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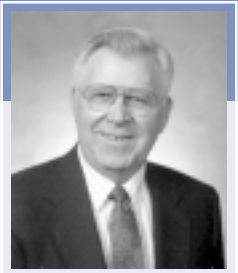
Reducing Nitrate in Water Resources with Modern Farming Systems

MSEA

Management Systems Evaluation Areas

IDEA No. 12



James F. Power

1929–1999

USDA-Agricultural Research Service (1955–1995)

Dr. James (Jim) Power died August 1, 1999 of leukemia at his home in Lincoln, Nebraska. It is with deep respect and fond memories that we dedicate this publication to his memory.

Throughout his career, Dr. Power distinguished himself by maintaining unparalleled research productivity, scientific leadership, service to soil science and society, and mentoring of family, friends, students, and scientists.

His high level of productivity as a scientist is legendary, with leadership and involvement in more than 100 research projects and more than 270 technical publications, including 3 books and 40 book chapters. His far-reaching contributions have included: pioneering no-till management in dryland areas, establishing relationships between nitrogen fertility and plant water use efficiency, mined-land reclamation, refining soil and crop managemnt systems for enhanced soil conservation and water quality, and most recently, defining agronomically and environmentally sound systems for use of biological resources that enhance the sustainability of agriculture.

In addition to his own distinguished research program, he coordinated many successful national research programs and developed a highly productive research team in applied soil science. His vision and leadership in mined-land reclamation was aptly reflected in passage of the Surface Mining Control and Reclamation Act of 1977.

Few people have made a greater impact than Dr. Power in the development of soil-land use production models suitable for maintaining the viability of the northern Great Plains of North America.

Dr. James Power leaves a legacy of integrity, strength of character, and outstanding contributions to science and society.

Reducing Nitrate in Water Resources with Modern Farming Systems

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IDEA No. 12

Executive Summary

Farming Systems impact economic and environmental viability

A farming system—the end result of many decisions integrated for risk management control in crop and animal production—is not a fixed recipe, but rather a flexible, responsive entity addressing economic and environmental concerns. To be successful over the long term, the farming system must enhance both the economic and the environmental viability of the farm unit.

In view of the environmental concern with nitrates in both surface and ground waters, the United States Department of Agriculture undertook a very extensive research and education program to evaluate the impact of farming systems on nitrate contamination of water resources and to develop or improve management practices to reduce nitrate loss.

MSEA research shows how farming systems affect water quality

The resulting Management Systems Evaluation Areas (MSEA) water quality project encompassed major research and educational efforts in five states, and satellite research and educational programs in four additional states. The information gathered sheds light on how current and alternative farming systems affect water quality.

Impacts for consideration in future policy development:

- Site-specific decisions are needed for each farm. Every farm has a unique set of resources and inputs: soils, climate, equipment, labor, capital and managerial skills vary from farm to farm.
- Tillage method and time influence nutrient cycling, management, and soil erosion. Reduced tillage methods, either ridge-till or no-till, are most suitable for managing soil nutrient and soil erosion.
- Corn-soybean crop sequence maintains net income and protects water quality better than a continuous corn cropping system.
- Management of irrigation water helps reduce nitrate losses from fields and reduces nitrogen enrichment of water resources.
- Using technology to assist in nitrogen fertilizer rate decisions is key to reducing nitrate contamination in water resources.
- Implementation of more site-specific management decisions is needed to meet the challenge of soil variability from farm to farm and within a given field in order to produce crops with the least risk to the environment.
- Weather has the largest influence on risk management in farming. All farming systems are directly affected by weather—a natural force creating unpredictable outcomes on crop production and environmental issues involving water quality.
- Farmers adopt new technologies when shown how a change in the farming system can reduce the economic and environmental risks involved in crop production.

Reducing Nitrate In Water Resources With Modern Farming Systems

"The one who grasps principles can successfully select the best methods. The one who tries methods, ignoring principles, is sure to have trouble."

- Ralph Waldo Emerson

Developing and managing a farming system that is both environmentally and economically sound requires careful consideration of many principles and their integration into decision making. The United States Department of Agriculture's (USDA) research discussed in this report outlines some of the principles that must be considered in order to improve water quality while maintaining financial viability in the production of crops and animals on our lands.

Farming activities may pollute water resources with nitrate. This is an important issue in the North Central States where more than 50 percent of the nitrogen fertilizer used in the United States is applied to enhance crop production. Nitrate concentrations in some water resources exceed the U. S. EPA's maximum contaminant level of 10 ppm of nitrate-nitrogen in public water supplies. In response to water quality concerns, the USDA began an extensive research and education project in 1990 to evaluate the impact of farming systems on nitrate in water resources and to develop practices for reducing nitrate contamination. This research, which involved a number of federal, state, and local agencies, was the greatest single USDA focal effort addressing nitrate concerns. [1/]

Primary research locations were in Iowa, Minnesota, Missouri, Nebraska and Ohio, with additional research sites in Kansas, North Dakota, South Dakota, and Wisconsin (Figure 1). Collectively, this extensive effort in research and education was known as the Management Systems Evaluation Areas (MSEA) project. The information gathered from the MSEA project sheds light on how current and alternative farming systems affect water quality.

[1/] ***USDA Agencies*** *included the Agricultural Research Service (ARS) and Cooperative State Research, Extension and Education Service (CSREES). Other participating federal agencies were the Environmental Protection Agency (EPA), U.S. Geological Survey (USGS), USDA Natural Resources Conservation Service (NRCS) and USDA Economic Research Service (ERS).*

Figure 1. The five major centers for the MSEA project were located in Iowa, Minnesota, Missouri, Nebraska, and Ohio. Satellite field sites were also located in North Dakota, South Dakota, Wisconsin, and Kansas. Collectively, these sites represented most of the soil and hydrological conditions in the Midwest where significant nitrate leaching occurs.

A farming system is the end product of many decisions made to manage risk in crop and animal production. The goal is to favorably impact the economic and environmental viability of the farm unit. Some management decisions that have a direct impact on water quality include:

- Selecting a tillage method suitable for soils and climate.
- Determining which crops to plant and the sequence in which to plant them.
- Selecting crop varieties to fit soil, climate and management.
- Applying nutrients in a judicious, efficient and proper manner.
- Responding to and avoiding threats from weeds, insects and diseases.
- Using animal manure for least risk to the environment.
- Managing crop residue to take advantage of nutrient cycling.
- Implementing the most appropriate soil conservation measures.
- Enhancing effective crop use of soil moisture through irrigation or subsurface drainage.

These issues must be carefully considered to avoid increasing nitrate contamination of water resources. Many other management decisions such as harvesting, storage and marketing of crops, labor allocation, equipment repair and replacement, etc., indirectly affect water quality. Ultimately, most risk management decisions are made to maintain financial viability. A financially weak operation may not be able to sustain the environmental quality of soil and water.

Farming Decisions are Unique to Each System

Each farm has different resources and problems that shape the farming system. Thus, the best decisions on one farm are not necessarily transferable to another. Some of these unique components are listed at the right.

Soil types and the most suitable tillage for each soil type differ as much from field to field as from farm to farm. Nutrient and water management, weed control practices and other farming inputs may differ from one soil type to another. Capital, credit, equipment, labor, knowledge and managerial skills also vary from farmer to farmer.

How farmers understand and respond to social and community pressures and customs varies from community to community and from farmer to farmer. Landowner concerns and priorities differ among farms. All of these factors influence the decisions that ultimately form the farming system for each individual producer and location.

FARM -SPECIFIC COMPONENTS

AVAILABLE RESOURCES

Capital

Credit

Equipment

Labor

CONCERNS

Pest Management

Soil and Water Cons

Nutrient Management

Time constraints

SOIL CHARACTERISTICS

SOCIAL ISSUES

Societal Pressures

Family Concerns

KNOWLEDGE

Managerial Skills

Technical Competence

LAND

Productivity

Ownership

Owner/Operator relationships

Weather conditions have an overwhelming impact on risk management. A farmer must understand the interactions between farming activities and weather. Tillage, fertilizer management, water management and crop selection must be adjusted as weather changes. The complexity of all the interactive forces and decisions involved in a farm operation is shown in Figure 2. All input decisions are made to increase the probability that a favorable event (outcome) will occur with the least risk.

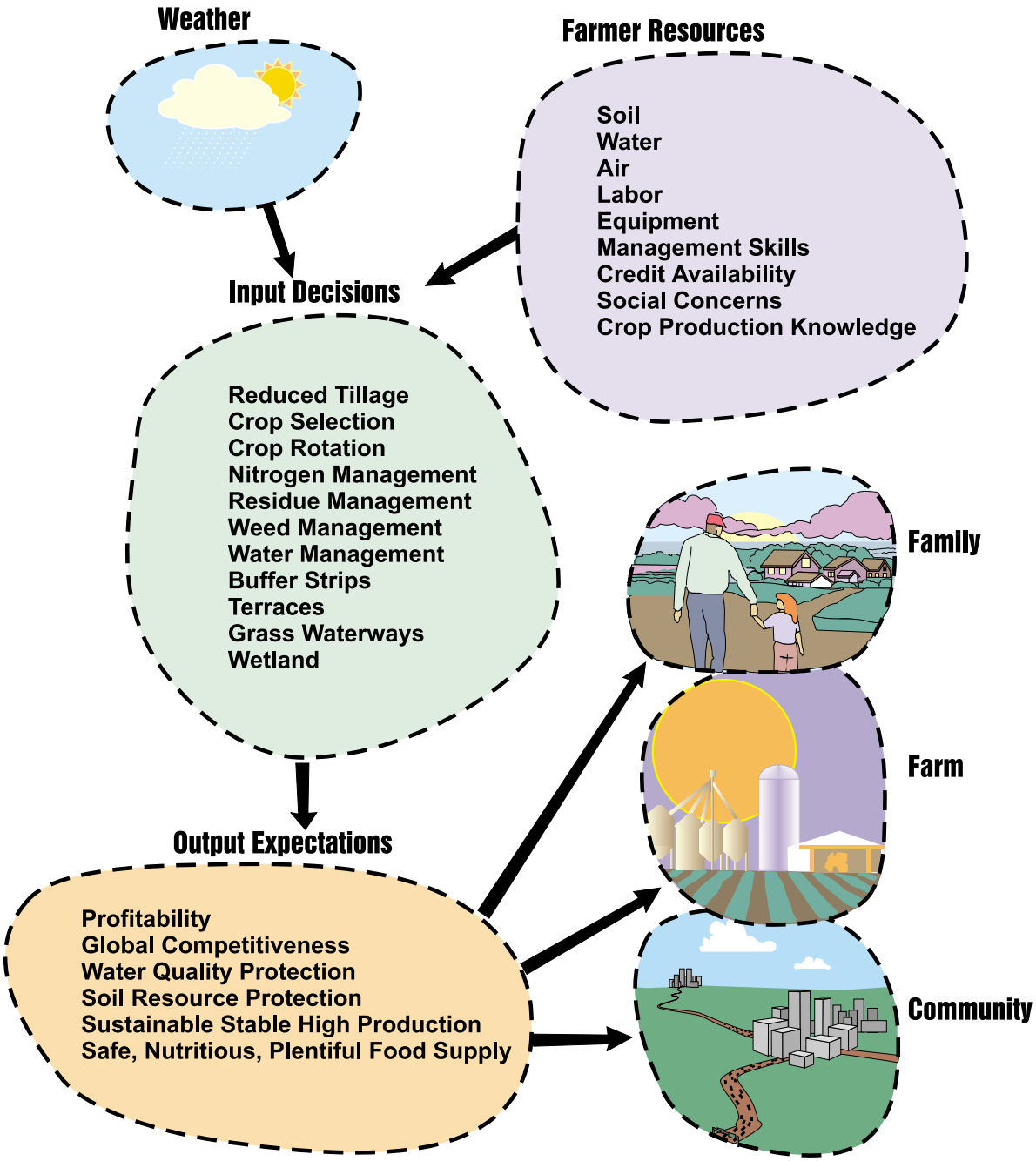


Figure 2. The complexity of all interactive forces in farming systems.

Tillage Methods Influence Nitrate Leaching and Reduce Erosion

Conclusions based upon MSEA studies and other research shows that clean tillage often increases nitrate pollution problems. Clean tillage is accomplished using a plow or heavy disk as the primary tillage implement. The action of the implement buries crop residue, placing it in full contact with the soil.

Under warm, moist soil conditions, residues from a soybean crop can rapidly decompose in a matter of several days, causing a release of nitrogen from the plant material into the soil. The released nitrogen is soon converted into the mobile nitrate form. Corn residues decompose somewhat more slowly, but the process is the same. In the spring, rapid release of nitrogen from residue can result in substantial leaching because a corn crop uses little nitrogen during May and June when rainfall is often excessive.

MSEA research results show that reduced tillage and no tillage slow early summer nitrogen release from the residue of the previous crop, and release more nitrogen in mid-and late summer when the crop's need for nitrogen is greater. MSEA research evaluated the effect of tillage on nitrogen release and showed that tillage methods can influence nitrate leaching (Figure 3) as well as reduce soil erosion and runoff.

The ridge-till method of reduced tillage is particularly suited for corn and soybean production in many areas of the Midwest (Figure 4). Ridges are built up by moving soil into the row with inter-row cultivation. When planting the following year, (late April, early May) ridge tops are scraped into the valleys between rows, leaving a clean, easily warmed soil in the row. Nitrogen fertilizers are banded into the shoulders of the ridge, reducing nitrate leaching from the band (Figure 4).

The next tillage occurs in June and July when additional nitrogen is applied side-dress and the ridge is re-established in preparation for another year. From fall harvest until the following spring planting, the field is left undisturbed with crop residue protecting the soil from wind and water erosion.

Tillage Impacts

Clean tillage tends to increase nitrate pollution problems.

In ridge-till, nitrogen fertilizers banded into the ridge reduce nitrate leaching.

MSEA research shows that ridge tillage is suited for corn and soybean production in many areas of the Midwest.

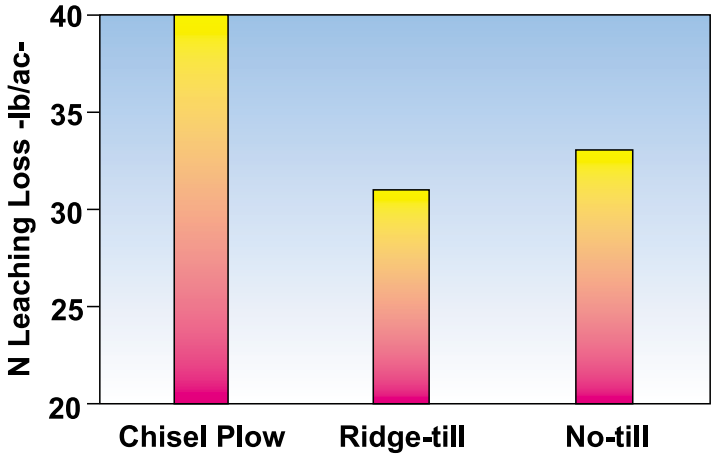


Figure 3. Tillage influences on nitrate leaching loss into subsurface drains. (Iowa)

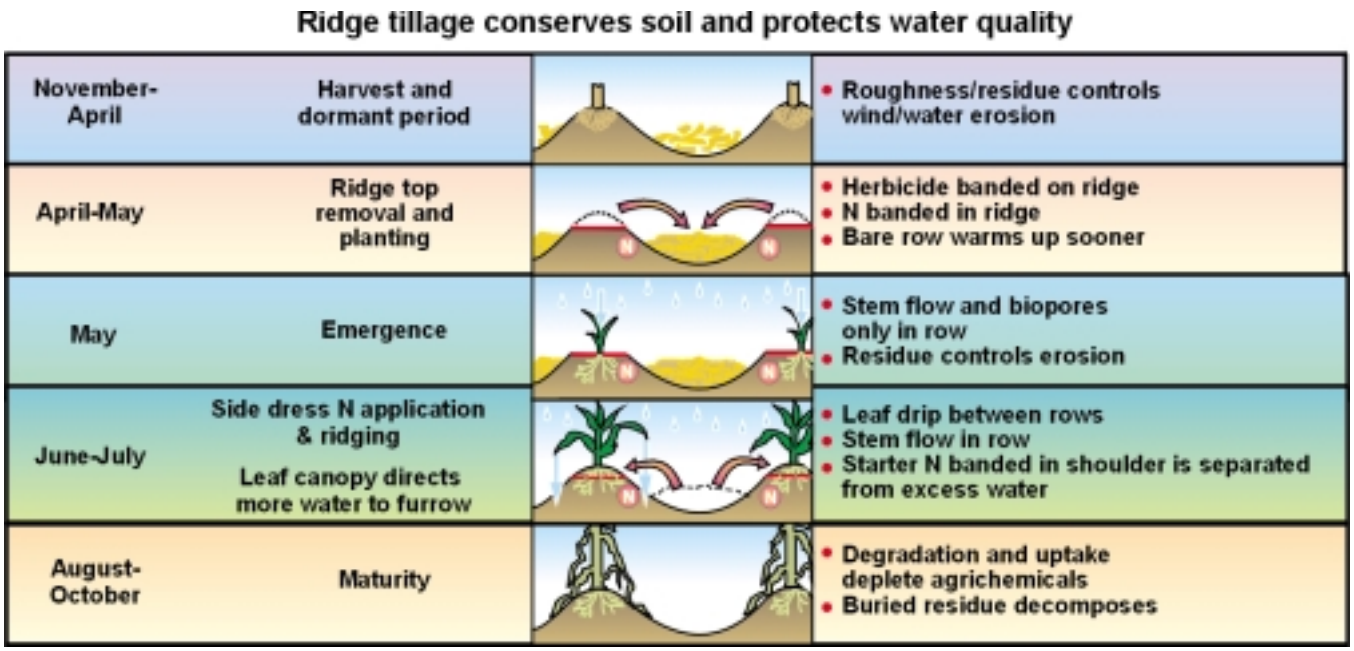


Figure 4. Annual cycle of ridge tillage operations related to management of nitrate losses. (Minnesota)

Crop Rotation Affects Nitrate Leaching

Corn and soybeans are the most popular crops in the Midwest because they are usually the most profitable. Cropping systems of continuous corn or a corn-soybean rotation are common. Wheat, alfalfa and forage crops are sometimes included in the rotation for special conditions or markets.

MSEA research results show that less nitrate is usually leached from a corn-soybean rotation than from continuous corn. This is especially true when nitrogen applied for corn production is reduced to account for nitrogen furnished by a previous soybean crop (Figure 5).

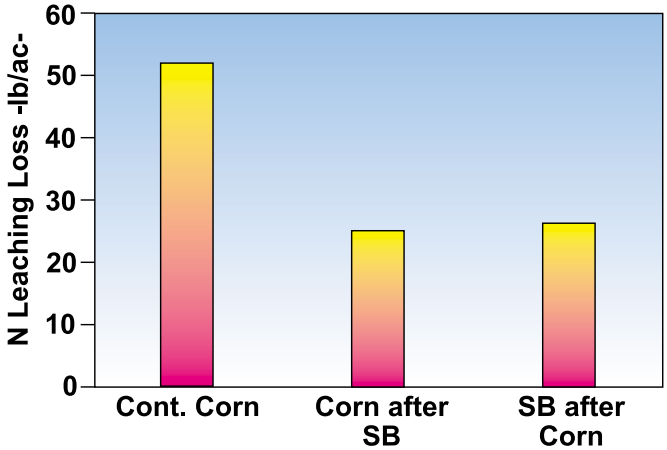


Figure 5. Crop rotation effects on nitrate leaching from the root zone. (Nebraska and Iowa)

Reduced nitrate leaching occurrs because:
(a) Nitrogen is applied every year to continuous corn and is only applied every other year at a reduced rate in a corn-soybean rotation.

(b) Soybeans are a good scavenger for soil residual nitrate remaining in the soil after the corn crop.

Alfalfa is very effective in removing residual nitrate from soil depths as great as 10 feet with its deep tap-root system. Because of the long growing season, the alfalfa crop uses more soil moisture than corn or soybeans. This increases the amount of rainfall which can be temporarily stored in the root zone, thus reducing excess drainage. Sometimes a cover crop, such as hairy vetch or winter rye, is used to reduce soil nitrate leaching during the winter months; however, cover crops have not proven to be reliable in the drier, northern climate of the Midwest.

Water Management Reduces Nitrate Pollution

Because nitrate moves down through the soil with water, farm practices which limit soil water movement below the root zone are very important in controlling nitrate pollution of water resources.

Irrigation

MSEA results in Nebraska show that water application is reduced substantially when sprinkler irrigation replaces furrow irrigation (Table 1). Matching irrigation amounts more closely to plant needs reduces nitrate leaching during the growing season. Nitrate leaching can also be reduced by changing from conventional to surge flow irrigation in furrows, and by irrigating every-other-furrow instead of every furrow. Applying nitrogen in the non-irrigated furrows may further reduce in-season nitrogen loss.

Table 1. Irrigation water applied, nitrogen applied in fertilizer and irrigation water* and nitrate-N in leachate from furrow and sprinkler irrigation during the growing season. (Nebraska)

Irrigation Method	Fertilizer N Applied (lbs/acre)	Irrigation Water Applied (inches)	Nitrogen Applied in Water (lbs/acre)	Total Nitrogen Applied (lbs/acre)	Nitrate N in Leachate (ppm)
Furrow	170	24	163	374	35
Sprinkler	110	7	48	161	4

*** Approximately 30 ppm nitrate-N in irrigation water**

Subsurface Drains Intercept Nitrates

Excess water is managed with subsurface drains on over a third of the cropland in the Midwest. The drains intercept 95 percent of the nitrate moving out of the root zone, and divert drainage water containing nitrate to surface waters. Whether or not the nitrate in surface waters becomes a concern depends upon the amount of dilution of subsurface drainage water by surface runoff. Subsurface drainage systems are so efficient in intercepting nitrate that there is usually little movement of nitrate into deeper aquifers in areas where shallow drains are required.

Subsurface drainage systems efficiently intercept 95 percent of the nitrate moving out of the root zone.

Other Techniques Also Reduce Nitrate Leaching

Nitrate concentrations can also be reduced by routing the discharge from subsurface drains through properly designed wetlands (Figure 6). Wetlands offer a means of reducing non-point source nitrate loss by 40 percent to 98 percent. Subsurface drains, properly designed, can be used during mid-summer for sub-irrigation of crops, again reducing the potential for nitrate leaching. Drainage of poorly drained soils improves nitrogen use efficiency by reducing nitrogen gas loss, and by increasing nitrogen release from soil organic matter.

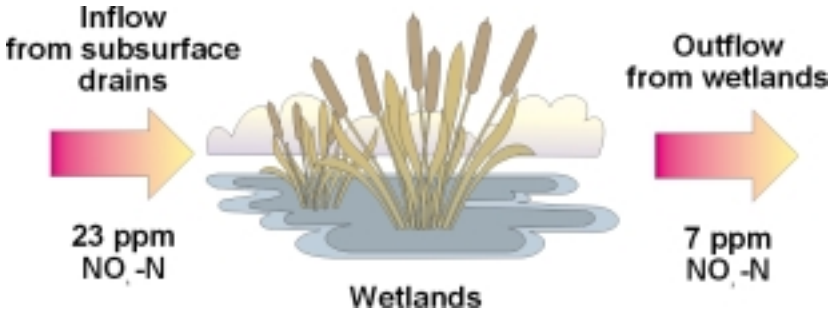


Figure 6. Wetlands reduce nitrates in drainage water. (Iowa)

The use of terraces, reduced tillage and land conservation measures reduces runoff, but increases water infiltration and the potential for deep nitrate leaching in areas that do not have a shallow water table.

MSEA research in the deep loess soils of Western Iowa shows that land conservation measures reduce water runoff, but increases the amount of nitrate found in the base flow of streams draining the watershed.

Additional MSEA research shows that over a period of years, the amount of leached nitrate was directly related to the amount of water percolating through the soil (Figure 7).

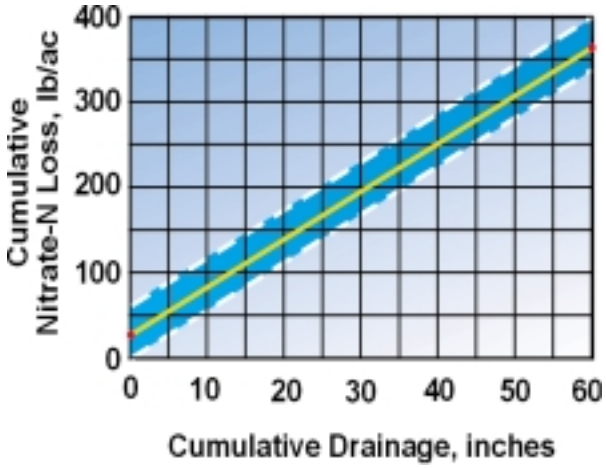


Figure 7. Nitrate leaching loss depends on the amount of water draining from the root zone. (Iowa)

Fertilizer Management Reduces Nitrate Leaching

In the Midwest, 50 percent to 80 percent of the corn acreage receives an application of nitrogen in late fall or in early spring before planting. Ammonia gas injected into the soil is the most widely used nitrogen product. After conversion to nitrate by soil bacteria, nitrogen, from any source or method of application, can leach downward during early spring before corn growth has a high demand for nitrogen and can be leached in the fall after the corn plant is mature.

Improved Nitrogen Management Technology

According to MSEA research, a number of practices can be used to reduce the potential for nitrogen leaching. By merely covering the knife slot left by the applicator and slightly compacting the soil over the slot, nitrate movement in soil can be reduced (Figure 8).

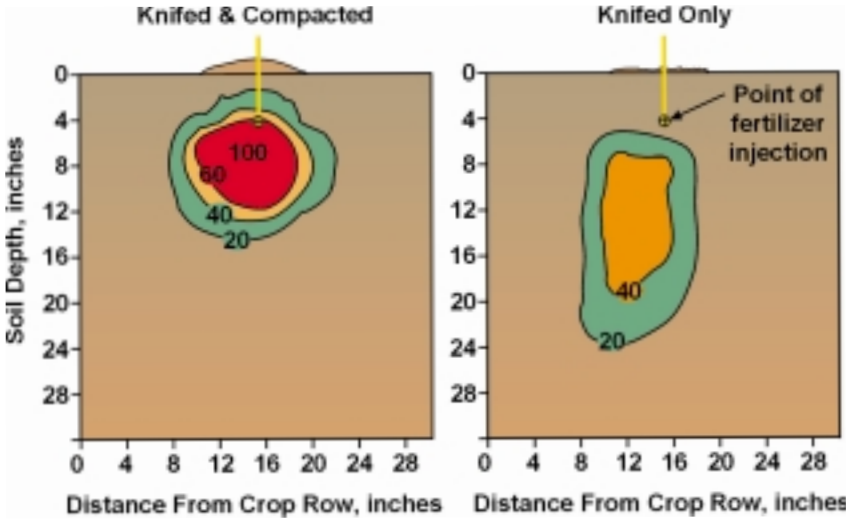


Figure 8. Effect of controlled compaction above the knife slot on nitrate concentration (ppm) and distribution 83 days after application. (Iowa)

Nitrification inhibitors (substances which slow the conversion of nitrogen forms to nitrate) can be used with preplant nitrogen fertilizer to limit nitrate leaching. Inhibitors extend by several weeks the time that nitrogen fertilizer is held in a non-mobile form after application. Appropriate soil tests used to assess the amount of soil nitrate before fertilizer application can help farmers make better decisions on nitrogen fertilizer rates.

Such tests can help prevent under-fertilization as well as over-fertilization (Figure 9).

Also, applying only a fraction of the anticipated crop nitrogen fertilizer needs before or at planting and then applying the remainder later when the crop is actively growing reduces nitrate accumulation in the soil and the potential for nitrate leaching.

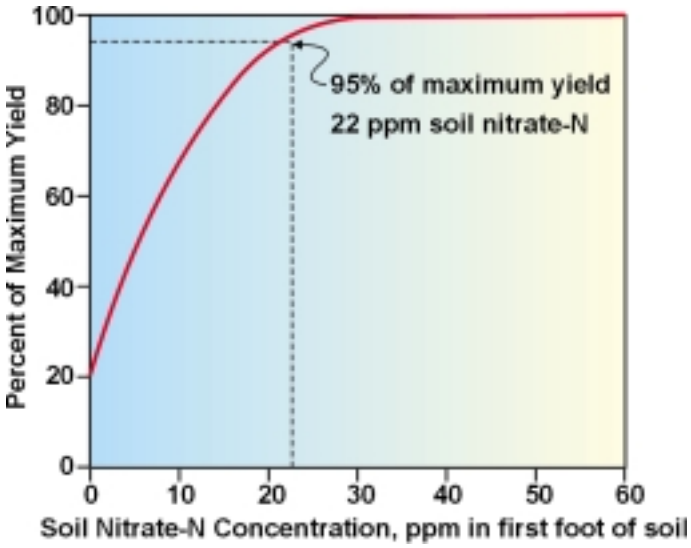


Figure 9. Relationship between soil Nitrate-N concentrations and corn yields. (MSEA Project Sites)

A New Fertilizer Management Technology

MSEA field research shows that greenness correlates closely with relative crop yield and crop response to nitrogen. Greenness can be measured with a plant chlorophyll meter (Figure 10), a computer scan of aerial photographs, inexpensive sensors mounted on sprinkler irrigation equipment or with field driven fertilizer application equipment.

MSEA research opened a new door for innovative nutrient management by showing that proper timing and appropriate rate of applied nitrogen fertilizer can be determined by monitoring crop greenness (Figure 11).

Since crop greenness can be influenced by several factors other than nitrogen availability, all of these systems require a reference crop strip on which adequate nitrogen has been applied to eliminate it as a growth-limiting factor.

Figure 10. Minolta SPAD-502 chlorophyll meter.

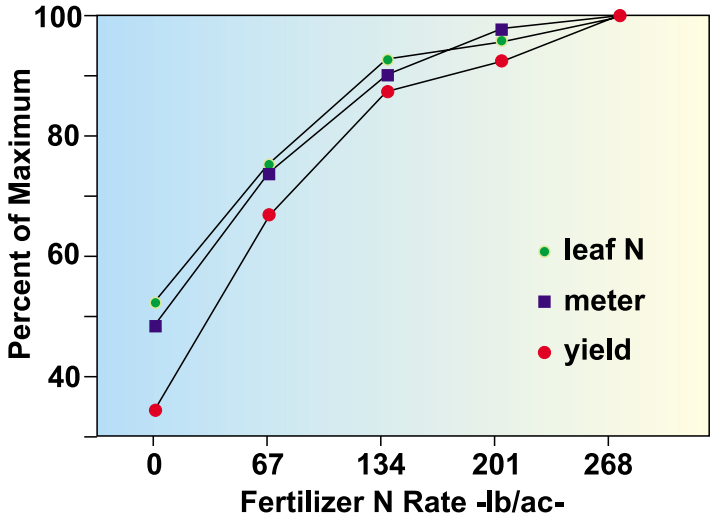


Figure 11. Leaf nitrogen, chlorophyll meter reading and corn yield all show the same response to nitrogen fertilizer amounts. (Nebraska)

Some practical problems can occur with these systems even though monitoring crop greenness has proven to be reliable. For example, wet weather may prevent nitrogen application equipment from operating during critical periods of nutrient uptake by the crop. Production costs may be increased due to an additional field operation and a shift to more costly sources of commercial nitrogen.

Soil Variability Impacts Nitrogen Management

Detailed soil survey maps usually show several soil types within a field. Each soil type has a distinctive set of properties including soil texture, soil thickness, nutrient supplying capacity, organic matter content, water infiltration, water holding capacity and other properties which are related to crop production and nutrient management. As a consequence of such soil variability, plant growth, nitrogen requirements and soil nitrogen availability may vary greatly within a field. The variability of one physical property (water storage) is illustrated in Figure 12.

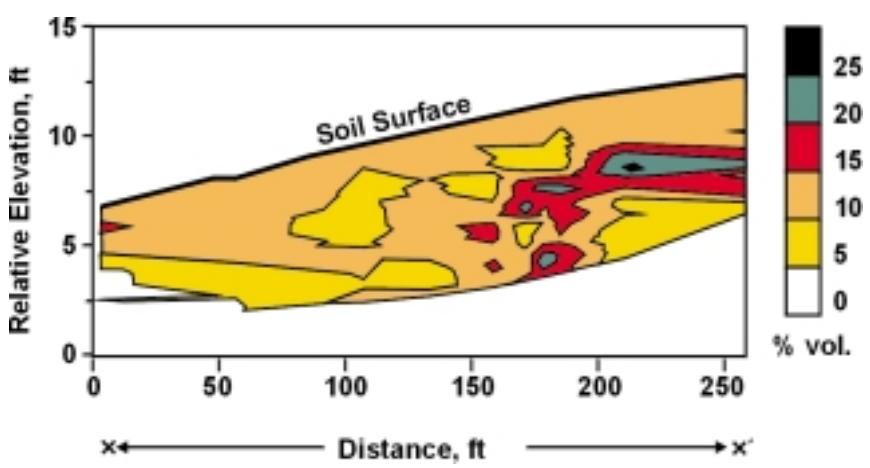


Figure 12. Variability of soil water storage across one field. (Minnesota)

Site-specific farming systems reduce nitrate accumulation in soil

Historically, fields have been managed as a unit, with all parts of the field receiving the same tillage, cropping and fertilizer practices. This results in some parts of the field receiving too much nitrogen fertilizer, while others may receive too little. Nitrate can leach from those areas receiving too much nitrogen fertilizer while yields and income are reduced in those parts of the field receiving too little. Yield and income can be maintained by applying added fertilizer to accommodate field variability, but this increases the risk of nitrate leaching from some parts of the field.

In MSEA research the variability in fields was documented and has led scientists to initiate research on precision or site-specific farming systems (Figure 13). In the site-specific approach each acre in the field is fertilized individually according to the best nutrient management plans. Part of the nitrogen needs of the crop may be applied before planting. Then the crop is monitored for greenness and the soil is monitored for nitrate content. Subsequently, nitrogen is applied to areas of the field at variable rates according to crop need. Such an approach will reduce accumulation of nitrate in soil and the nitrate leaching potential of the field.

Another approach for site-specific nitrogen management is to assess the productivity of the soil using automated sensors. Nitrogen fertilizer is then applied at a variable rate to match the soil productivity potential. Figure 13 shows a conventional management example (left) and variable rate nitrogen based upon a site-specific approach (right).

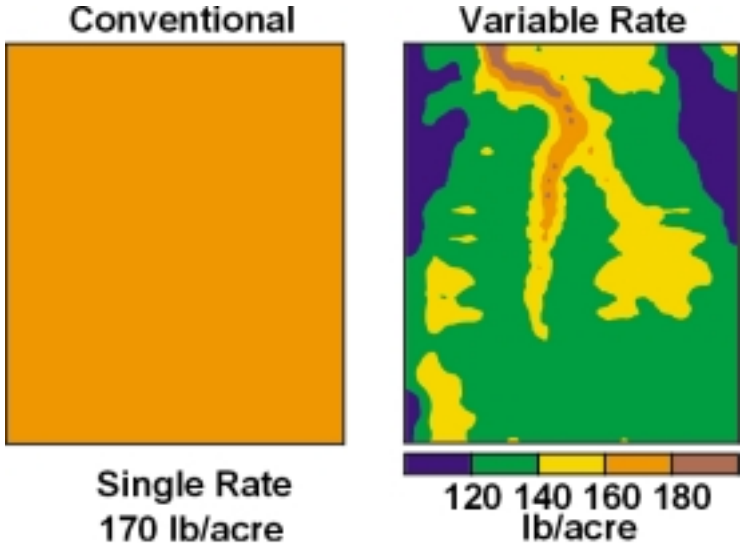


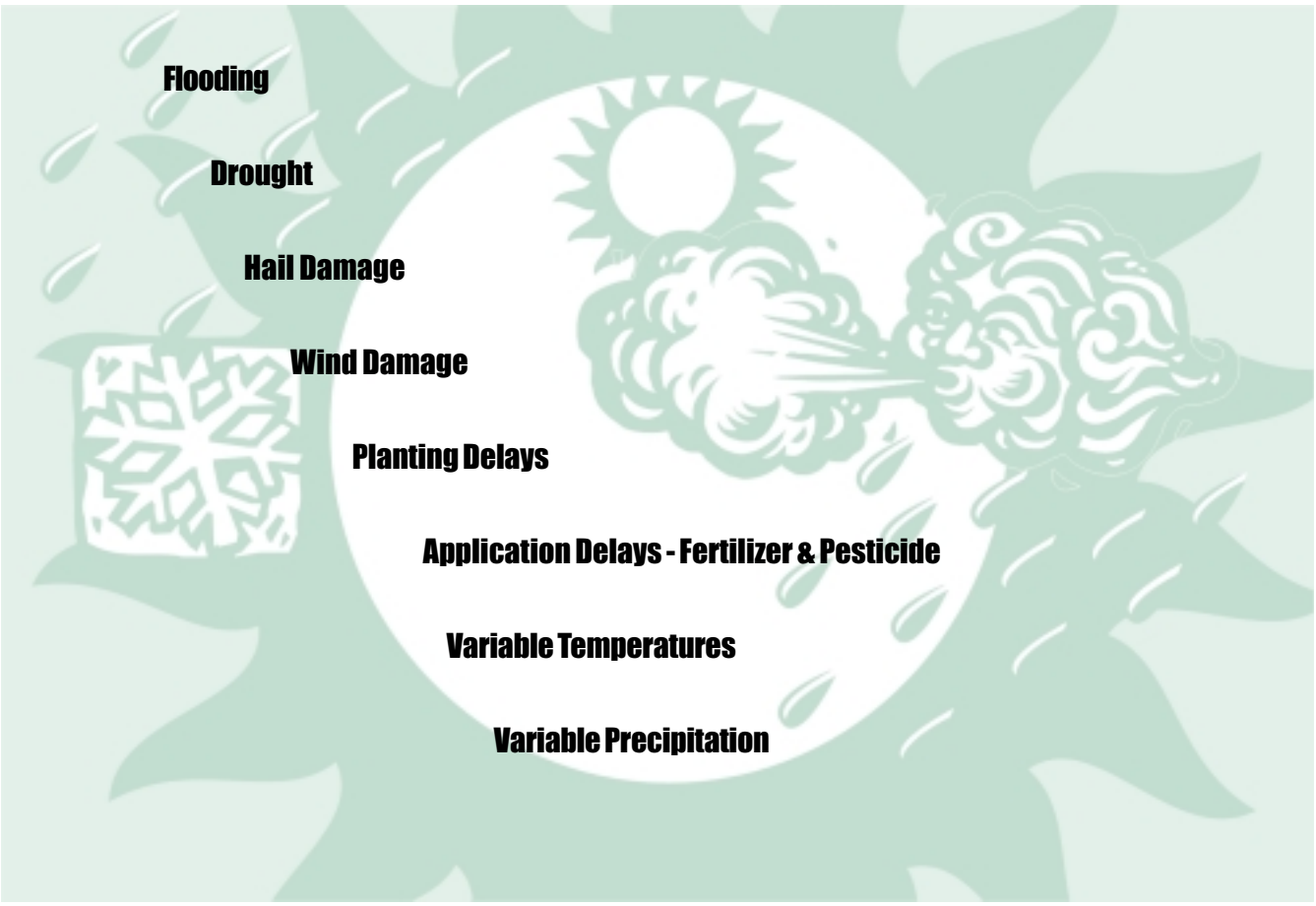
Figure 13. Conventional vs. site-specific fertilizer application. (Missouri)

Weather Interactions Influence Farming Systems

The amount of nitrate in soil is particularly influenced by weather. Air temperature and growing season rainfall vary greatly from year to year. Both air temperature and soil water content influence the rate of crop growth and nitrate uptake by the crop, as well as the rate at which soil organic matter releases nitrogen.

Soil nitrate also varies greatly both in amount and in spatial distribution from year to year. Abundant spring rainfall leaches much of the nitrate from the surface foot or two of soil, sometimes causing a period of nitrogen stress for shallow-rooted seedlings. Table 3 shows some potential influences of weather on farming systems.

Table 3. Potential influences of weather on farming systems.



Weather greatly influences the growth of crops in a farming system, making it difficult at or before planting time to judge the total nitrogen requirement of the crop for the entire growing season. Excessive rains at normal planting time can delay planting, resulting in a reduced yield potential (Table 4) and less nitrogen required for the crop. The lack of rainfall at planting time may delay crop emergence and early crop growth, simulating a later planting and resulting in reduced yield potential.

Table 4. Percent of maximum yield in relation to planting date. (Ohio)

Crop	Planting Dates					
	April 8 to April 22	April 23 to May 7	May 8 to May 26	May 27 to June 4	June 5 to June 25	October 2 to October 22
	----------% of Maximum Yield----------					
Corn	96	87	77	69	61	--
Soybean	--	--	96	88	74	--

Rainfall or temperatures, either well above or well below normal, can affect crop development, reducing grain yield and nitrogen needs. Physical damage to crops by hail storms or high winds can reduce yields. Likewise, pest and disease problems that affect yield are influenced by the weather. Crop yield data from all MSEA research sites exhibited approximately two-fold or greater year-to-year yield variation, mostly due to the influence of weather. Variation in corn yields is illustrated in Table 5 for continuous corn and for corn in a corn-soybean rotation.

Table 5. Variation in corn grain yields under continuous corn and a corn-soybean rotation. (Iowa and Nebraska)

Year	Rainfed - Iowa		Irrigated - Nebraska	
	Continuous Corn	Rotation Corn/Soybean	Continuous Corn	Rotation Corn/Soybean
	- - - bushels per acre - - -		- - - bushels per acre - - -	
1991	120	132	187	1st year of rotation
1992	134	141	170	205
1993	115[1]	116[1]	131[1]	136[1]
1994	168	185	120[2]	124[2]
1995	142	156	171	189
1996	147	155	183	189
1997	134	142	213	224
1998	125	143	190	212
Average	136	146	168	183

[1] Record rainfall in Iowa and Nebraska. Major windstorm at Nebraska Site.
[2] Windstorm caused extensive greensnap at Nebraska site.

Such yield variation affects nitrogen nutrient management in all farming systems. The challenge is to make the best nitrogen nutrient decisions with crop and weather considerations. The problem can be addressed to some degree by partial applications of nitrogen, as discussed previously under "Improved Nitrogen Management Technology."

Grower Education Leads to Change in Nitrogen Management

The ultimate success of farming systems research depends on the use of research results and new technologies in actual farm production. Growers have a keen interest in the economic and environmental viability of their farming system. Most continue to improve their nitrogen management in incremental steps as they overcome constraints of capital, equipment, management and labor. As such, change in nitrogen management takes time even with the most willing producers.

Many have already reduced inputs of nutrients to improve both the environmental and economical viability of their operation. Yet, according to a Nebraska MSEA survey, on approximately 50 percent of a 500,000 acre area, growers used more nitrogen than necessary in order to overcome soil and weather variability. On 40 percent of the acres, corn growers in the same survey used inputs that meet current technologies. On 10 percent of the acres, growers used too little nitrogen, risking lower yields.

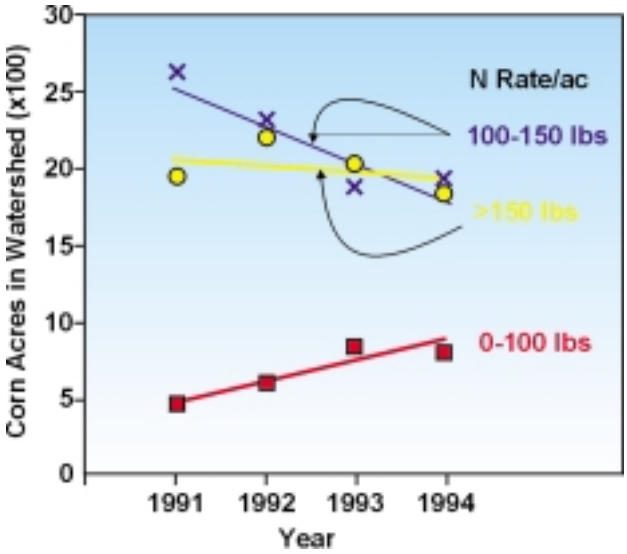


Figure 14. Changes in nitrogen fertilizer use for corn production, as the result of educational programs. (Iowa)

MSEA research, together with grower educational programs, was very effective in initiating farmer change to better nitrogen nutrition management. In an Iowa watershed, farmers who grew corn and soybeans in a crop sequence, saw the benefits derived from using less nitrogen on corn in research and demonstration plots. As they gained confidence in using less they adjusted nitrogen inputs voluntarily.

Similar farmer behavior has been observed in past surveys. Using tools of technology to assess their crop nitrogen requirement, corn growers were able to judge nitrogen needs with greater precision. Voluntary shifts in Iowa's Walnut Creek Watershed amounted to a reduction of 50 pounds of nitrogen per acre on approximately 20 percent of the watershed's corn acres in a four-year period (Figure 14).

Conclusions

Increases in world population and future demands for food and fiber will require greater crop yields and, consequently, greater nitrogen fertilizer and manure usage in future decades. We need to continue to improve our farming systems in order to reduce risks of degradation of our water resources and to maintain farm income.

Existing production practices must be improved and new practices need to be developed. MSEA research results show that many new farming practices developed within the past few decades do have considerable merit and are very helpful in controlling nitrate movement into water resources. For example, the various soil nitrate tests now in use provide our best guide in determining appropriate nitrogen fertilizer rates to use.

Ridge-till, no-till and other reduced tillage cultivation methods help to reduce nitrate leaching by keeping soil nitrogen mineralization rates timed closer to nitrogen uptake rates for a corn crop. In turn, such practices reduce soil erosion and save water. Sprinkler irrigation provides much better control of water and nitrate movement than furrow irrigation. These are a few examples of current technologies that were proven to be useful in maintaining water quality. However, all have limitations.

New and better technologies will be needed for the future. Any means by which a crop can be monitored for improved nutrient input decisions will be the focus of tomorrow's farming systems. One of the major new concepts developed and studied in the MSEA project was the use of crop greenness to monitor crop nitrogen needs during the course of the growing season, rather than trying to anticipate fertilizer needs early in the season. MSEA research provided several means by which crop nitrogen needs can be monitored, including aerial photographs and low cost greenness sensors. These technologies provide a scientific basis on which site-specific or precision farming systems can be developed, thus improving the farmer's capability to manage each acre according to its needs.

MSEA research shows effectiveness of monitoring crop nitrogen needs with low cost greenness sensors.

Precision technologies produce positive improvements in farming management.

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