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In addition to this bulletin, two others in the series have been published: "Nitrates, Nitrites, and Health," Bulletin 750, and "Environmental Decision Making: The Role of Community Leaders," Bulletin 756. Other bulletins in preparation for the series deal with nitrogen in wells and farm ponds, and management of nitrogen for crop production. A book on nitrogen in relation to food, environment, and energy is also being prepared as a part of the series.

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CONTENTS

In recent years the role of agricultural chemicals as water contaminants has become a matter of increasing concern among people who are interested in the quality of the environment. Before controls are undertaken, however, the problem of reducing contamination should be examined from various perspectives. This bulletin looks at the economic effects that six alternative methods might have in the agro-environmental complex if attempts are made to control the use of commercial nitrogen fertilizer. Although much of the work concerns Illinois, many of the results of these analyses can be applied elsewhere as well.

During the 1950's and 1960's the nitrate content of ground and surface water increased substantially, especially in the Midwest. This increase was apparently related to the expanded use of commercial fertilizers and more intensive farming. Increased quantities of both phosphorus and nitrogen in nonflowing water can stimulate algal growth, which eventually adds to the decaying organic matter and may reduce oxygen to critical levels for aquatic life.

Human and animal health can also be endangered by excess concentrations of nitrates, which are a form of nitrogen. Under certain conditions bacteria in the intestinal tract of both humans and animals reduce nitrates to nitrites. When absorbed into the bloodstream, nitrites change hemoglobin into methemoglobin, which cannot carry oxygen to body tissue. Oxygen levels are lowered, and when more than 70 percent of the hemoglobin is changed into methemoglobin, death may result. Infants under six months of age, especially those with digestive disorders, are particularly vulnerable. In addition, according to Lijinski (1971), some of the nitrosamines formed by the reaction between nitrites and certain organic compounds produce cancer in laboratory animals.

Researchers are still uncertain about the possible link between human health hazards and the use of commercial nitrogen fertilizers and other sources that raise the nitrate content of water. In some areas of the United States the nitrate concentration in water, expressed as nitrate-nitrogen, chronically exceeds the standard of 10 parts per million, in some cases up to ten times this level, yet no serious health problems have been linked to nitrates in these areas. Even so, the possibility that hazards may develop warrants an investigation of the economic effects of various control measures.

Commercial nitrogen fertilizers are only one source of nitrates. Nitrates are also derived from mineralizing soil organic matter, precipitation, fixation of atmospheric nitrogen by soil organisms, animal and human metabolic wastes, and organic wastes from industries that process food, paper, and pulp. It should be emphasized that the nitrate ions from these other sources are as subject to leaching as the ions from commercial nitrogen fertilizer. The amount of nitrate moving into water would probably be the same if the same amount of nitrogen were supplied from sources other than nitrogen fertilizer. However, because nitrogen fertilizer adds a significant quantity of nitrates to water, it is prudent to examine the consequences of policy alternatives that might control this source but still meet food production needs (Aldrich, 1972).

NITRATE CONTROLS AND WATER QUALITY

In addition to entering into biological changes in the soil, nitrate can go to ground or surface water or to the atmosphere by volatilization following denitrification. This report deals with leaching into waters and the grain farmer's contribution to the potential nitrate problem.

In recent years there has been a spectacular increase in the quantity of commercial nitrogen fertilizer used. In 1940 a little over 400,000 short tons (363,000 metric tons) of nitrogen in commercial fertilizer was used in the United States. Between 1965 and 1977 the application of nitrogen more than doubled in this country, and now stands at about 10 million tons (9.1 million metric tons). In 1977 Illinois alone applied 978,000 tons (887,000 metric tons). About 40 percent of all nitrogen fertilizer is used for corn production. According to recent indications, the rates of application on the most heavily fertilized cornfields in the Midwest have nearly reached a plateau.

The effect of commercial nitrogen fertilizer on corn yield has received attention for some time, and as a consequence, reasonably good estimates of this relationship under a range of conditions are available (Swanson *et al.,* 1973). In contrast, our knowledge concerning the amount of applied nitrogen that is recovered by the crop and the amount escaping into water is not at all clear. As one investigator explains: "Only rarely have . . . tests shown nitrogen recoveries in the crop plus soil greater than about 95 per cent of the applied nitrogen; values of only 70 to 90 per cent are fairly common, and a few are as low as 60 per cent. . . . Such results, obtained under ideal conditions where no leaching occurred, help to explain why nitrogen recoveries in the crop under average field conditions often are no greater than 50 to 60 per cent of that applied" (Allison, 1966).

Taylor (1973) attempted to statistically estimate the relationships between nitrate content of some Illinois streams and agricultural activities, including fertilizer use, in watersheds draining into these streams. The results of the study were inconclusive, in part because the study was based on available water quality and fertilizer use data that had not been collected specifically for estimation of these relationships. In addition, biological theory has not yet developed to the point that it can provide much guidance regarding the variables that should be included in the estimated relationships.

It is possible that actions will be proposed to reduce agriculture's contribution to the overall nitrate problem even though this contribution is not well defined. The Illinois Pollution Control Board did, in fact, conduct hearings in 1971 on regulations that would have controlled nitrogen fertilizer applications. The Board decided that there was an insufficient basis for establishing regulations (Illinois Pollution Control Board, 1972). Various ways of controlling nitrate pollution are currently being considered in the implementation of Section 208 of the Federal Water Pollution Control Act. Different methods of control would of course produce different effects; this report presents the economic effects that selected nitrogen-related policies would have on the amount and location of crop production and farm income.

Alternative Methods of Control

The six public policy alternatives to be considered are: (1) education, (2) per-acre restrictions on commercial nitrogen fertilizer rates, (3) an excise tax, (4) a market for rights, (5) restrictions on nitrate concentrations in leachate in a watershed, and (6) restrictions on the nitrogen balance at the farm level. Although the main task of this report is to present economic evidence, these proposed alternatives may also provide additional background information for decision makers, who must attempt to weigh the trade-offs between the economic effects and other relevant consequences, the most important of which relate to environment and health. The various control methods are obviously not mutually exclusive; a combination of two or more could be adopted. Because this report considers only the economic consequences to farmers, a socially optimal policy must be determined within a more comprehensive framework that includes environmental, health, and tax effects, as well as some of the ways consumers might be affected (Gros and Swanson, 1976).

Principal Analytic Tool

In the sections on per-acre restrictions, excise tax, and restrictions on the nitrate balance at the farm level, the analyses presented are based on a common logic, that of linear programming. This method uses an optimization technique that permits many variables to be considered simultaneously. Described technically, the procedure maximizes or minimizes a linear criterion function, subject to a set of linear equalities or inequalities. In economic applications the criterion function is usually net returns (income) in a maximization problem or costs in a minimization problem. Various constraints, such as the amount and location of land resources of differing quality, are taken into account. Applied to individual farms, the method permits a more detailed analysis of the interrelationships among enterprises and consideration of a wider range of technical alternatives than is possible with conventional, less formal methods. At the regional or national level, the method allows an analysis of the influence that markets and regional variations in soil productivity and climate have on the location of agricultural production.

The analytic capability of linear programming is especially important for estimating the effects of nitrogen-related control measures. Restrictions on nitrogen fertilizer will, for example, have "ripple" effects throughout the agricultural economy by altering the competitive advantage of crops that depend in varying degrees on nitrogen fertilizer. As a result of changes in competitive positions among crops, land use patterns change. The crops disadvantaged by nitrogen controls are replaced to some extent by those crops not directly affected by the controls. To illustrate the point, in one of the models used, the total digestible nutrient requirement for livestock could be met by substituting one feed for another. The possibility of substituting different kinds of grain in a producing region to meet feed and food requirements tends to moderate the economic impact of public policy intervention.

Types of Linear Programming Models

Five mathematical programming models were used to analyze the effects of nitrogen fertilizer control measures. These models differ primarily in the unit of analysis, namely, the nation, the Corn Belt, Illinois, a watershed, and a farm. Assumptions about the demand for crop production are related to the unit analyzed. These demand assumptions influence the price and production effects of programs that control the use of nitrogen fertilizer. As the price and production effects vary, the

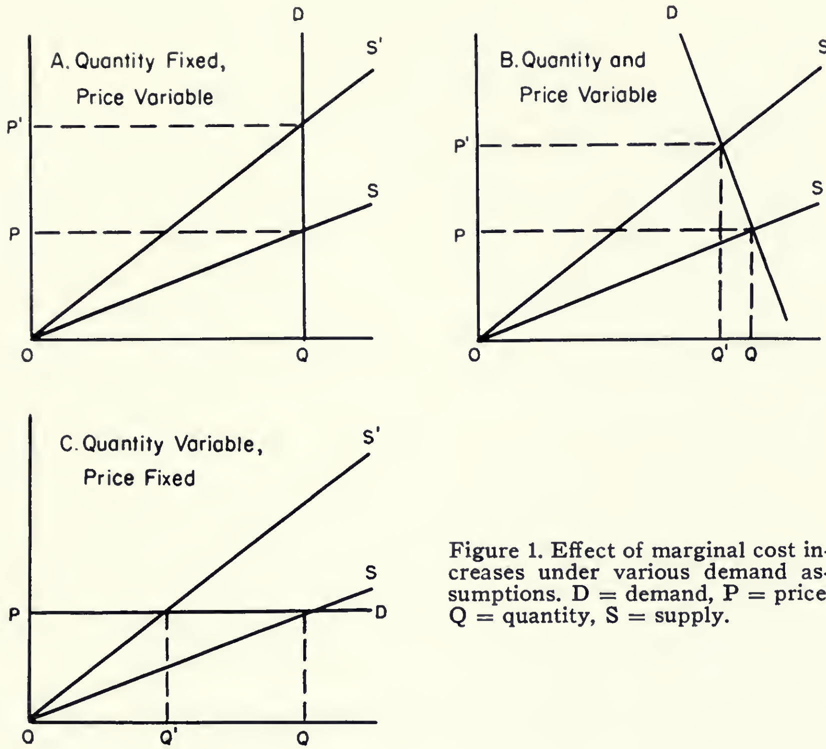


Figure 1. Effect of marginal cost increases under various demand assumptions. D = demand, P = price, Q = quantity, S = supply.

consequences of nitrogen controls on total revenues (gross income) will also vary. Figure 1 illustrates the difference in the demand concept among models, and provides a framework for classifying the five models used.

In each of the three types of demand assumption patterns in Figure 1, a control on the use of nitrogen fertilizer increases the marginal cost of crop production. Marginal cost, that is, the increase in total production cost occurring when output is increased by one unit, is based on variable cost. In all three types of demand patterns, supply (marginal cost function) increases in a similar way from S to S′ when a control is imposed. The effect on price and quantity, however, varies because the demand assumptions are different.

In Figure 1A the demand is a fixed quantity, or perfectly inelastic with respect to price. Thus the full effect of a marginal cost increase is reflected in price. Before the control is imposed, the total revenue (quantity times price) is OQ × OP; after the supply curve rises to S′, total revenue increases to OQ × OP′. The national model discussed in later sections of this report uses this type of demand assumption. The national model is of course much more complex than Figure 1A indicates because this model includes many crops and regions, each with its individual crop supply and demand functions, and with all of the regions linked in a transportation network. Nevertheless, the figure represents the concept of a fixed demand, which is central to interpreting the results of the analysis.

The Corn Belt model also has a number of crops and regions, but the demand assumptions for two major crops, corn and soybeans, are those illustrated in Figure 1B. In this pattern, consumption is reduced as increased marginal costs are reflected in increased prices. For crops other than corn and soybeans the inelastic demand of Figure 1A is used. Note that an increase in the marginal cost from S to S′ may cause total revenue either to increase or decrease, depending on the slope of the demand curve. In Figure 1B the total revenue increases after nitrogen fertilizer controls are imposed, from OQ × OP to OQ′ × OP′. The demand assumption presented in Figure 1B is preferred for analysis of controls having economic effects at the regional and national levels, but often the increased complexity of implementing this concept leads to the use of the concepts in Figures 1A and 1C.

The state, farm, and watershed models have crop demands that are perfectly elastic (Figure 1C). Thus, as marginal costs increase from S to S′, there is no increase in price, and total revenue decreases from OQ × OP to OQ′ × OP. In the national model some of the results pertain to a situation in which nitrogen controls are imposed only in Illinois. In this case, either Figure 1C with a perfectly elastic demand or Figure 1B with a somewhat elastic demand would characterize the demand assumption for Illinois, even though the national model otherwise follows the pattern in Figure 1A.

The different demand concepts underlying the models used should be kept in mind as the economic effects of the various nitrogen control alternatives are presented in later sections of this report. There are also other differences in model formulation, but they are not as important as those discussed above. The following sources contain detailed descriptions of the five models: national, Taylor and Swanson (1975); Corn Belt, Taylor and Frohberg (1977); state, Palmini (1975); watershed, Onishi (1973), Onishi *et al.* (1974), Onishi and Swanson (1974); and farm, Walker (1974), Walker and Swanson (1974).

EDUCATION AS A MEANS OF VOLUNTARY RESTRICTION OF NITROGEN FERTILIZER

If farmers are applying more nitrogen fertilizer than necessary to meet their economic goals, then an educational program could be an effective way to convince them to voluntarily reduce the amount applied. Farmers would save money in the long run and water quality would improve. But are most farmers actually applying too much fertilizer? To answer this question, we did three separate analyses to determine optimal levels of nitrogen fertilizer for corn in Illinois. Two of these studies used experimental data; the third examined the experiences of farmers themselves.

Experimental Data

Using experimental data from eight locations in Illinois, Swanson *et al.* (1973) statistically estimated the effects of various amounts of nitrogen on corn yields (response function). In some instances the timing of application was included in the estimates. These response functions were then used to calculate how the corn-nitrogen price ratio would affect the economically optimal rate of application for each year.

In this study we started with the assumption that it was known with certainty what the corn yields would be in relation to the amount of nitrogen applied. The optimal level in our analysis ranged from 100 pounds per acre (112 kg./ha.) at Brownstown to 290 pounds per acre (325 kg./ha.) at DeKalb.

We then dropped the assumption of a known response function, and used three game-theoretic decision models to estimate the best rates of nitrogen application. The models and their criteria were: choose the fertilizer rate giving the highest simple average over time (La Place); maximize the minimum return (Wald); and minimize the maximum regret (Savage). These three models use the concept of a game against nature in which the farmer chooses the nitrogen fertilizer level that corresponds to his expectation of the kind of natural phenomena, such as weather, that will characterize the coming season. The La Place criterion assumes that the average season will occur, and the Wald criterion assumes the worst possible season. The Savage criterion, or minimizing the maximum regret, assumes that the farmer will choose that amount of fertilizer which, in retrospect, will result in the smallest loss or regret. The loss is determined by subtracting the realized net return from what the return would have been had foresight been perfect. Given the assumption of each of the three decision models, the optimal amounts of nitrogen fertilizer to be applied ranged from 100 to 240 pounds per acre (112 to 269 kg./ha.). In general, these amounts exceed the levels actually applied by farmers; hence, we have little evidence here that educational programs based on these experiments would reduce the levels of nitrogen.

Frohberg and Taylor (1975) incorporated uncertainty into a decision model in another way: they used regression equations to estimate the influence of risk due to weather variations on the response of corn to nitrogen. Rainfall and temperature data from seven experimental fields in Illinois for the period May 20 through August 23 for the seven years 1967 through 1973 were used to estimate the effect of weather plus nitrogen on corn yields. These data, which were essentially the same as those used in the Swanson *et al.* study (1973), were divided into two sets, depending on the crop rotation pattern used for each field. Hartsburg, Aledo, Kewanee, and Toledo had corn followed by soybeans, while Carthage, DeKalb, and Brownstown had corn followed by corn. The response to applied nitrogen is different in the two rotation patterns because soybeans, through a biological process known as nitrogen fixation, convert nitrogen in the air into a form that the following corn crop can use. Hence, two regression equations were used, one for each rotation pattern.

With these two equations we then determined the optimal rates for nitrogen fertilizer application. It was assumed for this analysis that the decision criterion was to maximize expected or average profits subject to the risk of not recovering the cost of the fertilizer. Two levels of risk were considered: a loss in one year out of one hundred, and a loss in one year out of twenty. The results show that, on the basis of recent price relationships, the weather-related risk constraint is not effective. In other words, farmers who are sensitive to this kind of risk should apply nitrogen fertilizer at the rate that maximizes expected profits. In all seven areas the optimal rates were more than 150 pounds per acre (168 kg./ha.).

Comparison of Experimental and Actual Data

In advising individual farmers on optimal rates of nitrogen application and in analyzing alternative control methods, it is important to consider how closely the experimental conditions correspond to the actual experiences of commercial farmers. Taylor and Swanson (1973) approached the issue in two ways, first, by comparing experimental re-

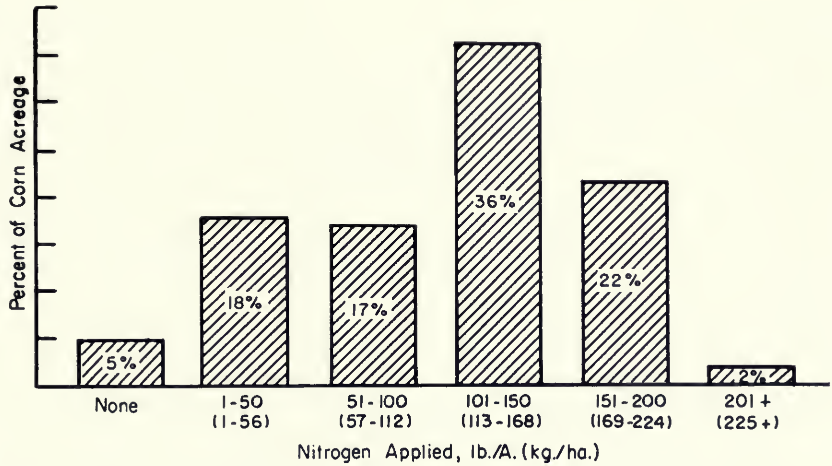


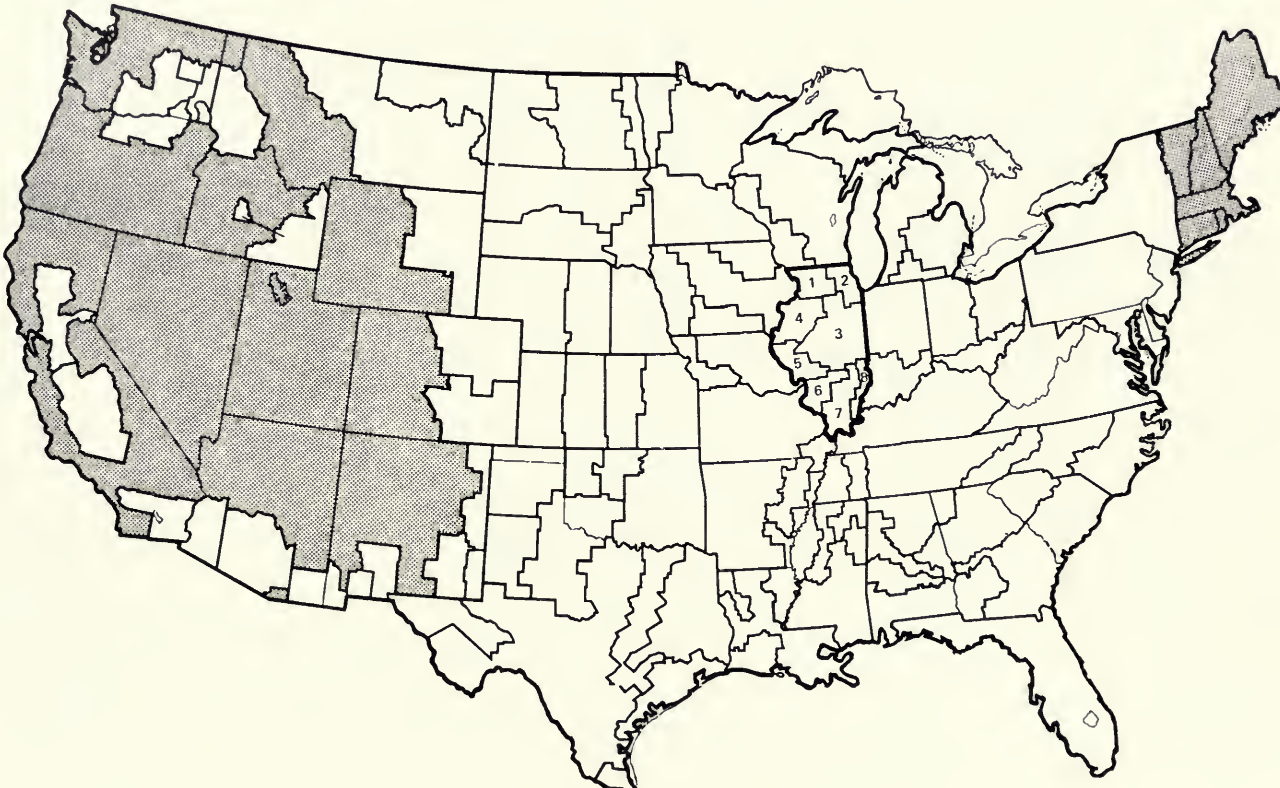
Figure 2. Proportion of Illinois corn acreage receiving specified amounts of commercial nitrogen fertilizer, 1971.

sponse functions with the results of a survey of yields on commercial farms and, second, by comparing experimental results with some response functions, developed by the U.S. Department of Agriculture, that were based on the judgments of agronomists familiar with both experimental data and farm practices. Taylor and Swanson concluded that, while the experimental response of corn yields to nitrogen appeared to be consistently higher than the response experienced by commercial farmers, the economically optimal fertilization rates for commercial farms were only slightly lower than the optimal rates for the experimental situations.

Next, we compared these optimal rates with the rates farmers actually use. Figure 2 shows an estimated nitrogen fertilizer rate distribution for Illinois. The average rate in 1971 was about 113 pounds per acre (127 kg./ha.), which is well below the optimal experimental rates indicated for many situations in the state. It might be argued that farmers who apply more than 150 pounds of nitrogen are overapplying. However, extension personnel and others intimately familiar with Illinois farming claim that most farmers in this category have yields that justify these rates.

We must then conclude that any reduction in fertilizer use is likely to reduce the profits of an individual farmer. Consequently, an educational program would probably not reduce the nitrogen load (the total

Figure 3. Producing regions. Some of the boundaries as drawn include more than one region. Crop production in the shaded areas is exogenous to the model.



amount of nitrogen added minus the amount removed by crops). In fact, if farmers were better informed about response functions and price ratios, an educational program could possibly increase the nitrogen load, because in terms of economic returns, more farmers apparently underapply than overapply nitrogen.

PER-ACRE RESTRICTIONS ON THE USE OF NITROGEN FERTILIZER

If adopted as public policy, a mandatory per-acre restriction on the use of commercial nitrogen fertilizer would set limits on the amount of nitrogen that could be applied to any one crop. The objective of such a policy would be to reduce the degree of water contamination. Restrictions would, however, have other effects as well, as our analyses of the national, Corn Belt, and state models will show.

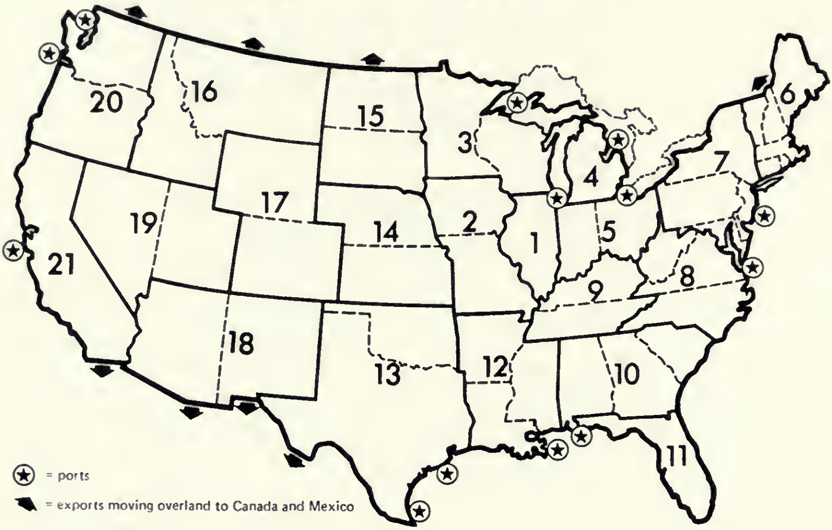
National Model

The quantitative framework used in this analysis is a national linear programming model of U.S. crop production. Eight crops are included in the model: feed grains (corn, sorghum, oats, and barley), food grains (wheat and rye), and oilseeds (cotton and soybeans). The method of solving the model enables us to determine the crop acreages that minimize the production and transportation cost (total cost) of meeting the fixed demands for domestic livestock feed and food for direct human consumption, and for export (Figure 1A).

Agricultural production and distribution regions in this country are interdependent. To reflect this interregional relationship, the U.S. Department of Agriculture divided the United States into producing regions and consuming regions (Figures 3 and 4). Producing regions are delineated principally on the basis of uniformity of the soil. Each producing region has at least one crop production activity or enterprise, for example corn, which is considered agriculturally important for that region. A particular crop may be a dryland enterprise, an irrigated enterprise, or both.

The producing regions do not blanket the entire country (Figure 3), but they do include more than 99 percent of the feed grain, cotton, and soybean acreage, and about 97 percent of the small grain acreage. Any production of these commodities outside of the producing regions is not

Figure 4. Consuming regions.



treated within the model, but is predetermined at estimated 1973 production levels.

The consuming regions, which follow state boundaries (Figure 4), specify regional commodity demands and also make it possible to determine interregional commodity transportation within the model. The total demand, including domestic and export, for each of the consuming regions is broken down into the following parts for all eight crops: domestic demand for seed, food for direct human consumption, specified grains for all livestock except cattle, sheep, and swine, and feed in the form of digestible nutrients and digestible protein for cattle, sheep, and swine; and export demand, specified by port or by overland route in the case of corn or soybeans moving to Mexico and Canada. Added together, the regional demands make up the total national demand for each crop. These demands are treated as requirements for solutions to the national model, with each solution giving the crop acreages that minimize the total cost of meeting domestic and export demands.

There are three basic assumptions related to fertilizer use for the analyses involving the national, Corn Belt, and state models. First, farmers applying nitrogen at rates lower than the restriction level will not change their practice, and farmers applying more than this level will reduce their rate to comply with the restriction. Second, phosphorus and

Table 1. — Changes Required in Total U.S. Acreage[a] to Meet Low and High Export Demands Under Commercial Nitrogen Fertilizer Restrictions — National Model

Location of restriction Export level	Nitrogen restriction on corn, sorghum, wheat			
	No restriction	150 lb./A. (168 kg./ha.)	100 lb./A. (112 kg./ha.)	50 lb./A. (56 kg./ha.)
	million acres (ha.)			
Illinois only				
Low export	214.6 (86.9)	214.1 (86.7)	214.6 (86.9)	215.2 (87.2)
High export	228.4 (92.5)	229.4 (92.9)	229.9 (93.1)	231.8 (93.9)
Entire U.S.				
Low export	214.6 (86.9)	211.4 (85.6)	214.9 (87.0)	230.7 (93.4)
High export	228.4 (92.5)	226.0 (91.5)	229.9 (93.1)	246.5 (99.8)

[a] Land required for corn, soybeans, sorghum, cotton, wheat, and other small grains.

potassium applications do not change with changes in nitrogen restriction levels. Third, the distribution pattern of nitrogen application among farmers is based on the mean fertilizer rate, together with an assumption about the mathematical form of the distribution (Taylor and Swanson, 1973).

We conducted two main investigations, one for nitrogen restrictions in Illinois only, and the other for nationwide restrictions. Although the restrictions apply only to corn, sorghum, and wheat, the acreages of other crops may also be affected in the process of meeting the demand at minimum cost. Both analyses determined the following: first, the acres necessary to meet high and low export demand predictions when nitrogen restrictions of 150, 100, and 50 pounds per acre (168, 112, 56 kg./ha.) are imposed (Table 1); and second, some more detailed effects of these restrictions (Table 2).

The low export demand level corresponds approximately to the national exports in calendar year 1970 for the eight crops in the model. The high demand level, which is a little greater than the actual exports for the 1972 crop year, represents the following increases above the low export levels: 40 percent for corn and sorghum, 15 percent for soybeans and cottonseed, and 93 percent for small grains.

In general, restricting the use of nitrogen will lower the yields. Therefore, if domestic and export demands are to be met, the number of acres planted to some crops must be increased. When low export levels are considered, nationwide restrictions require a far greater increase in the total crop acreage than do restrictions in Illinois only (Table 1). The bench-mark solution with no restrictions in Illinois requires a total of 214.6 million acres (86.9 million ha.) to meet the low export demand, while the 50-pound-per-acre restriction only in Illinois needs 215.2 million acres (87.2 million ha.) nationwide, an increase of less than 1 percent. However, if the restriction of 50 pounds per acre is enforced throughout the entire United States, the acreage needed for crops increases 16 percent.

A similar comparison of the high export figures was made. With no nitrogen restrictions in Illinois, the bench-mark requirement is 228.4 million acres (92.5 million ha.). When a 50-pound limit is imposed in Illinois only, the total required to meet the high export demand increases to 231.8 million acres (93.9 million ha.), or about 3.5 percent. If, however, the same 50-pound limit is set throughout the United States, the acreage needed to meet high export levels leaps by 18 percent over the no-restriction levels, to 246.5 million acres (99.8 million ha.). Such an increase would have serious environmental consequences, as mentioned later in this section.

Note in Table 1 that, under the low export demand with a 150-pound restriction in Illinois, the total U.S. acreage required is about 500,000 acres (200,000 ha.) less than with no restriction. Further, the total U.S. acreage required does not increase at the 100-pound limit. In both cases there is no acreage increase because the amount of nitrogen applied is reduced to levels that are more economical than those of the 1970 bench-mark solution. Data not shown in Table 1 indicate that, as a result of the 150- and 100-pound limits, corn acreage in Illinois rises slightly to compensate for the yield reductions. At these levels of nitrogen limitation Illinois can maintain its competitive position in corn production. With a restriction of 50 pounds, however, corn acreage in Illinois is reduced nearly 50 percent. When restrictions are applied to the entire United States, the corn acreage required to meet the low export demand increases slightly at the 100-pound level. The same general pattern prevails for the high export demands.

The above analysis assumes a rather short time span between the imposition of controls and their effects. We have assumed that crop yields for a given amount of nitrogen fertilizer are the same as yields in the early 1970's. Thus we ruled out the adoption of new yield-increasing technology, which would tend to offset the yield losses from nitrogen restrictions. Should a new technology that is not dependent on high levels

Table 2. — Effects of Imposing Per-Acre Restrictions on Commercial Nitrogen Fertilizer in Illinois — National Model

Change	Nitrogen restriction		
	150 lb./A. (156 kg./ha.)	100 lb./A. (112 kg./ha.)	50 lb./A. (56 kg./ha.)
Illinois			
Net income per farm[a]	0.4%	−4.0%	−17.0%
Nitrogen on unit area of corn	−10.0%	−30.0%	−62.0%
Nitrogen on unit area of wheat	−2.0%	−10.0%	−39.0%
Total nitrogen used	−9.0%	−29.0%	−81.0%
		million acres (ha.)	
Corn	+0.03 (+0.01)	+0.04 (+0.02)	−5.70 (−2.31)
Soybeans	−0.02 (−0.01)	+0.03 (+0.01)	+4.40 (+1.78)
Rest of Corn Belt[b]			
Corn	−0.10 (−0.04)	+0.03 (+0.01)	+3.60 (+1.46)
Soybeans	+0.10 (+0.04)	+0.30 (+0.12)	+4.60 (+1.86)

[a] Income derived from corn, soybeans, wheat, and oats.
[b] Indiana, Iowa, Missouri, and Ohio.

of nitrogen be adopted, our estimates of land needed under each situation are too high. Nevertheless, the *differences* in model solutions — the focus of this analysis — would not be significantly biased by the changes in crop production technology likely to occur in the next five to ten years.

The increased demand for land resulting from nitrogen restrictions, combined with expanding export markets, may have soil conservation and environmental quality consequences. As poorer land is brought under cultivation, soil erosion will increase, producing more sediment than at present. While a per-acre restriction on nitrogen might reduced nitrates in water, restrictions could at the same time result in an increase in sedimentation.

This overview hides some noteworthy regional changes. Table 2 presents a few consequences of imposing a nitrogen restriction in Illinois only. A 50-pound-per-acre maximum will decrease nitrogen use in Illinois by 81 percent and the average income per farm by 17 percent. At the same time, nitrogen applications in the rest of the Corn Belt will rise by 20 percent (data not shown). The dissatisfaction of Illinois farmers with inevitable reductions in corn acreages and associated income while farmers in neighboring states appear to gain at their expense would be considerable. Also, from the standpoint of environmental improvement not much would be gained, because many of Illinois' nitrate problems would simply be transferred to other states.

Corn Belt Model

This model is a linear programming representation for the production of six crops, namely, corn, soybeans, wheat, oats, hay, and pasture, which are economically important to the Corn Belt. In this model the Corn Belt includes all of Illinois and Iowa, together with parts of Indiana, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin. Solutions to the Corn Belt model are obtained by maximizing the sum of consumer's and producer's surpluses minus the variable costs of producing the six crops. Consumer's surplus is measured by comparing what consumers are willing to pay for food and what they actually pay. Producer's surplus, or the return to the fixed resource (land), represents rent to the landowner. Estimates of demand and supply as functions of price are required to implement the concepts of consumer's and producer's surpluses.

Corn and soybeans are of major economic importance to the Corn Belt, which produces 70 percent of the nation's corn and 60 percent of the soybeans. Therefore, the demand for these two crops is introduced into the model in the manner indicated in Figure 1B, and both prices and quantities for these two crops are determined within the model. In contrast, the demands for the other four crops are treated as fixed quantities (Figure 1A).

The Corn Belt is divided into seventeen geographic regions, each with eleven land capability units that reflect variations in the suitability of soil and climate for crops. Crop production activities in these units can vary in several ways: by crop rotation, with an average of eleven rotations per unit; by conservation practice, namely, straight row, contouring, and terracing; and by tillage methods, namely, fall plow, spring plow, and chisel plow. Rotations, rather than single crop activities, were included to reflect the influence of the previous crop on the fertilizer and pesticide requirements of the current crop.

In this application (Taylor and Frohberg, 1977), the Corn Belt model was used to assess the effects of reducing the average rate of nitrogen application from 140 pounds per acre (157 kg./ha.) to a maximum of 50 pounds per acre (56 kg./ha.). Imposing this limit reduces consumer's surplus by $3.3 billion and increases producer's surplus by $2.0 billion, leaving a net decrease of $1.3 billion (Table 3). Producer's surplus, or

Table 3. — Effects on Producer's and Consumer's Surpluses, Crop Prices, and Nitrogen Load Resulting From Per-Acre Restrictions on Commercial Nitrogen Fertilizer — Corn Belt Model[a]

Change	Nitrogen restriction		
	140 lb./A. (157 kg./ha.)	100 lb./A. (112 kg./ha.)	50 lb./A. (56 kg./ha.)
Producer's surplus (million)	0	$ 21	$ 2,036
Consumer's surplus (million)	0	−321	−3,325
Crop price			
Corn			
per bushel	$ 2.46	$ 2.56	$ 3.08
per metric ton	96.86	100.80	121.28
Soybeans			
per bushel	$ 5.26	$ 5.24	$ 5.82
per metric ton	193.31	192.57	213.89
Nitrogen load[b]			
short ton (1,000)	2,095	1,595	1,100
metric ton (1,000)	1,901	1,447	998

[a] The Corn Belt model includes all of Illinois and Iowa, together with parts of Indiana, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin.
[b] Total from inorganic and organic sources.

rent, increases as a result of the fertilizer restriction, because land becomes more scarce and hence more valuable as a source of crop production. The average annual rent for Corn Belt land changes from $87 to $111 per acre ($215 to $274/ha.), an increase of about 27 percent.

Corn prices rise from $2.46 to $3.08 per bushel, an increase of 25 percent. But the nitrogen load, that is, the total nitrogen added minus the nitrogen removed in harvested crops, decreases by 47 percent. Whether such a reduction in the nitrogen load would meet or surpass water quality goals is not of course indicated by these results. We can say, however, that a nitrogen fertilizer reduction of about two-thirds in the Corn Belt as a whole would have a substantial economic impact on both farmers and consumers.

State Model

The national model gives some indication of both nationwide and state changes when various nitrogen restrictions are enforced only in Illinois. A more detailed model (Palmini, 1975), also in linear programming format, divides the state into eight producing regions (Figure 3). The state model considers the amounts and kinds of livestock as variables that have the potential for responding to nitrogen fertilizer control methods. Like the national and Corn Belt models, the state model is short run, so the technology used in production does not change. The three models are also similar in that only the direct variable costs of production are considered; taxes and depreciation are excluded.

The state model differs from the other two models primarily in its treatment of demand. The model assumes that, in a sense, the state is composed of eight large farms, one for each region, and that the price of the crop is not affected by the quantity sold or the distance of the region from the consuming center. This competitive market assumption is illustrated in Figure 1C. Because prices do not change as production is reduced by nitrogen fertilizer restrictions, the income reductions estimated in the state model are greater than they would have been with the demand assumptions in Figures 1A or 1B. Comparisons of income reductions among models is difficult because the base periods and levels of fertilizer restriction are not identical.

Another feature of the state model that distinguishes it from the other two is the use of flexibility constraints on shifts in production of crops and livestock. These constraints were established by reviewing past year-to-year shifts that farmers made in their crop acreages and livestock numbers. The flexibility constraints prevent drastic and unlikely shifts in production systems because of established patterns of farming, fixed investments, and other factors.

The crop yield response to nitrogen fertilizer is assumed to be that reported by the U.S. Department of Agriculture (Ibach and Adams, 1968). Because the controls considered are used only in Illinois, it is also assumed that nitrogen fertilizer is not smuggled into Illinois from other states.

We estimated the effects on farm income, using nitrogen restrictions of 120, 80, and 40 pounds per acre (134, 90, and 45 kg./ha.) measured from the bench-mark application rate of 144 pounds per acre (161 kg./ha.). Although the effect of a 120-pound limit was rather minor, the effect of a 40-pound limit was substantial (Table 4).

Because clover, when grown as a green manure crop, contributes nitrogen to the soil, we hypothesized that its competitive position in the crop sequence would improve as a result of controls on nitrogen fertilizer. The results of our analysis, presented in Table 5, show that the clover acreage is the same at the 120- and 80-pound levels, but nearly doubles when the application rate is restricted to 40 pounds per acre (Palmini, 1975). We concluded that the cost of nitrogen supplied by

Table 4. — Losses in Illinois Net Income per Farm Resulting From Per-Acre Restrictions on Commercial Nitrogen Fertilizer in Illinois — State Model

Losses in Illinois	Nitrogen restriction		
	120 lb./A. (134 kg./ha.)	80 lb./A. (90 kg./ha.)	40 lb./A. (45 kg./ha.)
Net income per farm	$92	$551	$1,450
Percent of net farm income, 1969	1.4%	8.7%	22.9%
Percent of net farm household income, 1969	0.9%	5.3%	14.0%

Table 5. — Effects on Corn Production, Clover Acreage, and Commercial Nitrogen Fertilizer Use Resulting From Per-Acre Nitrogen Restrictions Imposed in Illinois — State Model

Illinois	Nitrogen restriction		
	120 lb./A. (134 kg./ha.)	80 lb./A. (90 kg./ha.)	40 lb./A. (45 kg./ha.)
Corn production			
billion bushels	1.2	1.0	0.8
million metric tons	30.5	25.4	20.3
Clover area			
acres	126,800	126,800	215,000
hectares	51,400	51,400	87,000
Nitrogen use			
short tons	618,500	374,900	156,000
metric tons	561,000	340,000	141,500

clover is very high and that this source is not an economical substitute for commercial nitrogen fertilizer until the supply of commercial nitrogen is drastically curtailed. In terms of foregone grain production, the opportunity cost of land for clover is simply too high even if corn is disadvantaged by fertilizer constraints at the 80-pound level.

AN EXCISE TAX ON NITROGEN FERTILIZER

A control method that involves an excise tax simply means that farmers who purchase commercial nitrogen fertilizer will be charged at the market price plus a levy or excise tax. Both the national and the state (Palmini) models, with a few modifications, were used to examine the economic consequences of such a tax.

National Model

We analyzed three excise taxes, namely, 3, 6, and 12 cents per pound of nitrogen (6.6, 13.2, and 26.4 cents/kg.). These taxes are assumed to be levied only in Illinois. The response of farmers to the nitrogen fertilizer tax depends in part on the relationship of crop yield to fertilizer application. Because yields increase at a diminishing rate, a given increase in fertilizer price with or without a tax causes the application rate per acre to be reduced more at high yield levels than at low. Thus, the initial tax of 3 cents per pound reduces the amount of nitrogen applied to corn in Illinois by 17 percent, calculated from the bench mark (Table 6), while the second 3 cents (a total of 6 cents) results only in an additional 8 percent reduction. The highest tax considered, 12 cents per pound, reduces nitrogen use on corn by 32 percent.

The data, presented in Table 6, show the effects of the taxes in Illinois and also the resulting changes in the rest of the Corn Belt. Even the smallest of the three taxes has an appreciable effect. Illinois crop farmers suffer an immediate 5-percent decline in income, a 40-percent drop in fertilizer applications, and a loss of 3.1 million acres of corn (1.3 million ha.), although this loss is more than compensated for by an increase of 4.0 million acres of soybeans (1.6 million ha.).

Table 6. — Effects of Imposing an Excise Tax on Commercial Nitrogen Fertilizer in Illinois — National Model

Change	Excise tax on nitrogen		
	3¢/lb. (6.6¢/kg.)	6¢/lb. (13.2¢/kg.)	12¢/lb. (26.4¢/kg.)
Illinois			
Net income per farm[a]	− 5.4%	− 9.6%	−12.3%
Nitrogen on unit area of corn	−17.0%	−25.0%	−32.0%
Nitrogen on unit area of wheat	−29.0%	−40.0%	−60.0%
Total nitrogen used	−40.0%	−61.0%	−76.0%
		million acres (ha.)	
Corn	−3.1 (−1.3)	−5.7 (−2.3)	−7.7 (−3.1)
Soybeans	+4.0 (+1.6)	+6.6 (+2.7)	+8.8 (+3.6)
Rest of Corn Belt[b]			
Corn	+2.3 (+0.9)	+4.6 (+1.9)	+6.0 (+2.4)
Soybeans	−4.5 (−1.8)	−5.7 (−2.3)	−7.8 (−3.2)

[a] Income derived from corn, soybeans, wheat, and oats.
[b] Indiana, Iowa, Missouri, and Ohio.

The crop acreage changes in the rest of the Corn Belt (Indiana, Iowa, Missouri, and Ohio) are also of interest. With an Illinois tax of 3 cents, the Corn Belt exclusive of Illinois increases corn acreage by 2.3 million acres (0.9 million ha.) when Illinois decreases its acreage by 3.1 million acres (1.3 million ha.). The net result is that the Corn Belt loses 800,000 acres of corn (324,000 ha.). This shift means that part of the feed grain requirement must be met from production outside of the Corn Belt. In terms of total corn and soybean acreage, Illinois would seem to gain by the tax, because its soybean acreage increases 4.0 million acres (1.6 million ha.) at 3 cents and 8.8 million acres (3.6 million ha.) at 12 cents, while the state loses only 3.1 and 7.7 million acres of corn (1.3 and 3.1 million ha.) at the two extreme tax levels.

State Model

The state model examines excise taxes of 3, 9, and 15 cents per pound of nitrogen (6.6, 19.8, and 33.1 cents/kg.) imposed on nitrogen fertilizer in Illinois. For this investigation we used the same eight producing regions outlined in Figure 3, with each region selling in a competitive market where the crop price is not affected by the quantity sold. The consequences of these taxes are presented in Table 7.

Enactment of a 3-cent excise tax in Illinois reduces net farm income about 6 percent, compared with the slightly smaller reduction of 5.4 percent in the national model (Table 6). A 3-cent tax only in Illinois reduces the total nitrogen fertilizer used in the state by 40 percent in the national model but by only 18 percent in the state model. Again, the difference in demand assumptions plays an important role.

Table 7. — Effects of Imposing an Excise Tax on Commercial Nitrogen Fertilizer in Illinois — State Model

Change in Illinois	Excise tax on nitrogen		
	3¢/lb. (6.6¢/kg.)	9¢/lb. (19.8¢/kg.)	15¢/lb. (33.1¢/kg.)
Net income per farm	−6%	−16%	−23%
Total nitrogen used	−18%	−33%	−43%
Corn area			
acres	+5,000[a]	−681,000	−833,000
hectares	+2,000	−276,000	−337,000
Soybean area			
acres	−4,000	+535,000	+535,000
hectares	−2,000	+217,000	+217,000

[a] Rounded to nearest thousand acres and hectares.

In the national model a fixed quantity of feed grains is required nationwide. Areas outside of Illinois can be used to produce this quantity, permitting Illinois to reduce its corn acreage and hence its use of nitrogen fertilizer. In the state model a 3-cent tax actually increases corn acreage slightly, by 5,000 acres, or less than one-half of 1 percent. However, these acres are needed for corn silage to make minor adjustments in livestock systems. At the higher tax levels corn acreage decreases and soybean acreage increases. Although data are not included in Table 7, small grain acreages were also involved in the changes in cropping patterns.

A MARKET FOR RIGHTS TO USE NITROGEN FERTILIZER

The concept of a market for rights to purchase commercial nitrogen is basically simple, although the operational details may be complex. On the basis of the water quality standard specified for the year, a public agency, such as the Illinois Environmental Protection Agency, decides how much nitrogen fertilizer is to be used that year. In the form of coupons or certificates issued annually, rights to purchase a given quantity of fertilizer are sold on the open market, with purchasers bidding for these rights. The procedure might start with the agency asking a representative sample of users to indicate the quantity they would order at various prices. With this information the agency can then decide what price to set to ensure that approximately the number of rights the agency wants to issue will be sold.

After the initial disposition of rights by the agency, individual users can buy and sell rights among themselves and to nonusers. Nonusers, such as environmental groups, can influence the amount of fertilizer used by trying to change the number of rights through the political system or by buying rights and then not using them. The discussion that follows assumes that nonusers do not purchase any rights.

National Model

Using the national model, we examined the effects of imposing rights for five different quantities of nitrogen in Illinois only. These five quantities, namely, 864, 519, 336, 224, and 198 thousand short tons (784, 471, 305, 203, and 180 thousand metric tons), were selected to correspond to the assumed decline in the amount of nitrogen used when excise taxes of 3, 6, 9, and 12 cents per pound are imposed (6.6, 13.2, 19.8, and 26.4

Table 8. — Regional Crop Acreages Resulting From a Market for Commercial Nitrogen Fertilizer Rights Imposed in Illinois — National Model

Crop and region	Quantity of rights, 1,000 short tons (metric tons)				
	864 (784)	519 (471)	336 (305)	224 (203)	198 (180)
	million acres (ha.)				
Corn, grain sorghum					
Illinois	11.4 (4.6)	8.4 (3.4)	5.7 (2.3)	3.9 (1.6)	3.7 (1.5)
Other Corn Belt states[a]	18.7 (7.6)	21.0 (8.5)	23.3 (9.4)	24.9 (10.1)	24.8 (10.0)
Rest of U.S.	37.5 (15.2)	40.1 (16.2)	41.4 (16.8)	41.5 (16.8)	41.4 (16.8)
Total	67.6 (27.4)	69.5 (28.1)	70.4 (28.5)	70.3 (28.5)	69.9 (28.3)
Small grains					
Illinois	4.3 (1.7)	3.4 (1.4)	3.4 (1.4)	3.4 (1.4)	3.5 (1.4)
Other Corn Belt states[a]	7.9 (3.2)	8.0 (3.2)	9.3 (3.8)	10.7 (4.3)	11.2 (4.5)
Rest of U.S.	95.4 (38.6)	96.4 (39.0)	95.2 (38.5)	97.8 (39.6)	98.5 (39.9)
Total	107.6 (43.5)	107.8 (43.7)	107.9 (43.7)	111.9 (45.3)	113.2 (45.8)
Soybeans					
Illinois	3.2 (1.3)	7.2 (2.9)	9.8 (4.0)	11.8 (4.8)	12.0 (4.9)
Other Corn Belt states[a]	16.9 (6.9)	14.6 (5.9)	11.2 (4.5)	9.0 (3.6)	9.1 (3.7)
Rest of U.S.	19.6 (7.9)	16.8 (6.8)	17.0 (6.9)	16.2 (6.6)	15.8 (6.4)
Total	39.7 (16.1)	38.6 (15.6)	38.0 (15.4)	37.0 (15.0)	36.9 (14.9)

[a] Indiana, Iowa, Missouri, and Ohio.

cents/kg.). In Illinois 864,000 short tons is the bench-mark figure for use of nitrogen fertilizer with no restriction or excise tax on nitrogen. The analysis involved determining the acreage changes that would occur in Illinois, in the other Corn Belt states (Indiana, Iowa, Missouri, and Ohio), and in those states outside of the Corn Belt. Table 8 presents the corn and grain sorghum, small grain, and soybean acreages for the five nitrogen levels. The results underline the national acreage redistribution that occurs when a control method is introduced in only one state. Although the precise changes in the various regions are determined by the interdependent relationships in the model, several general trends may be noted.

CHANGES IN ACREAGES

As might be expected, the imposition of a market for nitrogen fertilizer rights in Illinois disadvantages that state in corn and sorghum production. For the smallest quantity of rights, 198,000 short tons, the acreage of these crops in Illinois drops by about two-thirds, from 11.4 to 3.7 million acres (4.6 to 1.5 million ha.). Because a fixed quantity of corn and sorghum must be produced nationally, increases in acreages of these crops occur both in the other Corn Belt states (an added 6.1 million acres or 2.4 million ha.) and in states outside of the Corn Belt (an added 3.9 million acres or 1.6 million ha.). Note that as a result of a market for rights in Illinois, a total of 2.3 million additional acres (0.9 million ha.) are needed nationally to produce the required corn and sorghum, that is, 69.9 versus 67.6 million acres.

In addition to the shifts in location of corn and sorghum production, small grain acreages in the various regions also change. The pattern for small grains parallels that for corn and sorghum — a decrease in Illinois and an increase outside of Illinois. However, the shifts are not as dramatic as those for corn and sorghum, because on a national scale Illinois' small grain production is of less importance than its corn and sorghum. Also, small grain crops are not affected as much by the restrictions on available nitrogen fertilizer. As in the case of corn and sorghum, more total acres are required to meet the national needs for small grain. At the most restricted level of rights, 5.6 million additional acres (2.3 million ha.) would be required, that is, 113.2 versus 107.6 million acres.

The location of soybean production is changed substantially by the market for rights in Illinois. In general, the shifts are in the opposite direction of those for the other crops considered. With the smallest quantity of rights, soybean acreage in Illinois increases almost fourfold, from 3.2 to 12.0 million acres (1.3 to 4.9 million ha.). This increase is accompanied by a reduction in the other states within the Corn Belt and outside of the Corn Belt. Because Illinois soybean yields are higher than the yields in other states, 2.8 million fewer acres (1.2 million ha.) are needed nationally to meet the demand than when there is no market for rights.

CHANGES IN YIELDS, COSTS, AND INCOME

All of the changes discussed above are of course solely redistributions within producing regions. The changes indicate nothing about how yields are affected, although it is reasonable to assume that corn and sorghum yields will decrease as these crops leave the Corn Belt. Less productive land will be used to meet the demand, thereby increasing the cost of production per bushel (Table 9). An 8-percent cost increase occurs as we

Table 9. — Costs of Producing Selected Crops Under a Market for Commercial Nitrogen Fertilizer Rights Imposed in Illinois — National Model[a]

Crop	Quantity of rights, 1,000 short tons (metric tons)				
	864 (784)	519 (471)	336 (305)	224 (203)	198 (180)
Corn					
per bushel	$ 1.23	$ 1.25	$ 1.27	$ 1.30	$ 1.33
per metric ton	$ 48.43	$ 49.22	$ 50.01	$ 51.19	$ 52.37
Index	100[b]	102	103	106	108
Soybeans					
per bushel	$ 3.05	$ 3.04	$ 3.05	$ 3.04	$ 3.05
per metric ton	$112.09	$111.72	$112.09	$111.72	$112.09
Index	100	100	100	100	100
Wheat					
per bushel	$ 1.36	$ 1.38	$ 1.40	$ 1.42	$ 1.45
per metric ton	$ 49.98	$ 50.72	$ 51.45	$ 52.19	$ 53.29
Index	100	101	103	104	107
Oats					
per bushel	$ .62	$ .61	$ .60	$ .59	$ .60
per metric ton	$ 43.75	$ 43.04	$ 42.34	$ 41.63	$ 42.34
Index	100	98	97	95	97

[a] All costs are for the 1969-71 base period, and are based in part on the opportunity costs of the model. Opportunity costs represent net income foregone in order to increase the production of a given crop by 1 bushel.

[b] Base price corresponding to a quantity of rights equal to 864,000 short tons (784,000 metric tons).

go to the smallest quantity of rights. In the long run, the increased costs must be covered by the price of these grains. Soybean costs are not affected, but wheat, because of its high nitrogen requirement, follows roughly the same pattern as corn. The cost of producing oats, a rather minor crop, is lowered slightly. Apparently in the process of rearrangement, oats become more favorably located with respect to the cost of production.

Production costs, and hence price increases, are the most obvious for corn and wheat because they require more intensive nitrogen application than any other crops. Price changes for output are reflected in farm income changes. The 1969 Census of Agriculture estimated that those Illinois farms producing only corn, wheat, soybeans, and oats earned an average of $6,327 annually. With the quantity of rights set at 519,000 short tons, this income would decline 6 percent; at 198,000 tons it would be reduced by 12 percent. Even though the price of corn and wheat rises, the increase is insufficient to offset the smaller acreages of these crops in Illinois.

RESTRICTIONS ON NITRATE CONCENTRATION IN GROUNDWATER BELOW THE ROOT ZONE

If all of the nitrogen fertilizer applied were to be taken up by the crop, the agricultural use of nitrogen would not affect the nitrate concentration of water in the soil. In reality, a certain amount of nitrogen inevitably leaches into the soil and groundwater below the root zone of the plants. In this phase of our investigation we analyzed the effects of varying the allowable level of nitrate concentration below the root zone. Of particular interest are the effects that this control method would have on cropping systems, management practices, and farm income. We asked the question: If farmers were required to meet various standards for nitrate concentration, what would be the best cropping systems and management practices for maximizing net farm income excluding land costs? We also examined the results of measures taken to control soil erosion and sedimentation, although these problems are not central to the study. Because the choice of crops and management practices also affects soil erosion, we briefly considered these interactions by simultaneously putting certain restrictions on both nitrate concentration and sedimentation.

Watershed Model

Using a linear programming model developed for a watershed (Onishi, 1973; Onishi *et al.,* 1974; Onishi and Swanson, 1974), we studied the Forest Glen watershed near Danville, Illinois. This watershed contains 1,200 acres (486 ha.), about two-thirds of which are considered suitable for crops. The area is of practical interest because it has been proposed that a reservoir be constructed nearby at the head of a tributary of the Vermilion River and that public recreation facilities be provided. Water quality standards would be a major consideration for such a facility. The cropland in this area is classified into tracts by ownership of land, type of soil, slope length and gradient, and elevation above the surface of the proposed reservoir. Four different elevations were taken into account, because the distance from the initial erosion affects the amount of sediment entering the reservoir.

The goal of an assumed five-year planning period is to maximize net farm income. There are three constraints on maximizing income: (1) acreages of different types of land available for particular crops for each of the five years, (2) the allowable nitrate concentration in the leachate below the root zone, and (3) the amount of sediment entering the reservoir. Alternative cropping systems (crop combinations, tillage methods, and nitrogen fertilizer levels) are taken into account for sixty-three separate tracts for each of the five years. The land availability constraint provides a way to make sure that acreages for all crops and land left idle equal the total area available for the various tract classifications.

Three basic assumptions were made with respect to cropping systems and management practices. First, the nineteen farmers in the watershed concentrate on cropping operations with no livestock enterprises. Second, any one of three tillage methods can be used for corn grown on the same land year after year: conventional, plow-plant, and chisel plow. However, only the conventional method is used for the following rotations involving corn (C), soybeans (S), wheat (W), wheat with alfalfa as a catch crop (W_x), and alfalfa meadow (M): C-C-S-W_x, C-S-W_x, and C-S-W-M. Finally, nitrogen applications of 50, 100, and 140 pounds per acre (56, 112, and 157 kg./ha.) are available for consecutive plantings of corn. Rate adjustments are made for corn in the rotations to allow for the nitrogen furnished by the legumes (soybeans and alfalfa).

The universal soil loss equation (Wischmeier and Smith, 1965) and a sediment-yield ratio equation based on drainage areas (Roehl, 1962) were used to calculate sediment coefficients. To estimate the amount of sediment entering the reservoir, the gross erosion predicted for each cropping system was adjusted by sediment-yield ratios.

An equation for the potential nitrate-nitrogen (NO_3-N) concentration in water leaching below the root zone was developed by Stout and Burau (1967). In this equation, corn fertilized at the rate of 100 pounds or less of nitrogen per acre does not release any nitrogen into groundwater because the nitrogen uptake by the grain portion of the corn is greater than the amount of nitrogen supplied. Theoretically, no nitrogen leaches into groundwater because the equation assumes an equilibrium between nitrogen application and uptake; in reality, some nitrogen is released in the leachate even at the lower rates. Accordingly, we made an adjustment in the equation by assuming that the amount of nitrogen available in a given area for a crop is the sum of the amount applied plus the amount already in the soil. The amount already in the soil is estimated by calculating the nitrogen taken up by the crop if no nitrogen fertilizer is applied. The total amount of nitrogen thus calculated was inserted in the Stout-Burau equation to estimate the potential NO_3-N concentration in the leachate below the root zone.

SEDIMENT CONTROL MEASURES

On the basis of selected sediment control measures, we analyzed two groups of problems. The first group requires complete dredging of the

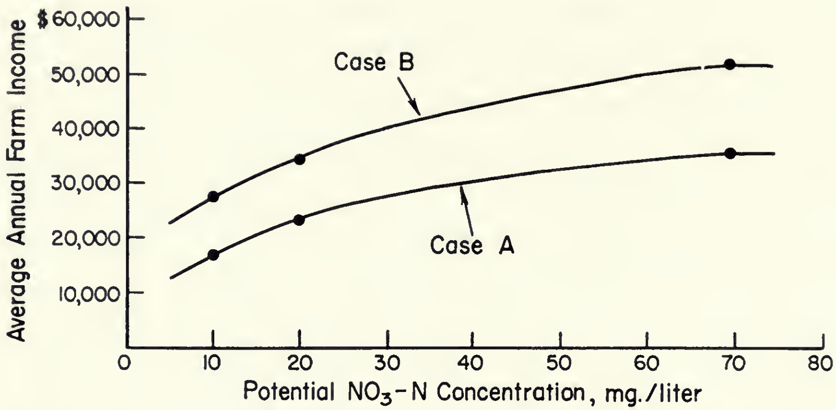


Figure 5. Effect on net farm income when potential NO_3-N is restricted in leachate below the root zone. Case A: Charges made for dredging all sediment from reservoir. Case B: Charges made for dredging sediment in excess of 8,498 short tons (7,711 metric tons) accumulated over five years.

reservoir, with the farmers bearing the cost. In this case there is no upper limit on sedimentation in the reservoir. The second group of problems sets an upper limit of 8,498 short tons of sediment (7,711 metric tons) accumulated over the five-year period. Dredging is required for any sediment above this limit, with the farmers bearing the cost. It is estimated that sediment accumulating at this rate would fill half of the proposed reservoir in three hundred years. For each of these two groups we assumed three situations for potential NO_3-N concentration in sediment: upper limits of 10 and 20 milligrams per liter, and no upper limit.

CHANGES IN INCOME

Several general patterns emerge when crop production is constrained by dredging charges for sediment released into the reservoir and at the same time by placing limits on potential NO_3-N in the leachate below the root zone (Figure 5). In this figure the curve rises from left to right as the allowable nitrate concentration in the root zone increases. Conversely, as the restriction on this concentration is tightened, the curve descends from right to left, quite rapidly when the level is reduced from 20 to 10 milligrams per liter. In terms of income, farmers lose more when they are required to pay for dredging all of the sediment from the reservoir (case A) than when charged for dredging only the sediment above the 8,498-ton limit (case B). However, in both cases A and B the rates of income reduction increase as nitrate restrictions are tightened.

A TOTAL-FARM NITROGEN BALANCE

Because crops do not absorb all of the nitrogen fertilizer applied, the amount remaining in the soil becomes a potential source of water contamination. A surplus of residual nitrogen produces a positive balance, while a deficit produces a negative balance. This section examines how this balance is affected when restrictions are put on the total amount of commercial nitrogen fertilizer available to individual farms. With his given allotment of nitrogen fertilizer, the farmer is free to choose the cropping system and fertilizer rates that will maximize his farm income above direct costs. We have varied the size of the allotment in order to examine the effects of such a control program on the nitrogen balance and farm income.

Farm Model

To estimate the average annual farm income above direct costs, we used a five-year linear programming model for an Illinois farm of 293 acres (119 ha.), which is the average size for Champaign County. Although this is a cash-grain farm, the analysis can be extended to a grain and livestock farm. We developed an accounting procedure for determining the nitrogen balance. A detailed discussion of the method and results is presented in Walker (1974). The nitrogen accounts recognize two sources of nitrogen, namely, commercial nitrogen fertilizer and legume crops (soybeans, alfalfa, and clover). The nitrogen from these two sources either remains on the farm or is removed in harvested crops. The balance is positive if the sum of the two sources is greater than the amount removed in harvested crops, and negative if the sum is less. Nitrate pollution of water becomes more likely as the nitrogen balance becomes increasingly positive.

The model activities are production, purchasing, marketing, and financial management. Crop production encompasses corn, soybeans, wheat, alfalfa, and sweet clover, each of which is produced by different methods and in different rotations. Purchasing and marketing activities include buying inputs and selling farm outputs, with all grain being sold at harvest. Financial management includes credit, debt, and investment or loan management. These financial activities run on an annual basis for the entire five-year planning period.

The resource constraints are land, labor, and capital. Land is considered homogeneous. The number of acres remains constant because no land is purchased or sold. The constraint on labor is the amount of labor available in each month of the year. Capital is limited to operating expenses only; no long-term investment credit is considered.

The solutions for the model give the nitrogen balance, farm income, and optimal cropping systems for each of the commercial nitrogen fertilizer allotments. These allotments, established by a regulatory agency, are the amounts that the farmer may purchase each year. The five levels considered available for this 293-acre farm are as follows:

Level	Total-farm		Per unit area	
	short ton	metric ton	lb./acre	kg./ha.
I	0	0	0	0
II	7.33	6.65	50	56
III	14.65	13.29	100	112
IV	21.98	19.94	150	168
V	29.30	26.58	200	224

At each of these five allotment levels the resulting nitrogen balances for the entire farm range from −11.59 short tons (−10.52 metric tons), when no commercial nitrogen fertilizer is allowed and only corn is grown, to 8.54 short tons (7.75 metric tons), when commercial nitrogen is, for all practical purposes, unlimited and hence not an effective constraint on the choice of cropping systems and fertilizer practices.

OPTIMAL CROPPING SYSTEMS

Table 10 presents the optimal cropping systems resulting from each fertilizer allotment combined with the given nitrogen balance. Various cropping systems are possible in this model. For example, 40 percent of the farm can be planted to corn and 60 percent to soybeans. The following year these two crops are rotated, and so on throughout the five-year planning period. Crops in the possible systems are corn–C, soybeans–S, wheat with a meadow catch crop–W(M), and legume meadow–M.

With a commercial nitrogen fertilizer allotment of zero (level I), the optimal cropping system begins with 100 percent of the farm acreage being planted to continuous corn (only corn planted year after year) and shifts to continuous soybeans at the zero point on the nitrogen balance scale (Table 10). As the crop combination shifts to 20% $C_{150(168)}$, 60% S, 20% M, the nitrogen balance becomes positive. Note that even though no commercial nitrogen is available, the nitrogen use rate for this crop combination, as indicated by the subscript, is 150 pounds per acre because of the nitrogen contributed by the legume meadow.

CHANGES IN INCOME AND NITROGEN BALANCE

At level I the cropping system that produces the highest income with no commercial nitrogen used is continuous soybeans (Table 11). Weed, disease, and insect problems, however, may occur with this cropping system. At level III with a total-farm fertilizer allotment of 14.65 short tons, the highest income occurs when there is a positive nitrogen balance of 2.5 short tons. The cropping system that maximizes income at this allotment level is 60% $C_{165(185)}$, 40% S. At the highest level, 29.30 short tons

Table 10. — Optimal Crop Combinations and Total-Farm Nitrogen Balances for Various Commercial Nitrogen Fertilizer Allotments, 293-Acre Cash-Grain Farm, Champaign County, Illinois

Nitrogen balance, short tons (metric tons)	Total-farm fertilizer allotment, short tons (metric tons), levels I-V				
	I 0	II 7.33 (6.65)	III 14.65 (13.29)	IV 21.97 (19.94)	V 29.30 (26.58)
−11.59....... (−10.52)	$C_{0(0)}$[a]	$C_{0(0)}$	$C_{0(0)}$	$C_{0(0)}$	$C_{0(0)}$
−10.00....... (−9.07)	90% $C_{0(0)}$ 10% S	$C_{19(21)}$	$C_{19(21)}$	$C_{19(21)}$	$C_{19(21)}$
−7.50....... (−8.40)	60% $C_{0(0)}$ 40% S	$C_{49(55)}$	$C_{48(54)}$	$C_{48(54)}$	$C_{48(54)}$
−5.00....... (−4.54)	40% $C_{0(0)}$ 60% S	80% $C_{63(71)}$ 20% S	$C_{78(87)}$	$C_{78(87)}$	$C_{78(87)}$
−2.50....... (−2.27)	20% $C_{0(0)}$ 80% S	60% $C_{86(96)}$ 40% S	90% $C_{105(118)}$ 10% S	$C_{106(119)}$	$C_{106(119)}$
0..........	S	40% $C_{129(144)}$ 60% S	80% $C_{129(144)}$ 20% S	$C_{129(144)}$	$C_{129(144)}$
2.50....... (2.27)	20% $C_{150(168)}$ 60% S 20% M	25% $C_{200(224)}$ 75% S	60% $C_{165(185)}$ 40% S	$C_{152(170)}$	$C_{152(170)}$
5.00....... (9.07)	25% $C_{150(168)}$ 25% S 50% M	25% $C_{200(224)}$ 50% S 25% $W_{60(67)}$(M)	50% $C_{200(224)}$ 40% S 10% $W_{60(67)}$(M)	83% $C_{179(200)}$ 17% S	$C_{172(193)}$
7.50....... (8.40)	No solution possible	30% $C_{200(224)}$ 10% S 30% $W_{60(67)}$(M) 30% M	50% $C_{200(224)}$ 20% S 20% $W_{60(67)}$(M) 10% M	80% $C_{200(224)}$ 10% S 10% $W_{60(67)}$(M)	$C_{192(215)}$
8.54....... (7.75)	No solution possible	30% $C_{200(224)}$ 20% S 10% $W_{60(67)}$(M) 40% M	60% $C_{200(224)}$ 10% S 10% $W_{60(67)}$(M) 20% M	80% $C_{200(224)}$ 5% S 15% $W_{60(67)}$(M)	$C_{200(224)}$

[a] Crops in the possible systems are corn – C, soybeans – S, wheat with a meadow catch crop – W(M), and legume meadow – M. Subscripts indicate the total legume and commercial nitrogen rate in lb./A. (kg./ha.). When soybeans or corn alone is the optimal crop, 100% is understood.

Table 11. — Crop Combinations and Nitrogen Balances That Maximize Income for Total-Farm Commercial Nitrogen Fertilizer Allotments, 293-Acre Cash-Grain Farm, Champaign County, Illinois

	Total-farm fertilizer allotment, short tons (metric tons), levels I-V				
	I	II	III	IV	V
	0	7.33 (6.65)	14.65 (13.29)	21.97 (19.94)	29.30 (26.58)
Crop or crop combination........	S[a]	40% $C_{129(144)}$ 60% S	60% $C_{165(185)}$ 40% S	$C_{152(170)}$	$C_{200(224)}$
Farm income above direct costs.........	$26,617	$28,378	$30,447	$32,436	$34,025
Nitrogen balance, short tons (metric tons)...	0	0	2.50 (2.27)	2.50 (2.27)	8.54 (7.75)

[a] Crops in the optimal systems are corn – C and soybeans – S. Subscripts indicate the total legume and commercial nitrogen rate in lb./A. (kg./ha.). When soybeans or corn alone is the optimal crop, 100% is understood.

(level V), the allotment is completely used when the nitrogen balance is 8.54 short tons. The cropping system here is 100% $C_{200(224)}$, that is, continuous corn with the nitrogen application rate increasing up to 200 pounds per acre. Both farm income and the nitrogen balance are at their highest when the fertilizer allotment is completely used.

Using Table 11, we can compare the effects on net farm income, nitrogen balance, and optimal cropping systems for each commercial nitrogen fertilizer allotment. Comparison of the nitrogen balance and income permits us to assess public gains in terms of reduction in the nitrogen balance and private losses to farmers. Because solutions for the farm model were obtained by establishing both a nitrogen fertilizer allotment and a nitrogen balance at intervals of 2.5 short tons, the optimal cropping systems are approximations; the exact solutions fall between the arbitrarily chosen levels of the nitrogen balance.

By comparing the change between levels V and IV with the change between levels III and II, we can see the relative effects on income and the nitrogen balance. Farm income drops $1,589 (from $34,025 to $32,-436) for the V to IV allotment reduction, and $2,069 (from $30,447 to $28,378) for the III to II reduction. The sacrifice in income for the same absolute reduction in the nitrogen fertilizer allotment becomes greater as the allotment decreases. The corresponding decline in the nitrogen balance between levels V and IV is 6.04 short tons (from 8.54 to 2.50

tons). In contrast, the nitrogen balance declines by only 2.50 short tons (from 2.50 to 0 tons) between levels III and II. Thus the first reduction in allotment, V to IV, is less expensive in terms of income loss than the third reduction, III to II, but more effective in terms of decreasing the nitrogen balance and hence the water pollution potential.

SUMMARY

In this bulletin we examine six control methods that might be used to reduce nitrate concentration in water. We focus primarily on the estimated effects that these methods might have on agricultural production and farm income. Except in the watershed study (pages 26 to 28), we do not consider how effective these various control measures might be in reducing the nitrate concentration in water. Also, we do not analyze the relative costs of administering the different programs. Three basic types of control are considered: education, regulation, and economic incentives.

Education

Education might be a way to reduce nitrate concentration in water if farmers are applying more nitrogen fertilizer than necessary to maximize economic returns. The data available from commercial farms and farm experiments, however, indicate that in terms of the farmer's economic interests there is very little overapplication of nitrogen fertilizer. We concluded that an educational program based on economic self-interest would have very limited value in reducing fertilizer applications and hence decreasing nitrate concentration in water.

Regulation

Regulating the use of nitrogen fertilizer can be accomplished in several ways. First, limits can be established for per-acre application rates for major crops. Some type of surveillance by an administrative agency would of course be needed to enforce these limits. Second, the nitrate concentration in the leachate can be restricted, but again some system of inspection would be necessary to determine if the leachate concentration were acceptable. Third, limits can be placed on the total nitrogen fertilizer available for a single farm, thus permitting the farmer to allocate his quota among crops as he prefers. Enforcement procedures are apt to be simpler for this method than for either of the other two regulatory

methods. In contrast to an educational program, regulation does have the potential for effectively reducing nitrogen fertilizer use. However, the impact on agricultural production and the implications of this impact should be included as a part of the basis for choosing a control method.

Economic Incentives

Two types of economic incentives are discussed in this bulletin: first, a tax on nitrogen fertilizer, which would probably reduce application rates because of the diminishing-returns relationship between the amount of fertilizer applied and the crop yield; and second, a market for rights to purchase commercial nitrogen. Both of these measures would require less administrative supervision, but might also in practice be less effective than direct regulatory methods. Nevertheless, economic incentives have a greater potential for reducing nitrogen fertilizer use than informational programs, which are designed to improve decision making on nitrogen application rates at the level of the individual farm.

Conclusions

Units of analysis varying from the nation to an individual farm were used to assess the changes in crop production and farm income resulting from the various control methods. However, not all of the controls were evaluated at all units of analysis. Although the regulatory controls and the economic incentives have different administrative arrangements, our principal concern in this study has been the consequences to agricultural production if nitrogen fertilizer use were to be reduced, regardless of the method.

Reducing nitrogen rates nationwide to 100 pounds per acre (112 kg./ha.) on corn, sorghum, and wheat would require a very minor increase in acreage to meet either low or high export demands. However, if export demands are high and the nitrogen limit is set at 50 pounds per acre (56 kg./ha.), then 16 percent more land would be required than when there are no limits on fertilizer use. Controls only in Illinois reduce Illinois' competitive advantage in corn production, and even though the nation's soybean production becomes more concentrated in Illinois than under the current no-restriction system, Illinois farmers would experience serious economic setbacks as the level of restriction increases. A 50-pound-per-acre limit in Illinois only, for example, would reduce Illinois farm income about 17 percent, as shown in the national model.

When fertilizer use is initially reduced to a range between 10 and 25 percent, the effects on cropping patterns, acreage requirements, and income are moderate. The impact becomes increasingly severe, however, when nitrogen use is further restricted. In the total-farm analysis, a reduction of 25 percent in the nitrogen allotment causes a decline of about 5 percent in farm income above direct costs, whereas a reduction of 75 percent in the allotment results in an income decline of nearly 20 percent.

Improvements in health and in the quality of the environment are the reasons for examining the effects of various control measures. Therefore, for a complete evaluation of these measures public policy makers should place the production and income consequences of controls side-by-side with the expected benefits. The combined information will then form the base upon which policy decisions can be made.

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