crops ill-suited to a given region may require more intensive external inputs, such as pesticides and fertilizers, to overcome the associated plant stress responses and to achieve acceptable yield levels. Productivity of current crops falls far short of their potential, largely because of production in unfavorable environments (16).

Soil- and water-management techniques offer a mechanism to adjust or modify the agroecosystem to enhance crop production and thus affect the requirements for external inputs. For example, soil-management practices designed to improve the friability and moisture-holding capacity of soils can facilitate crop root development. This in turn may improve the plants' nutrient extraction capability, thereby reducing the need for external nutrient inputs.

Crop Management

Crop management refers to the numerous decisions that most directly relate to the crop, including cropping pattern (e.g., rotation, intercropping) and

Photo credit: U.S. Department of Agriculture, Agricultural Research Service

Maintaining a winter cover crop, interplanting one crop into another, and reduced tillage systems, involving leaving crop residue on the soil surface, may provide slow release of plant nutrients and promote nutrient "scavenging" from soils that otherwise might become available for leaching to groundwater. Conversely, some reduced tillage systems may require intensive use of herbicides and promote infiltration of water through the plant root zone. Care is needed to balance factors in designing farming systems.

crop or cultivar choice. Certain crop-management alternatives and techniques may complement or enhance nutrient and agrichemical management activities. Crop-management decisions may have direct impacts on agrichemical use and on how such compounds will behave and move through the agroecosystem. Crop choice alone has instant implications for the pesticide and fertilization regime a producer will use. For example, greater amounts of nitrogen fertilizers and pesticides are used to produce corn and cotton than are used to produce other crops (225,226). Similarly, certain cropping patterns such as a legume-based crop rotation may provide a mechanism to supply plant nutrients and break pest cycles for a subsequent crop and thus reduce agrichemical requirements.

Cropping Patterns

Successive planting of different crops in the same field--crop rotation—was a common practice in early U.S. agriculture. Practitioners maintained a diversified production system in order to provide livestock forage and various other crops. However, with expanded use of chemical fertilizers and pest control compounds and availability of high-yielding crop varieties, the practice of crop rotation declined in favor of continuous production of one or two crops (6).

Crop rotation and associated crop diversity may retard pest buildup by creating conditions that hinder development of pest populations and enhance the soil-nutrient content (162). Thus, such production systems tend to have lower agrichemical require-

Table 4-12-Common Crop Rotations Used on Land Producing Soybean-1988

Previous crop 1987	1986	AR	GA	IL	IN	1A	KY	IA	MN	MS	MO	NE	NC	OH	TN	Total area
		Million acres planted														
		3.25	0.9	8.8	4.3	7.95	0.98	1.8	4.9	2.4	4.3	2.4	1.47	3.9	1.4	48.75
		Percent														
soybean	Corn		7	7	16	6	18	10	7	1	17	12	9	24	8	10
soybean	Soybean	40	34	5	9	3	8	44	2	58	24	3	16	11	38	15
soybean	Other	13	7		2	1	2	7	3	18	7	2	4	8	6	4
Corn	Corn	nr	8	11	19	7	13	4	7	nr	6	17	4	7	4	8
Corn	soybean	1	4	61	41	74	34	nr	51	1	24	43	32	30	9	41
Corn	Other	nr	3	4	3	5	11	nr	6	nr	3	8	8	9	9	4
Wheat	Other	1	11	3	2	1	9	2	10	2	5	8	6	6	8	4
Rice	Soybean	17	nr	nr	nr	nr	nr	14	nr	4	nr	nr	nr	nr	nr	2
Rice	Other	5		nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr
Fallow[a]	Other	9	10	5	4	3	1	13	4	15	3	1	6	2	4	5
	Total	86	84	96	96	100	96	94	90	99	89	94	85	97	86	93

[a]Fallow includes land idled under farm Commodity program provisions.

NOTE: Entries made as nr indicate that data for that item was not reported.

SOURCE: U.S. Department of Agriculture, Economic Research Service, *Agricultural Resources: Inputs, Situation and Outlook,* AR-1 5 (Washington, DC: U.S. Government Printing Office, August 1989).

ments (136). Continuous cropping-planting the same crop on the same land in successive years-has the lowest degree of diversity and tends to be associated with intensive agrichemical use. More pesticides are needed to combat the pest populations that may develop in response to the consistent food source and field conditions. Such cropping systems may represent a greater potential for agrichemical contamination of groundwater in hydrogeologically vulnerable regions because of the higher levels of agrichemical input associated with continuous cropping.

Federal commodity programs have been said to discourage crop rotations and diversity (136). However, continuous cropping is not as widespread as this might suggest. Continuous cropping is most prevalent for cotton in the Southeast, corn on irrigated lands in Nebraska, winter wheat in Oklahoma and Texas, soybeans in Mississippi, and rice in California. In the major corn-producing states, 38 percent of the corn acreage was in rotation, while 26 percent was in continuous cropping during 1985-88 (228).

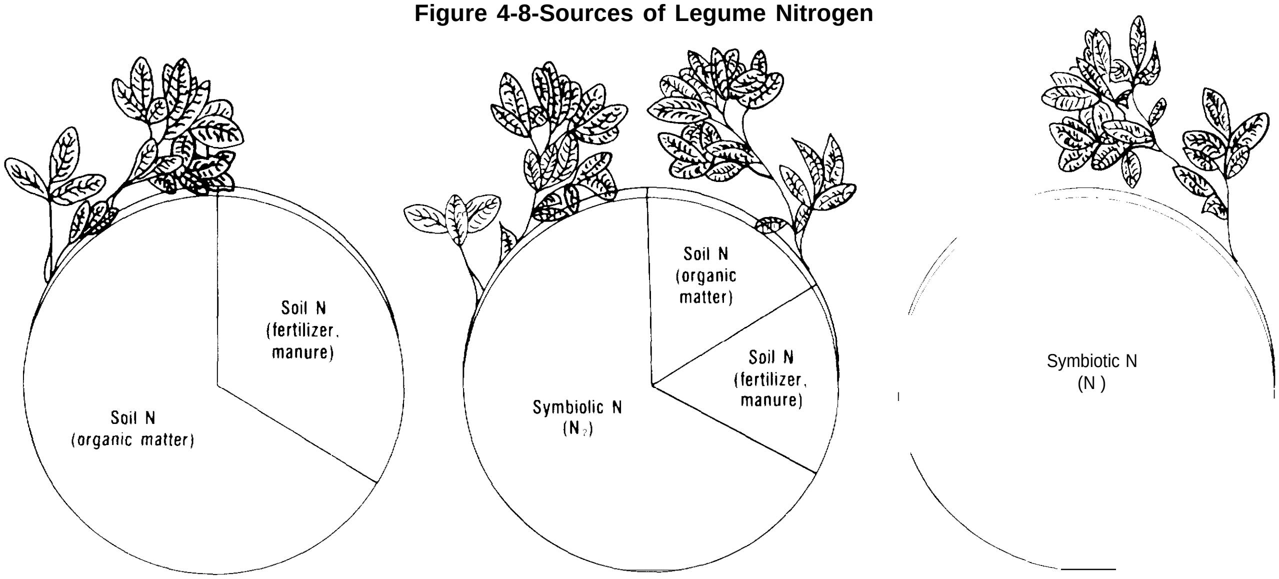
Nevertheless, most crop rotations commonly used by farmers in the United States do not lend a high degree of crop diversity (table 4-12). Although at least 80 percent of the cropland in most States is characterized by some form of crop rotation, in many States only two or three rotations are widely used (228).

Sod-based crop rotations are used to minimize wind and water erosion. They also can be used to provide some nitrogen for later crops. Total soil loss is greatly reduced, although soil conservation is not equally distributed over the rotation. On many soils, crop rotations favor higher yields and improved crop quality (212) largely from enhanced soil structure and composition, addition of nitrogen, and other rotation effects. Rotation effects refer to the enhanced yield commonly associated with crop rotation beyond what might be attained under a continuous cropping regime. Such effects are noted under legume- and nonlegume-based rotations and thus are not necessarily solely attributable to deposition of nitrogen (9,87,90). Improvements in soil structure and composition, moisture storage capacity, and organic content and reductions in pest infestations are likely factors contributing to rotation effects (136),

Cropping sequence influences the water content of surface soils, on a gravimetric and volumetric basis (1 17). The volumetric water content is significantly greater in the upper soil profile under a legume-based rotation as compared to a fertilizer-based system (41,171). While legume-based cropping systems may increase organic content of the soil, the improved soil texture and porosity associated with such systems may have a greater effect on the availability of soil water to plants (86).

Legume-based crop rotations have been long known to improve the yield of subsequent nonlegume crops (154). Legumes derive nitrogen from three principal sources: through commercial fertilizer or manure application; by mineralization of

Figure 4-8-Sources of Legume Nitrogen



SOURCE: C.C. Sheaffer, D.K. Barnes. and G.H. Heichel, "Annual Alfalfa in Crop Rotations," Station Bulletin 588-1989, Minnesota Agricultural Experiment Station, St. Paul, MN, 1989.

indigenous soil organic matter; and by symbiotic nitrogen fixation (figure 4-8). The role of atmospheric nitrogen (N_2 or dinitrogen) fixation by legumes as one factor in the yield improvement became known early in this century (56). Use of legumes as "green manures"[5] in U.S. cropping systems peaked in 1940, when an estimated 13.0 million acres (3.5 percent of harvested cropland) were planted (179). The knowledge that forage legumes were capable of fixing atmospheric nitrogen fostered the belief that nearly all legume nitrogen was derived from this process, despite evidence that soil nitrogen substituted for atmospheric nitrogen in legume nutrition (3). Thus, the fertilizer replacement value commonly was based on the nitrogen content of the biomass incorporated as a green manure (196,185), without regard to the possible legume uptake and recycling of soil nitrogen. A net enrichment or renewal of the soil resource by fixed nitrogen in legumes can only occur when the legume is grown and managed with attention to returning the above-ground plant material to the soil rather than exporting it as hay or grain (84,85).

Different hay and pasture legumes grown on a soil with the same initial nitrogen concentration in the profile derive different amounts of nitrogen from symbiosis (table 4-13). The amount of nitrogen fixed varies with species, growth stage, and inherent soil fertility and may be further influenced by crop management practices, life form (i.e., annual v. perennial), and environment. Factors that promote high rates and high seasonal totals of nitrogen fixation in legumes include:

- optimum mineral nutrition at a pH slightly below neutrality (pH 6.5 to 7.0),
- long growing season,
- low concentration of plant-available soil nitrogen,
- optimum water availability, and
- absence of insects or pathogens.

The amount of legume-fixed nitrogen made available to a nonlegume crop depends on plant, environmental, soil, and management factors. In an intercrop situation where the legume and nonlegume are grown concurrently, observations have indicated that some nitrogen transfer occurs, conferring a benefit to the nonlegume (86). The amount of nitrogen transferred seems to vary depending on the species intercropped. The method and mechanism of transfer are unclear, however.

Under a rotational cropping system, several factors determine whether the nitrogen returned to the cropping system is a net input or simply a return of

[5] Green manure refers t. plant materials, generally legumes, used as a nitrogen Source for crop growth. Plowing under of these crop residues promotes decomposition and release of inorganic nitrogen that is then available for crop uptake.

Table 4-13-Variation of Dinitrogen Fixation Capacity With Legume Species

Species	Nitrogen from symbioses by harvest[a]	Dry matter Yield (lbs/acre)
Hay and pasture legumes:		
Alfalfa[b]	**63**	**6,809**
Red clover[b]	**65**	**6,230**
Birdsfoot trefoil[b]	**40**	**4,880**
	Harvest	***at grain maturity***
Grain legumes:		
Soybean[c]	**76**	**2,494**
Soybean[d]	**52**	**7,837**

[a]Mean percent over three harvests.
[b]Established in soil with 3.7% organic matter and an initial nitrate concentration of 12ppm at the O- to 6-inch depth.
[c]Established in soil with 1.8% organic matter and an initial nitrate concentration of 12ppm at the O-to 8-inch depth.
[d]Established in soil with 4.8% organic matter and an initial nitrate concentration of 31ppm at the 0- to 8-inch depth.

SOURCE: G.H. Heichel, "Legumes as a Source of Nitrogen in Conservation Tillage Systems," The ***Role of Legumes in Conservation Tillage Systems,*** J.F. Power (cd.) (Ankeny, 1A: Soil Conservation Society, 1987), *In:* Heichel, G. H., 1989.

soil-derived nitrogen, temporarily sequestered in the legume crop. For example, under certain conditions only 40 percent of total accumulated nitrogen in soybeans is freed from atmospheric nitrogen. After harvesting the crop for grain, a net export of nitrogen from the cropping system is observed. Under different conditions the same crop may fix nearly 90 percent of total accumulated nitrogen and post-harvest soil conditions will show a net nitrogen input (86).

Legume-based rotations remain a significant part of agricultural production practices. Food and feed crop legumes are the nitrogen-fining species of the greatest agricultural importance in the United States and totaled at least 89.7 million acres in 1986 (220). However, the impact such systems have on nitrate contamination of groundwater has not been well studied. Nitrogen from legumes may appear in groundwater due to mineralization of the organic forms of plant nitrogen to nitrate in soil solution, and when precipitation or irrigation sufficiently exceeds evapotranspiration to allow water loss from the root zone. Nitrogen may be released from legumes by: 1) direct release from the nodules (20,1 12); 2) decomposition of dead roots or nodules; and 3) soil incorporation of legumes. Any of these situations in combination with a leaching event may increase the risk that legume nitrogen will appear in groundwater (180).

Although the circumstances that promote nitrogen loss from legumes to groundwater may be easily predicted, only meager experimental evidence exists for leaching of legume-derived nitrogen to groundwater in U.S. cropping systems. Available evidence is limited in interpretation because the sources of nitrate lost from the root zones of legumes have not been unambiguously identified by origin-e.g., nitrate from living or decomposing legumes, from mineralization of soil organic matter, from fertilizer, or from other origins (86).

Intercropping—Intercropping refers to a variety of cropping patterns including mixed intercropping, strip intercropping, and relay intercropping. *Mixed intercropping* describes the growing of two or more crops simultaneously with no distinct row arrangement, while *strip intercropping* implies a distinct row arrangement of the intercropped plants. ***Relay*** *intercropping* is the growing of two or more crops with the second crop planted into the frost crop a.tier it has reached maturity but is not yet at harvest stage. These cropping patterns are used commonly in tropical agriculture to provide a diversity of agricultural products, to discourage the spread of pests across a field, and to allow for greater exploitation of the soil profile and nutrients than monoculture systems (214).

Intercropping combinations that include a nitrogen-fixing species may offer the additional benefit of providing nitrogen to adjacent crop(s) and thus reduce the need for nitrogen fertilizer applications. Similarly, use of deep-rooted species, such as alfalfa, may offer a mechanism to draw nitrate up from the lower soil profile and thus make it available for nearby, shallower rooted crops (152). The highly mechanized agricultural practices common in the contiguous United States may pose a constraint to widespread use of intercropping techniques.

Conservation Plantings-Conservation plantings, such as contour cropping, have been designed to reduce soil erosion and and surface runoff. While erosion control may have been the impetus for development of these practices, they may also provide beneficial effects on groundwater quality when used in combination with new strategies such as inclusion of nitrate-scavenging crop varieties. For example, strip cropping using a deep-rooted crop as one of the components may offer some potential for reclaiming nitrate in the lower soil profile (alfalfa roots may reach nearly 3 feet in one cropping season). Further, as the alfalfa roots draw soil moisture and nitrate up the profile, the nutrient

Photo credit: University of California-Berkeley-M.A. Altien

Intercropping systems offer potential for reducing agrichemical needs. Incorporation of nitrogen fixing species as one component of the intercropping system may offer nutrient provision benefits to the adjacent crop. Other combinations may include "trap crops" that provide barriers to pest movement through a field.

becomes available to nearby or interplanted crops as well (190)

Certain conservation practices that have been promoted since the 1930s as methods to reduce soil erosion from wind and water also serve to increase soil moisture and are valuable tools for protecting water resources (23 1,230). Hedgerows, shelterbelts, and field border strips consist of fast-growing, resilient herbaceous and woody vegetation planted between fields to trap snow on fields or to prevent snow from collecting in vehicle travel lanes. These plantings provide soil moisture benefits for subsequent crops and may offer additional benefits by taking up excess nitrate. However, they are located commonly along field edges, fencerows and tractor paths and thus would only provide for nitrate uptake along field perimeters, Similarly, establishment of cover crops offer a mechanism to reduce nitrate losses to groundwater in regions of the country where rainfall exceeds evapotranspiration. Such crops may take up soil nitrate remaining from the cropping season and thus reduce the potential for leaching to groundwater (183,207).

Riparian zones consist of vegetation typically adapted to seasonal periods of submersion and drying out. Riparian zones may be planted along cultivated fields to help moderate the movement of sediment and adsorbed chemicals into riverine ecosystems. Agricultural nonpoint-source pollution could be minimized by the establishment of riparian border vegetation (184). Similarly, planting of such areas to deep-rooted crops can create an upward flux of soil moisture and thus ''scavenge' nitrate from the lower soil profile (190).

Grassed terraces and waterways offer some potential to improve agricultural land productivity (18,2 12). They serve as buffer areas to slow agricultural runoff and sediment flowing toward surficial water supplies, and to further provide soil stabilization. Terrace and waterway establishment, however, tends to be expensive and may require soil disturbance. Narrow-based terrace construction costs in Illinois are about $300 to $400 per acre (18). Further, maintenance may be required to control possible weed outbreaks.

However, conservation plantings also may have undesirable effects. They may compete with the crop for soil moisture and nutrients or constitute barriers to certain production practices (e.g., center-pivot irrigation systems) or use of large mechanical cultivators (213). Use of deep-rooted species as in conservation plantings may ameliorate competition for these resources in the upper soil profile under some conditions.

Cultivar Improvement

Fifty percent of the overall yield increases in U.S. agriculture have been attributed to the use of improved crops and cultivars (16,44). While past efforts sought to increase yields, currently research scientists are investigating potential avenues to reduce agrichemical losses to the environment through a variety of cultivar development techniques (e.g., conventional breeding, genetic engineering). Developing plant varieties that are more suited to various cropping environments, for example, may offer an opportunity to reduce agrichemical use. Similarly, a plant able to use nutrients more efficiently could require fewer fertilizer applications. Ongoing ARS adaptation activities include developing crop varieties with tolerance for various soil pH levels, salt accumulations, and water stress. Crops less subject to stress are more likely to survive minor pest infestations and other adverse conditions (loo).

Genetic engineering approaches to enhance crop productivity is of significant interest to seed, agrichemical, and biotechnology companies (59). Research has focused on introducing genes that may enhance stress tolerance (e.g., drought tolerance), pest tolerance (e.g., toxin production), and nitrogen self-sufficiency (e.g., introduction of nitrogen-fining genes). Successful manipulation of a number of crop plants has occurred already, and engineered varieties are expected to become available in this decade (59).

Genetically, plant resistance is conditioned by major- and minor-effect genes. Major-effect genes are easier to manipulate and have given dramatic results in laboratory experiments, however, their effectiveness commonly is less in the field. Generally, major-effect genes are more effective than minor-effect genes in heterogeneous cultivars such as certain wheat varieties developed in Iowa and Washington. Minor-effect genes seem to be more successful in the homogeneous cultivars common to Western mechanized agriculture (214). Current areas of crop improvement research that may have implications for agrichemical use include: pest resistance, herbicide resistance, nitrogen self-sufficiency, and enhanced nitrogen-use efficiency.

Pest ***Resistance—Advances in*** development of insect-resistant plants have to date been largely achieved through the use of a protein found in the bacterium *Bacillus thuringiensis* (B.t.). The protein is lethal to certain insects such as moths and butterfly larvae and some strains produce a protein toxic to beetle and fly larvae. Toxicity to other insects, animals, or humans has not been noted (59).

Field tests of tomato and tobacco plants with the B.t. gene have had positive results. In one study, tomato plants with the B.t. gene were not adversely affected under conditions that resulted in complete defoliation of plants without the gene (59).

Given the potential of this technology to reduce insecticide application, significant benefits to groundwater protection might be achieved if research were directed toward development of such resistance for high-use crop species. The expense of genetically engineered varities may pose a constraint to implementation. Further, concern exists over the possibility of development of pest resistance to the toxin.

Although plant diseases are the results of bacterial, viral, or fungal infections, research efforts have focused on developing resistance to viral infections. Success has been achieved in developing resistance to the tobacco mosaic virus through use of a gene responsible for inhibiting uncoating of the virus once inside the plant cell. Similar results have been demonstrated against alfalfa mosaic virus, cucumber mosaic virus, and potato X and Y viruses in tomatoes, tobacco, and potato. Greenhouse and field tests of tomatoes with the resistance gene showed no yield loss after viral inoculation as compared to 23 to 69 percent loss in untreated plants (59).

Development of resistance to fungal and bacterial infections has met with little success to date (59).

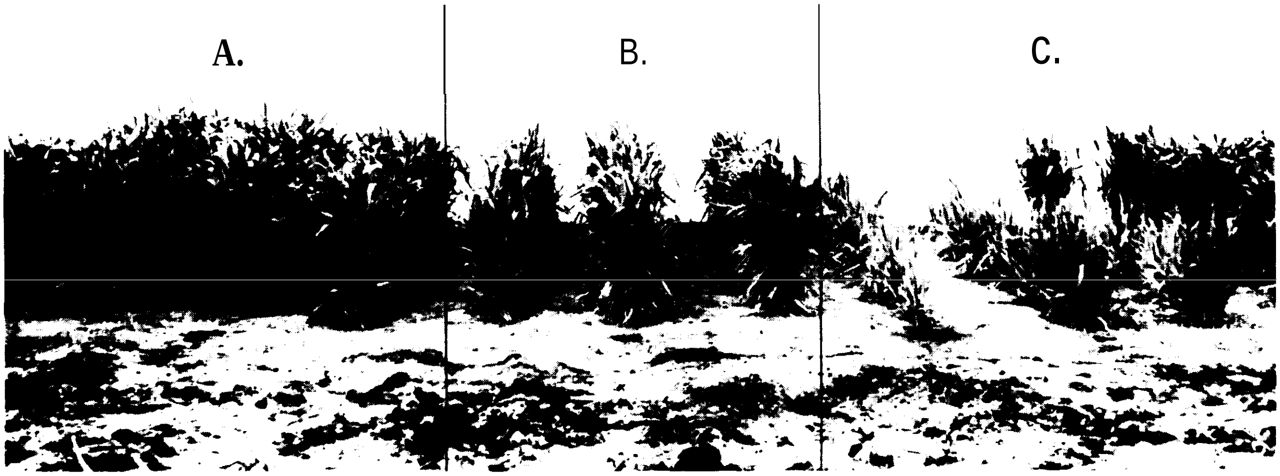


Photo credit: Phytopathology

Wheat can be partially protected from the fungal disease "take-all" by treating seeds with Pseudomonas bacteria prior to planting. A = plot with no fungal infection; B = treated wheat in infected plot; C = untreated wheat in infected plot.

Billions of dollars in crop losses per year are attributed to fungal-caused disease and postharvest spoilage (209). Given the low efficacy of fungicides relative to other pesticides as well as the method of application (generally soil incorporation), investigation into developing resistant plants could have important implications for groundwater protection. EPA recently has proposed a ban on most uses of EBDC, a widely used fungicide, because of its potential carcinogenicity. One of the alternatives to EBDCs, chlorothalonil, has been detected in well water (147).

Herbicide Resistance—Research on developing herbicide resistance in crop plants largely has concentrated on broad-spectrum herbicides that exhibit low soil mobility and rapid biodegradation. It is suggested that such development might result in a shift in herbicide use to more environmentally safe compounds (59).

Engineering approaches currently focus on: 1) reducing sensitivity of plant to the herbicide, and 2) conferring detoxification capability to the plant (59). A certain herbicide may act by inhibiting activity of an enzyme essential to plant (weed or crop) life. To reduce sensitivity of the crop plant to this herbicide, a gene sequence might be introduced that would promote overproduction of the target enzyme or production of an herbicide-tolerant variant of the enzyme. Detoxification of an herbicide is achieved by introducing bacterial genes that produce enzymes that inactivate the herbicide. Resistance to certain herbicides has been achieved by the detoxfilcation and sensitivity reduction approaches (59).

However, concerns exist over the potential for conferring herbicide resistance to weed species. Concern also exists over the potential for increased herbicide use stemming from availability of this technology. Proponents of the technique argue that the compounds for which resistance would be developed would be more environmentally acceptable and effective and thus could result in reduced herbicide use (59).

Alternatively, certain plant-growth regulators (PGRs) are being investigated as a potential avenue for herbicide resistance. These protestants or safeners may be applied to a crop (usually seed) so that when herbicides are applied to the crop row only the nonprotected plants are killed (214).

Examination of chemical residues and breakdown products remains to be done for certain of the herbicides for which resistance may be developed. Currently, herbicide resistance research is being conducted for such crop species as soybean, cotton, corn, oilseed rape, and sugarbeet.

Nitrogen Self-Sufficiency-The transfer of nitrogen-fixing ability to crop plants has been suggested as an opportunity to reduce excess nitrogen in agricultural soils that may be available for leaching, potentially to groundwater. Nitrogen-fixing genes are found only in certain microorganisms (procaryotes) many of which are symbiotically associated with plant species. Research and development efforts have focused on development of methods to confer nitrogen-fixation capability to crop plants and thus create a more self-sufficient plant. To date, however, transfer of nitrogen fixation genes to plants (i.e., from procaryotes to eucaryotes) largely has been unsuccessful.

Legumes develop highly specific symbiotic associations with various species of *Rhizobium*. A specific strain of the bacterium will infect only certain groups of legumes—' 'cross-inoculation groups. ' It has been determined that certain proteins (lectins) are responsible for allowing the plant and bacterium to recognize each other and enter the symbiotic association. Research has been conducted on introducing the protein responsible for recognition from a plant in one inoculation group to a plant in another (pea to clover). Some success was observed in that the clover plant developed nodules, however, they exhibited abnormalities. Nonetheless, such results suggest that there may be potential for genetic engineering to modify the plant genome sufficiently to make symbiotic nitrogen fixation a possibility (116).

These technologies remain an ongoing research area and no guarantee exists that development of nitrogen-fining crop plants would reduce nitrate contamination of groundwater even if commercial fertilizer use is reduced. Some evidence exists for release of nitrogenous compounds from actively growing nitrogen-fixing species and thus potential for nitrate formation and movement to groundwater under leaching events (86). Further, the nitrogen-fixing process itself may operate at some cost to the host plant and how this may affect crop productivity is unclear.

Nitrogen Use Efficiency-The nitrogen use efficiency of a crop plant is a significant factor in making wise fertilizer application decisions. Nitrogen use efficiency describes the capability of a plant to take up and assimilate available nitrogen and this attribute may vary among species and even among cultivars of the same species. Increased efficiency then may be displayed either by: 1) increased crop yield and nitrogen uptake with equal or lesser amounts of applied fertilizer, or 2) equal crop yield and nitrogen uptake with lesser amounts of fertilizer (164). Crop breeding to select for greater nitrogen use efficiency may have the potential to reduce nutrient requirements; however, numerous environmental and management factors mediate observed nitrogen uptake, making such selection difficult. Nongenetic factors that affect nitrogen use efficiency include: 1) planting geometry and planting dates, 2) tillage and residue management, and 3) irrigation management (180).

Manipulation of genetic materials in order to improve nitrogen accumulation is currently an area of research. However, little success has been achieved to date. Estimates are that development is at least several decades away (214).

Soil Management

Agricultural productivity is clearly linked to the management of soil resources. Certain soil characteristics can be maintained to provide alternatives to purchased inputs and to reduce energy and labor requirements in crop production. For example, maintaining soil organic matter contributes to friability and "natural' nutrient content, facilitating cultivation and potentially reducing the need for external inputs. Thus, soil management practices may indirectly affect agrichemical use. However, the tillage system effects with the greatest importance to groundwater contamination largely center on how various systems affect water movement and nitrogen transformations in the soil.

Tillage practices most directly affect the soil properties that influence the movement of water in and through the soil (e.g., structure, organic matter content, soil microbial populations) and thus affect potential agrichemical movement. Under conventional tillage systems (i.e., moldboard plow) water tends to remain in the upper profile or move laterally, whereas under reduced tillage systems that promote moisture infiltration, deep percolation may be an enhanced pathway (207). Environmental variables such as intensity and duration of rainfall and soil composition further influence the depth and route of water movement. Similarly, different soil types respond differently to the wide variety of tillage systems, making only general conclusions possible (207).

Conservation or reduced tillage systems are any of a variety of noninversion types of tillage including mulch-till, ridge-till, and no-till. Under these systems, seedbed preparation and planting techniques leave protective amounts of residue mulch (e.g., corn stalks, wheat stubble) on the soil surface. Initially promoted as a mechanism to reduce soil erosion, reduced tillage also tends to produce soils with higher levels of organic matter and soil fauna.

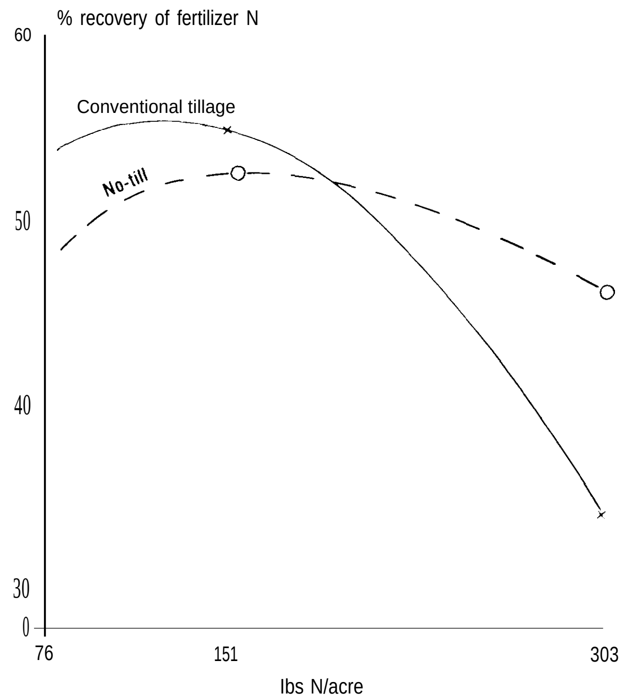
Because the soil is less disturbed by cultivation in reduced tillage systems, burrowing animals (insects, earthworms, etc.) may create extensive networks of charnels through which water may preferentially flow (27). One study estimated that twice as much water flowed out of the root zone under no-till as compared to conventional till. This effect was attributed to reduced evaporation and increased number of conduits from the surface through the soil profile (190). This condition may promote movement of agrichemicals to groundwater; however, data are limited (190,165).

Tillage systems may affect soil organic matter content significantly. Commonly, under conventional tillage systems where the soil is significantly disturbed, organic matter decreases through oxidation (212), whereas under reduced tillage systems surface residue accumulation and soil organic matter content may be quite high, Surface residue accumulations and increased soil organic matter content common under reduced tillage systems may increase the potential for immobilization of applied nitrogen. Evidence suggests that this effect may be due to low populations of the nitrifiying bacteria responsible for the conversion of organic nitrogen to nitrogen in the upper 15 cm of the reduced tillage soil profile (207). While this might represent an opportunity to retard vitrification and thus potential nitrate-leaching losses, the immobilized nitrogen also may be unavailable to the plant, potentially retarding its growth.

As tillage and cropping practices influence the physical soil properties, they also may affect the soil microorganism activity necessary for mineralization of organic nitrogen. Thus, these factors may be of great importance to crop nutrition and groundwater quality (41). However, strategies with which to manage organic nitrogen mineralization in relation to rainfall and crop nitrogen demand are lacking (86).

The additional reliance on herbicides for weed control in certain reduced tillage systems may exacerbate agrichemical loss to groundwater (12 1,27). However, field data vary widely, indicating that environmental parameters significantly influence the propensity for agrichemical movement. Some analysts report that reduced tillage systems require more herbicides only in the first few years, with herbicide use declining as practitioners become familiar with the tillage techniques. Despite these concerns, most agronomists conclude that soil conservation benefits of conservation tillage outweigh potential groundwater quality impacts (1 11).

Figure 4-9—Recovery of Fertilizer N by No-Till and Conventionally Grown Corn



SOURCE: J.O. Legg, G. Stanford, and O.L. Bennett, "Utilization of Labeled-N Fertilizer by Silage Corn Under Conventional and No-Till Culture," *Agronomy Journal*, vol. 71, 1979, pp. 1009-1015.

Tillage systems also may affect plant recovery of fertilizer (figure 4-9) and thus fertilization schemes. Reduced nitrogen efficiency associated with the various forms of reduced tillage systems initially seems more related to volatilization and immobilization of applied nitrogen fertilizer than vitrification and nitrate leaching. However, in moist cropping regions, ample opportunity may exist for mineralization of immobilized N, nitrification, and subsequently nitrate leaching (166).

Although injection of fertilizers may address this need to some extent, such application methods are problematic in reduced tillage systems because of maintained surface residues, A study in Indiana showed that under no-till conditions yields were greater when fertilizer was injected than when it was surface applied (164). Possible reasons for the lower yields from surface-applied fertilizers include volatilization, immobilization, or denitrification.

Fertilizer research over the last 30 years largely has focused on conventional tillage (primary tillage with a moldboard plow with various secondary tillage practices). Thus, fertilizer recommendations have been based on a crop management system that is much different from the various reduced tillage systems that are now gaining popularity (166).

Acreage under some form of conservation tillage rose from four million acres to 98 million acres between 1963 and 1986 (33 percent of total planted cropland). The highest use of conservation tillage is in the Corn Belt, totaling 34 percent of planted acres in 1988 (227). Although estimated acreage under conservation tillage has dropped by nearly 28 percent since 1986 (possibly due to acres idled under Federal acreage reduction programs in 1987 and 1988), adoption is expected to increase again. One SCS projection, assuming an improved farm economy in the 1990s, indicates that 63 to 82 percent of total planted cropland acreage could be in conservation tillage by the year 2010 (228). Clearly, research to identify the action and interactions of agrichemicals in reduced tillage systems is needed. Advance of reduced tillage systems requires new concepts of fertilizer and chemical placement, including significant changes in application techniques and new equipment (73).

Water Management

An important factor in attempting to prevent movement of agrichemicals into groundwater is proper management of water sources-natural and artificial-used in crop production. Water management practices in non-irrigated agricultural regions are closely related to soil management, and are designed to maintain soil moisture at levels sufficient to allow crop growth. Soil management techniques that promote maintenance of soil organic matter and increased water infiltration can contribute to enhanced soil moisture storage. In some areas, fallow seasons are necessary to allow for soil moisture recharge.

In humid regions, excessive water may pose a constraint to cultivation. Under these conditions, alternatives to reduce the flux of water and soluble agrichemicals below the crop root zone include cropping patterns to promote plant moisture uptake and installation of drainage systems. Drainage systems serve to remove excess moisture from the soil and numerous studies have focused on the relative amounts of agrichemicals contained in tile drains. Potential for contamination of groundwater largely may be related to drainage-water disposal practices and, to a lesser extent, to improperly functioning drainage systems (212). If drainage outflows are disposed of through agricultural drainage wells or sinkholes they may represent significant groundwater contamination potential (see ch. 3).

Weather prediction may play a significant role in overall water management approaches. Accurate and timely prediction of precipitation conditions could allow producers to adjust their agrichemical application plans accordingly. For example, under drought conditions, applied fertilizers remain unused by the crop and thus excess nitrogen is available for movement through the soil or to other media. Alternatively, agrichemicals applied prior to a major precipitation event maybe washed off plant surfaces, leach through the soil profile, or run off the land. Improved weather prediction capacity and dissemination of this information could assist producers' in making appropriate rate and timing decisions for agrichemical inputs.

Under irrigation systems additional opportunities exist to improve water management. Application of excessive quantities of irrigation water or nonuniform distribution of irrigation water can cause runoff or deep percolation of water and dissolved agrichemicals to groundwater (77). Most irrigation acreage expansion since 1945 has occurred with the installation of sprinkler irrigation systems in areas located over major groundwater aquifers. Nitrate and pesticide contamination of groundwater have been measured in several regions, with much of it likely due to agricultural practices. Significant potential for nitrate and pesticide contamination exists in many major U.S. groundwater areas. Vulnerable areas are concentrated in the humid, subhumid, and Central Great Plains regions, the same regions where sprinkler systems are the dominant mode of irrigation (208),

Sixty-eight percent of total groundwater withdrawal is applied to the land though various irrigation systems. Irrigated acreage is concentrated largely in the 17 western states (85 percent), the Mississippi Delta, Florida, and South Georgia (figure 4-10). Total U.S. irrigated acreage stabilized in the 1980's largely due to low farm commodity prices

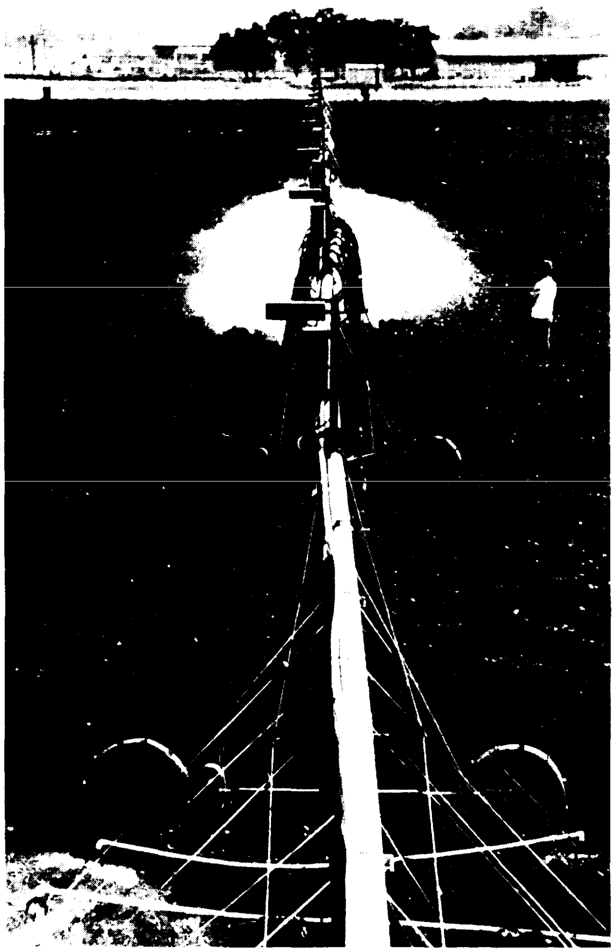


Photo credit: U.S. Department of Agriculture, Agricultural Research Service

Improving water-use efficiency in irrigated and "chemigated" agriculture can reduce the potential for agrichemical contamination of groundwater. Here, a laser-aligned, traveling trickle-irrigation system is being tested in California cotton fields.

and increasing irrigation costs, particularly energy-related expenses. Agricultural commodities produced using irrigation systems generated 30 percent of the total value of the U.S. market (78). Clearly, irrigated acreage plays a significant role in U.S. agricultural production (figure 4-1 1).

Attributes of irrigation systems that may affect agrichemical contamination of groundwater include scheduling, timing, rates, drainage, and system type (e.g., sprinkler, drip, furrow). Uniformity of distribution is a key factor of major importance when evaluating the potential for irrigation practices to promote groundwater contamination. Uneven distribution across a field may result in overapplication and thus promote deep percolation of water and contained solutes. Advances in irrigation technology such as the Low Energy Precision Application (LEPA) system enhance uniformity of distribution as well as increased water use efficiency. The LEPA system was developed by agricultural researchers in Texas and is designed to apply irrigation water and agrichemicals in small amounts and in precise locations to maximize the benefits to the crop. An economic comparison over 4 years of LEPA, drip, sprinkler, and furrow irrigation systems showed LEPA to be most profitable (139).

A mobile irrigation planting system (MIPS), developed by researchers at the Texas Agricultural Experiment Station, is an expansion on the LEPA system. The MIPS combines the capability for seed planting and irrigation, allowing growers to plant and irrigate with the same equipment (139). The system contains a facility for seed germination and gel coating for seed protection, a transfer and injection system, and a distribution and planting unit (cf: 115).

Proper scheduling and rate of irrigation can promote effective and efficient water use. Improper scheduling can lead to the application of too much or too little water. Overapplication of water may result in deep percolation or runoff of water and applied agrichemicals. While transit time for water to move from the soil surface to the groundwater table may range from a few days to centuries, excessive irrigation has a great potential to hasten this downward movement.

In the arid parts of the Western States where rainfall is not adequate to maintain an acceptable salt balance, irrigation may be used to flush salts below the crop root zone. Most irrigation practices include management practices for salinity control. Irrigation applied to promote deep percolation of surface salts may also transport other contaminants.

Four categories of irrigation systems are prevalent today: surface (use of gravity to distribute water), sprinkler (use of pressurized pipes to distribute water to sprinklers or nozzles for discharge through air to plants and soil), subirrigation (water supplied to crop root zone via capillary action by raising water table in soil using unlined surface channels or unpressurized underground pipes) and microirrigation (water distributed in closely spaced small-diameter pres-

Figure 4-10-Areas of Irrigated Land in the United States

SOURCE: U.S. Department of Agriculture, ***Agricultural Statistics*** (Washington, DC: U.S. Government Printing Office, 1986), p. 374, ***In:*** **Threadgill,** E. D., 1989.

stied conduits above, on, or below ground, with distribution from miniature sprinklers or emitters at low flow rates and pressures). The sprinkler system is the preferred type of irrigation system on most irrigated acreage added during the last few decades (208).

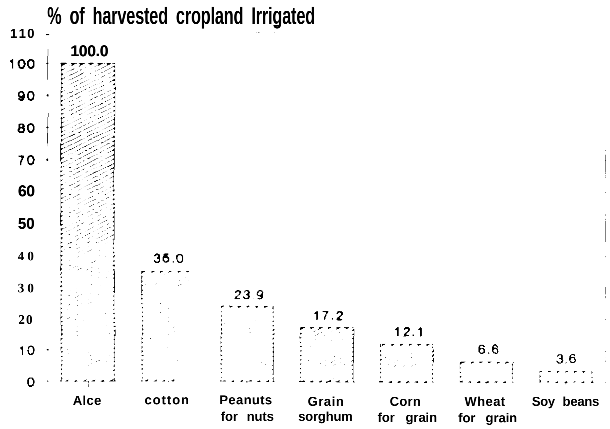
Costs of irrigation systems are quite variable, depending on system type, soil type, topography, field shape, and water source. Generally, capital costs are greatest for subirrigation systems and least for surface systems; sprinklers and microirrigation are intermediate. The reverse seems to be true for energy costs: surface systems are highest and subirrigation lowest. Although certain sprinkler systems may have high labor costs, irrigation systems such as microirrigation and center-pivot sprinkler systems lend themselves to automation, thus reducing labor requirements.

Potential effects of irrigation on agrichemical contamination of groundwater vary among the four categories of irrigation systems. Deep percolation of water below the root zone is more likely to occur with surface systems than with other types. Moreover, significant quantities of water applied in surface irrigation can run off the field and be discharged into surface water resources unless the water is contained or recycled into the irrigation system. This return flow or tailwater can transport chemicals from a variety of sources (e.g., directly added, picked up from the soil surface).

Sprinkler systems installed in areas with high slopes may promote runoff when improperly designed or operated. This runoff may contain chemicals from a variety of sources. Subirrigation systems frequently are designed to irrigate and provide drainage for the plant root zone. Although deep percolation should not be a problem in subirrigated areas, any drainage waters could potentially transport chemicals from the field into offsite drainage systems (208).

Quantity and timing of irrigation have direct impacts on the potential for movement of agrichem-

Figure 4-1 I—Percentage of Harvested Cropland Irrigated for Major Program Crops



SOURCE: U.S. Department of Agriculture, 1989 Agricultural ***Chartbook,*** Agricultural Handbook No. 684 (Washington, DC: U.S. Government Printing Office, March 1989).

icals through the soil profile. Excessive water can increase the amount and rate of percolation of a water-soluble pesticide through soil into groundwater, as well as runoff of trace residues (either dissolved in water or adsorbed to soil particles) (73,208).

Effective management of any irrigation system depends primarily on irrigation scheduling. Determinations of when to irrigate and the amount of water to apply are made almost daily during growing season. The decision of when to irrigate may need to be made in advance if the system requires movement, or additional labor, or is dependent on placing an order for the water. The amount of water to apply similarly is dependent on many factors, including soil type; stage of crop growth; precipitation since last irrigation, or predicted during next few days; and probable lapsed time before subsequent irrigation can be scheduled (208).

Three basic approaches exist for irrigation scheduling: 1) allowable soil-water depletion; 2) soil-water tension; and 3) allowable plant-water stress. Scheduling based on allowable soil-water depletion involves irrigation before predetermined limits for these criteria are reached (208). For example, the predetermined limit could be when 50 percent of the available water contained in the plant root-zone at field capacity has been depleted. Irrigation is applied to bring the soil moisture to field capacity, or another desired limit.

Soil water tension is defined as the force required for a plant root to extract moisture from the soil complex and varies with soil type and condition. Irrigation scheduling based on the soil-water tension approach is designed to supplement soil water before the plant roots can no longer effectively extract water. The amount of water to be applied is based on the relationship between soil-water tension and the soil-moisture depletion and is highly field specific.

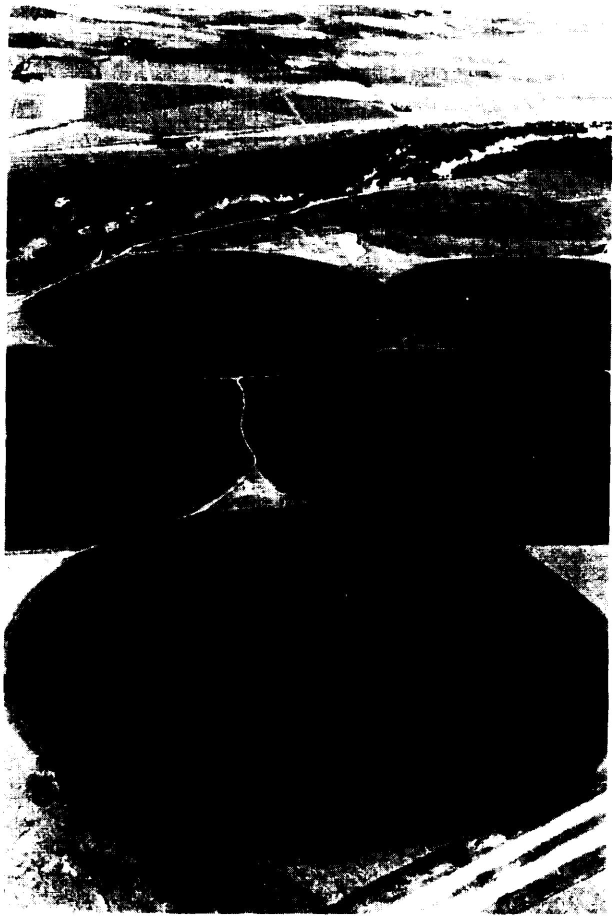
Irrigation based on plant-water stress involves measurement of the water stress in some part of the plant and irrigating before a critical limit is reached. This method only identifies when irrigation is needed and does not define the amount of water to be applied.

Several technologies exist to enhance imigation scheduling decisions. For example, soil-moisture measuring devices and automated microprocessor-based scheduling systems may improve irrigation timing and amount. Gypsum blocks set into the soil have been shown to be an effective mechanism for determining relative soil moisture. Use of such indicators can facilitate accurate determination of soil moisture needs and thus assist in appropriate irrigation scheduling decisions. Surge-flow and cablegation systems can lower potential for deep percolation and high-volume tailwater from surface irrigation systems (208).

Clearly, existing and emerging technologies may enhance the efficiency of irrigation practices. In particular, significant advances could be made by more widespread use of advanced irrigation scheduling techniques and the adoption of improved irrigation uniformity technologies. Consideration of weather patterns may also be important in scheduling decisions to avoid excessive percolation of water and contained solutes through the soil profile. This may be particularly true for irrigation scheduling or application that is not based on relative soil-moisture content,

WASTE MANAGEMENT

Agrichemical wastes arising from certain agricultural activities have been implicated as groundwater contaminants. Nitrate leaching from manure storage has been noted under feedlots in numerous studies (197). Pesticide contamination of well water also has been linked to inappropriate mixing and loading of pesticide application equipment near wells. Seepage



credi artmen ricultu gricultural Research Service

g ched g an m bu ar mp g g manag me S wn pi g m at p d w ari co mo ag mical cr d St ar wise irrigation management is critical in reducing agrichemical losses under such circumstances.

of effluents from livestock-feed silage have also been noted as groundwater contaminants.

Entry of these wastes into groundwater may represent point-source contamination. In many cases, however, leaching through soils has also been identified as a route of entry. Such agrichemical losses to the environment represent an economic loss to the practitioner. Thus, approaches that increase the efficacy of waste-management practices should provide economic benefits to producers as well as the environment.

Agrichemical Wastes

Pesticide and fertilizer spills and leaks at commercial facilities have been responsible for numerous detections of chemicals in groundwater (75). In some cases pesticide concentrations in soils and water around the pesticide mixing, loading, and equipment-cleaning areas of these facilities are close to formulation concentrations (76,145) (table 4-14). On-farm storage, mixing, and loading areas can present a similar, although smaller scale, threat to groundwater. For example, a typical pesticide field application rate is one to four pounds per acre. In terms of concentration, spilling 1/4 pound of a chemical in a 100 sq.ft. area around a well head is roughly equivalent to the application of 100 lbs per acre. Improper management of on-farm mixing and loading areas is believed to be a major factor causing farm well-water contamination that exceeds enforcement standards of alachlor and atrazine (48). Pesticide concentrations exceeding 50 micrograms per liter in well water suggests that mixing, loading, storage, and disposal sites are likely entry points (104).

Agrichemical Storage

Pesticide labels contain brief, explicit instructions for storage. Ideally, pesticide containers should be stored in a fire-resistant facility on a raised pallet or on a raised and drained concrete platform (99). Most farmers use existing buildings for pesticide storage, although the buildings have not necessarily been designed for that purpose. If these buildings have an earthen or wooden floor, spills or leaks present a groundwater contamination threat, particularly if they are located in areas of permeable soils and fractured bedrock, or near a well. Guidelines for safe storage facilities are available (cf: 40,125).6

Early-season buying incentives offered by agrichemical dealers tend to conflict with minimizing the amount of pesticides stored on-farm. On the other hand, minimal storage may represent a risk to a producer in the event of emergencies or poor weather windows. Opportunities to reduce agrichemical losses during storage lie in upgrading the quality of storage areas and educating users on storage hazards and economic benefits of planning for next year's production strategies (73).

[6]Detailed plans for a pesticide storage and mixing building are available from the Midwest Plan Service, Ames, IA 5~11.

Table 4-14--Contamination From Pesticide Mixing and Loading Areas

	Maximum concentrations detected		
	In pools and soils in loading and rinse areas	Groundwater in affected wells and seeps	Local background groundwater
Herbicides:		micrograms/liter	
Atrazine	70,000	65.0	No-0.65
Alachlor	270,000	145.0	No-1.30
Cyanizine	225,000	36.0	No-0.26
Metolachlor	270,000	50.0	No-0.80
Metribuzin	52,000	8.0	No
Trifluralin	(1,000+)	0.2	No
Insecticides:			
Carbofuran	(1,000+)	No	No
Fonofos	(1,000+)	1.3	No-0.3
Fumigants:			
EDB	10-100	1.0	No
1,2, dce	10-100	2.0	No
Carbon Tet	10-100	66.0	No
Chloroform	10-100	4.0	<1.0
		miligrams/liter	
Nitrate	137-480	18-41	
Nitrate-Nitrogen	30-105	4-9	

SOURCE: G. Hallberg, "Pesticide and Nitrate Concentrations From 8 Case Studies Where Groundwater Has Been Contaminated in the Vicinity of Farm-Chemical Supply Dealerships," *In*: Hall, F., 1989.

Agrichemical Mixing and Loading Areas

Pesticides and fertilizers commonly are loaded and mixed at the same location on the farm. Often the site is near a well for convenience in filling spray tanks (240), and many of these sites lack facilities for spill containment (60). The same site is sometimes used to rinse equipment after application. As a result, chemical residues can accumulate in soils and are available for leaching to groundwater (40). Concrete pads and water tight dikes can contain spills and allow recovery of the spilled chemical. If the concrete pad slopes to a collection basin, the same area can be used for rinsing application equipment (98). However, on-farm lagoons, catchment basins, or other surface storage containment may not be designed to prevent movement of spent material into water sources (60).

Pesticide losses during mixing and filling of tanks and hoppers offers much greater potential for contamination of surface and groundwater than losses during application. Back-siphoning from spray equipment into wells is a common cause of residues contaminating drinking water. Pumping equipment could be required to have antibackflow devices. Technology to prevent back-siphoning is already available; however, economic incentives or regulation may be needed to promote its use (73). While EPA regulations require back-siphoning equipment on chemigation wells, such regulations do not exist for other mixing and loading practices.

Thus, a need exists to improve technology and procedures for storage, handling, and mixing of pesticides and other agrichemicals. The potential for dilution and water recycling in pesticide mixing, loading, and disposal activities needs investigation (73). Additional commonsense strategies that may reduce the potential for well contamination from pesticide preparation include restricting mixing/storage of agricultural chemicals within 500 feet of a well, and continuous supervision of the sprayer/tank during filling operations (73).

Transfer Systems

Some systems for loading, transferring, and mixing pesticides eliminate the need to open containers and handle materials and thus may reduce the potential for spilled materials or rinse water to contaminate groundwater at this stage. Such systems meter and transfer chemicals from the shipping container to the mixing or application tanks and commonly rinse the emptied container (15). Individual farmers have developed a variety of ways to use couplings, valves, and hoses to transfer and mix chemicals in a closed system (175).

Pesticides packaged in premeasured, soluble bags that may be put directly into mixing tanks have some potential to reduce the possibility of spillage. Further, such packaging reduces human exposure during the mixing process. Similarly, returnable systems allow a producer to return the container and remaining pesticide mix to the dealer. Such systems are receiving increased interest and are a major emphasis of the National Agricultural Chemical Association's member companies (64). However, additional resources for research on suitable technologies for returnable systems as well as the potential for such systems to reduce agrichemical waste are needed to promote their development and use (73).

Disposal Practices

Three types of pesticide waste with potential to contaminate groundwater are produced on the farm: leftover pesticides, empty containers, and rinse water from washing equipment and containers. Some pesticides are listed as hazardous or acutely hazardous wastes in the Federal Resource Conservation and Recovery Act (RCRA). Many other pesticides not specifically listed in Federal and State laws are classified as hazardous because they exhibit hazardous characteristics identified in the laws (99,244).

Pesticides are packaged in a wide variety of containers of varying material composition, size and shape, creating problems for users in pouring, storage, rinsability after use, and disposal (73). Pesticide containers that seem empty generally contain chemical residues. For example, several ounces of some pesticide formulations can remain in an unrinsed 5-gallon container despite normal efforts to empty it (40). Some residues remain even after draining and rinsing (table 4-15). Triple-rinsed containers can be legally disposed of in sanitary landfills, but few landfills now accept them because of concern over liability. However, improper disposal of empty containers or excess unused pesticides can cause localized groundwater problem in disposal areas (73).

Rinse water from cleaning application equipment and containers also contains chemical residues. Rinse water includes solutions left after field spraying, water from washing the outside of the sprayer or spray tank, and spray left in booms and hoses. Rinse water should be sprayed on fields at the proper rate of application for the chemical; however, often it is simply dumped or disposed of on the ground (240). A number of facilities have been designed and tested for disposing of leftover pesticides and rinse water (235). These disposal systems might be feasible for use at commercial facilities, but there is a continuing need for inexpensive on-farm systems (240).

Table 4-15-Pesticide Residues After Rinsing Containers

Active ingredient in the 1 oz. of liquid remaining in a 5-gallon container

Rinsing stage	Pesticide residue (grams)
After draining	14.2
After 1st rinse	0.2
After 2d rinse	0.003
After 3d rinse	0.00005

SOURCE: R. Doersch, J. Wedberg, C. Grau, and R. Flashinski, Pest *Management Principles for the Wisconsin Farmer,* 2d ed. (Madison, WI: University of Wisconsin—Extension, 1988), *In:* Jackson, G.W., et al., 1989

The most cost-effective approach to improving the situation is to minimize the amount of waste. Cost-effective waste effluent treatment systems could address this need to some extent. Some such systems have been developed (e.g., ICI Sentinel System) aided by Federal grants; however, this effort could be expanded to promote more rapid development of similar systems (73).

Livestock Wastes

Animal agriculture accounted for a significant part of the gross agricultural receipts in the United States in 1988, exceeding the contribution of crops ($80.2 billion **or 53** percent of the total) (197). However, livestock and poultry production operations can sometimes contribute to excess nutrients, salts, organic matter, and other constituents as contaminants of groundwater if manure and wastewater are not properly managed. Constituents in livestock and poultry manure that can cause groundwater contamination primarily include pathogenic organisms, nitrate, and ammonia. Presence of such constituents in livestock drinking water may adversely affect livestock health (34). Under special conditions other constituents such as potassium, sodium, chloride, and sulfate also may be leached and impair groundwater quality.

Certain livestock production practices may promote nutrient contamination of groundwater. Potential sources of groundwater contamination include open unpaved feedlots, runoff holding ponds, manure treatment and storage lagoons, manure stockpiles, and land application of manure and wastewater. Dead animal disposal and animal dipping-vats may contribute to localized groundwater contamina-

Photo credit: State of Florida Department of Environmental Regulation

Improper disposal of pesticide wastes and pesticide containers may pose significant hazards to groundwater quality. Pesticide containers that seem empty still may contain chemical residues and some residue may remain even after draining and rinsing.

tion. Manure accumulations around livestock watering locations, intermittent-use stock pens, and livestock-grazing operations that vary from sparse rangeland to intensive pastures may also influence surface and groundwater quality. In many cases the relationships between the practice and pollution potential have been identified. For these, technologies exist to reduce the potential adverse impacts of livestock production on groundwater resources.

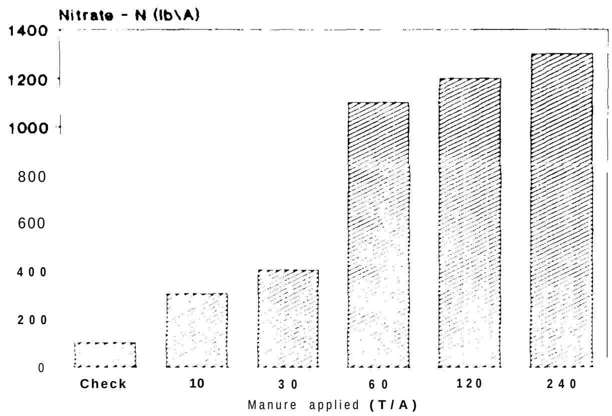
To prevent discharge to surface waters, livestock manure and wastewater may be collected, stored, and then land applied. However, application rates must be developed that account for the nitrogen content existing in the soil to avoid applying excessive amounts that may leach through the soil profile (figure 4-12). Under wastewater irrigation systems, application should be uniformly less than the soil-infiltration rate to prevent surface runoff. Further, manure and wastewater should be applied to soils at annual rates that match crop-yield goals and expected plant uptake of nutrients to assure that nutrients are used efficiently and that groundwater contamination is not likely.

Livestock and poultry manure generated from concentrated and confined animal feeding facilities may be a valuable resource for fertilizer, feedstuff, or fuel. Manure is widely used as an organic fertilizer in many areas. Certain types of manure also may receive limited use in specialized situations as a feedstuff, as a substrate for anaerobic digestion to produce biogas, or as a fuel for combustion/gasification for electric power generation. However, these latter uses return all or a part of the original manure fertilizer value as a residue that eventually is applied to land.

Overall, the general routes to groundwater contamination from livestock production operations are the same as those from other forms of agriculture: leaching, runoff, and direct infiltration. Animal production facilities and practices that create the potential for such mechanisms to operate include:

- intermittently occupied livestock facilities, continuous-confinement facilities, and manure stockpiles and storage bunkers;
- liquid-manure storage ponds or treatment lagoons and runoff collection channels;
- dead animal disposal pits;
- feed silos and grain-storage pits and stockpile; and
- land application of manures, livestock insecticide-application sites (spray pens and vats), and

Figure 4-12—Nitrate in Pullman Soil After Five Annual Applications of Manure



SOURCE: A.C. Mathers and B.A. Stewart, "Manure Effects on Crop Yields and Soil Properties," *Transactions of American Society of Agricultural Engineers, vol. 27, No. 4, 1984,* pp. 1022-1026.

disposal sites for insecticide containers and residues.

Indirect introduction of agrichemicals or nutrients into groundwater may occur in a number of ways. In addition to these, potential also exists for direct introduction of runoff or leachate through activities conducted in the vicinity of active or abandoned wells.

Manure Production and Distribution

Total U.S. manure production (dry basis) by all livestock and poultry species has been estimated at nearly 158 million tons annually. This amount contains some 6.5 million tons of nitrogen, nearly 2 million tons of phosphorus, and nearly 4 million tons of potassium (197). Direct losses via volatilization, leaching, and runoff are estimated to reduce the nutrient content of manure significantly.

Based on land-application values from a 1974 study of manure production, current economically recoverable manure production would supply an estimated 184 pounds of nitrogen/acre, 67 pounds of phosphorus/acre and 122 pounds of potassium/acre for nearly 15 million acres of U.S. cropland (238,197). However, according to estimates, "extensive" production of livestock on pastures and rangelands accounts for a large proportion of the manure produced. This manure recycles back through the soil and plant system but is largely uncollectible and is therefore 'unmanageable.' Extensive production systems account for about 88 percent of the total for beef cattle as well as sheep. For dairy cattle, as much as one-half or two-thirds of manure produced might be voided on pastures, depending on the types of production systems, season, climatic region, and herd size. However, as dairy operations increase in size the trend to total confinement is expected to continue (197).

Livestock concentrations in extensive systems may vary by two or three orders of magnitude from 10 to 5,000 pounds liveweight per acre, depending on climate, soils, topography, and management intensity. Accordingly, manure voided varies from no more than 0.5 to 7 dry tons per acre per year and nitrogen deposition ranges from approximately 1 to 500 pounds per acre per year for sparse rangelands and intensively grazed improved pastures, respectively (198). While nitrogen deposits may be a factor in sustaining forage production on more intensively grazed, improved pastureland, nutrient return may be almost inconsequential on more extensive rangeland.

For intensive animal-production systems (predominately in confinement), the predominant sources of voided manure seem to be dairy cattle, swine, beef feedlot cattle, broilers, turkeys, and laying hens. Figure 4-13 shows manure production and nitrogen concentration (as-voided basis) within intensive systems versus extensive livestock production systems as a function of animal density and spacing per unit liveweight.

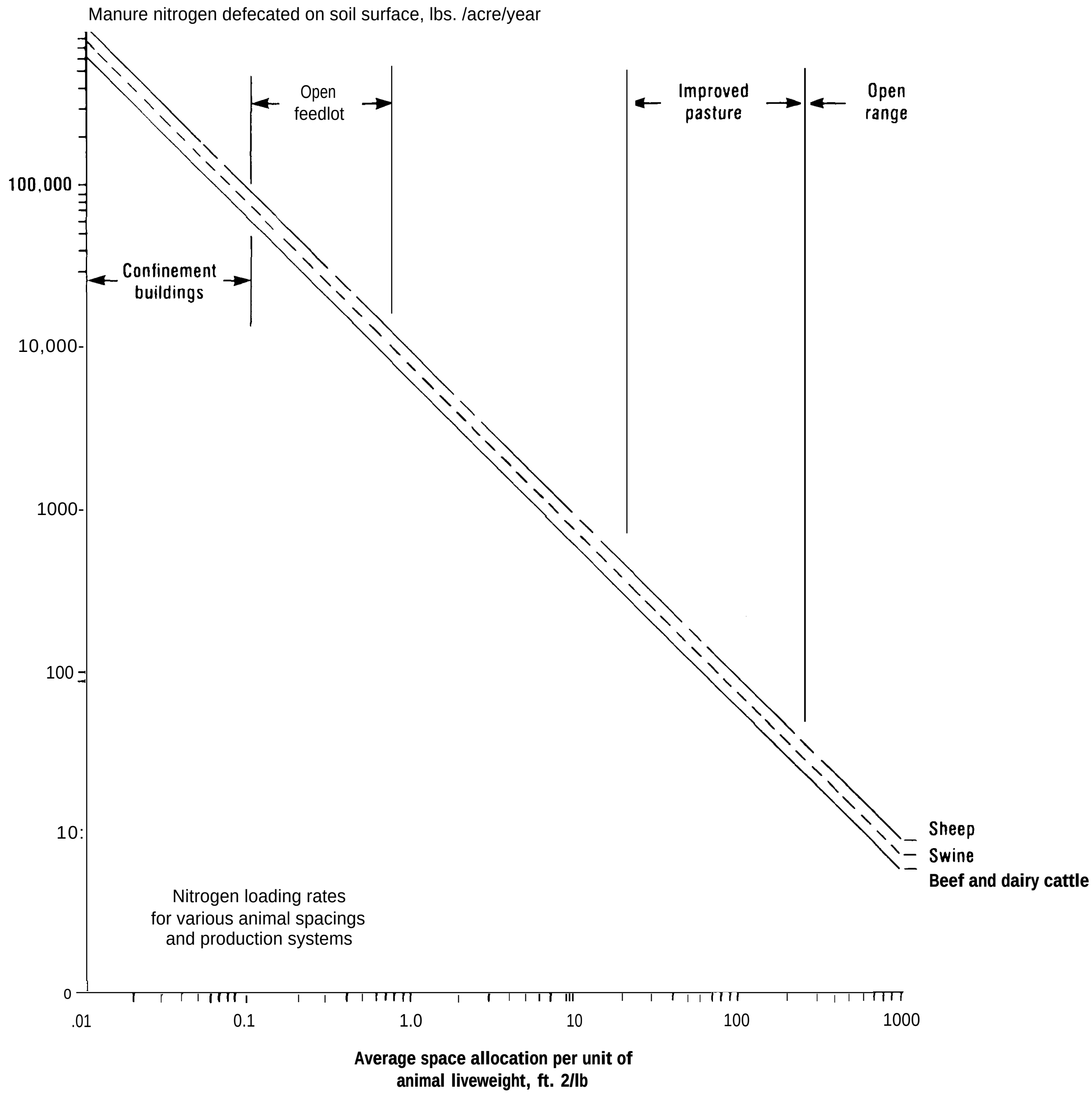
For purposes of water pollution control, intensive livestock production systems are defined in the EPA regulations for feedlots as:

> . . . animal feeding operations (where animals are) stabled or confined and fed or maintained for a total of 45 days or more in any 12 month period, and. . . crops, vegetation, forage growth or post harvest residues are not sustained in the normal growing season over any portion of the lot or facility. (234)

This definition covers many animal species, types of facility, animal densities, climate, and soils. It uses a single, visually determined criterion—absence of vegetation. Under such conditions, manure production and animal traffic are great enough and frequent enough to prevent germination or growth of forage. This condition implies that:

- crop uptake is not a pathway for nutrient removal, thus runoff, volatilization, and leaching pathways may be proportionately larger than from vegetated surfaces;

Figure 4-13-Average Amount of Manure Nitrogen Defecated per Unit Area as a Function of Animal Spacing



SOURCE: J.M. Sweeten and D.L. Redden, "Nonpoint Sources: State of the Art Overview," Transactions *of the* ASAE, vol. 21, No. 3, 1978, pp. 474-483.

- **runoff volume** is greater and time of concentration is shorter as compared to a vegetated surface; and
- a vegetation falter to slow and capture suspended sediments is lacking.

These conditions, which increase the potential for nutrient contamination of groundwater, may persist long after livestock are moved from the confinement area.

Livestock Waste Collection Trends

Certain aspects of livestock production practices have potential to influence groundwater quality because of the waste management practices with which they may be associated. Livestock operations are increasingly moving toward the use of confinement buildings and larger feeding facilities and away from labor-intensive manure-handling systems. In such confinement buildings there is increased use of manure flush systems or mechanical scrapers, which provide for manure collection as often as several times a day.

Flush, Lagoon Irrigation Systems—These sys-tems use large volumes of water to remove and transport manure from confinement areas. Lagoons or holding ponds are needed for storage and treatment of manure prior to land application. The effluent produced usually has considerable nitrogen content such that land application quantities are limited based on the soil or plant capacity to assimilate the amount applied. Solids concentrations, however, are low and volumes generally are sufficient to favor application by irrigation rather than hauling. Low, frequent, uniform applications are needed to avoid runoff and excessive nutrient leaching.

Mechanical Scrapers, Storage Pit, Tank-Wagon Transport Systems—These types of systems also are used to collect livestock manure from confinement buildings on a daily basis. Mechanical scrapers are used to remove the waste with minimal amounts of supplemental water. Consequently a much smaller storage structure is needed—generally concrete tanks or small earthen pits. The relatively high solids concentration make it convenient to use tank-wagons or trucks for direct transport to fields where application may be by surface spreading or soil injection. Due to the relatively high nutrient concentrations, much lower volumetric application rates per acre must be observed as compared with lagoon effluent.

Open Feedlots With Solids Collection and Run-off Control-open feedlots may be less likely to pose a potential hazard to groundwater quality in areas characterized by at least a 30-inch moisture deficit and moderate winters. Manure in solid form is scraped at intervals (weekly, annually) and stacked in pens or outside stockpiles prior to land application. Rainfall runoff is collected in runoff holding ponds and irrigated on croplands or pasturelands. In dry climates, evaporation is the method often used for disposal of feedlot runoff.

Management Practices and Effects on Groundwater Contamination

Leaching from feedlot surfaces, stockpiled manure, and land-applied manure and effluent, and seepage from runoff holding ponds can potentially contaminate groundwater. General trends toward consolidation of ownership, more frequent manure collection, off-site marketing of solid manure, use of comporting to reduce volume, reduced application rates, and expansion of land ownership by feeding operations may reduce this potential. Land application of holding-pond effluent does not seem to be increasing, and installation of overflow water systems that reduce storage capacities of such holding ponds seems to be increasing.

Feedlot Surfaces—Research in several states, in arid and humid climates, has determined that an active feedlot surface develops a compacted manure/soil layer (2 to 4 inches thick) that provides an excellent moisture seal. This layer may reduce downward water movement significantly (129,128), thus restricting leaching of salts, nitrates, and ammonium into the subsoil and underlying groundwater (table 4-16) (186). The compacted, inter-facial layer is composed of bacterial cells, organic matter, degradation products, and soil particles.

The soil surface essentially self-seals if an anaerobic layer of compacted manure is left undisturbed above the manure/soil layer. This seal may retard the formation and leaching of nitrate in favor of denitrification (193,23). The best soil profile to retard nitrate and nitrite movement and retain salts near the surface was found to be a sand topsoil above a clay-loam subsoil (142).

Appropriate collection practices should be used to remove manure to avoid disrupting this surface-seal layer. Correct use of collection machines such as wheel loaders or elevating scrapers that leave the manure pack will maintain the residue layer and thus restrict leaching potential. This will result in collection of highest quality manure for crop fertilization or energy generation (199).

Measurements of groundwater quality under 80 cattle feedlots in the Ogallala Aquifer in the Texas High Plains indicated that about one-fourth had contributed to nitrate levels approaching or exceeding 10 ppm in the immediate vicinity of the feedlots. Seepage rates were estimated at 0.003 to 0.03 inches

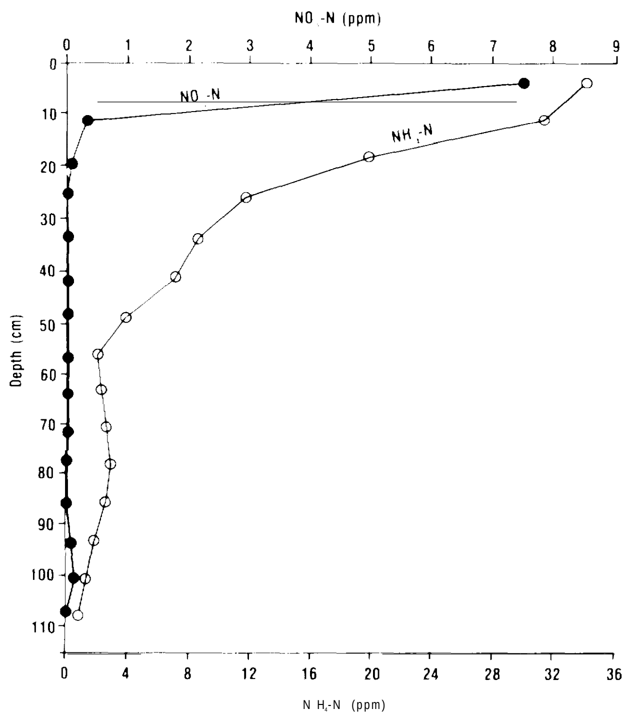
Table 4-16-Nitrate, Nitrite, and Ammonium-Nitrogen Concentrations Beneath Playa Used for Feedlot Runoff Collection (in ppm)

	Feedlot playa[a]			Non-feedlot playa[b]	
Depth (feet)	Nitrate	Ammonium	Nitrite	Nitrate	Nitrite
0	12.8	58.7	2.8	- -	- -
1	225.0	18.4	3.2	7.8	0.34
2	6.2	5.7	0.13	2.8	0.16
3	3.7	5.7	0.13	2.8	0.16
4	3.0	3.3	0.03	2.5	0.13
5	3.4	3.5	0.02		
6-13. : : : :: : : : : : : : :	0.3 -2.7	1.1 -2.8	0.02-0.12		

[a]Average of three center observationwells.
[b]Average Of two observation wells.

SOURCE: O.R. Lehman, B.A. Stewart, and A.C. Mathers, Seepage *of Feedyard Runoff Water Impounded in Playas,* **MP-944** (College Station, TX: Texas Agricultural Experiment Station, Texas A&M University, 1970), ***In:*** sweeten, J. M.,-l 989.

Figure 4-14—Ammonia and Nitrate Present in a Feedlot Soil Profile



SOURCE: G.E. Schuman and TM. McCalla, "Beef Cattle Feedlots: Impact on Underlying Soil," ***Abstracts*** (Fort Collins, CO: Western Society of Soil Science, June 1975).

Photo credit: State of Florida Department of Environmental Regulation

Livestock wastes can be a significant source of nitrate having the potential to contaminate groundwater. **Commonly feedlots leach little through their hard-packed floors, but may contribute runoff to nearby surface waters or leach through to groundwater after abandonment.**

per hour under feedlot surfaces and playas used for runoff collection (13 1).

Concentrations of nitrate and ammonia decrease rapidly within the top foot of the feedlot soil layer (figure 4-14) (186). Soil-water samples taken at three feet beneath cattle feedlots showed concentrations of nitrate, phosphorus, and magnesium and total solids similar to concentrations found under adjacent cropland (1,49,186,36).

Feedlots that have been abandoned without manure removal may have greater potential for groundwater contamination (1 19) than active operations. Cropping abandoned feedlots to deep-rooted crops such as alfalfa may have some potential for capturing nitrates that have migrated through the soil profile (212).

Holding Ponds and Lagoons—Leaching from livestock waste-treatment lagoons and runoff holding ponds has also been studied by researchers for at least two decades. It has been determined t h a t bacterial cells and fine organic matter generally clog soil pore-spaces along the bottom and sides of lagoons and holding ponds (14) creating a seal (37).

After several months of storage, soil coefficients of permeability of wastewater pond bottoms are generally one to three orders of magnitude lower than those of clean water ponds (177,108,13). Where the bottom and sides of manure storage ponds and lagoons have a moderate- to fine-textured soil the final permeability coefficient is usually reduced significantly (14). While infiltration time varies depending on soil type, it also is affected by the type of manure. For example, measurements taken of infiltration rates of swine and dairy slurry indicate that infiltration of swine slurry increases over time relative to dairy (figure 4-15).

Although livestock manure and wastewater provide beneficial self-sealing on the bottom and sides of lagoons and holding ponds, regulatory agencies further suggest that lagoons should be placed on relatively impermeable subsoils (45).

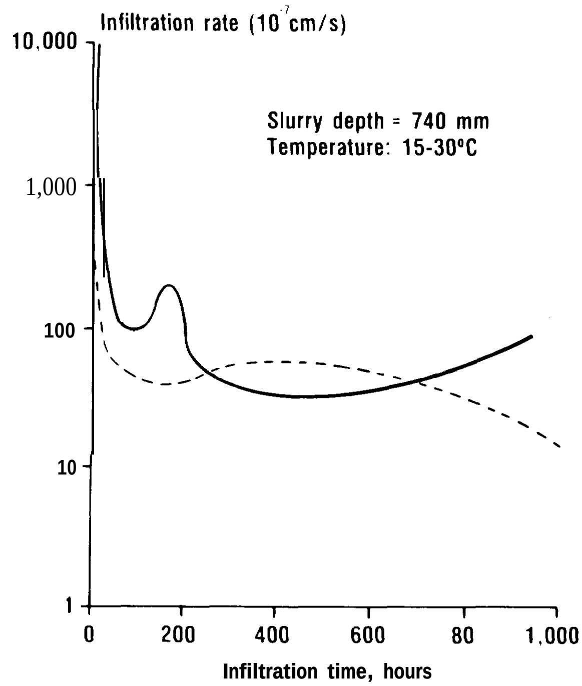
A study of the leaching of contaminants in feedyard runoff below a playa lake bottom indicated that nitrogen compounds did not move below 3 feet. At 2 feet and below the nitrate and nitrite concentrations were only slightly higher than for playas that did not receive feedyard runoff (109). A further study showed that nitrate concentrations decreased drastically within the top meter and that below one meter, nitrate concentrations were no more than 10 mg/1 nitrate-nitrogen (figure 4-16).

The potential for groundwater contamination is increased in arid regions when playa lake bottoms are excavated below the natural clay layer. An alternative is to stockpile the clay and reapply it to a compacted depth of one foot or more over the bottom and sides to serve as a clay liner (205).

Monitoring wells placed in the vicinity of livestock waste-treatment lagoons and holding ponds have been used to evaluate the distribution of groundwater contaminants caused by lagoon seepage (28,25, 187,176, 153). Nutrient or salt concentrations sometimes increase in shallow groundwater in the immediate vicinity of lagoons or holding ponds. However, these initial increases usually diminish after several months. These results are reasonably consistent with the observed reductions in permeability caused by self-sealing.

Researchers are working on new methods for locating and quantifying groundwater pollution near animal waste lagoons to replace expensive, time-consuming soil-sampling techniques. An above-ground electromagnetic (EM) sensor is used to detect conductivity plumes or gradients that suggest leakage of livestock waste materials from lagoons. Efforts are under way to correlate the relationship of specific EM signals and groundwater contamination to form the basis for determining groundwater pollution from waste lagoons (30).

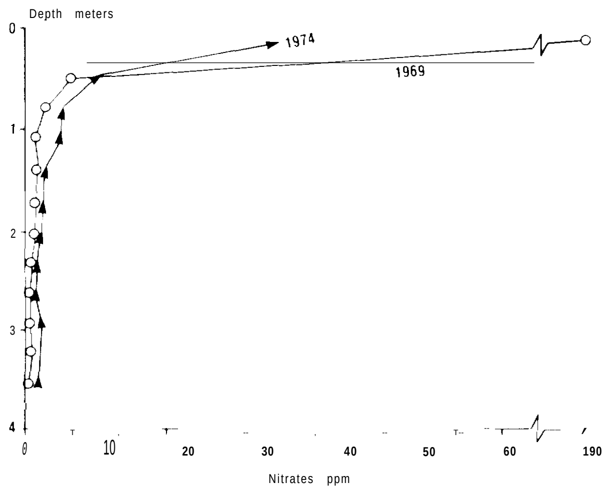
Figure 4-15-infiltration Rates for Swine and Dairy Manure Slurries Over Coarse Sand



SOURCE: S.F. Barrington and P.J. Jutras, "Selecting Sites for Earthen Manure Reservoirs," *Agricultural Waste Utilization and Management*, Proceedings of the Fifth International Symposium on Agricultural Wastes, American Society of Agricultural Engineers, 1985, pp. 386-392.

U.S. Environmental Protection Agency (EPA) regulations for confined livestock and poultry operations deal with surface-water protection and do not include requirements for groundwater protection. Several States and local entities do have groundwater protection requirements. For example, the Texas Water Commission regulation that governs confined, concentrated livestock- and poultry-feeding operations considers groundwater protection for lagoons and holding ponds (205). The regulation requires that all wastewater-retention facilities be constructed of compacted, low-permeability soils (e.g., a clay or clay loam) at a minimum thickness of 12 inches.

Figure 4-1 6-Nitrates, Dry-Weight Basis Beneath Feedyard Playa



SOURCE: R.N. Clark, "Seepage Beneath Feedyard Runoff Catchments," *Managing Livestock Wastes,* Proceedings of the Third International Symposium on Livestock Wastes, American Society of Agricultural Engineers, St. Joseph, MI, pp. 289295, 1975,

Livestock waste management techniques exist that may reduce the potential for groundwater contamination from livestock production practices. Further effort is needed to promote development and adoption of such practices. Areas of significant importance include:

- increased development of manure treatment and use technologies, particularly in relation to comporting, biogas generation, thermochemical conversion, fiber recovery, and marketing of such products (box 4-H);
- development and extension of economic guidance for land application of manures, to include soil testing to define appropriate application rates, and understanding of nutrient-release rates; and
- quantification of the magnitude of nutrient losses from lagoons, storage tanks, and land application as a function of design, operation, and climatic variables in order to develop nutrient management plans and nutrient mass balance models,

The design, location, and management of permanent and temporary livestock-waste storage facilities are factors that may contribute to or prevent well-water contamination by nitrate and bacteria (35). Storage and handling facilities will minimize leaching if they are constructed of concrete or other impermeable materials and properly managed. Management includes routine inspection and maintenance of above-ground systems to ensure that they do not rupture; filling facilities only according to design specifications; and applying the wastes so as not to exceed the nutrient uptake capacity of the application area (98).

Increasing the agronomic use of manure might be fostered through joint efforts among States, cities, industry, and agriculture to promote manure processing and use on public and private lands. Development of incentives for manure use in cropping systems, particularly in high manure-production areas, may offer opportunity to enhance agronomic use of this resource as opposed to treating it as a waste disposal problem (box 4-I).

Concomitant activities to increase awareness of the potential of manure as a groundwater contaminant might be achieved through revision of EPA effluent guidelines to include groundwater protection requirements. Federal and State programs that work toward cost-sharing or other economic incentives for livestock producers to adopt and implement water quality protection practices, particularly in areas where greatest vulnerability exists, could promote such adoption. Technical assistance (SCS), education (CES), and research (ARS) must be able to promote and support practitioner adoption and thus may require some enhancement. For example, demonstration livestock production operations in areas having a high or low groundwater-pollution potential could serve to disseminate information on appropriate best management practices that contain provisions for groundwater protection.

Silage

Corn, legumes, and grasses commonly are stored in moist, partially fermented conditions for use as livestock feed. When stored and compacted in silos and other facilities, these wet crops lose moisture, which drains out of the silo as effluent. Effluent production from silage varies with the material stored and its moisture and nitrogen content. Of these, moisture seems to be the most important factor affecting effluent production. Several studies have determined that materials stored at 65 percent moisture content or higher can produce effluent. For grass silage, the amount produced varies from a trickle at 75 percent moisture to 79 gallons per ton at 85 percent moisture (195). About three-quarters of the effluent is produced in the first 3 weeks of

Box 4-H—Natural Zeolites: Some Potential Applications in Agricultural Waste Management

Zeolites, a suite of porous fine-grained minerals found in certain near surface, sedimentary rocks, have special physical and chemical properties that could make them valuable to farmers in agricultural waste management.

Some 50 species of a certain group of natural minerals called zeolites have their atoms arranged so that they form hollow cages with tiny openings through which other ions or molecules of the right size can pass. Larger ions or molecules are screened out from the cages and channels of the zeolites. Because of these unique properties and behavior, zeolites are referred to as "molecular sieves, "

In addition, zeolites have the ability to hold various chemical elements (ions) loosely so that they can be exchanged for other chemical elements. This ion exchange property of zeolites, coupled with the unique properties of their porous structure, accounts for the interesting and potentially important usefulness of zeolites in agriculture. With steadily increasing knowledge of zeolites and their applications (158), today it seems evident that those minerals can play an increasingly important role in agriculture, especially in animal waste management.

Zedites could have an important role in animal waste management because they can adsorb ammonia from animal wastes (134). Zeolites have a potential for use to help minimize water pollution from agricultural runoff and to make animal manure easier to handle and to move from animal pens to agricultural plots.

Swine manure, for example, is malodorous and is composed of only about 10 percent solids (132), making it difficult and undesirable to handle. A zeolite-rich mudstone was used in a swine-raising activity in Japan to reduce the manure's offensive odor and to improve its handling, characteristics. The zeolite-treated manure proved suitable as a fertilizer for rice production (94).

Other work in Japan on large hog farms also illustrates the usefulness of zeolites (141). A zeolite filter composed of a granular zeolite, used to process contaminated water remaining after initial manure/water filtration, removed the ammonium ions and other microsubstances, and trapped many of the remaining suspended solids. Transparency of the effluent showed marked improvement after zeolite treatment and chemical and biological oxygen demand was significantly reduced.

Recently, Romanian researchers showed similar results to those of the Japanese (1 23). They used nonactivated, ground volcanic tuff containing 67 percent zeolite in a series of filters, each with a different zeolite size fraction ranging from 0.5 to 10 mm. The ammonia-nitrogen content decreased 91.3 percent and the nitrate content decreased 99 percent from the initial metallic screens through the final zeolite filter.

Such studies illustrate that zeolites can play an important role in animal waste management by trapping ammonia. Zeolites could be spread on the floors of animal enclosures to trap ammonia and reduce the odor and moisture content of manure. Similarly, zeolites could be placed in manure holding ponds and lagoons to trap ammonia. Periodic removal of the nitrogen-enriched zeolites could provide a fertilizer source for croplands.

Zeolite-amended diets, in the case of poultry, have been shown to reduce the moisture content of feces by 25 percent (249). Such moisture reduction could improve the potential for using poultry manure as a nutrient source. Swine fed a 5 percent zeolite diet produced more compact and less malodorous feces than control groups (243).

Mixing of ammonium-saturated zeolites with ground rock phosphate or other phosphorus-bearing minerals with low volubility enhances release of phosphorus in plant-available forms (10,24,106). Greenhouse experiments mixing ammonium-saturated zedites with ground rock phosphate in ratios of 3:1 to 4.5:1 show increased phosphorus uptake by plants and increased biomass production (10).

Mixing livestock manures with zeolites offers an opportunity for farmers to reduce potential nitrogen leaching through the soil profile, In addition, these materials offer a mechanism to improve soil fertility as well as promote release of phosphorus from soil matter. Zeo-agriculture success will depend on interdisciplinary approaches involving mineralogists, chemists, and agriculturalists. Thorough assessment of zeolite uses in animal waste management just as in other agricultural uses is strongly needed (149).

storage, although it can continue to flow for up to 3 months. The composition of the effluent varies with the material stored; it may be highly acidic and corrosive to steel and concrete (200).

Groundwater contaminated with silage effluent may have a disagreeable odor and show increased levels of acidity, ammonia, nitrate, and iron. Cases of water contamination from silage effluent have been documented. In one case, thousands of gallons of sweet-corn silage juices drained through a limestone sinkhole and contaminated wells a mile from the site (250,25 1).

Box 4-I—Best Management Practices for Controlling Potential Contamination of Surface and Groundwater From Animal Wastes

- Annual soil testing to determine nutrient content and evaluation of efficiency of nitrogen use in the production system.
- Nutrient analysis of the waste prior to application to match with crop requirements.
- Determination of application rates based on crop needs and soil reservoir.
- Timing of application to match maximum crop uptake such as spring or summer.
- Application by broadcast and incorporation or injection to avoid volatilization or loss in runoff.
- Installation of vegetative filter strips to control sediment and nutrient losses in feedlot and dairy runoff.
- Restrict access of animals to streams, lakes, and other impoundments and rotational grazing to maintain sufficient vegetative cover on pastureland.

SOURCE: North Carolina State University, Biological and Agricultural Engineering Department, *State of the Art Review of Best Management Practices for Agricultural Nonpoint Source Control,]: Animal Waste* (Raleigh, NC: North Carolina State University, August 1982).

Silage poses little pollution threat when it is harvested and stored properly (146). Improper handling can lead to significant effluent flow from storage facilities. Silage commonly is stored on uncovered ground or in structures not designed to contain silage juices (99). Silage storage facilities include vertical silos; trench silos; temporary stacks; and temporary, plastic storage-tubes; none of which were designed for groundwater protection. Collection of silage effluent in water retention structures such as clay- or plastic-lined ponds can reduce leaching potential.

Effluent production may be reduced by varying cutting and harvesting time, adding a silage preservative (e.g., formic acid), and adding moisture-absorbent materials to the silage as it is stored (252). Addition of absorbent materials has also been shown to raise nutrient value of the silage. Allowing materials to wilt in the field for 24 hours prior to storage has been shown to reduce moisture content by 10 percent and effluent production by as much as 100 percent (252).

RESEARCH APPROACHES IN AGRICULTURAL TECHNOLOGY DEVELOPMENT

Two concurrent thrusts for research and technology development are needed in taking a comprehensive approach to reducing groundwater contamination from agriculture. The first thrust addresses more immediate needs to improve agrichemical management and encompasses technology categories for point-source controls, efficient application management, and some agrichemical use reduction. This short-term thrust assumes that agrichemical use will remain the central feature of nutrient and pest management practices in U.S. agriculture. A second research thrust aims to increase farmers' technology options in the longer term and emphasizes technology categories for agrichemical use reduction and alternative practices. The long-term thrust assumes that farmers in the longer term will use ecological principles and biological methods as the central means to manage nutrients and pests in integrated farming systems.

These two research thrusts are not mutually exclusive, but they involve different research questions, emphasize different scientific disciplines, and are likely to use different linkages among basic and applied researchers, commercial fins, and agricultural producers. Moreover, the current agricultural research and delivery system will accommodate the short-term thrust much more easily than the long-term thrust, which requires more interdisciplinary research and greater integration of the biological, social, and agricultural sciences.

Because the current research and technology delivery system is more amenable to moving the short-term thrust forward, researchers and producers could focus on this thrust exclusively and fail to recognize the opportunity costs of neglecting long-term information and management needs. The agricultural research system is likely to need strong public support and incentives to advance the long-term research thrust rapidly enough to achieve sufficient knowlege that can be translated into feasible practices (box 4-J).

Box 4-J—Progression in Research and Development Efforts Needed To Minimize Agrichemical Contamination of Groundwater

R&D feature	Short-term thrust	Long-term thrust	
Study regions	Identify hydrogeologically vulnerable regions.	Identify agroecological regions with common natural resource and agricultural production characteristics.	
Regional characteristics	Determine extent of groundwater contamination and types and characteristics of contaminants.	Identify cross-media agrichemical management problems.	
Site-specific processes	Clarify agrichemical fate and transport to groundwater.	Identify agroecological processes **and interactions, and agricultural productions that affect agrichemical fate and transport.**	
Site-specific products	Develop agrichemical formulations that are less likely to leach in vulnerable sites, more efficient application equipment, and improved handling facilities.	**Develop improved agrichemicals, plant varieties, biopestiades, and other products that maintain or enhance beneficial ecological processes.**	
Site-specific practices	Development and adapt practices (e.g., BMPs) that prevent or reduce agrichemical transport to groundwater.	**Develop integrated agricultural systems that optimize beneficial** ecological processes, minimize adverse environmental impacts, reduce production costs, and maintain farm profitability.	**Mission** Maximize **Farmer Options**
Site-specific services	Increase information dissemination on groundwater vulnerability, appropriate agrichemical selection and management through existing information-transfer organizations (e.g., agricultural extension services, commercial firms, consulting services).	Increase information dissemination and education efforts on ecosystem processes; offer advisory and management services for improved multi-objective decisionmaking; adapt existing extension framework and develop new services to provide information and advisory or management services.	
Farmer decisionmaking assistance	**Facilitate agrichemical recordkeeping and use of realistic yield goals.**	Emphasize long-term farmland resource management planning to integrate agricultural production and natural resource protection.	
Assistance delivery	Emphasize commercial sector and traditional "top-down" delivery from researcher to farmer.	Facilitate commercial sector support of integrated decisionmaking at the site; encourage on-farm observation and experimentation.	

Components of the U.S. Agricultural Research System

Public- and private-sector agricultural researchers play key roles in developing agricultural technologies and management practices. Such research includes improving agrichemical products, developing individual or combined management practices, and designing integrated farm management systems that are less likely to contaminate groundwater with agrichemicals. The following discussion focuses on researchers' roles, opportunities, and constraints in developing environmentally related agricultural improvements.[7]

Federal Agricultural Research

Federal agricultural researchers work within the USDA Agricultural Research Service (ARS) as well as research divisions of the Economic Research Service (ERS) and the Soil Conservation Service (SCS) Technical Centers. Other Federal research groups conducting environmentally related agricultura1 research are EPA research laboratories, USGS research offices, and the Tennessee Valley Authority (TVA) National Fertilizer and Environmental Research Center (NFERC). Despite extensive Federal agricultural research, efforts have not been adequately coordinated and planned to ensure consistent research methodologies in the development

7 A previous OTA report has reviewed the United States agricultural research system, its organizational structure, roles of research participants, and planning and finding mechanisms (21 1); and a recent Special Report covers agricultural research and technology transfer policy issues for the 1990s (216).

of environmentally appropriate farm management practices (140).

State Agricultural Experiment Stations

State-employed agricultural researchers work in the land-grant universities and State Agricultural Experiment Stations (SAESs). SAES systems are composed of field sites, research farms, and laboratories that provide site-specific agronomic information based on a State's climate, soil, and water resource conditions.

Each SAES receives Federal formula (Hatch Act) funding for agricultural research through the USDA Cooperative State Research Service (CSRS). Individual researchers at many SAESs also receive Federal competitive grants for specific research projects, as well as grants from trade associations and commodity groups for applied research and product testing. Formula funds generally are directed toward basic and applied research that meets the needs of each State's producers and rural communities. Competitive grants, on the other hand, emphasize basic research in specific areas. Thus, formula funds are more likely to be directed toward development, testing, and dissemination of agricultural practices most suited to the State's hydrogeologic, climatic, and economic conditions than are competitive grant funds.

Investment in agricultural research to answer questions about impacts of agriculture on environmental quality varies widely from State to State. States that are most likely to provide timely, site-specific information on groundwater protection are those that allocate substantial amounts of State funding for this type of research.

Private-Sector Research

Agricultural researchers in the private sector apply basic research findings to the development of commercial products and production techniques. Commercial agricultural firms historically have relied on basic research results from the public sector to develop commercial crop production technologies. Public-sector research in the basic agricultural sciences, thus, has provided the technical foundation for commercial applied research. Since development and commercialization of technologies resulting from basic research may be lengthy (e.g., 10 to 20 years or more) (178), the breadth and depth of the basic research base in the public sector is a critical consideration for new technology development.

All components of the agricultural research system can contribute to the identification, testing, and adaptation of practices with potential to reduce agrichemical contamination of groundwater. Although a broad basic research base is needed, Federal and State governments also need to devote adequate funding to applied research that addresses the site-specific nature of environmental problems in agriculture. Many commercial agricultural technologies have been widely adopted because markets are large enough to support high-volume production, resulting in relatively low-cost products to farmers. However, market niches for innovative agricultural technologies designed to address specific environmental conditions may not be large enough to encourage commercial firms to develop these technologies. Such technologies also may be too expensive for farmers in environmentally sensitive areas to afford. Alternatively, if farmers in such areas cannot use certain comparatively low-cost inputs (e.g., some pesticides), they may be at a competitive disadvantage with farmers in other areas where agriculture-related environmental problems are fewer.

Best Management Practices

The agricultural Best Management Practice (BMP) concept originated with EPA programs established to reduce agricultural nonpoint-source pollution and has been expanded to mean individual methods designed to reduce adverse impacts on soil, surface water, or groundwater resources. Best management practices (BMPs) are defined in the Federal Water Pollution Control Act Amendments of 1976 as:

> . . . a practice or combination of practices that is determined by a State (or designated area-wide planning agency) after problem assessment, examination of alternative practices and appropriate public participation to be the most effective practicable (including technological, economic, and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals (52).

When this definition was written, water quality was essentially synonymous with surface-water quality, thus in the course of BMP development considerations of other off-site impacts (e.g., effects on groundwater quality) largely were unexamined.

Partial solutions to environmental pollution problems in agriculture have involved the development

Box 4-K—Maximum Economic Yield

The Maximum Economic Yield (MEY) approach, developed and advocated by the Potash and Phosphate Institute and the Foundation for Agronomic Research, is based on more intensive cultivation of the higher quality land to generate equal or higher production on reduced acreage. An estimated 90 percent of the soil losses in the United States come from 10 percent of the cultivated land. These soil losses maybe largely due to cultivation of highly erosive lands, thus removing such lands from production is suggested as a mechanism to reducing U.S. soil erosion.

The MEY operates on the principle that early and rapid development of a denser crop canopy will reduce soil and nutrient losses due to runoff events. Higher yields above and below ground promote greater root proliferation leading to soil stabilization, increased soil moisture holding capacity, and enhanced soil infiltration rates. Greater leaf area established by the associated denser canopy reduces impact of precipitation on the soil surface. It has been suggested that such an environment might reduce the potential for contaminants to move through the soil profile, despite associated increases in agrichemical use. If the root mat developed under an MEY field is sufficiently dense, it may promote plant uptake of available nitrogen. However, this effect is also dependent on the nutrient accumulation patterns of the crop being grown as well as environmental parameters that affect leaching.

Best management practices for crops and nutrients are incorporated into the MEY concept that promotes such techniques for nitrogen management as split applications, cover crops to reclaim residual soil nitrate, soil testing to determine soil nutrient level, tissue testing, application of vitrification inhibitors, and accounting for nitrogen credits. Applied crop management practices include: conservation tillage, contour stripcropping, terracing, crop rotations, water and sediment control basins, and use of cover crops.

SOURCE: Potash and Phosphate Institute, *The Vital Role of Phosphorus in Our Environment,* Publication No. 11-87-A (Atlanta, GA: 1987).

of pollution-reducing BMPs by agricultural researchers in the public sector. BMPs have been used by SCS and State conservation agencies to control soil erosion and address nonpoint-source surface-water contamination. This approach included components that addressed: 1) structural controls such as terraces and buffer strips to control pollutant transport in runoff, 2) source controls that affect rates of agrichemical applications, 3) agronomic management affecting timing and placement of agrichemicals, and 4) integrated pest management (8). Private organizations have incorporated BMPs into agricultural managment schemes as well (box 4-K).

BMPs to protect surface waters from agricultural sources of contamination might include technologies and management practices that:

- maintain a soil cover (crop residues, canopy development, and/or rough surface) in order to reduce the impact of precipitation on the soil surface and to slow runoff velocity;
- increase soil permeability to enhance infiltration and thus minimize erosion and reduce runoff; and
- minimize or reduce soil-solution concentrations of agricultural chemicals, heavy metals, toxics, and plant nutrients to reduce the potential for contamination of water sources during heavy precipitation events (8).

USDA and EPA only recently have begun to develop BMPs specifically to reduce nonpoint-source contamination of groundwater. BMPs for groundwater protection need to account for infiltration, volubility and soil affinity of the potential contaminant, relative agrichemical loading, timing, and the ability of the practice to alter any or all of these conditions. Research could identify which combinations of BMPs are best suited to a State's soil, hydrogeological, and agricultural conditions in a systematic fashion.

Groundwater contaminants may be sorted into two broad categories: 1) those that maybe managed by practices affecting the physical system (e.g., sediment, pathogens, and heavy metals) such as maintaining vegetative cover and soil pH and land leveling; and 2) those that may be managed by practices affecting inputs (e.g., pesticides, nitrogen and phosphorus, and easily oxidizable organics) such as rate and timing of applications (8). Development of management plans that effectively incorporate practices designed to manage both types of contamination may be problematic. Practices designed to manage one contaminant or resource concern may conflict with efforts to manage another.

For example, conservation tillage (primarily designed for erosion control) is suggested to exacerbate movement of agrichemicals through the soil profile. Although highly successful in reducing sediment losses, it seems that this practice should be examined for its effect on other resource conservation goals.

The broad number of environmental variables that comprise an agroecosystem make determination of BMPs complex, Specific practices must be developed on a site-by-site basis to account for variations in the geologic, hydrologic, and climatic attributes of a given agroecosystem. A key problem facing researchers is the development of combinations of BMPs that address several environmental pollution problems, rather than just one. To minimize environmental impacts, BMP combinations therefore need to fit into a total farm management system, which considers local environmental and economic conditions. Further, the skills and motivation of the practitioners are an added component that cannot be extracted from the overall equation, Although no single formula is likely to exist for developing and implementing BMPs, the broadly stated goals of BMP development may serve as a guide.

The initial concept of BMPs as a package of agricultural practices designed to meet conservation and quality goals for a specific resource may no longer be appropriate given broadened concerns over partitioning of agricultural chemicals to other media (e.g., agriculturally generated nitrous oxides and methane losses to the atmosphere). An expanded approach that includes identification of practices designed to mediate or mitigate losses across media could address this need.

Farmstead Assessment Programs

Farmstead Assessment programs are under development in several States as a mechanism to: 1) assess potential farmstead sources of groundwater contamination; 2) educate farmers about management practices to prevent groundwater contamination; and 3) clarify the relevant laws, regulations, and sources of assistance in farmstead management for farmers.

Increased documentation that agriculture is a contributor to agrichemical contamination of groundwater has focused on agronomic practices as the major pathways of contamination. Insufficient consideration has been given to potential for farmstead practices and structures to cause groundwater contamination (98).

Farmstead describes the area centered on the farm residence, including: barns, silos, and related buildings; structures and facilities used for storage and handling of agrichemicals and household and livestock waste; and potable water wells for human or livestock use. Management and maintenance of these structures and facilities may have a major influence on groundwater quality in general and most significantly on that used on the far-m itself.

As currently developed, a farmstead assessment includes the following steps:

- evaluation of soil, geologic, and hydrologic conditions to identify the pollution potential of the individual farmsite;
- evaluation of farmstead structures and activities affecting pollution potential (e.g., well design and location; agrichemical handling, storage, and disposal; silage storage facilities and management; petroleum-products storage and disposal; septic system location and management; farm and household hazardous-waste disposal and recycling; and milkhouse-waste handling); and
- integration of the above evaluations to form an assessment of farmstead groundwater-contamination potential, and suggestions for structural and management changes to reduce that potential.

Expertise is being developed in the assessment of groundwater contamination potential from farmstead activities. However, current efforts lack the support system needed to: 1) educate practitioners on the links between activities and contamination potential, 2) demonstrate the long-term management changes needed to protect groundwater, and 3) provide financial and technical support to implement management plans (98).

Integrated Farm Management Systems

Integrated approaches to developing farm management plans are needed. Existing resource management plans may provide a base for development of broader management systems. For example, integration of a farmstead assessment plan with complementary management plans designed to reduce adverse environmental impacts from agronomic activities may provide a base for development of whole-farm management systems.

Resource Management Systems

The Resource Management System (RMS) is a land-management concept proposed and developed by the Soil Conservation Service (SCS). The RMS combines multidisciplinary input to develop a farm management and conservation plan coupling the landowner's goals for resource use and SCS goals of reducing erosion and nonpoint-source contamination. This farm management approach links agricultural production and conservation. SCS provides technical assistance to the farmer in developing such farm plans. The farmer then decides on what part of his/her land the plan will be applied.

SCS's RMS integrates conservation practices and management for the identified primary use of land or water. At a minimum the RMS is supposed to provide protection for the resource base by meeting acceptable soil losses, maintaining water quality, and maintaining acceptable ecological and management levels for the selected resource use in accordance with the Field Office Technical Guide (FOTG). Currently there are six resource concerns incorporated in RMS development:

- erosion control-reduction of sheet and x-ill erosion to the soil loss tolerance level for the most vulnerable soil within the field;
- water disposal-management of surface or subsurface water in drainage systems to protect the quality of linked water sources;
- livestock waste and agrichemical management—for pesticides: adherence to label recommendations, regulations, appropriate timing and application method, and alternative control methods in highly vulnerable areas; for nutrients: application based on plant need, soil tests, accounting for nitrogen credits, appropriate timing, chemical form, and application rate;
- resource management—mitigation of adverse effects on water quality or quantity from plant or animal production and vice versa;
- water management—management of irrigation, drainage, and land to protect water quantity and quality; and
- off-site effects—resource management to avoid potential adverse effects on groundwater or surface water from agricultural production activities (232).

The RMS approach is undergoing revision to broaden its application for conservation of resources. Under the revised protocol, there will be five categories of resource concern: 1) soil, 2) water, 3) air, 4) plants, and 5) animals (233). The inclusion of air as a resource of concern expands the RMS approach to address potential impacts of resource use on the atmosphere.

The RMS approach is adaptive-as new resource concerns arise an evaluation and revision process may be conducted. The procedure for such revision is outlined in the SCS field office guide and involves the following six steps:

- assess and evaluate water-resource information with plant and soils information,
- determine effects of agricultural production on water quality and quantity,
- evaluate current RMS on water resources,
- identfy applicable practices with beneficial effects on water resources,
- evaluate combinations of practices, and
- select combinations of practices.

Once the evaluation is complete, the revised RMS is developed incorporating practices to address the resource concern (232,233) (box 4-L).

Integrated Crop Management

An Integrated Crop Management (ICM) program was recently approved by ASCS as an approach to reduce excess use of nutrients and pesticides while maintaining farm income. The practice is being tested under the Agricultural Conservation Program on a limited basis in 1990 with a goal of reducing agrichemical use by 20 percent. A maximum of 20 producers from 5 counties per State may take part in the demonstration program. These demonstration sites are to represent a cross section of farming types within the State. The overall program goal is to encourage adoption of practices that integrate nutient management practices and integrated pest management into an overall crop management system. ICM practices are intended to reduce water, land, and atmospheric contamination by agrichemicals through use reduction.

The program provides cost-sharing assistance for development and implementation of integrated crop management systems (224). Eligibility requirements for participating in cost sharing include the following: 1) producers must have an ICM system developed in writing that reduces the level of agrichemi-

Box 4-L-Evaluating and Revising RMS—An Example

Below is a sample of how an RMS might be evaluated and revised given water quality concerns. The site of production is the Southern Coastal Plains, characterized by nearly level terrain, and deep, somewhat poorly drained soils on uplands and floodplains. Major environmental concerns were for water disposal, water management, and resources management. Detections of nitrogen and phosphorus in farm drainage ditches raised concern about possible contamination of ground and surface water, leading to the revision of the initial RMS. In absence of pesticide analysis of associated water sources, it was assumed that leachable pesticides were also moving with the water. While the initial RMS was developed based largely on site characteristics, the revised version incorporates management practices designed to address the detections of nutrient contamination of adjacent water sources.

Resource Management Systems	Erosion control	Water disposal	Animal waste & Agrichem management	Resource management	Water management	Off-site effects
Initial RMS						
Conservation cropping sequence	X			x		x
Crop residue use	X			x		
Surface drainage main or lateral		x			x	
Surface drainage field ditch		x			x	
Land smoothing		x			x	
Revised RMS						
Conservation cropping sequence				x		x
Crop residue use	X			x		
Surface drainage field main or lateral		x			x	
Surface dranage field ditch		x			x	
Land smoothing		x			x	
Pesticide management			x	x		x
Nutrient management			x	x		x
Structure **for water control**			x	x	x	x
Regulating water in drainage systems			x	x	x	x

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, Conservation Planning Division, ***National Planning Manual,*** Parti 501 (Washington, DC: 1984).

cal input historically used on the land, and 2) producers must have sufficient documentation to verify the rates and methods of agrichemical application before and after system development. Approval of the system is also dependent on the availability of appropriate technical resources. Technical assistance may be provided by CES, SCS, or certified private consultants. The ICM system may incorporate such tactics as soil and tissue testing, pest scouting, biocontrol, crop rotation, soil enhancement and conservation measures, and use of green manures or host crops (224).

SUMMARY AND POLICY IMPLICATIONS

The U.S. agricultural sector will be facing new issues and opportunities in the 1990s. The agricultural research system is being called on to respond to newly articulated environmental concerns associated with agricultural production practices; concerns for food safety and the environment seem likely to increase in importance. Meeting these challenges will require an agricultural research system with an effective national strategy. It will also require advances in science and technology of a scale and scope the system has not previously experienced (216).

Increased understanding of cross-media effects of technology implementation will enhance the potential for developing agricultural practices that address the broad spectrum of environmental concerns (e.g., soil erosion, surface water and groundwater pollution, atmospheric releases). Whether the agriculture research and technology development base is sufficiently broad, or the current structure is adequate to address the plethora of environmental concerns related to agriculture, however, is under question (216).

Integration of agriculture and environmental protection will mean that agricultural technologies and practices cannot be designed in isolation from their interactions within agroecosystems. Research and development efforts will need to examine the array of impacts arising from implementation. Integrated approaches to the development of agricultural practices and technologies have been taken, and further efforts are being made in this direction. For example, USDA's Low Input Sustainable Agriculture Program is designed to provide information on the productivity of low-input systems and the interaction of agricultural inputs within the agroecosystem (box4-M).

Enhancing Knowledge of the Agroecosystem

Agricultural researchers without a solid understanding of the sciences fundamental to agroecology (e.g., agronomy, hydrogeology, ecology), or not operating within a multidisciplinary or interdisciplinary framework, may develop products or practices without consideration of the broad array of potential impacts that might be generated from their implementation. A systems approach is needed in developing agricultural technologies designed to minimize agrichemical contamination of groundwater. Such an approach is likely to depend on increased understanding of agroecosystem components; the general principles of cycling, transport, and fate of agrichemicals within those systems; how certain technologies may affect their function; and how these interactions may affect groundwater vulnerability.

Congress could establish an Agroecosystem Research Initiative that directs and coordinates federally funded basic research on improved understanding of agroecosystem components and processes. The knowledge gained from such basic research could then support technology research and development efforts to design agricultural products and practices that could contribute to reducing groundwater contamination. An initial step in implementing an Agroecosystem Research Initiative could be to establish a coordinating body responsible for outlining an overall approach to the initiative. Topic-specific working groups could then be established that would evaluate the extent of knowledge on certain agroecosystem components and their interactions and report these findings to the coordinating body. The coordinating body could consequently identify research priorities and protocols for gathering the necessary information. Finally, research results could be synthesized and distributed throughout the agricultural research system.

Such an initiative could be implemented by USDA, or through a joint effort of several Federal agencies (e.g., USDA, EPA, USGS, NSF, and NOAA) to ensure that the research conducted and information gathered would support efforts to address the wide array of environmental concerns arising from agricultural production. For example, examination of nitrogen transformations in various agroecosystems might be approached differently by the various involved agencies. While one agency might identify the importance of quantifying nitrous oxide emissions to the atmosphere, others would likely approach the same research from a surface or groundwater contamination aspect, and still others might focus on changes in crop yields or quality. Such cross-agency discussion likely would broaden the research question. Further, tapping expertise housed within each cooperating agency might lead to quicker attainment of the research goal than if the required expertise had to be developed within any single agency.

Working groups could be established to prepare reports on the state of research knowledge in specific topic areas. Each working group could: 1) analyze the existing information base from which research currently operates, 2) identify areas of most urgent research need and the tasks required to fill this need, and 3) develop common research protocols so that experiments could be replicated across agroecosystems and thus develop a meaningful information base. These working groups should be interdisciplinary to incorporate a systems approach in agricultural research and thereby be able to identify key research questions related to numerous objectives.

Working groups might best be established across Federal agencies and might follow a model such as the Technical Integration Group, or perhaps be based on other extant informal groups. For example, the ARS Nitrogen Research Workshop, held in 1989 to identify the extent of current knowledge of nitrogen in the agroecosystem, could be expanded to into one such working group. Mechanisms would be needed to provide for regular work group meetings, evaluation of results, and reporting of work group findings to relevant administrative offices for consideration in setting or revising research priorities.

Common protocols used in initial agroecosystem research efforts could provide an information base through which variations in ecosystem response to agricultural technologies could be determined. This

Box 4-M—USDA Low-Input Sustainable Agriculture Program

The Low Input Sustainable Agriculture (LISA) Program was created by USDA in response to the Agricultural Productivity Research Subtitle in the 1985 Food Security Act (Public Law 99-198). The Agriculture Productivity Act provides authority to conduct research and education programs on low-input farming systems to promote profitable farming, conservation of natural resources, and environmental protection (225). LISA was designed to respond to growing farmer interest for more cost-effective and environmentally oriented agricultural production practices. The Program received initial funding for the fiscal year 1988 and USDA policy on low-input farming systems was issued in January of 1988.

The Department encourages research and education programs and activities that provide farmers with a wide choice of cost effective farming systems including systems that minimize or optimize the use of purchased inputs and that minimize environmental hazards. The Department also encourages efforts to expand the use of such systems.

Grants are provided under LISA authority for research and education projects designed to assist agricultural producers in reducing purchased external inputs. Such projects emphasize substituting management, information, and on-farm resources for external inputs and may include techniques such as crop rotation, farm diversification, resource conservation practices, and mechanical and biological pest control approaches. Proposal response to the program has been significant (e.g., finding to support acceptable LISA proposals fell short by roughly fivefold in each of the first 2 years of the program).

LISA is administered through four regional host institutions (Northeast, North Central, Southern, Western) and is organized and directed by the Cooperative State Research Service (CSRS) with the cooperation and participation of several USDA agencies. Project proposals are reviewed in each region by committees of research scientists, practitioners, and educators. A key feature of LISA projects is the involvement of practitioners, interdisciplinary research teams, and private research and education programs.

Most projects are long-term studies requiring several years development and replication to generate meaningful results. *Some* have added to ongoing work allowing expansion/collection of additional data. Short-term projects designed to present known findings through a variety of mechanisms (e.g., video tapes, computer software development) are also funded under LISA.

Funding levels for the LISA program have increased roughly 14 percent in the last 2 years ($3.9 million in 1988 and $4.45 million in 1989). However, this has been insufficient to fund all of the acceptable proposals. For example, roughly $20 million would have been needed to fund acceptable proposals in 1989 (182).

LISA projects are providing the scientific basis for understanding the productivity of low-input systems and providing comparisons between these and conventional systems that emphasize high yields generally through the use of fertilizers, pesticides, and other purchased inputs. While the conventional approach tends to view resource conservation and environmental quality as potential constraints to maximizing profits, the LISA approach strives to integrate these aspects of agricultural production. LISA projects are demonstrating that certain low-input production methods can be profitable when implemented properly (1 18),

Controversy exists over the ability of low-input agriculture approaches to produce sufficient food to meet domestic and international needs; suggesting that LISA would require a significant part of the U.S. population to return to or enter farming. Further, it is argued that ‘‘conventional agriculture’ approaches are sustainable and environmentally sound (241 ,169). In fact, even the term LISA is subject to a variety of definitions. LISA advocates define low-input to mean low purchased inputs, but increased management and information inputs and thus not necessarily low total inputs (182,1 18). Critics tend to focus on the reduction of purchased inputs and suggest that agricultural profitability and thus sustainability depend on availability and use of purchased inputs (241,169). However, this apparent bifurcation in agricultural production approaches is not so widely divided as it may seem on the surface. Agreement exists as to the need for a sustainable system to be profitable and that any input must be properly managed to avoid adverse environmental and economic impacts.

Ten guiding principles of LISA

1. If a farming method is not profitable it cannot be sustainable.
2. Farmers need accurate, readily usable information on the impacts of LISA methods on farm profits, resource productivity, and the environment.

Continued on next page

3. Some farmers can now profitably use low-input methods.
4. Properly designed and executed research and education efforts can enhance profitability of low-input methods.
5. Net results of adoption of low-input methods must be evaluated in terms of the whole farm system (e.g., labor and capital requirements, agroecological interactions, environmental impacts).
6. Success will depend on multiorganizational approach (e.g., interdisciplinary efforts, practitioner involvement, public and private organizations).
7. CSRS and soil conservation agencies (SCS, CES) must be full partners in design and implementation of the program.
8. Administration should be at the regional level to promote decisionmaking by persons with an understanding of the site-specific conditions associated with region.
9. Sustainable systems are highly site-specific and their success depends on practitioner skills and attitudes.
10. Establishment of sustainable systems on the farm should be carefully planned and implemented gradually (118).

effort could provide a base from which to correlate specific ecosystem features with response differences and thus be used to identify adaptive research needs for specific technologies across agroecosystems.

Undertaking a comprehensive Agroecosystem Research Initiative, however, may involve some structural and strategic changes in the participating organizations. For example, it would likely require increased emphasis on biological, ecological, and systems sciences and thus might involve shifting research funds and staffing to place higher priority on these sciences. Research funding also probably would have to be increased and allocation formulae or programs modified to address priorities established by the Initiative.

Environmental research in agriculture also maybe more costly and time consuming than production research, requiring different research designs and measurement techniques. In addition, jointly conducted agroecosystem research may have to incorporate a large administrative component to achieve the level of coordination necessary for effective planning and evaluation of results.

Federal funding levels for agricultural research have remained relatively stable for the past three decades due to Administration and congressional arguments against funding increases because of agricultural surpluses, the budget deficit, and other competing priorities. Some new Federal funding has been allocated under the Water Quality Initiative, but this has not been directly aimed at increasing understanding of agroecosystems. Redirection of these funds could slow efforts to develop and extend practices already identified as having beneficial effects on reducing potential contamination of groundwater. Still, allocation of funds to directed research efforts under an Agroecosystem Research Initiative would accord with expressed priorities for addressing environmental problems in agriculture and so may attract new appropriations.

Long-term research activities commonly are accomplished through base funding to the 57 State Agricultural Experiment Stations (SAESs) and, less commonly, through grants for special initiatives. Although base funding provides for dispersed research addressing a large number of commodities and agroecosystems, no formal mechanism exists to direct how base funds should be spent by the States. Thus, implementation of an Agroecosystem Research Initiative through individual SAES efforts without additional appropriations may be problematic and lead to fragmentary efforts.

Congress could direct the General Accounting Office (GAO) to analyze the relative merits and costs of implementing an Agroecosystem Research Initiative through: 1) the 57 SAESs, 2) Lead Agroecosystem SAESs, or 3) Regional Agroecosystem Experiment Stations. Funding allocated under the Initiative could be apportioned among the existing SAESs for conduct of specific research tasks related to characterization of agroecosystems. However, such an extensive division of funding could result in each station receiving too little to conduct useful or timely research. Alternatively, appropriating substantial funding to each station would likely have too large a price tag in this time of budgetary austerity.

Specific SAESs could be identified to fulfill the role of Lead Agroecosystem Experiment Station (LAES). Stations identified as LAESs would coordinate research and funding to research units in cooperating SAESs, and would disseminate information. However, the substantial autonomy of SAESs could create difficulties in coordinating efforts across State boundaries as well as in evaluation of research efforts. Further, the LAES would likely require a substantial administrative component to organize and accomplish these new tasks with attendant increases in staffing to allow completion of normal duties as well as the newly assumed coordination responsibilities.

Alternatively, Regional Agroecosystem Experiment Stations could be established to centralize research activities and reduce constraints likely to be associated with coordinating separate stations. These RAESs might be drawn from existing SAESs or be newly identified sites. USDA could conduct an assessment of the site characteristics (e.g., climate, soils, hydrogeology) of existing agricultural research stations and categorize each station by agroecosystem to form the base for identification of potential RAESs or LAESs. Based on the analysis provided by GAO, the most cost-effective approach to providing infrastructure and staffing necessary to implement an Agroecosystem Research Initiative could be determined.

Priority Setting for Groundwater Protection Programs

U.S. agriculture is highly diverse and unevenly distributed across the country. Cropland acreage, predominant commodity (crop or livestock), and type and intensity of agrichemical use vary by region (203). Some areas may be more vulnerable than other areas to agrichemical contamination of groundwater by virtue of the larger agrichemical volumes applied and greater land areas involved in certain cropping systems. Similarly, centers of concentrated livestock agriculture, with attendant high volumes of waste production, may present areas of special concern. Regional factors, such as climate, hydrogeology, and types of agrichemicals used, will also affect the relationship between crop production activities and potential for groundwater contamination.

Research priorities can be established for the development of production practices that reduce groundwater contamination and other adverse impacts on the environment according to: 1) geographic area, depending on agricultural production intensity and hydrogeologic vulnerability; 2) need for data, information, or other types of knowledge, which depends on the number and urgency of the purposes they would serve; and 3) need for certain technologies and practices, which depends on the numbers and locations of farmers who could use them. Research priority setting would involve evaluation of the use and suitability of existing practices and ongoing research initiatives as they operate in the agricultural production system.

Identification of major information gaps and areas where greatest actual or potential environmental hazards exist offers a mechanism for developing research priorities to reduce the adverse environmental impacts associated with agricultural production. For example, baseline information on patterns and locations of agrichemical use could be a tool for identifying regions with the highest potential vulnerability to groundwater contamination. Basic and applied research efforts to reduce groundwater contamination potential then could focus on these regions. Once collection of natural resource and agrichemical use-data and assessment of the extent of current knowledge are complete, conditions will be improved for prioritizing needed basic research.

Some data and research gaps are known currently and could provide a focus for certain agricultural research activities. For example, past research on fertilizer and pesticide efficacy and movement largely has been conducted under conventional tillage regimes. However, use of reduced tillage methods is increasing. Thus, a need exists to examine the effects of alternate tillage systems on agrichemical movement and fate. Research conducted under USDA's Low Input Sustainable Agriculture (LISA) program addresses this need in part. Increased funding for LISA might shift the balance to favor greater attention on reduced input systems and thus promote development of products and practices more responsive to the diversity of U.S. farms.

Similarly, lack of understanding of mineralization rates of soil organic matter constrains improved nitrogen application practices. Some research within ARS could be refocused or redirected to ensure investigation of the fate of applied nitrogen (fertilizers, manures, and legumes) at a network of geographical sites that may be vulnerable to groundwater contamination. The focus would be on obtaining complete nitrogen balances at all sites in the network to support development of annualized nitrate-loss rates from cropping systems to groundwater. This information would be critical in determining a benchmark of acceptable' nitrate loss—a certain amount of nitrate is normally lost from unfertilized fields and thus a loss rate set below this level may be impossible to achieve.

Congress could direct USDA to expand information gathered under an Agroecosystem Research Initiative to develop agroecoregion maps that would delineate agricultural regions displaying similar ecological attributes. These maps could provide a tool for prioritizing and coordinating research efforts. Enhanced applications of an Agroecosystem Research Initiative might include development of 'agroecoregion maps' that display areas exhibiting similar site and farming system characteristics. Information and research results should be broadly applicable within regions. Further, agroecoregion maps might provide a broader base from which adaptive research could be performed and information shared.

Preliminary identification of agroecoregions could be done today and revised as additional resource attribute and land use data become available, and knowledge of important agroecosystem parameters and processes improves. For example, data from USDA's planned National Pesticide Use Survey and the National Agriculture Census could be correlated with USGS and EPA water quality data to identify agroecoregions highly vulnerable to groundwater contamination from agricultural sources. Based on this analysis, priority agroecoregions might be identified. Activities such as data collection, agroecosystem modeling, and GIS development efforts then might be directed preferentially to these regions.

Developing priorities on an agroecoregion basis may provide a mechanism for enhancing information sharing and avoiding duplication of certain research efforts. Thus, establishment of applied research priorities for the development of agricultural technologies to reduce groundwater contamination might be underpinned by characterization of agroecoregions.

Adaptive Research

Adaptation of technologies and practices to specific environments or cropping systems is an important aspect of reducing the potential for agrichemical contamination of the environment generally and groundwater specifically. Given the diversity of agricultural regions, production practices, and practitioners, the adaptation of practices suited to these factors becomes critical. Within the Federal agricultural research system, such adaptive research is carried out by the SAES; however, the extent of these efforts varies widely by State.

Site-specific problems also are addressed within farmer organizations that test and share information on innovative practices (commonly referred to as farmer-to-farmer referral networks). Groups such as Practical Farmers of Iowa, for example, conduct on-farm research with the assistance of land-grant university researchers. This type of organization can help fill information gaps and provide support to farmers who want to minimize environmental pollution problems.

Several aspects of federally funded research at SAESs may interfere with timely development of farm practices that have positive impacts on protecting groundwater quality. Agricultural researchers at land-grant universities and SAESs have greater incentives to conduct basic, disciplinary research than applied, interdisciplinary research. Because of the substantial autonomy of each SAES and the individual researchers, no formal mechanisms exist to coordinate research, determine where data gaps exist, or ensure that such gaps are addressed in applied-research efforts (21 1). Further, a lack of systematic evaluation of SAES research at the national level hinders monitoring of the amount of federally funded research being conducted on management practices to reduce agrichemical contamination of groundwater.

Individuals responsible for the conduct of adaptive research are rarely involved in development of the initial program or practice. This factor is seen as a major constraint to implementation of existing IPM research and program efforts. Research programs within USDA could be enhanced **through an** increased stress on the importance of transitional and applied research, particularly with regard to the specific constraints to adoption embodied by various agricultural sectors. Increased staffing likely would be required to extend current and developing IPM technologies adequately and thus promote adoption by growers. The extant agrichemical industry infrastructure for extending advice and products currently may overshadow developing low chemical-input approaches to pest control. For example, in Fresno County, 5,500 farms are serviced by over 500 licensed pest control advisors, a majority of which are pesticide retailers. Only three Fresno County CES staff have pest-control management responsibilities, only one direct IPM responsibilities (1 1).

Nitrogen management decisions also are dependent on information derived from site-specific, adaptive research. Policies that encourage conversion from contemporary nitrogen-use practices to ones posing reduced risk to groundwater should be crafted with consideration of individual enterprises and site conditions. Direct subsidies, tax credits, low-interest loans, rezoning, direct buyout, coupling, cross-compliance, or combinations thereof are potential policy tools. However, whatever policy is adopted, procedures for compliance will have to emerge on a farm-by-farm basis given the site specificity of nitrogen-use decisions.

If agricultural research efforts are to address resource protection to a greater extent, the traditional focus of agricultural research and education on commodity production will need to be expanded to include farming systems that reduce adverse environmental impacts and promote resource protection in agricultural production. Traditional incentives for researchers in land-grant universities will probably need to be changed to foster interdisciplinary work and a systems approach to research. Potential for Federal intervention in adaptive research is limited to ‘carrots’ of finding because States have primacy over their educational institutions, and professional organizations are primary actors in setting incentives for researchers (21 1).

Congress could authorize and fund a new USDA research and demonstration program to ensure that adaptive research on agricultural technologies is designed specifically to be suitable to agroecological site conditions and socioeconomic adopter conditions. To accomplish this, National Agricultural Test Sites could be established within identified agroecoregions for site-specific, adaptive research. Alternatively, such a role could be fulfilled by Regional Agroecosystem Experiment Stations identified under an Agroecosystem Research Initiative. These stations might also serve as demonstration sites where agricultural technologies shown to have a beneficial effect on protecting groundwater quality could be shown to farmers.

Technology development and adaptation research and grant proposals related to these test sites could be required to include statements of who the potential adopters would be, and identify mechanisms through which technology or practice adoption could be encouraged. Research finding could be made contingent on: 1) identification of likely adopters; 2) specification of the farming system improvement expected (e.g., reduced agrichemical waste); and 3) estimation of costs and benefits accruing to the profiled adopters in terms of funds, time, and effort. Adaptive research and extension results could be compared to this information to assist with development of future adaptive research and to draw general lessons for successful adaptation and extension activities.

Proposal specifications probably would require increased interaction between adaptive researchers and extension specialists. Such increased interactions could provide benefits in technology development and extension; however, they would also increase demands on already strained work schedules. Increased research and extension staffing might be required to ensure adequate planning, evaluation, and extension of research results within agroecoregions.

Research Coordination

Improved coordination among and between public and private efforts could have beneficial effects on development of technologies designed to reduce agrichemical contamination of groundwater (e.g., pesticides and application equipment). Research coordination at the public level will be particularly important in developing systems-oriented agricultural management practices designed to reduce adverse impacts on soil, surface water, and groundwater resources. Best Management Practices (BMPs) have been developed and used by SCS, EPA, and CES. However, the approach commonly has been designed to address a single resource concern and thus potential adverse impacts on other resources may have not been examined. Integrated approaches are being developed that consider a site’s soil, hydrogeological, and agricultural conditions to address this need. Coordinated development of such approaches by agencies having relevant expertise or experience would speed their development, reduce duplicative efforts, and contribute to successful efforts.

Coordination of federally funded agricultural research could be improved within and among States through mechanisms by which State and Federal agency personnel, local governments, and producers work together to identify public research questions. Each State's SCS Resource Conservationist and technical staff could work more closely with CES, other State agencies, and producer groups to develop appropriate management practices for conservation planning. SCS Resource Conservationists and their staff currently conduct studies of conservation practices in cooperation with the State's land-grant university and State agricultural experiment station,

Congress **could direct USDA, EPA, and USGS to coordinate technology research and development efforts with State land-grant universities to ensure conformation of farm practice recommendations.** Funding could be earmarked for coordination and communication efforts needed among land-grant and SAES researchers and the relevant State and Federal agencies in each agroecoregion. Coordinating groups might be drawn from topic-specific working groups established under an Agro-ecosystem Research Initiative, or be subgroups that would interact with these larger working groups. Such a structure might yield beneficial impacts for overall research coordination and exchange of information.

One possible mechanism for research coordination is through the inter-regional groups of land-grant universities. However, researchers within regions may not formally meet to identify key research questions and agree upon methodology, and if they do, it may be on an ad hoc basis (83). Even if researchers meet within or between regions, no formal mechanism exists to evaluate their efforts and to communicate results to other regions. Earmarked funding could specify the coordination and communication efforts required among land-grant and SAES researchers and among the relevant State and Federal agencies in each region.

For example, researchers on a regional nitrogen project could agree on research questions and methodologies that would be replicated in selected areas to provide the most useful information. State agencies, SCS, and EPA regional staff could assist researchers in selecting target areas for intensified research efforts. Funding could be provided for initial planning and follow-up meetings to ensure consistency and final evaluation and communication.

However, coordination of public and private research activities would not necessarily be improved through such a mechanism. Further, public and private coordination may become increasingly important in research areas receiving little public or private funding (e.g., pesticide application technology) in order to avoid duplicative efforts and promote complementarily of efforts.

Coordination between public and private efforts may be critical to technology development with potential impact on agrichemical contamination of groundwater. For example, Federal effort in development of pesticides or agrichemical application equipment is small. For example, ARS efforts in herbicide equipment development fell from 8.7 to 1.7 scientist-years between 1972 and 1982; similar trends can be noted for insect and disease control equipment (60). Additionally, major developers of pesticide application equipment currently comprise just a few small companies that specialize their products for specialized markets (60,73).

Currently, farm equipment manufacturers are not in a position to spend large amounts on the development of this technology without passing these expenditures along to the user by increasing equipment cost. Neither do these companies have research capability for chemical application technology and few have the resources to develop equip ment from other technology. Thus, input from the public sector can be critical in advancing the state of the art in this arena.

Coordination of advances in application equip ment with development of associated agrichemical products could facilitate adoption of improved agrichemical application practices. For example, while enhanced use of chemigation techniques may offer some potential to reduce frequency and volume of chemical applications and promote more uniform distribution, lack of agrichemical formulations designed specifically for chemigation systems hinders achieving these benefits. Research shows that formula alteration of certain pesticides and subsequent chemigation has allowed significant reduction in amount of active ingredient applied while achieving needed pest control (208).

Congress could direct USDA to establish a public-private research and development coordination body that would be responsible for reviewing Federal research proposals for complementarity of activities in both sectors. The role of the current Users Advisory Board-to identify and report research and technology transfer problems to Congress and USDA-could be expanded to fulfill such a role. The mission of this group would be to promote coordinated research and development among the various agricultural research and development entities. It might also serve as a mechanism to track research and development directions and, thus, provide some input as Federal agencies set their agricultural research priorities. For example, continuous review of ongoing agricultural research in the public and private sectors could facilitate identification of areas where little effort is being directed and these could be reviewed for a potential increased Federal research role.

Clearly, appropriate technologies and management practices will be critical to reducing the potential for adverse environmental impacts associated with current agricultural production practices. However, of equal importance is development of technology-transfer mechanisms that will promote the adoption of such practices. Current avenues of technology transfer may need to be improved and expanded in order to address this aspect of integrating agricultural productivity and environmental quality.

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