IMPROVING FERTILIZER AND CHEMICAL EFFICIENCY THROUGH "HIGH PRECISION FARMING"*

by

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EXECUTIVE SUMMARY

This report is the third in a series by the Center for International Food and Agricultural Policy, part of its Project on Agricultural Competitiveness and Environmental Quality (PACE). It is the companion to the second report in the series, "Agricultural Competitiveness and Environmental Quality: What Mix of Policies Will Accomplish Both Goals?" That report focused on institutional changes. This one focuses on known, developing, and future technologies -- what we call "high precision farming" -- which can increase fertilizer and chemical efficiency in corn, soybeans and wheat production. These technologies have the potential to improve our competitiveness as a nation, as well as the quality of our soil and water resources.

The report contains seven major sections. It first considers no-cost and low-cost management decisions that improve production and input efficiency, without materially increasing costs. Second, it examines the potential of soil testing for optimizing input use. Third, opportunities for improved method, placement, and timing of inputs are evaluated. Fourth, rates of application, combinations of nutrients and interactions with other cultural and management practices are considered. The fifth section discusses benefits of crop rotations and the need to provide proper nitrogen credits for legumes and applied livestock manures to improve resource use and prevent nitrogen leaching. It also evaluates the advantages of conservation, ridge-till and no-till systems, problems of soil compaction, and the advantages of irrigation in high production systems. The sixth section evaluates crop protection chemicals used for weed, insect and disease control and their interactions with other practices. The seventh discusses emerging and future technology developments likely to affect agricultural production.

The no-cost, low-cost decisions discussed include adapted varieties or hybrids, planting date, seeding rate or plant population, and row width. Varieties or hybrids selected for disease or insect tolerance or resistance, as well as productivity and harvestability, can require fewer inputs per harvested acre. Corn hybrids utilizing the same levels of fertilizer and chemical inputs, for example, may differ in yield by 50 bushels or more per acre, while varietal differences in soybeans can be up to 20 bushels or more. For wheat varieties, yield differences can be 15 bushels or more. Delaying corn or soybeans planting beyond a narrow "window" planting time may decrease yield by 2 bushels per acre per day. Delayed spring wheat planting beyond March 30 can decrease yields nearly 0.9 bushel per day. On the other hand, delayed fall planting of winter wheat helps escape Hessian fly infestation or root rot disease. Increasing corn to optimum population levels can increase yields by 20 to 40 bushels. Narrowing soybean rows can increase yields by 16 bushels.

Soil testing can aid in the determination of environmentally and agronomically appropriate levels of phosphate and potash fertilizers, as well as micronutrients. Once soil nutrient test levels are sufficient, profitable responses to applied nutrients are small, and should be discontinued on both efficiency and environmental grounds. When test levels are high or very high nutrient applications in fact may not be needed for several years. Soil test levels for phosphorus and potassium have been increasing in some regions of the country, while in others tests are still low. Soil organic matter tests give an indication of the organic carbon and nitrogen in a soil. Soil nitrate-nitrogen soil tests have been used for years to improve recommendations in the small grain growing areas of the Pacific Northwest and the Great Plains. Nitrate-nitrogen soil tests are now being implemented as a guide to nitrogen fertilizer recommendations for corn in the humid region. Spring nitrate-N tests as a guide for preplant or sidedressed N should be particularly effective following drier years when the probability of residual or carryover nitrogen is high.

Although heavy broadcast application of nutrients has been used to build nutrient levels in soils, more precise application methods are available to get nutrients down into moist soil, increasing availability to crops and decreasing erosion or runoff losses. Applied in this way, more moderate nutrient application rates can also be used over several years to achieve sufficient test levels. If capital is limiting, lower rates of banded or row-placed fertilizer will usually increase fertilizer efficiency. By exploiting these more precise application methods, not only is runoff reduced, but better timing and placement of nutrients can markedly increase yields. Newer types of placement, such as "spoke-wheel point injection", appear to be superior. Point injection can be used for sidedressed nitrogen applications, or for injecting fertilizer directly into the row in ridge-till and no-till systems, which should further increase yields and efficiency and decrease possible runoff losses.

Fertilizer rates, nutrient combinations and management practices interact to increase production efficiency and reduce environmental damages. Evidence of improved nutrient efficiency is apparent in fertilizer use statistics, which show that total phosphate use in the U.S. peaked in 1977, and nitrogen and potash use peaked in 1981. All have since continued to decrease, but in general per acre crop yield levels continue to increase, which may be due to several factors, some of which are considered in this report. In 1989 total phosphate use was below 1967 levels, while nitrogen use was below the 1977 level, and potash use was just above the 1973 level. Compared with other developed countries, nutrient use in the U.S. even in 1981 was below that of the Netherlands, Japan and France, which used 235, 105 and 62 pounds of nitrogen per acre of cropland, respectively, compared with 21 pounds per acre in the U.S. Potash use per arable acre ranged from 172 to 26 pounds per acre (based on FAO 1981 figures) for the EEC countries, Japan and Korea, with the U.S. the lowest. Of course, crop mixes and intensities are different in these countries than in the U.S.

As nutrient applications are combined with other management and cultural practices, per acre yields can be expected to increase along with reduced environmental impacts, although changing the nutrient combination or management practice can also increase the level of an input needed to achieve highest profit. Because of these interactions, it is important not to focus on only one or a few inputs, ignoring the possibility of substitutions and complementarities. Applying nitrogen alone to no-till corn, for example, caused yields to decrease over time. When nutrient rates and combinations are integrated with specific corn hybrids, nutrient use efficiency can also be improved.

Crop rotations are being used to break disease, insect and weed cycles and, where legumes have been included, to provide nitrogen to subsequent crops. The predominant legumes are alfalfa and soybeans, although vetches, medics and peas are used in some areas. Nitrogen fixed symbiotically by species of rhizobia microorganisms and legumes should be credited in nitrogen fertilization of subsequent crops, such as corn or small grain. Corn following soybeans may yield 25 bushels more than continuous corn, even with adequate levels of applied nitrogen. Also, nitrogen credit needs to be given for the nitrogen applied in animal manures. These credits help to make fertilizer N recommendations more accurate, thereby decreasing N losses. Yields of soybeans following corn are also greater than for continuous soybeans.

Conservation tillage, ridge-till and no-till systems decrease soil erosion and water runoff, decreasing nutrient and pesticide losses in sediments and to surface waters. No-till systems on some soils also decrease downward movement of nitrates and herbicides through the profile sub-strata. Increased microbial activity associated with crop residues appears to increase herbicide or insecticide degradation and decrease leaching. Reduced tillage and no-till help conserve soil moisture by increasing infiltration rates and decreasing soil evaporation, thereby increasing effective moisture. Excellent corn, soybean and wheat yields can be achieved with reduced tillage systems. Ridge-till systems for corn and soybeans grown in rotation have particular advantages because of the weed control effects of ridging and the opportunity to band herbicides, as well as decreasing the need for insecticide to control corn rootworms.

Irrigation studies indicate that lack of controlled moisture is a major limiting factor in U.S. crop production. Long-term maximum yield research experiments in the humid region on corn and soybeans have shown that where other factors are non-limiting, average yield increases from irrigation alone are greater than the average yields of most states. Therefore, use of moisture conserving practices that increase infiltration and decrease evaporation are important. Where nutrient leaching can be a problem, it is important to apply irrigation water based on the moisture holding capacity of the soil and daily crop moisture demands. Tile drainage of soils with excess moisture can be just as important as irrigating soils and crops under moisture stress.

Weed, insect and plant disease control are extremely important parts of crop production. Experiments conducted on crop varieties, plant populations, seeding dates, row widths, nitrogen, phosphate or potash applications usually have had state-of-the-art weed, insect, and seed or disease treatments used. The results of these experiments would have been dramatically different in their absence. Even with the use of crop protection chemicals millions of dollars of crop losses and damages occur annually. However, insects and weeds develop resistance to both insecticides and herbicides. New and improved formulations of herbicides and insecticides have decreased rates of application, and crop scouting and integrated crop management programs have caused shifts to postemergence herbicide application and the use of insecticides only when threshold counts or numbers indicate economic damage is likely. This has decreased total use, particularly of insecticides. New row insecticide containers are now designed to fit onto corn planters, and individual water soluble herbicide packets have been developed to decrease exposure to handlers. Hoods have been designed to fit over crop rows, to better target applications of herbicides and prevent drift from fields. Chemical formulations are increasingly designed to be more environmentally neutral, decomposing more rapidly and moving less from the point of application. New biocontrols that have herbicidal and insecticidal benefits are being researched and in some cases patented, and farmers are more aware of the benefits of rotations in breaking weed, insect and disease cycles. Many of the environmentally hazardous herbicides, insecticides and soil fumigants have already been banned or are under restricted use regulation.

New developments combining computers, satellites, soil sampling and testing, soil survey information, and field application equipment are being researched and marketed. Soil survey information is now digitized and specific farms or fields can be displayed on computer screens, identifying soil areas sensitive to erosion, leaching, water ponding or physical and chemical characteristics. Soil survey data can be combined with soil test information in on-board computers in fertilizer-herbicide applicator equipment, so that rates and combinations can be varied while moving across fields. Such site specific recommendations and applications will increase using the "farming by soils" or "farming by the foot" approach.

Developments from biotechnology are now being tested that should offer future benefits to both crop productivity and crop protection. Plants can be changed genetically to produce more of specific substances, such as amino acids or fatty acids, which change their quality for processing. Genetically engineered herbicidal resistance is being introduced into crops. This protects the crop from the herbicide and allows a low amount of environmentally-benign herbicide to be used, taking out a broad spectrum of weeds in one application. The herbicide-resistant crop produces greater amounts of a specific enzyme that metabolizes the herbicide, allowing the crop to grow normally. Genetically engineered bacteria are also being used to produce a crystalline protein that is toxic to larvae of some insects, such as the European corn borer. There may be similar research and developments with other organisms that have biocidal effects on insects and/or nematodes. Also, virus resistance has been introduced in crops through "genetic cassettes" that carry transgenetic viral protein which acts like an immunization or vaccination in protecting the crop.

In conclusion, large gains can be made in fertilizer and chemical efficiency in U.S. agriculture through the application of "high precision farming", in which integrated crop management takes advantage of current and emerging technology from university and industry research and development efforts. High precision farming will be more management intensive, but will continue to add to our agricultural competitiveness as a nation, at the same time resulting in marked environmental and resource use improvements.

IMPROVING FERTILIZER AND CHEMICAL EFFICIENCY THROUGH "HIGH PRECISION FARMING"

INTRODUCTION

The first report of the Project on Agricultural Competitiveness and the Environment (PACE) reviewed the relationships between input use and the production of corn, soybeans, and wheat in the major producing states and the U.S., as influenced by agricultural events and policies from 1950 through 1988 (Runge, et al., 1990). This is one of two follow-up reports examining the institutional and technological innovations needed to reduce the environmental impacts of agricultural fertilizers and chemicals while retaining competitiveness at the farm level.

The first follow-up study looked at a variety of public and private institutional reforms (Creason and Runge, 1990). This report focuses on scientific and technological innovations. We believe that the technological possibilities emerging from current research can improve both our future competitiveness and the environmental impact of agriculture on land and water resources. Doing so will require greater management and monitoring of soils and crops, and more precise and timely application of inputs at the farm level. These efforts, which we refer to as "high precision farming", must be encouraged by careful evaluation of the practical issues and problems involved. Such an evaluation and integration of information is the purpose of this report.

When researchers conduct an experiment, they make an effort to be certain they are testing the effects of the treatments being applied. Therefore, when varieties or hybrids, dates of planting, row widths, applied fertilizers, or irrigation are studied, the experiments are usually conducted with best control of weeds, insects or diseases available. Usually only one or two treatments are varied in any given experiment. While farming involves constant experimentation, it is not "controlled" in this manner. The farmer must decide what "package of technology" to select from the alternatives available from university research and industry in a given year.[1] It is important to emphasize that the adoption of this new technology is fraught with risks and uncertainties not faced by researchers. As a result, technologies are adopted at the farm level more slowly than they come "on line" due to new research. Despite this lag, exciting new developments in farm technology are emerging and being adopted that promise to improve both farm-level efficiency and environmental quality. This report reviews some of the most important of these techniques.

The report has seven major sections. It first considers a variety of no-cost and low-cost management decisions, including hybrid or variety selection, planting dates, row widths, and other agronomic details that increase yields and soil and fertilizer nutrients and chemical efficiencies. Second, it examines the potential of chemical soil testing to determine nutrient needs to optimize fertilizer use. Third, opportunities for improved placement and timing of inputs are evaluated. Fourth, rates of application, combinations of nutrients and interactions with other cultural and management practices are considered. A fifth section discusses the benefits of crop rotations, conservation tillage and

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[1] References to commercial products or trade names are made with the understanding of no discrimination or endorsement by the Center for International Food and Agricultural Policy, University of Minnesota. Examples are for illustrative purposes only.

the problems of soil compaction and irrigation in high production systems. It also emphasizes the need to provide proper nitrogen credits for legumes and applied livestock manures to decrease nitrogen leaching. The sixth section evaluates emerging technologies of weed, insect and disease control and crop protection. The seventh and final section discusses future technology improvements likely to affect agricultural production.

I. ADOPTING NO-COST OR LOW-COST MANAGEMENT AND CULTURAL PRACTICES

Farmers can make changes in their production systems that cost little or nothing, yet improve input efficiency and increase profitability. In general, these changes may cut down on input use, or allow higher yields for a given level of use. Some involve selection of variety or hybrid; others are a matter of timing, planting date, or choosing crops suited to soil conditions, climate, and management levels.

First consider hybrid or variety selection. Varieties or hybrids released by plant breeders reflect a compromise, between the ability to produce good yields on the one hand, and robustness to variations in weather, plant diseases and insect infestations on the other. Varieties and hybrids are selected for their resistance or tolerance to soil or air borne disease organisms, or specific insects and pests, as well as their standability and harvestability. These choices, combined with management levels, help determine the additional requirements of fertilizer and pesticide applications.

In the case of corn, seed companies are breeding and introducing new lines continually; the market "life" of a hybrid is about five years. In addition to yield, hybrid choice will affect factors such as corn ear drop, lodging resistance, or disease and insect tolerance, as well as grain quality. It does little good to produce a high yield, if the corn crop is on the ground (lodged) or is infested with rootworm and cannot be harvested. Experimental data from the University of Illinois, in which 24 different corn hybrids were tested at three different locations and management systems (Lambert, 1985), showed major differences in yields (Table 1). The "high yield" and "farm-test" locations had few limiting factors, allowing an expression of the hybrid genetic yield potentials. From these data it should be apparent that hybrids are available that have the capacity to produce high yields, and take up and use high amounts of plant nutrients.

The efficiency with which nutrients are recovered by the crop and the yield achieved determines the amounts that leave the field in grain and remain in the residues and soil. Hence, hybrid choice can have major environmental implications by affecting plant recovery of applied nutrients. Estimated total nutrient uptake to produce the 259 bushel average yield in the high yield environment shown in Table 1 would be 290 lb N, 109 lb P_2O_5, and 375 lb K_2O per acre. Nutrient removal by the harvested grain would be 186 lb N, 73 lb P_2O_5 and 61 lb K_2O per acre. Ultimately these nutrients have to be replaced in order to maintain the fertility of the soil.

With soybeans, variety selection is also extremely important, for the same reasons. Very different yield levels can be achieved with the same level of inputs. Data from the Iowa Experiment Station provide soybean yields that indicate how varieties differ (Figure 1). High yielding soybeans also remove relatively high rates of nutrients, but can usually fix about half of the crop's nitrogen needs.

Soybean varietal selection can make striking differences when infestations of organisms, such as soybean cyst nematodes (SCN), are considered. Varieties have been developed that have resistance to SCN. If nematodes are not present the susceptible varieties do well, but if they are, the resistant cultivars show major yield advantages (see Table 2).

Table 1. The highest, average, and lowest yields of 24 corn hybrids tested under three environments and management systems in Illinois.

High Yield Environment

(Flanagan soil type)

Highest yielding hybrid	308 bu/a
Average yield of 24 hybrids:	259 bu/a
Lowest yielding hybrid:	219 bu/a

LSD 0.05 = 29 bu
C.V. = 6.7 %

Normal Environment

(Drummer soil type)

Highest yielding hybrid	255 bu/a
Average yield of 24 hybrids:	196 bu/a
Lowest yielding hybrid:	143 bu/a

LSD 0.05 = 38 bu
C.V. = 11.8 %

Herman Warsaw's Farm-Test Area

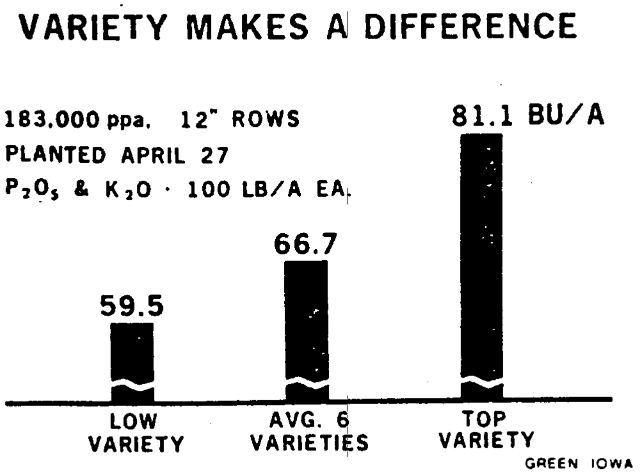
(Saybrook soil type)

Highest yielding hybrid:	337 bu/a
Average yield of 24 hybrids:	251 bu/a
Lowest yielding hybrid:	183 bu/a

LSD 0.05 = 63 bu
C.V. = 15.4 %

Source: Lambert, 1985.

Figure 1. Soybean varietal selection under high management can make a significant difference in the yield achieved.



Source: News and Views, Midwest. No Date (a).

Table 2. Soybean varietal differences in environments with and without soybean cyst nematode (SCN) infestations.

Soybean variety	SCN reaction	Soybean yield-bu/a No SCN	SCN	Decrease
Hardin	susceptible	50.7	19.3	31.4
Bell	resistant	44.2	35.4	8.8
M 86-1322	resistant	43.1	39.4	3.7
Sibley	susceptible	43.0	15.4	27.6
	Advantage	7.7	24.0	

Source: Stienstra and MacDonald, 1989.

Wheat varietal selection can also be important. Examples from The Montana Small Grain Guide (1985) are illustrative of differences among winter and spring wheat varieties for two yield levels (Table 3).

Table 3. The effects of winter and spring wheat varietal selection on yields under different yield environments.

Winter wheat variety	Medium yield	High yield	Advantage
	bu/a		
Bennett	42.5	68.7	26.2
Centurk	42.5	77.0	34.5
Cheyenne	40.0	70.0	30.0
Froid	36.2	61.1	24.9
Norwin	51.7	75.1	23.4
Advantage	15.5	15.9	

Spring wheat variety	Medium yield	High yield	Advantage
	bu/a		
Aim	40.2	70.9	30.7
Butte	39.1	64.8	25.7
Mckay	44.1	72.0	27.9
Olaf	41.6	65.4	23.8
Tioga	38.0	57.5	19.5
Advantage	6.1	14.5	

Source: Schafer, et al., 1985.

A second low-cost decision with impacts on input use is planting date. Planting dates can be used to escape insects, such as the Hessian fly, that attack wheat. Planting dates sometimes are based on soil and/or air temperatures, which affect seed germination and growth. They may also be delayed by tillage for weed control. In considering recommended planting dates it is usually best to get the crop in as early as possible, commensurate with soil and moisture conditions. This requires good farm level planning and early preparation of equipment.

Examples of the impacts of planting date on soybean yields from University of Illinois studies are illustrative (Table 4). Note that planting date was more important than varietal selection. Caviness (1989) indicated that in Arkansas (where pests are more prevalent) a 50 percent yield advantage existed for earlier soybean plantings.

Table 4. Planting date can be very important as a low-cost decision to improve soybean yields.

Soybean Yields-bu/a
Location-Urbana (central Illinois)
Date of planting

Variety	May 7	May 21	June 8	June 19	Advantage
Corsoy	56	62	49	42	20
Beeson	57	55	52	47	10
Calland	56	51	47	40	16
Advantage	1	11	5	7	

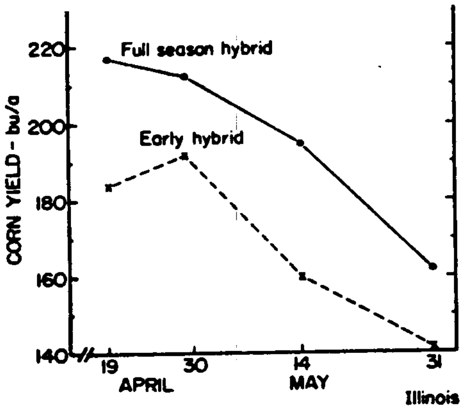
Soybean Yields-bu/a
Location-Carbondale (southern Illinois)
Date of planting

	May 3	May 17	June 7	July 1	Advantage
Cutler	62	46	54	28	34
Dare	72	45	37	32	40
Advantage	12	1	17	4	

Source: Illinois Agronomy Handbook, 1985-1986.

Planting corn on time can also be extremely important for higher yields and efficient use of nutrients and inputs. Earlier planting dates produce shorter plants, with fewer, more erect and shorter leaves (which tend to be photosynthetically more efficient). These plants mature earlier, produce higher yields and have a higher grain ratio or harvest index than those planted later. An example from the Illinois Agricultural Experiment Station is illustrative of the yield benefits of timely planting (Figure 2). An earlier maturing hybrid or crop usually means that less fuel or energy will have to be used in drying the grain.

Figure 2. Plant corn early and use a full season hybrid.



Source: Potash Newsletter M-150.

Early planting for spring wheat is also very important. In South Dakota in an eight-year study of early seeding dates, average yields were 24 percent higher than those in which seeding was delayed 16 days. In Minnesota each day planting was delayed after March 30 decreased wheat yields nearly 0.9 bu/a (Lueschen, et al., 1985). The influence of wheat planting date decisions in a given environment is apparent from Table 5, showing results from Manitoba (Briggs, 1986). In northern areas it is best to seed winter wheat before mid-September. In Wisconsin late August seedings have been the highest yielding. On the other hand, delaying winter wheat planting until October in the Northwest helps escape root rot or take-all disease. (Take-all can be controlled through rotation with legumes, such as peas.) It bears emphasis that very different yields are achieved with the same energy, labor and other inputs, suggesting how important timing is to efficient and environmentally responsible management.

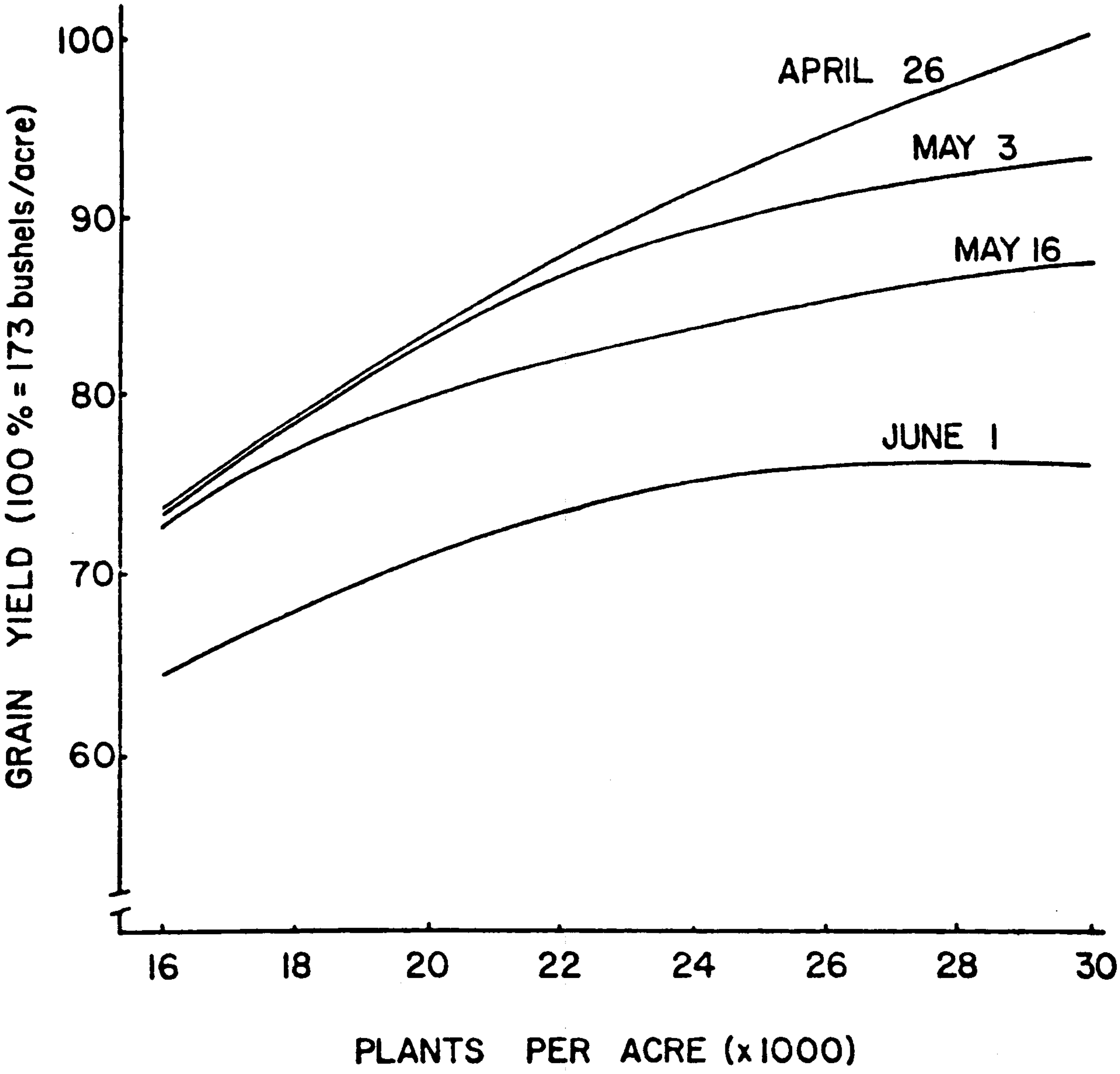
Table 5. The effect of earlier seeding dates on the yield of two spring wheat varieties planted at two locations in Manitoba.

		Wheat yield-bu/a		
Location	Variety	Seeding date		
		May 4	May 21	Adv.
Minto	HY320	85.2	69.5	15.7
	Oslo	76.7	60.6	16.1
		May 8	May 22	
Portage	HY320	70.1	53.1	17.0
	Oslo	71.3	50.9	20.4

Source: Briggs, 1986.

A third low-cost management or cultural practice is selecting the proper seeding rate or plant population. This decision interacts with decisions on planting dates and other management factors. In corn studies conducted in southern Minnesota, for example, higher plant populations were favored by earlier planting dates (Hicks, 1985, see Figure 3). Similar results are apparent from other locations. When different plant populations are compared with two planting dates the interaction is clear (Table 6). For the earlier planting date increasing population boosted efficiency by 32 percent.

Figure 3. Plant populations and planting dates interact to increase corn yields and the efficiency of input use.



Source: Hicks, 1985.

Table 6. Increasing plant populations and planting date work together to increase corn yields.[1]

	Corn yield-bu/a			
	Plant population-plants/a			
Planting date	18,000	26,000	34,000	Advantage
May 9	205.7	250.7	271.2	65.5
May 30	195.7	220.0	211.6	15.9
Advantage	10.0	30.7	59.6	

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[1] All plots received 200 lb of NH_4^+-N/a. The hybrid was DeKalb XL361, a three-way cross. The current trend is to use single-cross hybrids.

Source: Arjal, et. al., 1978.

Research in Illinois has shown that for corn, it is not only the population used, but the distribution of plants within the row, that affects overall inputs used. Having planters properly set and using proper planter speed can be important in achieving uniformly spaced plants and the desired plant population. The advantage for uniform distribution and hybrid selection is apparent in Table 7.

Table 7. The effect of within-row corn plant spacing for two corn hybrids planted in 30-inch rows at 24,000 plants per acre.

	Corn yield-bu/a		
Plant spacing	Hybrid A	Hybrid B	Advantage
1 every 8.7 in.	195	209	14
2 every 17.4 in.	181	204	23
3 every 26.1 in.	185	202	17
4 every 34.8 in.	169	190	21
Advantage	26	19	

Source: Agronomy Department, University of Illinois.

For soybeans, Indiana researchers have found that earlier planting and increasing plant populations also tend to work together to increase yields for a given level of inputs (Swearingin and Schweitzer, 1984). At optimum populations the advantage for the earlier over the later planting dates averaged over 23 bu/a for the two varieties studied.

Seeding rates for wheat need special consideration (Oplinger, et al., 1985). In the past rates were suggested in terms of bushels per acre, but because the number of seeds per pound or per bushel varies so greatly for different varieties, and even among seed lots of a given variety, more precision is required. It is now suggested that a seeding rate should be based on the number of seeds per length of row or square foot planted. Still, in North Dakota, spring wheat yields were increased 16 percent by increasing the seeding rate from .5 to 2 bushels per acre (Spilde, 1986), although increasing seeding costs by a factor of four is costly. Black and Bauer (1986a) recommend that for spring wheat a rate of seeding should be used to establish a minimum of 150 seedlings per square yard (180 per square meter).

A fourth low-cost intervention with implications for input efficiency involves row widths. Narrowing row widths with a given plant population improves the distribution of plants, and can improve uptake of nutrients, decreasing interplant competition for water, light, and plant nutrients. Corn row widths have been decreased to a standard planter width of 30 inches, and future intensive management may decrease them even more.

Soybeans also respond to decreased row width. In a three-year study conducted by Bundy and Oplinger (1984), decreasing row width from 30- to 8-inches produced the results shown in Table 8, increasing yield an average of 16 bushels per acre. Mason, et al. (1980) found a 17 percent increase in soybean yield by narrowing row width in Iowa. While narrower rows may entail the purchase of a new planter, they can sometimes be achieved by plugging outlets using a grain drill or double planting. However, narrower rows, which cannot be cultivated, could require more chemical weed control.

Table 8. Effect of row width on soybean yields over a three-year period.

	Soybean yield-bu/a		
	Year		
Row width[1]	1981	1982	1983
8 inches	56	85	77
30 inches	46	63	61
Advantage	10	22	16

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[1] Populations were 195,000 plants/a for the 8-inch rows and 155,000 for the 30-inch rows.

Source: Bundy and Oplinger, 1984.

In the case of winter wheat, in the humid region yields can be increased by going from 6- or 7-inch to 4-inch row width. Improved distribution of plants, with a higher seeding rate, contributes to the greater yield. In the arid and semi-arid wheat growing areas, lower plant populations that allow tillering of the crop, related to the amount of moisture available, give somewhat more flexibility than creating undue moisture stress by populations that are too high.

Other small details that cost little can be used to protect yields for a given level of inputs, increasing efficiency and recovery. Selection of weed-free seed with high germination is wise. Seed treatment for protection from soil-borne fungi or organisms capable of infecting and destroying the seed or seedling is a must. Seeding depth is another detail that can make a difference in emergence and early seedling vigor. Soil moisture is a consideration in depth of planting. Planting early in cold soils may require a shallower planting depth than for later planting dates when soil temperatures are warmer.

In dryland wheat areas of the northern Great Plains another inexpensive decision is the cutting height of the grain crop, which affects subsequent snow depth on the field and improves insulation of the following winter crop (in the case of winter wheat) and increases soil moisture (Black and Bauer, 1990). In a four-year study in North Dakota, researchers found that increasing the remaining stubble height of the previous crop from 2 to 8 inches had a very beneficial effect on yield for the three varieties of wheat planted (see Table 9).

Table 9. The effect stubble or cutting height on the four-year average yield of three winter wheat varieties.

	Yield of winter wheat-bu/a (4-yr avg.) Variety			
Stubble height inches	Roughrider	Mironovskaya	Centurk	Advantage
2	30.5	28.3	20.7	9.8
8	41.1	39.2	38.4	2.7
Advantage	10.6	10.9	17.7	

Source: Black and Bauer, 1990.

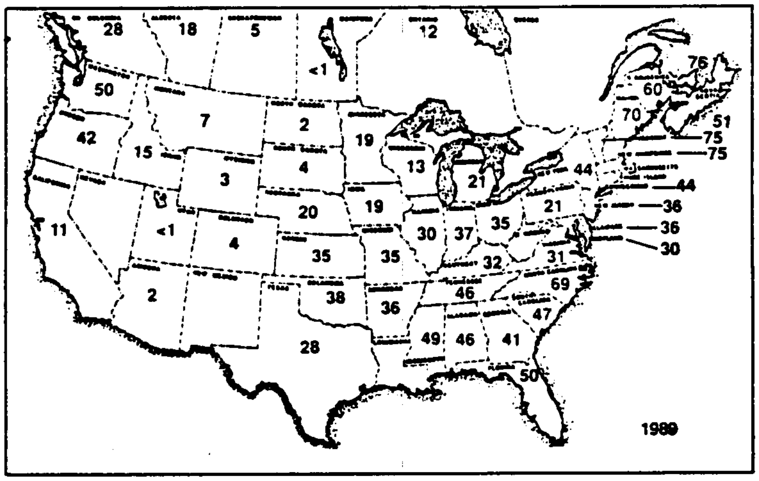
II. SOIL TESTING TO IMPROVE FERTILIZER AND CHEMICAL USE

Tests have been developed to measure the soil's ability to supply a nutrient or nutrients for crops, and through research to predict limestone and/or fertilizer needs. The soil test result provides an index or estimate of the nutrients available to a growing crop (Corey, 1987; Evans, 1987). This index is critical to more accurately applying fertilizers and manures, thus decreasing potential adverse impacts on surface water and groundwater. Interpreting these test results over time allows limestone, phosphate, potash and other nutrient needs to be determined and controlled with more precision at the farm level (Adams, 1984; Alley and Zelazny, 1987). Soil tests have become a reliable guide in fertilizer use, but could be used far more than they are today at little additional cost to farmers (Walsh and Beaton, 1973; Danhke and Vasey, 1973; Brown, 1987; and Westerman, 1990).

Tests for soil organic matter (which contains the organic carbon, nitrogen, phosphorus and sulfur fractions of soil) are also made (Volk and Loeppert, 1982). Soil organic matter levels can be increased by returning the residues from higher crop yields to the soil (Larson, et al., 1972). Soil organic matter interacts with some herbicides and influences the amount of herbicide needed for effective preemergence weed control on different soils. However, the organic matter results alone do not precisely indicate a soil's ability to mineralize and release nutrients to a crop, a process also controlled by soil microorganisms. Soil microorganism activity is influenced by soil acidity, moisture, temperature, and energy relationships (Follett, et al., 1987). Soil organic matter on most soils provides the major pulse of potentially leachable nitrates during the fall and spring when crops are not growing (Johnston, 1989). Here, we concentrate primarily on phosphorus and potassium soil tests, phosphate and potash recommendations, as well as on nitrogen tests, particularly the nitrate-nitrogen test.

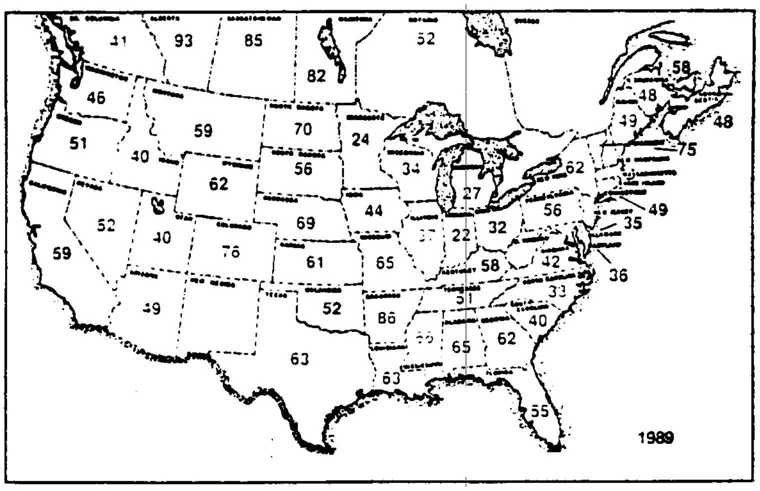
Each state's soil testing program has produced summary maps showing the percentage of soils testing in different categories. Generalized U.S. maps in Figures 4, 5, and 6 indicate the percentages of soil samples analyzed for pH (acidity), phosphorus and potassium that were found to test below pH 6 or "medium" or less in P or K (Soil test summary for phosphorus, potassium and pH, 1990). This is an indication that these soils periodically need limestone and would respond to applications of phosphate or potash fertilizers. At a national level, the percentages vary with the soils and states considered, reflecting differences in native soils, climatic conditions, cropping patterns, length of time cropped and

Figure 4. U.S. map based on pH soil test summaries indicating the percentage of soils testing below pH 6.



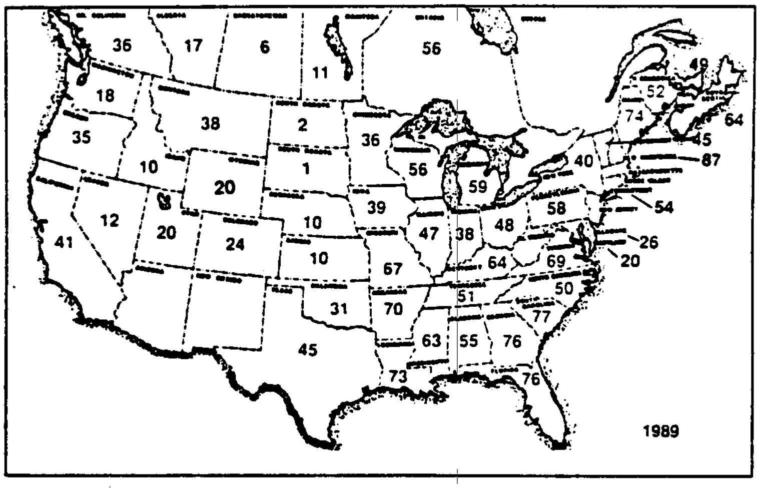
Source: Better Crops, Potash and Phosphate Institute, Spring 1990.

Figure 5. U.S. map based on phosphorus soil test summaries showing the percentage of soils testing medium or less in extractable phosphorus.



Source: Better Crops, Potash and Phosphate Institute, Spring 1990.

Figure 6. U.S. map based on potassium soil test summaries showing the percentage of soils testing medium or less in exchangeable or available potassium.



Source: Better Crops, Potash and Phosphate Institute, Spring 1990.

levels of lime and fertilizer use over time. Individual states produce more detailed maps based on test results and soil associations. While test levels in some states have been increasing, nationally, they are far from optimal levels. Minnesota has been a leader in developing and using computer digitized soil survey information systems, a technology being adopted in other states (Robert, 1988). Each soil type has a productivity index or rating for different crops (Rust, et al., 1984). Soils of major land resource areas vary greatly in their inherent productivity (Larson and Robert, 1989).

As fertilizer phosphate and potash are applied to soils in amounts that exceed crop nutrient removal, soil fixation or loss by erosion, test levels tend to increase (Evans, 1989). Although applications should continue until test levels reach adequate or sufficiency levels, as soil test levels increase, the probability of obtaining a crop response to applications of additional fertilizer decreases. Researchers at Purdue University have suggested the relationships shown in Table 10.

Table 10. Probability of crop response to applied fertilizer nutrient decreases as the level of soil test for that nutrient increases.

Soil test level or category	Probability of crop response to applied nutrient
Very low	> 95 %
Low	70-95 %
Medium	40-70 %
High	10-40 %
Very high	< 10 %

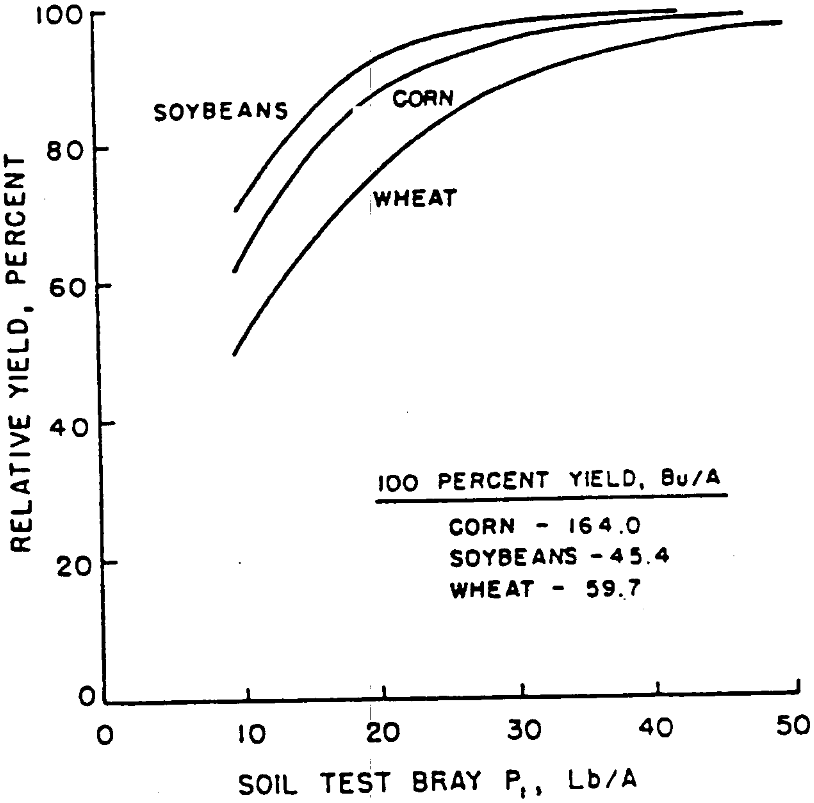
Source: Spies, 1984.

Different soils take different amounts of these fertilizers to increase the test results by one pound. For example, for some soils in Minnesota, it may take 20 pounds of P_2O_5 to increase the phosphorus soil test 1 lb/a or .5 ppm, while for some soils in Illinois it would require only 9 lb/a. The amount of fertilizer required depends upon the initial test level and the physical-chemical characteristics of the soil. Research in Montana indicates that additional measurements could materially improve predictions of potash fertilizer needs (Miller and Skogley, 1988).

We now consider several specific soil tests beginning with phosphorus. Phosphorus is one of the major chemical elements in all living cells and plays an extremely important role in a plant's energy reactions (Khasawaneh, et al., 1980). It is a major factor in crop production, but it also is a potential pollutant, leading to excessive growth of algae and other plants if it reaches lakes and streams (Porter, 1975). Precautions must be taken to decrease runoff losses. Plow down, deeper placement and conservation practices can be used to reduce such losses. In general wheat needs a greater level of phosphorus than corn or soybeans, and likewise tends to be more responsive to applied phosphate.

Regardless of crop, when soil test levels are adequate, the likelihood of increasing yields by further increasing phosphates is very low, and amounts of phosphate should only be added to maintain the desired test level or to replace that removed by the crop. Soybean, corn and wheat yields for increasing test levels are shown in Figure 7 (Johnson and Gascho, 1989). Once farmers or dealers in an area know their soils and monitor the tests, phosphate use on many soils can be closely controlled. Li and Barber (1988) in long-term studies on Indiana prairie soils found

Figure 7. The relative yield curves for corn, soybean, and wheat with increasing phosphorus soil tests.



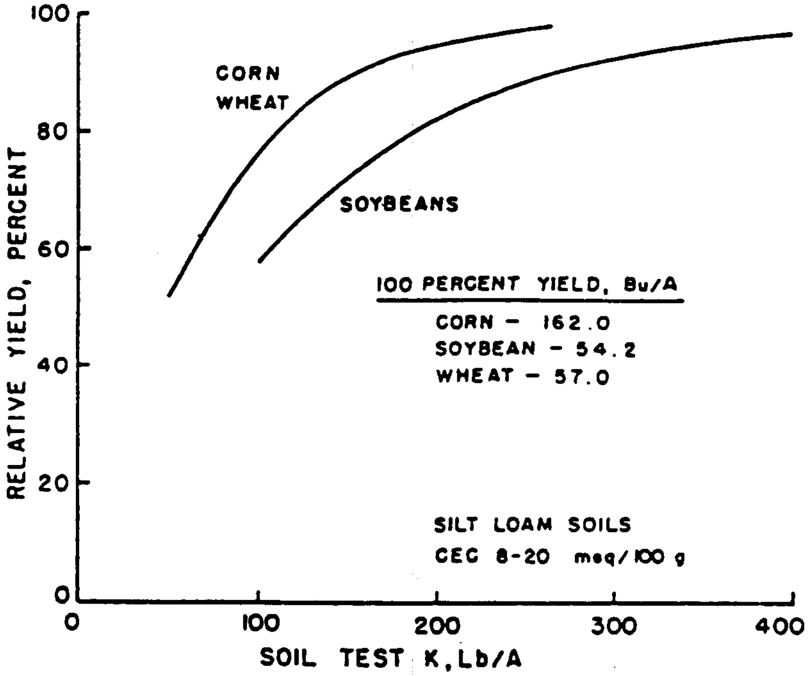
Source: Johnson and Gascho, 1989.

that 225 lb of P_2O_5/a per four years or 56 lb of P_2O_5/a annually were necessary in high yield situations to maintain soil tests and profitable yields.

A second soil test result of importance is for potassium, which is no less important than phosphorus (Munson, 1985). Potassium influences many of the cellular and basic processes such as photosynthesis, protein synthesis, and carbohydrate transport in crops. Potassium requirements of crops are greater than for phosphorus, and often similar to nitrogen. However, potassium is environmentallv benign, compared to either nitrogen or phosphorus. Relative yield-soil test relationships for potassium are shown in Figure 8 (Johnson and Gascho, 1989). Fertilizer potash, crop residues, animal manure, urine or ash may be applied to soils to increase soil test potassium levels. As K test levels become sufficient no further yield increases are found.

Wheat and other small grains tend to be less responsive to potassium than either corn or soybeans. Long-term results from studies reported by Barber (1980) and Li and Barber (1988) indicate little response of winter wheat to applied potassium unless test levels are very low. They found that soils that were testing from 31 to 46 ppm or 62 to 92 lb in exchangeable K/a, when provided adequate levels of other nutrients, had the capacity to produce long-term yields of only 56 bushels of corn, 40 bushels of soybeans, but 59 bushels of wheat, with little reduction in K soil test levels over time. However, with applied potash corn and soybean yields were over 150 bu/a and 58 bu/a, respectively, and much more profitable (25-year average). The optimum rate of potash on these soils for the cropping system used was 376 lb of K_2O applied every four years or 94 lb of K_2O per year (Li and Barber, 1988). Some soils require measurements in addition to exchangeable potassium to accurately predict potash needs (Skogley, 1976; Miller and Skogley, 1988; Grove, et al., 1990). Also, conditions of excess or low soil moisture, or soil compaction increase the probability of crop response to potash on some soils.

Figure 8. Relative yield curves for corn, soybean and wheat with increasing levels of soil test potassium.



Source: Johnson and Gascho, 1989.

The principle potassium (muriate of potash) source contains chloride, considered to be a limiting nutrient for wheat and other small grains in the northern Great Plains (Jackson, 1986; Fixen, et al., 1986a; 1986b). Chlorine is considered to be a micronutrient, but crops can take up rather high levels of chloride. Wheat responses to sources of potassium (these include sulfate, nitrate and magnesium sulfate) from a research standpoint need further study, but from the farmer's standpoint, it makes little difference whether the potassium or chloride produces the response, as long as it is profitable. The key point is to closely monitor potassium or chloride in the soil. Soil chloride levels need to be about 25 ppm to be adequate for small grains.

A third, and critical, soil test is for nitrogen. Nitrogen tests are of particular importance because of nitrogen's role in production and its tendency to runoff or move through tilelines into streams or rivers, and leach to groundwater. Researchers have been working on various tests to predict crop nitrogen needs for many years (Fitts, et al., 1955; Stanford and Hanway, 1955; Hanway and Dumenil. 1955; Munson and Stanford, 1955). Dahnke and Vasey (1973) reviewed the different tests for N. By the early 1950s Pacific Northwest researchers had developed a deep soil profile nitrate-nitrogen test, which when combined with the depth of soil moisture and estimated seasonal rainfall could successfully predict nitrogen fertilizer needs. This approach has now been adopted over a large area of the northern Great Plains. Yet in 1990, tests for N are still not used as extensively as they should be, particularly in the humid region.

Nitrogen soil tests are similar to those for phosphorus and potassium. When adequate nitrogen is present, there will be little response to applied nitrogen, and no more need be applied. Evidence is clear that soil profile nitrates increased as applied N exceeded the amounts needed for optimum yields, and the potential for leaching loss also increased (White, et al., 1958; White and Pesek, 1959; Fenster, et al., 1978; Gilliam, et al., 1985). Researchers in Vermont were the first in the humid region to implement nitrate-nitrogen test for making N recommendations (Magdoff, et al., 1984).

Minnesota, transitional between the humid and semi-arid region, also began using the nitrate-N test for corn (Rehm, et al., 1984).

Although the nitrate-nitrogen soil test was widely used by the 1960s for predicting nitrogen fertilizer needs of wheat and other small grains in the Great Plains (Westerman, 1990), its adoption for corn lagged. There was little reason why it should have, because nitrogen is very important for corn production. More emphasis is now being placed on nitrate soil testing in the humid region (Thicke, 1989; Soil Nitrate Testing Workshop, 1989). Anything that can be done to predict nitrogen needs more accurately and improve use-efficiency from an environmental standpoint should be done (Aldrich, 1980).

An example of such prediction is the University of Vermont's release of the first field nitrate-nitrogen soil test kits for samples taken when corn is 8 to 12 inches high (Jokela, 1988). Blackmer, et al. (1989), in Iowa also developed a spring nitrate-nitrogen test patterned after Vermont's that measures the amount present in the top 12 inches (30.5 cm) of soil. A field kit marketed as "N-TRAK" has been developed. These can be used by farmers and dealers to check for spring nitrates and make N recommendations. Another simple nitrate electrode "Cady" is available for rapid field tests. Many believe that nitrate-N soil tests run by university or commercial testing laboratories will be more accurate. Also, others feel that deeper sampling is needed to more accurately measure the nitrate in the root zone (Bundy and Malone, 1988; Schmitt, et al., 1989; Malzer, 1990, personal communication). Beauchamp, et al. (1989), are successfully using soil nitrate-N tests with deeper sampling to predict fertilizer N needs of corn in Ontario. There is increasing evidence that on some soils it may be desirable to also measure ammonium-N.

The validity of nitrogen tests depends on realistic yield goals and recommendations. Many yield goals set by farmers are too high (Hergert, 1987). Killorn (1989), while conducting N-rate studies on six farmer's fields and calculating the most profitable rates of N, found that farmers had applied an average of ninety pounds more N than was needed.

Legg, et al. (1989), found that some farmers in southeast Minnesota that had livestock and raised alfalfa tended to overapply nitrogen to corn, because they did not give proper nitrogen credits for the manure being applied or the mineralizable N provided by legumes (nor did they use a nitrate-N soil test). Farmers growing continuous corn were applying rates of N that more accurately reflected the amounts needed based on the yields achieved. These results agree well with those reported from the Big Spring Basin, a watershed in northeast Iowa, in which economic and environmental gains were achieved by properly crediting N supplied by manure and alfalfa (R. D. Voss, 1989). It was found that farmers in the Basin could profitably reduce N rates and maintain yields through such N credits.

Keeney (1982), Gilliam, et al. (1985), and Roth and Fox (1990) have emphasized the environmental aspects of nitrogen, and the importance of using the correct nitrogen rates to reduce potential loss of N from the soil profile. As long as the N input from all sources does not exceed the amount needed to produce the crop, leaching losses are usually low. Of course, in fine textured soils or on coarse textured, sandy soils, under conditions of excess rainfall, N losses to the air due to denitrification or subsoil due to leaching can occur (Eichner, 1990). Leaching losses can also occur when the amount of rainfall and/or irrigation exceeds the moisture holding capacity of the soil in the root zone of the crop. That is particularly true on coarse textured, sandy soils.

While nitrogen, phosphorus and potassium are the most well-developed soil tests, other tests are also used. Soil acidity (pH) tests and limestone requirements will generally account for deficiencies of calcium (Ca) and magnesium (Mg), although in some areas specific magnesium tests are required. Unless soil pHs are closely monitored, serious crop yield losses can occur due to increased soil acidity from long-term nitrogen use (Pierre, et al., 1971; Westerman, 1981). There are also tests for sulfur, another secondary element, but sulfur needs are not accurately predicted by soil tests alone, particularly if only surface soil samples are tested.

Soil tests have also been developed for the essential micronutrients [boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn)] which are required in very small amounts. These have been reviewed by Viets and Lindsay (1973) and Reisenauer, et al., (1973). Other micronutrients determined to be essential for soybeans and/or the nitrogen fixation process include molybdenum (Mo), cobalt (Co) and nickel (Ni). Selenium (Se) is also beneficial to that process. The development and use of EDTA (ethylenediaminetetraacetic acid) and DPTA (diethylenetriaminepentaacetic acid) extractants by Lindsay and his colleagues in Colorado have improved micronutrient testing and helped establish indices and recommendations for the essential micronutrients. When these elements are deficient, the effects on plant growth are dramatic. Often micronutrient deficiencies can be found through plant analysis, which also can be an important diagnostic part of integrated crop and farm management (Munson and Nelson, 1990). If diagnosed early enough, corrective nutrient applications, often foliar, can be made in time to improve yields that cropping year.

III. METHOD, PLACEMENT, AND TIMING OF FERTILIZER AND CHEMICAL APPLICATIONS

The most common fertilizer application technique in the past has been the broadcast method. Once the rate to be applied was determined, the whole field received that rate, which was either plowed down, chiseled-, disked-, or cultivated-in with tillage operations. Except for moldboard plowing, the depth of nutrient incorporation is usually about half the depth of the tillage. Early research indicated that in most cases, broadcast plow-down was more efficient than surface disked-in applications, because the nutrients mixed into moist soil were positionally more available to the crop's roots, and less likely to be eroded from the field.

Early research had indicated that row placement of low rates of fertilizer for corn was more efficient than plow down, but as rates of row application increased, a problem of seed germination or seedling injury from nutrient salts developed. New equipment was engineered that provided more desirable placement. Side-band row placement emerged, in which nutrients are placed to the side and slightly below the seed at planting (Table 11). This method of placement is very effective from both an efficiency and environmental standpoint. Other types of placement, such as side dressing, knifing-in, or spoke-injection, in which the nutrients are concentrated or injected between or in the rows, were also developed. Timing of nutrient applications, as well as rates and combinations of nutrients, are also important. When fertilizers are banded, the concentration of the nutrients increases their recovery by the crop, limiting runoff.

With knifed-in or banded row fertilizer, the amounts of nutrients are applied in a continuous band, in much greater concentration than is

Table 11. Method and time of application are important in increasing the efficiency of an application of 10-34-0 fertilizer (100 lb/a rate) for corn.

Method, placement and time of application	Corn yield bu/a
None	153
Sidedressed (early June)	164
Broadcast (preplant)	176
Row (2" x 2" at planting)	200
Effect of best treatment	47

Source: Rehm, 1983.

achieved with broadcast and mixing into the soil with tillage. For example, anhydrous ammonia, which becomes a volatile gas as it is injected or knifed into the soil, reacts with soil moisture, forming ammonium-N (NH_4^+-N) which is held on negatevely charged soil cation exchange sites before it is nitrified by soil microorganisms to nitrate-nitrogen (NO_3^--N). It has always been knifed-in or injected to prevent ammonia loss to the air.

Fixen (1990) recently reviewed crop response information on point or spoke-injection and other placements. The point injection system that seems to be gaining favor uses a spoked-wheel that penetrates the soil, releasing given amounts of nutrients as the wheel turns (Baker, et al., 1989). These point injections concentrate the "packet" of nutrients for a given rate of application, even above that of continuous banding.

Knifed-in and point injection applications of fertilizer also hold advantages for conservation or reduced tillage systems in which one wishes not to disturb the crop residue, helping to prevent soil erosion. Side dressing anhydrous ammonia between alternate corn rows, 60 inches apart, have been shown to produce yields similar to those between every row, which also decreases fuel costs (Reichenberger, 1990).

In general, the closer nutrient application can be synchronized with the period or growth stage of the crop, the more efficient and environmentally benign the effect will be. However, there are many factors that influence timing of nutrient applications. For example, in areas of high rainfall, where leaching could be a problem, one might assume that it would always be better to delay applications of nitrogen to coincide with crop uptake. However, wet soils can prevent getting into fields. This has led to spring preplant application or sidedressing shortly after the crop has emerged. Nitrification inhibitors, such as N-Serve or DCD (Dicyandiamide), or urease inhibitors, such as NBPT [N-(n-butyl) thiophosphoric triamide], can be used with N applications to delay conversion of ammonium-nitrogen to nitrate-N in high rainfall or on sensitive soils (Schmitt, et al., 1989; Walters and Malzer, 1990a, b). However, where delayed sidedressing can be done, it may be as effective as inhibitors. With irrigation N applications can be applied in small, timely amounts for corn and wheat. This is especially true where drip irrigation or subsoil tubing is installed. The new point injection equipment for wheat, because it is less intrusive than knifing-in, may be useful in timing applications with proper soil conditions. Point injection or foliar N applications during seed-set are also being studied in soybean production. Tramlines, which are widely used in Europe, set established traffic patterns in the field for repeated nutrient, growth regulator or fungicide applications in intensive wheat production.

IV. FERTILIZER RATES AND COMBINATIONS OF NUTRIENTS INTERACT WITH OTHER MANAGEMENT PRACTICES

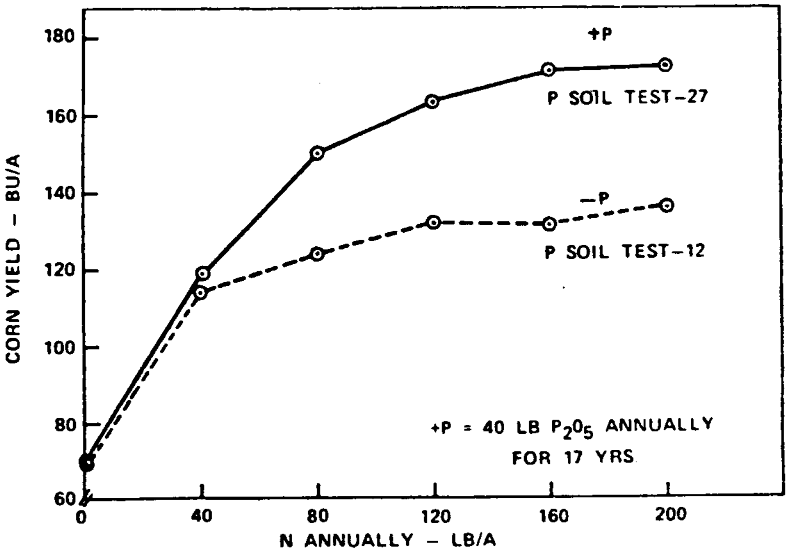
The interaction of various chemical inputs requires careful evaluation of nutrient needs by farmers. Application of one nutrient can be useless (and environmentally damaging), if another essential element or cultural practice is limiting yield more than the one being applied. Gains are being made in nutrient efficiencies due to improved use of soil testing, nutrient placement, timing of application, and management practices. Application of new technologies and removal of some, but by no means all, of the poorer soils from production through the government Acreage Reduction Program (ARP) and Conservation Reserve Program (CRP) have also aided in general increases in efficiencies. This is suggested by total input use trends. Total phosphate use in the U.S. peaked in 1977 and nitrogen and potash use peaked in 1981. In 1989, phosphate use was below 1967 levels, while nitrogen use was below the 1977 level, and potash use just above the 1973 levels. But greater gains are possible, especially on environmentally sensitive soils unprotected by acreage set-asides.

It is interesting to note that from a historical perspective, nitrogen leaching was probably more severe on many soils when they were broken out of prairie than it is today. When these soils were first tilled, average corn yields in the U.S. were only about 25 bu/a. Evidence indicates that little of the 200 to 400 lb/a of nitrate-nitrogen virgin soils were capable of releasing was recovered by such low yielding crops (Fenster, et al., 1978; Overdahl, et al., 1980). In the late seventies a virgin soil receiving no fertilizer nitrogen produced a six-year average yield of 133 bu/a indicating its capacity to mineralize organic nitrogen.

Modern management and higher yielding hybrids have the capacity to more effectively use and recover soil and fertilizer N, decreasing environmental losses.

However, nitrogen will not be effectively used by a crop if other essential elements are limiting the potential response. In studies conducted by Murphy in Kansas, for example, phosphorus applications improved crop responses to nitrogen (Figure 9). Similar results are found for nitrogen and phosphate applications on wheat (Halvorson, 1989). Without phosphorus, nitrogen applications are less efficient. It is also well known that ammonium sources of nitrogen, when combined with phosphate, enhance crop uptake and utilization of fertilizer phosphorus.

Figure 9. The effectiveness of nitrogen for corn is increased by having adequate amounts of soil and fertilizer phosphorus present (four-year average).

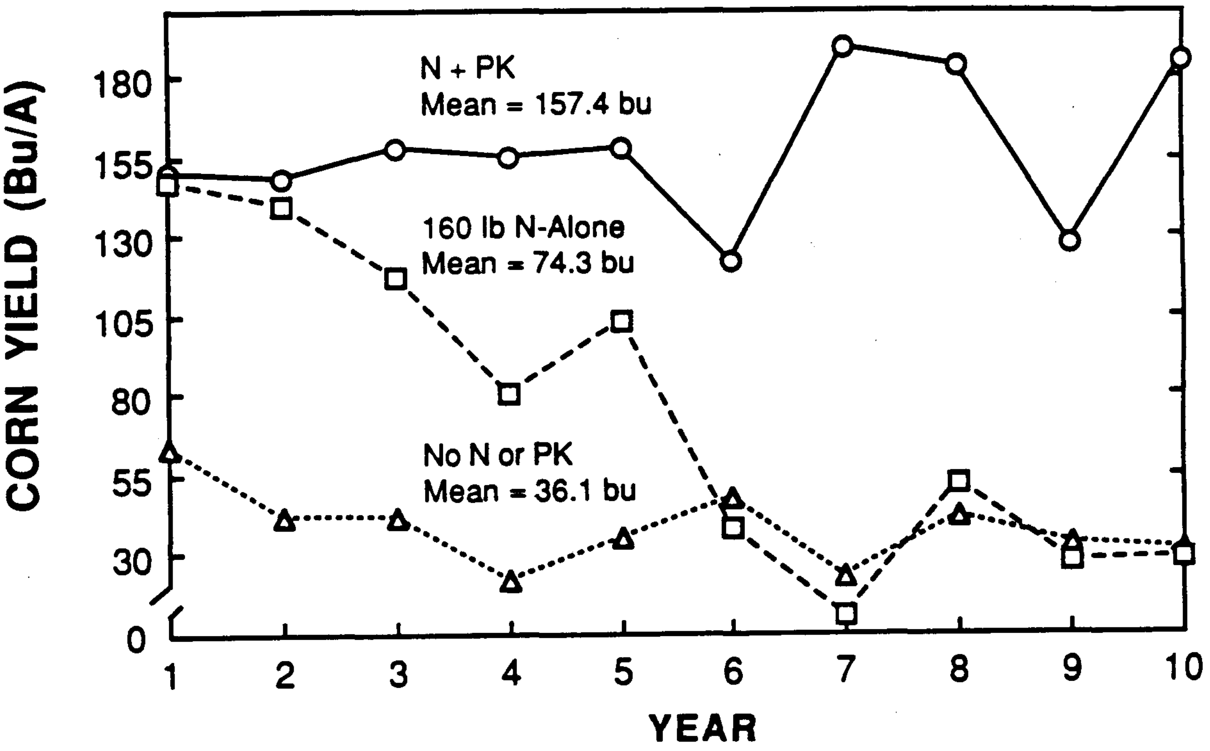


Source: News and Views, Midwest. No date (b).

In no-till corn studies conducted over a 10-year period by Bandel in Maryland (Personal communication, 1990), in which N alone (160 lb/a) was applied, yields dropped dramatically with time. The loss in yield was only

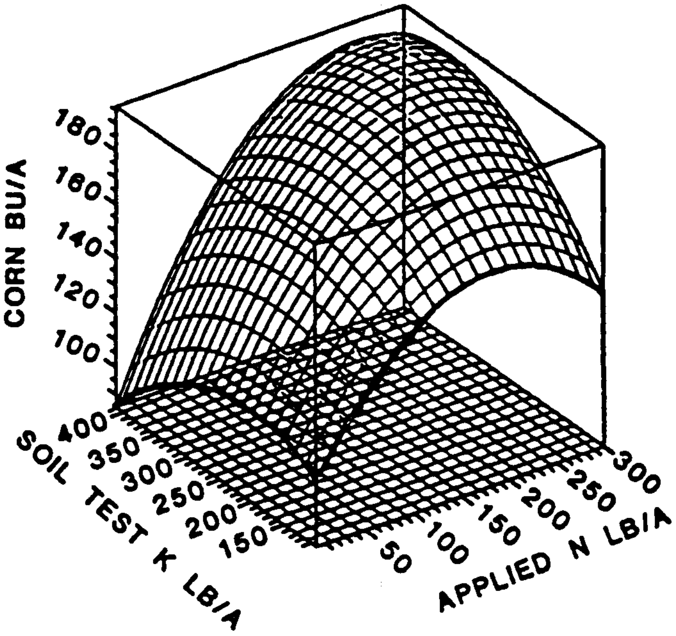
5 bushels the first year, but increased to 73.5 bushels by the fourth year, and to over 176 bushels by the seventh year. Averaged over the 10 years, the yield with N alone was 74.3 bu/a/year (Figure 10). By the end of period, without P and K, there was essentially no response to the 160 lb-N application. Where no N was applied, the yields averaged 36.1 bu/a. However, when N was accompanied by adequate phosphorus and potassium soil or fertilizer levels, the average yield was 157.4 bu/a, a 121.3 bushel increase due to the improved mineral nutrition. This study indicates how nutrients interact and affect crop yields over time. Nitrogen use-efficiency was increased an average of 114 percent per year by having adequate P and K present. Studies in Wisconsin (Moncrief, et al., 1979/80) on corn confirm this interactive relationship for nitrogen rates and soil test potassium levels (see Figure 11).

Figure 10. Adequate nitrogen, phosphate and potash improve and maintain corn yields over time. (Mean equals ten-year average.)



Source: Bandel, 1990. Personal communication.

Figure 11. Nitrogen rates and potassium soil test levels combine to form a visual corn yield production surface.



Source: Moncrief, et al., 1979/80.

V. BENEFITS OF CROP ROTATION, CONSERVATION TILLAGE, AND OTHER FARM-LEVEL MANAGEMENT DECISIONS

Crop rotations have been part of agronomic discussions and practical farming since Greek and Roman cultures flourished. The contribution of nitrogen fixed by legume crops in rotations, some of which is left in the soil for subsequent nonlegume crops, is well recognized. With the advent of nitrogen fertilizers, it was evident that fertilizer-N could be effectively substituted and used instead of legume-N for both small grain and corn crops. However, there are other benefits of rotation, such as breaking crop disease, weed or insect cycles, that need to be considered, and that are often cost-effective methods of control. To grow high yielding alfalfa, high soil test levels of nutrients are required, and the soil pH for well-buffered high organic matter soils needs to be in the range of 6.6 to 6.8. Seed and establishment costs are high. Part of the beneficial pH effect could be due to increased Mo availability on some soils. The nitrogen credits from the inclusion of legumes, such as soybean or alfalfa, affect the amount of N needed for profitable production and environmental protection (Peterson and Russelle, 1990). However, one should not be deluded that legume-N is any less subject to nitrification, leaching or denitrification than fertilizer-N or soil organic matter-N, once it is mineralized. Evidence indicates that continuous soybeans without applied N increase soil profile and tileline nitrates above those of continuous corn (Randall, et al., 1988).

Here, we will examine the benefits of crop rotations of legumes, such as soybeans, alfalfa, and clover, and the application of manure on various cropping systems. A 12-year study conducted in southern Minnesota by

Randall and his colleagues comparing continuous corn with corn-soybean rotations showed a 34-bushel advantage for corn grown after soybeans on the nitrogen control plots (Randall, et al., 1987; O'Leary, et al., 1989) (Table 12). The residual effects of the soybean rotation on corn yields on that treatment were equal to about 64 lb of nitrogen. Increasing N rates diminished the rotation advantage somewhat, but at the most profitable incremental rate of 160 lb N-rate there was still a 25-bushel advantage for corn after soybeans, indicating benefits other than N were an important part of rotation's advantages on these particular soils. Soil tilth improvement is often mentioned when soybeans are included in a rotation on fine-textured soil, and disease and corn rootworm cycles are broken as well. On high organic matter soils in northwestern Illinois corn after soybeans showed a 7-year average of a 5-bushell advantage over continuous corn on the nitrogen control, which was equal to that of about 114 lb N/a on continuous corn (Mainz, 1989).

Welch (1989) and Crookston (1990) have discussed the benefits of rotations to increased soybean yields. At three locations over a six-year period the most profitable rotation sequence of corn (C) and soybeans (S) was SSCSSC (Ndiaye and Crookston, 1990). Duffy (1990) in Iowa found that a high management corn-soybean rotation, among those compared, produced the highest net return.

Unless soybean yields are extremely high, indications are that residual-N or N in manures will add little to yields of beans. Randall (1990, personal communication) indicated that in four years of observations in which average yields were over 50 bushels per acre, no beneficial residual effects of N applied to corn were found on bean yields.

In Kansas for soybeans yielding 70 bushel per acre, results were similar (Maddux and Barnes, 1989). Research is currently being conducted on soybeans to evaluate the possible benefits of N applied (soil or foliar) during pod-fill or reproductive stages (R_3 to R_5) of development. Manure applications can, however, provide additional elements that are often deficient, such as phosphorus, potassium, sulfur and micronutrients, contributing to increased yield.

Double-cropping of winter wheat and soybeans has become a widespread practice in the humid southern two-thirds of the U.S. in areas with enough moisture to get the soybean crop established and a long enough season for beans to mature. Usually the beans are planted in narrow rows or drilled into the wheat stubble following harvest. Good weed control is essential for narrow row beans. Soybeans can be harvested in time to get a late fall crop seeded or a crop the following spring and take advantage of the N fixed by the soybeans. Where irrigation is available double-cropping has produced wheat yields of over 100 bu/a followed by 50 bu/a soybeans (F. R. Mulford, 1990, personal communication).

Table 12. The effects of rates of N for continuous corn and corn after soybeans on 12-year average corn yields.

	Corn yield-bu/a				
N rate lb/a	Cont. corn	Added	Corn after soybean	Added	Difference
0	75	--	109	--	34
40	100	25	134	25	34
80	115	15	146	12	31
120	125	10	153	7	28
160	133	8	158	5	25
200	136	3	158	0	22
Increase	61		49		

Source: O'Leary, et. al., 1989.

Alfalfa and animal manure also contribute to the nitrogen budget in cropping systems. The element added by alfalfa is N, while manures increase the availability of nitrogen, phosphorus and potassium, as well as other nutrients (Sutton, et al., 1985; Schmitt, 1989). However, if the alfalfa is grown in a moisture deficient area, it can further deplete soil moisture, lowering yields for corn or other crops in spite of increased N. In the humid areas the benefits of the residual nitrogen to the next-planted crop are very apparent.

A long-term study at the Iowa Clarion-Webster Research Center indicated the benefit of increased N availability to corn following alfalfa. Rates of N did not significantly increase the yield of first-year corn (Table 13), but second-year corn responded up to the 120 lb N-rate. Follow-up research on alfalfa in the Big Spring Basin in northeast Iowa, reported by Kapp (1990), indicates that farmers in the Basin area were not properly crediting the legume-nitrogen in making N fertilizer recommendations for corn, and were applying an average of 110 lb N/a on first year corn. Studies in southeast Minnesota by Legg, et al. (1989), also indicate that farmers dairying or feeding livestock were not giving proper N credits for either alfalfa grown or manure applications in determining their N use for corn (Legg, et al., 1988; 1990). In some cases, farmers were over-applying from 27 to 133 lb of N per acre beyond the amounts needed to achieve the economic optimum yields for the area. In contrast, farmers growing continuous corn without alfalfa or manure were more accurately determining the needed N-rates for corn. In sum, if one has need for alfalfa in a dairy or feeding operation or has access to other markets, such as hay sales to horse farms or race horse complexes, it is wise to use it or other legumes in rotations and to give them full credit in the overall "nitrogen account" of the farm (O'Leary, et al., 1989; Fox and Piekielek, 1988). Such accounting can be an important overall basis for reducing excess nitrogen while maintaining competitive yields (Table 14).

Table 13. Alfalfa provides adequate N for the first year corn, for crops grown in a corn-corn-oats-alfalfa rotation.

N rate lb/a	Corn yield-bu/a (3-year avg) 1st-year-corn	2nd-year-corn	Diff.
0	173*	114	59
60	177	155	22
120	178	168*	10
180	179	168	11

*Most profitable yield and rate of N.

Source: John R. Webb, 1986. Personal communication.

Table 14. The effects of nitrogen rates and crop rotation (corn-corn-corn-alfalfa-alfalfa) on average corn yields on a silt loam soil.

Corn yield-bu/a (10-year avg)

N rate lb/a	1st yr corn C-C-C-A-A	2nd yr corn C-C-C-A-A	3rd yr corn C-C-C-A-A	Cont. corn C-C-C-C-C	Difference
0	131*	89	72	34	97
50	131	114	112	86	45
100	139	129*	125*	103	36
200	132	130	126	127*	5

*Indicates the most profitable yield with 15 cent N and $2 corn.

Source: O'Leary, et al., 1989.

Research by Evans in west central Minnesota indicated that high rates of manure (32 tons/a/year), containing a total of 3,360 lb of N, applied over a 5-year period caused nitrate-N to accumulate in the soil, which could be recovered by subsequent crops (Evans, 1989). This was in an area of lower rainfall. Heavy manure or crop residues over time improve soil organic matter.

Rehm, working in southeast Minnesota on silt loam soils similar to those in the Wisconsin studies, showed that under high level management, soil productivity was increased most by alfalfa plus manure. This is shown by the 108 bushel yield-differential without any additional N applications (Table 15).

Table 15. Effects of alfalfa plus manure, manure, continuous corn and N rates on corn yields grown at three sites on similar soils.

	Corn yield-bu/a		
N rate lb/a	Alfalfa + manure	Manure	Cont. corn
0	215	176	107
40	223	192	124
80	209	202*	138*
120	210	191	139
160	207	188	139
200	212	199	148
Initial soil nitrate-N, 5 ft.	55 lb	45 to 191 lb	82 lb

*Apparent most profitable yield and N-rate. Manured areas may present special weed control problems depending upon straw sources.

Source: Rehm, 1988. Personal communication.

It is important that these differences in productivity are recognized and managed so that the nitrogen is not lost to the environment. They need to be measured and understood through soil testing. The benefits of legumes and particularly manure include increased micronutrient availability, improved soil organic matter, improved moisture holding capacity and infiltration rates, lower soil bulk densities (which affect the proportions of solids, air and water in soils), improved microbial activities and a host of other factors. Clearly a valuable resource is wasted if animal manures are not properly stored and applied and used in well-managed production systems.

The relationship between rotation of legumes and wheat is more complex. Because of the relatively high soil organic matter levels found in many of the soils formed under grass vegetation in the Great Plains, where wheat is grown, and because of their capacity to mineralize organic N, legume rotations show little advantage until the level of organic N is depleted. In other words, the rich prairies already have high levels of mineralizable N in their "accounts". Recent research by Sims and his colleagues in Montana, however, indicates that a number of legumes can now be successfully grown in the drier areas of the Great Plains, and that they are more effective than summer fallow in contributing nitrogen for wheat and other cereals, except where rainfall is very low (Sims, 1990).

In addition to crop rotations, a variety of other conservation practices are of considerable help in reducing environmental impacts of modern farming. These are listed below:

Contouring

Strips laid out according to the shape and slope of the land can be tilled and planted across the slope, increasing rainfall infiltration, reducing runoff and erosion losses of sediments, nutrients, herbicides and/or insecticides.

Contour Strip Cropping

Crops can be planted and rotated on the contour in alternate strips. This decreases movement of soil and water, and is particularly effective when combined with conservation tillage (see below). Leaving crop stubble in place can also lead to more snow accumulation, increasing soil moisture in drier areas.

Strip Cropping

Simple strip cropping with corn and soybeans in 8 to 12 row alternate strips can markedly improve corn yields, because of the effect of light on yields of the outside rows (Welch and Ottman, 1983; Welch, 1985).

Terraces

Terraces can be used on steep slopes to help hold water and soil sediments in the terrace channel, decreasing soil erosion and water runoff. These structures can be costly, but they are environmentally beneficial.

Use of Grassed Waterways or Buffer Strips

Grass sod areas kept in place in areas that would otherwise experience serious erosion, and as buffer strips along ditches, ponds, lakes or rivers, help trap and decrease the movement of soil sediments and runoff into surface water.

Cover Crops

These are planted after the primary crop in the fall for several purposes, such as reducing wind and water erosion, fixing nitrogen or decreasing the leaching of nutrients by recovering them in the crop for recycling.

Windbreaks

Shrubs or trees can be planted in periodic rows or strips to decrease wind erosion of soil. These can also trap snow to increase water available from snow melt in drier northern areas.

Conservation Tillage

Preparation of land for planting (tillage) is a major operation each year (Galloway, et al., 1985; Moncrief, et al., 1988). Its purpose is to ensure a good seed-bed that allows quick, uniform germination and seedling emergence, with as little stress as possible. Besides disrupting weed growth and development and some disease and insect cycles, it can alter crop responses to applied nutrients and chemicals. For example, mixing of preemergent herbicides into some soils for weed control helps "activate" them, while for others soils with high clay content such mixing inactivates them, making them ineffective. By aerating soils and stimulating microbial activity, tillage enhances the mineralization of soil organic nitrogen, phosphorus and sulfur, and the decomposition of organic residues.

For years the moldboard plow was the predominant farm tillage implement. It cut through the soil and turned under broadcast fertilizers or manures, parts of growing crops or surface residues of harvested crops. The plowed soil was then disced, cultivated or harrowed to prepare the seed-bed for the next crop. Early-fall tillage following a winter or short-season grain crop left time for the mineralization or release of soil organic and inorganic nutrients in moist soils during the fall and spring before planting. Today, the moldboard plow is used less and less, except for those soils on which fall plowing has been shown to improve seed-bed tilth in areas not subject to soil erosion. The chisel-plow, which leaves considerable residue on the soil surface, has come into favor.

Such conservation or minimum tillage methods leave 25 to 30 percent of the soil surface covered with crop residues after planting. Data (Table 16) show how surface residues help decrease runoff and soil erosion

(Mannering, 1983). For example, leaving a ton of residue per acre on the soil surface decreased the percent of rainfall runoff to only 0.5 percent and soil erosion losses decreased from 12 tons/acre to only 0.3 tons. These decreases in runoff and soil erosion dramatically reduce the amount and possibility of nutrient and pesticide losses from fields.

Table 16. Effect of increasing rates of surface crop residues on water runoff and soil erosion on a Sidell silt loam soil, with a 5 percent slope.

Crop residue tons/acre	Runoff Percent of Rainfall	Soil loss tons/acre
0	45	12
0.25	40	3
0.50	25	1
1.00	0.5	0.3

Source: Mannering, 1983.

Other conservation tillage methods increasingly in use include ridge-till and no-till planting for row crops, in which planting is done directly into ridges that are maintained or into the residue of the previous crop. Brown, et al. (1989), indicated that by 1987 some form of conservation tillage was used on 50 percent of Corn Belt cropland. Nationwide 32 percent of the corn crop acreage was under conservation tillage in 1989, 7.1 percent no-till; 2.4 percent ridge-till; and 22.5 percent mulch-till (Conservation Technology Information Center, 1989). Another 24.8 percent had from 15 to 30 percent of the previous crop residues on the surface. For soybeans 29.6 percent of the crop was under conservation tillage, 7.7 percent no-till, 1.2 percent ridge-till, and 20.7 percent mulch-till. Another 24.5 percent had from 15 to 30 percent of the residue on the surface.

Returning crop residues to the soil also conserves millions of tons of nutrients for crop production each year (Follett, et al., 1987). Therefore, residue management is an important part of nutrient and soil conservation (Larson, 1979). For example, about half of the dry matter accumulated by a corn crop is returned to the soil. It could potentially be used in alternative ways.

Moncrief, et al. (1990), compared the impact of various tillage systems in Minnesota on the amount of surface residue left on the field, an important factor in reducing runoff and improving moisture infiltration. Crop residues intercept the energy of the rain and decrease erosion, even on steep slopes. In no-till, residues can decrease runoff and loss of herbicides or other chemicals to surface waters. Moncrief found that the effects of tillage on the percent of surface area coverage by corn residue between corn rows was 77.3 percent for no-till, 60.6 percent for ridge-till and only 9.7 percent with the moldboard plow. Brown, et al., (1989) reported that in their studies in Iowa no-till had residue coverage of 72 percent of the surface, while reduced tillage coverage was 26 percent and conventional fall moldboard plow coverage was only 3 percent.

New evidence indicates no-till also decreases N leaching in some areas (Martin, 1990). Even though moisture infiltration into soil increases under no-till, there is little downward movement of either nitrate-N or agricultural chemicals through earthworm holes as had initially been theorized (Edwards, et al., 1988; 1989). The measured nitrate-N collected amounted to only 0.63 lb/a, even though rates of N adequate to produce from 143 to 175 bushels of corn per acre were used. The effects of no-till have conserved as much as 3-inches of moisture per year, through increased infiltration and decreased evaporation, which in some cases translated into corn yield increases of up to 10 percent over conventionally tilled corn (W. M. Edwards, 1990, personal communication; Marking, 1990).

In some areas no-till corn is contributing to increased disease problems because of surface residue inoculum. This appears to be the case for gray leaf spot of corn (Cercospora Zea maydis) (Luana and House, 1990).

Witt and Sander (1990) conducted a two-year study in which surface runoff and movement of three triazine herbicides were followed in three tillage systems. The effect of conventional, chisel plow (50 percent surface residue) and no-till (95 percent surface residue) tillage systems on the percentage of the applied product in runoff water is shown in Table 17. Under conventional tillage Bladex, which was applied at a higher (3 qt) rate than atrazine, showed the lower loss. The second year in particular, chisel-plow and no-till systems decreased the loss of the herbicide to surface runoff. The losses were, in general, very low. Downward movement by leaching under these conditions was least under conventional tillage. Under chisel-plow and no-till there was no movement of herbicide below the 17-24 inch depth, and then soil concentrations were only 0.3 and 0.6 ppb for those systems. After the third month and up to 11 months after application, herbicide residues were not found below the top 0-8 inches, and top soil concentrations ranged from 3 ppb in the no-till to 9 ppb in the conventional-till systems. This indicated greater degradation under no-till.

The best tillage system is closely related to soil type, drainage, climate, and the crops grown. However, results from Minnesota (Moncrief, et al., 1988) indicate that conservation tillage systems give good results for both corn and soybeans on a variety of different soil types (Tables 18, 19, and 20), although no-till corn yields were significantly lower on both fine and coarse (sandy) textured soils.

Table 17. Effect of tillage system on the herbicide loss in runoff water under corn in two growing seasons.

	Percentage of applied in runoff		
Herbicide	Conventional	Chisel plow	No-till
		1986-87	
Atrazine 4L	0.14	0.07	0.10
Bladex 4L	0.09	0.06	0.12
Princep 4L	0.13	0.06	0.10
		1987-88	
Atrazine 4L	0.26	0.01	0.01
Bladex 4L	0.07	0.01	0.004
Princep 4L	0.34	0.03	0.02

Source: Witt and Sander, 1990.

Table 18. Effect of tillage system on average corn yields on a somewhat poorly drained Webster-Nicollet clay loam soil. The tillage effect was significant for each year.

Tillage system	Corn yield-bu/a (6-year avg)
No-till	134
Till-plant, ridge	155
flat	151
Fall chisel plow	152
Fall moldboard plow	161

Source: Moncrief, et al., 1988.

Table 19. Effect of tillage system on average corn yields on an irrigated loamy sand soil (Mississippi sand plain). The tillage effect was significant for each year.

Tillage system	Corn yield-bu/a (4-year avg)
No-till	157
Ridge-till	173
Chisel plow	170
Moldboard plow	178

Source: Moncrief, et al., 1988.

Table 20. Effect of tillage system on average soybean yields, following corn, on somewhat poorly drained clay loam soils in southcentral, southwest and westcentral Minnesota.

	Soybean yield-bu/a		
Tillage system	Southcentral[1] (4-year avg)	Southwest[2] (3-year avg)	Westcentral (4-year avg)
No-till	47	46	49
Till-plant ridge	47	47	51
flat	46	46	51
Spring disc	49	47	49
Chisel plow	48	45	51
Moldboard plow	49	47	50

[1] Unpublished data, W. Lueschen.
[2] Unpublished data, W. Nelson.

Source: Moncrief, et al., 1988.

Moncrief, et al. (1987), examined costs of production for different tillage systems, including equipment, plant nutrients, insecticides, and herbicides. For machinery costs for corn and soybean production, ridge-till and no-till have the clear advantage. When other costs are considered for continuous corn, the ridge-till system comes out better than no-till, because under no-till nitrogen rates have to be increased somewhat. That is because lower soil temperatures in northern areas result in less mineralization of soil organic N (Schulte, 1985). Also, higher herbicide rates are needed to control weeds in no-till, whereas herbicide can be banded in ridge-till, decreasing the rate by half or more. Ridge-till costs were found to be $60.57/a, while no-till costs were $72.22.

For corn after soybeans, ridge-till shows a considerable advantage over no-till and other tillage systems because insecticides are dropped when no corn rootworm control is needed (as in continuous corn) and herbicide use and costs are cut in half (Moncrief, et al., 1987).

For soybeans ridge-till again comes out with the lowest cost. Soybeans usually do not receive any applied fertilizer N or rootworm insecticide. Herbicide use for ridge-till soybeans is slightly greater than with moldboard or chisel plow systems. Because of the higher herbicide costs with no-till soybeans, Moncrief and his colleagues found it to be the highest cost system.

Comparisons of the effects of conventional and no-till tillage on 5-year average yields of spring wheat yields in North Dakota (Spilde and Diebert, 1986) indicate only a 1.6 bushel per acre difference between the systems. The net return was 11 percent greater with the no-till system, because of lower energy costs. Mulch tillage has been used for many years in the small grain growing areas of the Great Plains.

Havlin, et al. (1990), reviewed the effects of crop rotation and compared tillage systems on soil organic carbon and nitrogen. They found that no-till significantly increased both components over conventional tillage for sorghum grown continuously on silt loam and silty clay loam soils. For continuous soybeans on one soil there was no difference between the tillage systems, while on the other, the surface inch showed higher levels of both components under no-till. Alternating soybeans and sorghum produced soil organic carbon and nitrogen levels that were intermediate between continuous sorghum or soybeans. They found that each crop of soybeans actually depleted soil N by 22 lb/a/year. These researchers reported that in Ohio for a corn-soybean rotation after 19 years organic carbon and nitrogen in the top 3-inches of soil were 1.5 and 1.3 times greater under no-till than conventional tillage. Decreasing tillage magnified the rotation effect.

Drainage

Tile and surface drainage in many areas have greatly improved the productivity of soils in the Midwest. Without drainage planting would be delayed in some years due to excess water so that the productivity of many soils could not be effectively used. Delayed planting may increase grain drying costs due to delayed crop maturity and lack of adequate time for normal dry-down.

We turn now to a brief discussion of soil compaction and irrigation, and their relationship to farm-level management. As machinery and equipment have become larger and heavier, increased loads are placed on soils, increasing the possibility of compaction (Swan, et al., 1987). This is particularly true if soils are tilled or passed over with heavy loads during combining or harvesting when they are wet. Normal traffic under conditions of ridge-till or no-till can also lead to compaction where planting is in the same rows or patterns year after year. Decreases in corn yield due to soil compaction may be 40 bu/a or more. Research in Wisconsin has shown that lower aeration associated with increasing soil compaction decreases soil potassium availability to corn (Wolkowski and Bundy, 1986, personal communication). These effects can be partially overcome by increasing potassium soil test levels and/or using banded row potash fertilizers applied at planting. Other research has shown that increased compaction may actually enhance phosphorus uptake by crops.

When other crop production constraints are controlled, such as available plant nutrients, weed competition, soil and aerial insects, nematodes, and crop diseases, water becomes the most limiting factor in the

U.S. crop production system. The advantages of irrigation can be seen in state average yields for corn in states like Washington and California, which have relatively small acreages, but where most of the crop is irrigated and under high levels of management. The overriding effects of drought on crop yields in the U.S. in 1980, 1983 and 1988 also emphasize the importance of rainfall and water.

On sandy soils, such as those in certain areas of Minnesota, Wisconsin or Nebraska, little if any crop would be produced in some years without irrigation. However, irrigation can lead to substantial leaching of nitrogen and chemicals on sandy soils, making them particularly vulnerable to groundwater problems. This places a premium on water use-efficiency and management. When irrigation timing and rates are properly controlled, there should be little leaching of nitrate-N unless excess rainfall occurs, exceeding the water holding capacity of the soil. In areas of water shortage, low pressure sprinklers and drip-irrigation increase water use efficiency.

If the amount of nitrate-N in irrigation water is great enough, it can decrease the nitrogen fertilizer that farmers need to apply (Rehm, et al., 1989). In dry regions or on sandy soils, it is not unusual to apply 12 to 14 acre-inches of water in a season. For example, Lohry (1989) found that irrigation water provided 117 lb of N/a, decreasing the optimum rate of N needed for corn from fertilizer to 67 lb/a in his experiment (Schepers, et al., 1988). Evidence from Nebraska studies indicate that through extension education farmers will adjust their rates of nitrogen based on yield goals, residual soil nitrate-N and N concentrations in irrigation water (Schepers, et al., 1990).

In some situations in the future, it may be possible to store tileline water containing nitrates and other nutrients and use it subsequently through supplemental subsurface permanent tubing or fertigation during periods of moisture stress.

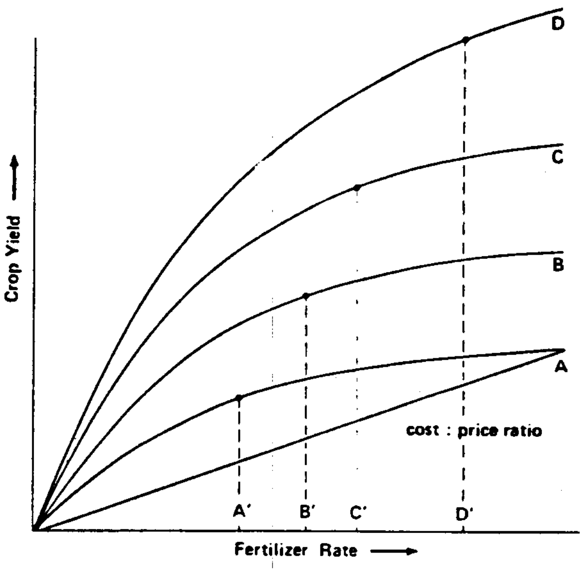
VI. AGRICULTURAL CHEMICALS AND THEIR INTERACTION WITH OTHER MANAGEMENT PRACTICES

As indicated above, new technologies combine and interact, changing both the yield levels and optimum requirements for other inputs (Figure 12). The environmental effects are a function of these integrated interactions, which may not be apparent if attention is restricted to only one technology or chemical examined in isolation.

Agricultural chemicals include those selected for plant growth regulating effects, herbicidal effects for weed control, soil fumigation or sterilization effects on soil microorganisms, insecticidal effects on insects or nematodes, or fungicidal effects on soil and aerial borne diseases of seeds, seedlings, crop roots, leaves and stems, or fruits.

Environmental sensitivity related to the use of these substances has stimulated a search for new and more benign products and technologies, in some cases aided by government policies, but often in spite of them (see Creason and Runge, 1990). Research into new and more environmentally safe agricultural chemicals or biocontrols has also become an increasing priority for both universities and industry. Improved communications about chemical risk, toxicology and safe use are available. The Minnesota Extension Service, for example, in cooperation with the Soil Conservation Service and the Agricultural Research Service, USDA, has recently developed an approach that gives ratings to different herbicides, insecticides or fungicides in terms of possible runoff, leaching and toxicological risks (Becker, et al., 1989). Each pesticide is identified by its common name, and the system relates to EPA's "Red Flags" or "alerts" based on the characteristics of the chemicals involved, such as water solubility, soil absorption and soil half-life. The toxicological advice for each substance

Figure 12. As new technologies are introduced to improve crop yields the most profitable rate of fertilizer or nutrient changes.



Source: Munson, 1982.

lists the acute oral, dermal and inhalation risk with a single word, such as "caution", "warning" or "danger". This approach has been suggested as a model that others states may well adopt (Finck, et al., 1990). It is part of a more complete, "Clean Water: You Can Make A Difference" handbook (Anderson and Breitbach, 1990).

As noted in the discussion of hybrid varieties in the first part of this report, different crop varieties or species have differing abilities to resist insects or diseases or to compete with different weeds in fields (Regnier and Janke, 1990). Some competitive varieties of soybeans have been reported to decrease the amount of herbicide required by half. Crops also vary in their tolerance or susceptibility of herbicides that are used to control weeds (Eastin, 1971). Also, the residue or green manure effects of crops, such as rye, may decrease the growth of certain weeds in crops planted after them.

Below, we consider current and future developments in the use of agricultural chemicals that may lead to environmental improvements in their use and effects. First consider the role of herbicides. Annual losses due to weeds in corn, soybeans, and wheat in the U.S. based on evaluations made in the late 1970s was $4.469 billion (Chandler, et al., 1984). In the Corn Belt, corn and soybean losses and wheat losses in the northern Great Plains due to weeds were placed at $2.25 billion annually, even with weed control, amounting to millions of bushels of grain. Decreasing weed competition with crops for space, light, nutrients and water, whether by timing planting, mechanical cultivation, herbicides, cultural practices, crop rotations, biocontrol or some combination of these methods, is and has been an important part of successful crop production. A selective herbicide that can take broadleaf weeds, such as mustard, out of a wheat or small grain crop is a remarkable technological achievement.

Thousands of organic compounds, natural and synthetic, were screened by agronomists, weed scientists and biochemists to find a few substances to selectively control weed species, and allow the crop to grow and develop normally. A great deal of study and research on plant metabolism, plant growth substances or hormones, and biochemistry preceded and has followed the development of herbicides. Herbicides have different modes of action, and physiologists and biochemists study different metabolic pathways to understand and design those that will be most effective for the target weeds. More attention than ever is now paid to lowering effective rates of active ingredient application and decreasing the length of time the chemical or its metabolites remain active after being applied. Results however indicate that herbicide-resistant weeds are produced after relatively short-term use of certain low rate, narrow mode of action, high residual chemicals, such as Glean for weed control in wheat (Durgan, 1989). On the other hand, Wisconsin researchers have found that Roundup effectively controls quackgrass applied at half the label rate (Anon, 1990).

Weed science and weed control involves using specific chemicals or combinations of chemicals, rotating their use, as well as rates of application, time of application, and conditions at the time of application, for different crops and weeds. Even the surfactant or wetting agent used to increase leaf absorption or the amount of soil organic matter or the pH of the spray water can change the results obtained (Dill, 1990). Weed control is a sophisticated science. Researchers, both public and private, are trying to develop herbicides that are effective, but more environmentally safe, benign or neutral in terms of hazard to surface or groundwater and public health.

Mechanical controls combined with herbicides are also being restudied. Gonsolus (1990) reported on the benefits of weed control from some early research in Iowa conducted by Lovely and his colleagues on soybeans and corn (Tables 21 and 22). This research showed that weed control is critical to maintaining competitive yields. In weed control-corn experiments in Minnesota results indicate only a few bushels of grain are harvested when weed control practices and/or herbicides are not used (Weed Research Project, 1989). However, postemergence herbicides are often accompanied by rotary hoe and cultivation. Herbicides alone may not be as effective as a hand weeded, weedfree treatment, except in plots where weed pressures are very low. Cultivation not only controls weeds, but may break up crusted soils, increasing soil aeration, the release of organic nutrients and crop yield.

Table 21. Effect of weed control by timeliness of rotary hoeing and cultivation on soybean yields and losses.

Treatment		Soybean yield-bu/a	Yield loss	
			bu/a	%
Weedfree		42	-	-
Weedy check		24	18	42.8
Rotary hoe	Cultivation			
none	2 times	34	8	19.0
2 untimely	2 times	39	3	7.1
3 timely	2 times	41	1	2.4

Source: Gonsolus, 1990.

Table 22. Effect of combinations of weed control by rotary hoeing, cultivation and herbicide on corn yield. Waseca, MN.

Rotary hoe	Cultivation	Herbicide	Corn yield bu/a	Increase bu/a	Added yield bu/a
none	none	none	40	-	
twice	none	none	91	51	51
none	once	none	104	64	13
none	twice	none	105	65	1
twice	once	none	139	99	34
twice	twice	none	149	109	10
twice	twice	applied	168	128	19

Source: Gonsolus, 1990.

Herbicide use on crops thus interacts with other management practices. Schmitt, et al., (1989) conducted studies on soybeans using different combinations of weed control including hand weeding, cultivation, rotary hoeing, and pre- and post-emergent herbicides in two row widths. A portion of the results is shown in Table 23. From these data one can get a sense of the value of weed control and of the interaction of the different methods with row width.

Table 23. Effects of combinations of weed control methods, hand weeding, cultivation, rotary hoeing, and a preemerge herbicide, on soybean yields grown in 30- and 10-inch row widths.

	Soybean yield-bu/a	
Weedy check	30-inch rows	10-inch rows
Unculivated	12.8	---
Rotary hoed[1]		
0	20.2	10.5[2]
1	37.4	18.2
2	35.4	15.9
Herbicide		
Trifluralin (0.75 lb/a)		
Rotary hoed		
0	42.7	44.2
1	49.1	42.1
2	51.7	45.4
Weed free[3]	52.8	60.5

---

[1] Weedy checks under rotary hoe in 30-inch rows were cultivated 4 times.

[2] The 10-inch rows could not be cultivated.

[3] Original data in publication corrected by Gonsolus (personal communication, 1990).

Source: Schmitt, et al., 1989.

Weed control guides available from the state Extension Services of universities and industry help farmers and dealers identify weeds by type and name and herbicides and rates to apply for their effect control. Minnesota (Gonsolus, et al., 1990), for example, lists the following considerations in selecting a herbicide:

1. Label approval for use
2. Ground and surface water pollution concerns
3. Use of the crop
4. Crop and variety tolerance
5. Potential for herbicide carryover that may affect following crops
6. Kinds of weeds
7. Soil texture, organic matter content, and pH
8. Formulation of the chemical
9. Application equipment available
10. Potential for drift problems
11. Tillage practices
12. Herbicide performance
13. Herbicide cost

Two herbicides that have been widely used over a considerable time are atrazine (over 30 years) and alachlor or Lasso (over 25 years). Both are very effective. There has been considerable concern about herbicides being detected in ground and/or well water. Atrazine has a soil absorption index of 100, a water solubility of 33 ppm and a soil half-life of 60 days and a medium rating for runoff, but a "large" rating for leaching through the soil (Becker, et al., 1990). Alachlor has a soil absorption index of 170, a water solubility of 240 ppm and a soil half-life of 15 days, with a medium rating for both runoff and leaching. In a recent nationwide well water survey of a statistical sample representing 6 million wells, atrazine was detected in 12 percent of the wells, with most of those below 0.5 ppb (Technical Bulletin, 1990). Only 0.09 percent of the wells were found to have atrazine levels at or above the maximum contamination or health advisory level proposed by the EPA. For alachlor 0.78 percent of the wells had detectable levels, with 0.02 percent at or above the proposed EPA maximum level of contamination.

These results are similar to those being found in well studies in other states as reported in the Iowa Integrated Farm Management Notes (1990). Iowa reported that 0.7 percent of the wells exceeded EPA's health advisory level of 3 ppb of atrazine. In Wisconsin and Ohio studies 0.5 percent of the wells were at the health advisory level for atrazine. In Nebraska, less than 0.2 percent of the wells contained more than the health advisory level of 0.4 ppb for alachlor. Other studies have indicated that those that became contaminated were usually shallow and/or improperly cased or were associated with point source contamination from mixing or loading sites (Fawcett, 1989). Bouwer (1990) has objectively reviewed the overall subject of chemical use and goundwater quality calling for rational solutions and cooperation where everyone works together to assess real risks and develop policies and practices that strike a balance between public health, the environment, and economics.

As concern over herbicides and pesticides has grown, biological controls have been developed that promise to reduce weeds, insects and other pests at lower risk to the environment. Of the newer biocontrols, the release of diseases or insects that attack weeds and/or reduce weed seed production is promising. A main concern is that the insect or fungus does not infect or cause economic losses to important domestic crops. Bioherbicides or mycoherbicides have also been developed. They are applied and used like traditional herbicides. They are currently being tested and are reported to be effective on some weeds (H. Abbas, 1990, personal communication). Thus far, they appear to cause no environmental contamination or human toxicity, and are reported to be highly selective. High selectivity can be a disadvantage, however, because a different substance is needed for each weed. Similarly, bacteria can be cultured that produce specific substances that have herbicidal properties. The substance can be used directly, modified, or used as a chemical model for synthesizing the herbicide.

Another development is the controlled release of herbicides. The USDA has studies of such methods underway in seven states. These products are encapsulated or infused into polymer granules so as to slowly release the herbicide, thereby decreasing the possibility of runoff, leaching, or volatility. They also may make it possible to decrease the rates of application, while extending the period of effective weed control (M. M. Schreiber, 1990, personal communication). Since these technologies are relatively new, their effectiveness and environmental benefits are still being determined.

In states such as Iowa, in 1990 lower rates of atrazine are being recommended for environmental sensitive areas, such as sandy, coarse-textured soils or silt loam soils in areas with sink-holes or karst topography. Effort is being made to make chemical applications safer for farmers and applicators. The chemical and farm equipment manufacturers have produced herbicide and insecticide containers that can be mounted on planters to minimize exposure to the substance. The containers can be returned for refill. Water soluble packets of chemicals and soluble Agtabs that are premeasured and can be directly added to water are available. Equipment companies have developed row-applicator hoods that run over rows to better target weeds and decrease drifts during application. Band application of herbicides effectively decreases the total amount used, often cutting it by half. Also, greater efforts are being made to study and model agricultural chemicals to understand their long-term movement through soils (Asmussen, et al., 1989; Leonard, et al., 1989).

On another front, computerized systems have been developed (such as WEEDIR in Minnesota) to aid in matching weed problems with appropriate herbicides. Such systems can be linked to SSIS (Soil Survey Information) as well as computerized insect control programs to more effectively target them, reducing total use (Robert, 1989).

We turn now to insecticides. As in the case of herbicides, insecticide use can be reduced simply through the choice of improved crop varieties or hybrids tolerant or resistant to attacking insects. Ridgeway, et al. (1979), reported that insect resistant cultivars for major crops save farmers over $300 million annually. Breeding for crop resistance to the Hessian fly and wheat stem sawfly for wheat and European corn borer for corn have been particularly effective. New corn hybrids are being developed that have resistance to both first and second brood corn borers. As discussed above, shifting dates of planting to escape infestations of insects is important, as are crop rotations to break insect cycles. Early planted corn, for example, is less susceptible to both corn borers and corn ear worms. Rotating corn and soybeans or corn and alfalfa help to interrupt corn rootworm in the Corn Belt. Shredding or chopping corn stalk residues left in the field following corn harvest to destroy corn and/or stalk borers or clean tillage are practices that decrease infestations. Care in cleaning tillage and harvest machinery and buying seed free of soil that might contain cysts of soybean cyst nematode are all part of preventive management.

When an insect or mite infestation does occur, tolerant or resistant crop varieties and crop scouting both need to be checked against threshold levels of the insects before an insecticide or miticide is recommended. The insecticide that is the most effective, with the least environmental side-effects, should then be used. New snythetic pyrethroid insecticides are now available and appear to be quite effective (Ostlie, 1989).

In some years, such as 1988, higher than normal temperatures caused special insect problems. For example, the higher temperatures in 1988 caused an increased infestation of spider mites in soybeans (Ostlie, 1988). During 1988 and 1989, because of the drought, a grasshopper infestation became serious in western Minnesota and the eastern Dakotas. Use of biological control using the protozoan organism, Nosema locustae, does not appear to be effective in controlling such large infestations of grasshoppers (Walgenbach, 1988). The seriousness of the infestation for 1990, even with increased rainfall and cooler spring temperatures, is still unknown. Indications are that numbers are decreased, but in some areas insecticide application may be the only method of crop protection.

Smith (1986) has evaluated the benefits of combining corn borer control with irrigation using Furadan as the insecticide in a high production system. The results are shown in Table 24. One can observe the synergistic benefits of combining irrigation and corn borer control, which produced nearly a 122 bu/a yield increase.

Table 24. Effects of Furadan for corn borer control and irrigation on corn yields.

Corn borer control	Corn yield-bu/a				
	Without irrigation	Borers tunnels/plant	With irrigation	Borers tunnels/plant	Adv.
None	119.6	8.1	157.5	6.0	37.9
Furadan	179.0	1.2	241.5	1.0	62.5
Advantage	59.4		84		

Source: Smith (1986).

Where corn rootworms are a problem, use of effective insecticides can interact to increase nitrogen use-efficiency and lower the N-rate needed to reach the most profitable yield level (Randall, et al., 1988). See Table 25. Note that the combined effect increased the yield over 107 bu/a, with the 100 lb N-rate. Corn rootworm beetles feed on the silks of corn affecting pollination, and the larvae feed on corn roots affecting nutrient and water uptake, root and stalk rot diseases and lodging of the crop, especially under continuous corn culture. Beetle counts help determine the need for treatment of the current crop. Rotating corn with soybeans in most cases provides effective rootworm control. But, if the beetle count is five beetles/plant, treatment is needed (Ostlie, 1989). Results from Illinois indicate that some hybrids following soybeans show significant yield incrases to counter or Lorsban 15G insecticides (Pedersen, 1989). Only about 40 percent of continuous corn actually needs treatment when crop scouting is carefully done.

There are other problem organisms or insects on corn such as nematodes, cut worms, wireworms and white grubs that periodically need control.

Table 25. Effects of corn rootworm control and N rates on corn yields.

	Corn Yield-bu/a Rootworm control		
N rate[1] lb/a	Without Counter	With Counter	Advantage
0	78.8	137.8	59.0
50	94.9	170.5	75.6
100	102.6	186.0*	83.4
150	114.5*	184.3	69.8
200	107.6	189.5	81.9
Advantage	35.7	51.7	

[1] Anhydrous ammonia applied spring preplant.

Source: Randall, et al., 1988.

We now briefly consider fungicides used as seed, soil and foliar treatments to control or prevent the development of fungi infections of seeds, seedlings, roots, and plant leaves (Kommedahl and Windels, 1979; 1986). When these organisms are controlled, crops can more effectively use and recover water and plant nutrients in soils. Plant diseases of crops relate directly to crop management practices.

Stienstra, et al. (1988), used three sites to study the effect of soybean varieties and a soil fungicide treatment on soybean yields (see Table 26). From these data from two sites it is apparent that on soils where _Phytophthora_ organisms are present, varietal selection is important. Diagnostic field kits are now available that test for the pathogen in soil (Davis, 1990). There are about 20 races of _Phytophthora_ pathogens that infect soybeans. Where the disease does occur, varietal selection and/or fungicide use are major decisions. Rotation, tillage, soybean variety, and even N-rate all can be important in soybean diseases such as brown stem rot (Oplinger, 1990, personal communication).

Table 26. Effect of a furrow treatment of Ridomil fungicide to control _Phytophthora_ root rot and soybean varieties on soybean yield.

	Soybean yield-bu/a		
	No treatment	Plus Ridomil	
Variety	Ruhter location		Advantage
54-254	12.3	27.5	15.2
Corsoy 79	34.8	39.6	4.8
BSR-101	35.8	43.0	7.2
Varietal diff.	23.5	15.5	
	Meyer location		Advantage
54-254	15.7	42.0	26.3
BSR-101	51.4	52.4	1.0
Varietal diff.	35.7	10.4	

Source: Stienstra, et al., 1988.

VII. IMPROVEMENTS FOR THE FUTURE

In this final section, we identify a number of improvements that need to be undertaken in reducing the environmental impacts of fertilizer and chemical use. While not exhaustive, the recommendations here are intended to illustrate an appropriate agenda in which research and policy are targeted to improving environmental quality, while maintaining agricultural competitiveness. These will require more intensive management and precision.

The first and most important aspect of this agenda relates to higher precision farming in relation to different soil types. "Farming by soils" requires the integration of soil survey information systems and research data bases for site-specific soil testing and applications of fertilizers and chemicals.

Soils and major land resource areas vary widely in their inherent productivity and their response to natural change, chemical treatment and technology (Pierce, et al., 1983; 1984; Larson, et al, 1983). However, digitized soil survey information systems (SSIS), such as developed and applied by Robert (1988) in Minnesota, combined with research data bases as applied by Larson and Robert (1989) can and are being used to develop specific information and recommendations for soils and soil types within fields. Such information helps identify sensitive soils for nutrient leaching or erosion and runoff potential, which can and should be used in targeting land for programs such as the Conservation Reserve Program (Runge, et al., 1986; Roloff, et al., 1988).

These SSIS data bases can also be used more generally in land use decisions. Soil sampling with equipment that provides geopositioning information related to satellites helps identify the "exact" location of the sample. The results of such samples can be used to make more site-specific recommendations using computers.

For example, new fertilizer and chemical application equipment, such as the Soilection System (available from companies such as Soil Teq Inc., LorAl and others) use on-board computers with programmed chips containing test results that enable the applicator to travel across the field, changing rates and combinations of applied nutrients and/or herbicides. This site-specific approach has been referred to as "farming by soils" (Fairchild, 1988; Jacobsen, et al., 1988; Buchholz and Wollenhaupt, 1989) and "farming by the foot" by the Farm Journal. High precision farming can improve efficiency, environmental protection, and profits, simultaneously.

In a related development, future soil tests for nitrogen may also be made "on the move" using electrochemical techniques, with on-board computers modifying the rates of application continuously. If these techniques can be combined with newer spoke-injection placement, and improved timing, further improvements in nutrient efficiency can be expected. Including soil organic matter test information, perhaps along with soil texture, should further improve the accuracy of rates of application for herbicides. Also, the geomarking of fields during the year to indicate the kind and degree of weed infestation along with scouting, will improve herbicide efficiency, especially with postemergence applications. Harvest combines are also being developed that will measure and record crop yields "on the move", which in turn can be related to SSIS and previous variable treatments. This information can be combined with soil test and SSIS to determine maintenance nutrient rates. These techniques will increasingly become part of the technology of precision farming, increasing input efficiency and helping to protect the environment.

A second major area of promise involves developments in fertilizers. One of the most interesting is a new, gel-type fertilizer. Research is underway at the National Fertilizer and Environmental Research Center at the Tennessee Valley Authority to evaluate the use of these nutrient formulations, which are less subject to loss and thus pose fewer problems of runoff and leaching (Mikkelsen, 1990). Nutrient efficiency will also be increased.

Another area of possible interest is foliar fertilization, which has been explored since the mid-1950s, touched off by some unduplicatable results on soybeans (Garcia and Hanway, 1976). However, responses up to 9 bu/a have been obtained from multiple nutrient and N applications during reproductive stages of growth of soybeans (Poole, et al., 1983; Gascho, 1990, personal communication). Foliar fertilization remains to be more thoroughly and systematically researched. For micronutrients a few ounces of foliarly applied nutrient can be more effective than several pounds applied to the soil. Konzak at Washington State University has developed a foliar fertilizer that may be used as a more efficient, effective source of phosphorus on acid soils (Konzak, personal communication, 1989).

Seed treatment and seed placed fertilizers are other technological possibilities. Early research on phosphorus has not been very positive. Special problems will need to be addressed in any seed treatment, especially with legumes. Possible adverse effects of the chemical source of nutrients on seed treated microorganisms necessary for nodulation and nitrogen fixation in crops, such as soybeans, will need special study. However, in some cases an ounce of an element seed applied, such as molybdenum, may replace several tons of limestone.

Cross-disciplinary research is also needed in order to relate plant breeding and biotechnology findings to current mineral nutrition work in soil science. Soil fertility studies need to be integrated with research on new varieties or hybrids to identify those that require and/or respond to different amounts or combinations of nutrients (such as the greater nutrient requirements of hybrid rice developed in China). By having such research information available, technology transfer is enhanced and farmers can take advantage of information as soon as the variety of hybrid is released (see Tsai, et al., 1985; and Kamprath, 1985).

In the future there will be more selection for crops that have greater root densities, to identify those that have the capacity to take up and recover a greater percentage of nutrients present or applied to soils. Also, plants will be selected on the basis of the ability of roots to interact with the rhizosphere and release and recover forms of nutrients that were previously unavailable (Ae, et al., 1990). Root inoculation with fungi may be developed that has the capacity to recover nutrients, such as phosphorus, for crops under intermediate soil test levels, rather than only at only low test levels.

In insect control the use of trap crops and phermones to disrupt insect reproduction cycles promise to become more important in biocontrol.

Biotechnology research is also a potentially high-payoff enterprise. However, government and regulatory responses have been uneven, sometimes preventing development and testing. Many feel that it is in the area of crop productivity where biotechnology will excel (Hardy, 1990). However, there may also be marked contributions to the quality aspects of production, as well as to crop protection (Giaquita, 1990). Schneiderman (1990) has indicated that, "Genetic engineering is the most important advance in agricultural science in this century." He further states that it can increase agricultural efficiency and the quality of the environment. However, the time frame for the benefits from biotechnology continues to be set forward. Little of what was anticipated for the '80s has occurred, and many of its benefits may not reach fruition for a decade or longer (Sundquist, 1989). Environmental concerns are still a major substantive issue regarding the release of new biotechnology products (Murdock, et al., 1990).

Our own view is somewhat cautious concerning the potential of this line of research. Sundquist (1989) has recently reviewed the emerging biotechnologies for corn. It is his belief that in the near term most of the gains that will be made in corn production will come from conventional technologies of plant breeding and improved management and cultural practices. We need to be reminded that it was variation of traditional plant breeding, not biotechnology, that enabled Yuan Longping to develop hybrid rice in Hunan province in China, which has increased the yield potential of rice by 30 percent, and promises to add an additional 20 percent to rice yields in the near-term (Tyson, 1990). New seed must be available each crop.

What are the specific areas of biotechnology research underway? The first is plant transformation. Once a gene is cloned it must be put back (transformed) into the genomic structure of the plant (Shoemaker, 1989).

Fischhoff (1988) indicated that these transformations are much more easily accomplished in dicots, such as soybeans, than in monocots, such as corn or wheat. However, indications are that such transformations have been accomplished in corn (Anon., 1990). Tissue culture and the use of direct selection or somaclonal variation have proven successful in selecting corn that is resistant to diseases such as southern corn leaf blight, as reported by Mock (1989).

Use of specialized legume seed inoculation with nitrogen fixing Rhizobium bacteria has been practiced around the world for years. Selection of more effective and genetically engineered strains of rhizobia is underway. These nitrogen-fixers have to be competitive with other microorganisms in soils, but indications are that once established, they can exist in the soil for years, along with literally billions of other soil microbes, many of which are detrimental to crop roots (Miller, 1990).

A second, and more controversial, effort is the development of herbicide-resistant crops. An example in which crops have been genetically engineered for herbicide tolerance involves the glyphosate herbicide, Roundup (Gasser, et al., 1988), which is a broad spectrum herbicide. The tolerance is related to the overproduction of a specific enzyme in the crop, which protects it from the herbicide action and permits normal development. Some have concerns that this will lead to increased use of herbicides that do not rapidly degrade. Tauer and Love (1989) have discussed the potential economic impact of herbicide-resistant corn. Also, there is concern that if the herbicide has a narrow or specific mode of action, weeds may develop resistance to it, as has already been the case with some low-rate herbicides. However, products that degrade rapidly will mean less carryover and decrease the likelihood of developing herbicide-resistant weeds.

Northup King researchers in Minnesota in 1989 tested a new, broad spectrum herbicide registered in Europe under the name of Basta (Mock, 1989). The active ingredient is glufosinate, which is produced by Streptomyces viridochromogenes. The organism produces the active ingredient and exudes it into the soil producing the herbicidal effect. The host crop species is protected because of the addition of an acetyl group to the glufosinate, which deactivates it. This has been successfully used with alfalfa. It remains to be seen if it will be useful in soybeans.

The use of genetically engineered herbicide tolerance or resistance may increase the use of certain herbicides, but overall it can contribute to a reduction in the total herbicide use. However, the effort seems to be developing for herbicides that are applied at very low rates and are environmentally benign and less toxic to wildlife.

A third area of biotechnology research is virus resistance. The possibility of protecting crops from viruses using transgenic viral coat proteins through insertion of "genetic cassettes" appears to protect crops from viral infection (Fischhoff, 1988). Indications are that transgenic plants are essentially free from viral infection. One might almost refer to this approach to plant protection as an "immunization" or "vaccination" technique. This approach may be used for fungal and bacterial plant diseases once it has been more fully explored.

A fourth area of biotechnology involves insect tolerance which can be genetically engineered through the use of genes from soil microbes that produce a crystalline protein that is pathogenic to larvae of specific target insects, such as the European corn borer (Fischhoff, 1988). In time, this technique may be used for insect control for a number of crops, which will carry their own "insecticide". In some cases the crop does not release the controlling substance until insect feeding occurs (Thornburg, 1990). Indications are that some of these organisms have been tested and approved and are environmentally safe, with the potential to replace insecticides that are not as environmentally neutral. Andrews (1990) has indicated that patents have been obtained for insecticides derived from bacteria that are "safe for humans".

It is important that government policies be favorable, not only to encourage biotechnology research, but encourage proper field testing of the products developed in well-regulated experiments to determine how they will work in crop production systems (Capalbo, 1990).

VIII. SUMMARY AND CONCLUSIONS

This report has surveyed a variety of technologies that promise to improve both fertilizer and chemical efficiency and environmental quality through "high precision farming." While it is not intended as a complete catalogue of such methods, we believe that it illustrates the potential for making economic, agronomic and environmental goals compatible. As noted in a previous report in this series (Creason and Runge, 1990), the policies currently in place could be much more supportive of adopting this technology than is the case.

High precision farming requires both more intensive management and information access. Crop accounting to determine weed, insect, and disease economic thresholds and targeting chemical treatments, narrows the "windows" of effectiveness for control and, in fact, may increase risk. Timeliness is extremely important in many operations. Rates of nutrients and/or chemicals are applied at variable rates, depending upon test results, soil characteristics or weed, insect or disease infestations, which require precision equipment for application. Using tests to monitor soil and plant nutrients, as well as nematodes or pathogens, such as the soybean cyst nematode or phytophthora root rots, will increase. Crop scouting and use of consultants will be an important part of integrated crop and farm management. Farming will be even more science-based.

There is reason for optimism that technological innovations in agriculture, combined with institutional changes, can usher in a new era of production which protects farm level efficiencies, while attending to important environmental goals. We believe that both are of paramount importance, and both are achievable, if technological progress and policy reforms in agriculture continue.

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