

# Impact of Production Changes on Income and Environmental Risk in the Southern High Plains

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## ABSTRACT

Regional and farm-level analyses are conducted to evaluate the economic and environmental impacts of water quality protection policies. The regional analysis evaluates reducing nitrate losses by reducing per-acre nitrogen use, taxing nitrogen use, taxing irrigation water use, and reducing furrow irrigation. Incentives to convert furrow systems to sprinkler and LEPA systems outperform the other policies. The firm-level analysis derives farm plans that limit the expected values of environmental indices for nitrates and pesticides, and reduce the probability that specified targets will be exceeded. The analysis demonstrates the importance of evaluating environmental risk as a stochastic process.

**Key Words:** converting irrigation systems, environmental risk, environmental risk models, regional environmental analysis, taxing irrigation water, taxing nitrogen use.

For more than a decade there has been considerable public concern over the effects of agricultural chemicals on surface water and groundwater quality. A 1987 report indicates that the drinking water of an estimated 50 million people could be contaminated with pes-

ticides and nitrates (Nielson and Lee). A well-water survey conducted by the Environmental Production Agency found detectable but tolerable levels of pesticides in about 10 percent of community wells and 40 percent of domestic wells (U.S. EPA). There is considerable evidence that some ground-water quality problems are related to agricultural production. In many locations, the public view is that nitrates and pesticides from agriculture have caused substantial environmental damage. Yet little research had been conducted to determine the extent, nature, and potential consequences of water quality degradation from the use of agricultural chemicals.

Funding for research on environmental impacts of agricultural production practices has gone through a cycle similar to, and perhaps related to, public concern. The U.S. Geological Survey (USGS), Environmental Production Agency (EPA), and U.S. Department of Agriculture (USDA) Water Quality Grants

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Program have supported interdisciplinary research on water quality. Numerous recent studies have focused specifically on income and environmental risk associated with the use of nitrates and pesticides in agriculture. Lee provides an excellent review of 21 recent agricultural studies on regional and farm-level impacts. Each of the studies relates agricultural chemical use to groundwater quality and farm income by integrating biophysical models of groundwater loadings with economic optimization techniques (Lee). Two studies mentioned by Lee provide some of the background for this manuscript (Mapp *et al.*; Teague, Bernardo, and Mapp 1995a) and two other studies provide empirical information and support for the conclusions (Wu *et al.*; Teague, Bernardo, and Mapp 1995b).

This manuscript summarizes regional and farm-level analyses of water quality policies in the Oklahoma Panhandle and Southern High Plains. These studies use biophysical models and optimization techniques to analyze water quality policies. The regional analysis evaluates policies to reduce the potential for nitrate pollution. Alternatives analyzed include restrictions and taxes on nitrogen use, taxes on irrigation water use, and incentives to convert conventional irrigation systems to low-pressure systems. The farm-level analysis goes a step beyond most recent studies by comparing the distributions of environmental outcomes achieved using voluntary actions with those achieved under restrictions on both nitrates and pesticides.

### **Regional Analysis of Water Quality Policies**

The focus of the regional analysis is on controlling potential nitrate water pollution in part of the Southern High Plains overlying the Ogallala Aquifer (Wu *et al.*). Several studies have identified parts of this area as having high potential for nitrate water pollution (Nielson and Lee; Kellogg, Maizel, and Goss). Thus, analysis of water quality protection policies is clearly justified.

Because of differences in soils, production systems, and climate, the overall region is di-

vided into northern and southern subregions. Cropland acres total 3.4 million in the north and 3.0 million in the south. Irrigated production accounts for 64 percent and 32 percent of crop acreage in the north and south. Conventional irrigation technology includes furrow and improved furrow systems, while more efficient systems include low-pressure sprinkler and low-energy, precision-application (LEPA) technology. Wheat, sorghum, corn, cotton, and summer fallow account for more than 95 percent of crop acres in both regions. The major cropping systems include wheat-sorghum-fallow rotation, irrigated corn, and dryland and irrigated wheat, sorghum, and cotton. Continuous wheat accounts for more than 80 percent of wheat acreage in both regions. The wheat-sorghum-fallow rotation accounts for 61 percent of sorghum acreage in the north, but only six percent of sorghum acreage in the south. Because of limited irrigation water, very little corn is grown in the south. Cotton is grown on 78 percent of cropland in the south, but on only 21 percent of cropland in the north.

### **Modeling Framework**

The modeling framework for both studies includes a geographic information system (GIS) and a crop growth/chemical transport simulation model. In the regional analysis, data from the GIS and the crop growth/chemical transport model feed into regional linear programming models for each subregion. In the farm-level analysis, the models provide data for an Environmental Target MOTAD model that considers risk from nitrates and pesticides.

The GIS describes the spatial distribution of soils, land use, county boundaries, aquifer boundaries, and aquifer hydrology. Overlying available soil, land use, and aquifer data using EARTHONE software provides estimates of the number of acres of each resource situation in each subregion. These acreage estimates eventually represent some of the resource restrictions in the mathematical programming model.

The impacts of alternative production systems on water quality are evaluated using EPIC-PST. This model was developed by

combining the EPIC model (Williams, Jones, and Dyke) with the pesticide subroutines from GLEAMS (Leonard, Knisel, and Still). EPIC-PST simulates simultaneously the effects of alternative management practices on crop yields and nutrient and pesticide losses due to surface runoff, sediment movement, and leaching below the root zone (Sabbagh *et al.*).

In each subregion, 20 to 30 principal soils account for more than 90 percent of cropland acres. EPIC-PST simulates crop yields, runoff, and percolation rates of each soil under dryland and irrigated cropping practices. Soils with comparable results are grouped into four representative soils for the north subregion and three representative soils for the south. Specific tillage practices including rotations, the quantities and timing of nitrogen and pesticide applications, and irrigation practices are then identified for each crop and representative soil. Each crop, soil, tillage system, irrigation system, irrigation level, fertilizer level, and pesticide strategy represents a unique crop-production activity. For each activity, 20-year EPIC-PST simulations are used to estimate crop production and associated nitrogen and pesticide losses due to runoff from the field and percolation through the root zone.

Producer responses to alternative water quality policies are represented in the mathematical programming models. Responses include crop, fertilizer, tillage, and irrigation decisions. In each subregion, producers maximize returns above operating and irrigation investment costs. Model constraints limit the total land area available for production by soil type and hydrologic situation, total irrigated and dryland production by resource situation, and the acreage of each crop produced on land characterized by various combinations of soil type and hydrologic situation. Irrigation system constraints limit the land area under production using each system, the acres that can convert from one irrigation system to another, and the acres that can convert to dryland production. Additional model constraints limited the quantity of fertilizer and pesticides applied for certain soils and hydrologic situations to represent water quality policies analyzed. The mathematical programming

model for the north has approximately 117,000 activities and 400 constraints, and the model for the south has about 48,000 activities and 300 constraints.

### **Implementing the Regional Analysis**

The four water quality policies analyzed are represented in the mathematical programming models. Under the nitrogen use restriction, the highest nitrogen application rate is identified for each subregion in the absence of water quality policies. Then a nitrogen use restriction, specified as a percentage of the highest application rate, is imposed to achieve each water quality protection goal. The nitrogen use tax corresponds to an increase in nitrogen price, while the irrigation water tax increases water application costs. Converting furrow systems to sprinkler or LEPA systems can be achieved by cost sharing. However, we determine the number of furrow acres that must be converted to achieve a given water quality goal (rather than the amount of cost-sharing necessary to induce the conversion).

### **Baseline Analysis**

The baseline analysis is designed to reflect the current production situation in the study area, and to estimate economic and environmental outcomes in the absence of water quality policies. Annual returns above operating costs, shown in Table 1, are estimated to be \$130 per acre in the north and \$103 per acre in the south. After deducting fixed costs, annual returns to land and management are estimated to be \$87 per acre in the north and \$55 per acre in the south. The higher income level in the north reflects differences in the physical characteristics of the two subregions. Because of limited water resources, crop choices are limited in the south. Cotton is planted on 78 percent of cropland in the south, and very little corn is grown. In the north, crop acreages are more evenly distributed, with wheat, sorghum, cotton, and corn accounting for 39 percent, 24 percent, 18 percent, and eight percent of total crop acres. The baseline results compare very

**Table 1.** Summary of Baseline Results for South and North Subregion

Baseline	Farm Income (\$)	Farm Income +Taxes (\$)	Nitrogen Application (lbs.)	Nitrate Runoff (lbs.)	Nitrogen Leaching (lbs.)	Losses Total (lbs.)
South:						
Total (000)	313,279	313,279	106,570	2,839	1,176	4,015
Per Acre	102.80	102.80	34.97	0.93	0.39	1.32
North:						
Total (000)	438,038	438,038	269,428	16,085	5,764	21,849
Per Acre	130.38	130.38	80.20	4.79	1.72	6.50

favorably with recent crop production practices in both regions.

Average annual nitrogen applications are 80 pounds per acre in the north and 35 pounds per acre in the south. The larger proportion of irrigated acres and the greater intensity of nitrogen applications on irrigated corn contribute to the higher application rates in the north. Annual nitrogen losses in the south, estimated from EPIC-PST simulations, are 0.9 pounds per acre from runoff and 0.4 pounds per acre from leaching (2.7 percent and 1.1 percent of total nitrogen applied). Nitrogen losses are relatively small in the south due to the large acreage of dryland cotton. Annual nitrogen losses in the north are estimated to be 4.8 pounds per acre from runoff and 1.7 pounds per acre from leaching (6.0 percent and 2.1 percent of total nitrogen applied). Nitrogen runoff and percolation rates are much higher in the north due to significant acres of irrigated corn and sorghum and widespread use of furrow irrigation on certain soils.

### Analysis of Water Quality Protection Policies

Baseline results indicate that the potential for nitrate water pollution is much higher in the north subregion. Thus, it could be desirable to seek a larger reduction in nitrogen losses in the north. In fact, high tax rates or strict regulations may not be needed in the south because of the low potential for nitrate water pollution. However, for comparison, the five percent, 15 percent, and 25 percent reductions

in total nitrogen losses are analyzed for both subregions under four policies: (1) reducing per-acre nitrogen use, (2) a nitrogen application tax, (3) an irrigation water tax, and (4) reducing furrow irrigation.

#### *Reducing Per-Acre Nitrogen Use*

Results of reducing per-acre nitrogen use to reduce N losses by 5 percent, 15 percent, and 25 percent in the south and north subregions are summarized in Table 2. To achieve five percent, 15 percent, and 25 percent reductions in N losses, per-acre nitrogen use is reduced by 46 percent, 49 percent, and 59 percent in the south and by 13 percent, 35 percent, and 53 percent in the north. The impact of this policy is somewhat greater in the north, with reductions in farm income and reductions in N losses in leaching exceeding those in the south. For example, to reduce total nitrogen losses by 25 percent, farm income is reduced by 16 percent in the north and by eight percent in the south. N losses in leaching are reduced by 69 percent in the north compared to 10 percent in the south.

The most prevalent producer adjustments to nitrogen use restrictions are to reduce nitrogen applications on irrigated acreage currently receiving applications in excess of the specified limit, to reduce the quantity of irrigation water applied, and to shift irrigated acres across soils and irrigation systems. For example, production of more nitrogen-intensive crops, such as corn and grain sorghum, shifts

**Table 2. Changes Relative to Baseline for Policies Reducing Per-Acre Nitrogen Losses by 5%, 15%, and 25%**

Reduction in N Losses (percent)	Reduction in N Use/Acre (percent)	Restricting Per-Acre N Use				Nitrogen Application Tax				
		Farm Income (\$)	Farm Income +Taxes (\$)	Nitrate Runoff (lbs.)	Losses Leaching (lbs.)	Farm Income (\$)	Farm Income +Taxes (\$)	Nitrate Runoff (lbs.)	Losses Leaching (lbs.)	
										Nitrogen Tax (percent)
South:										
5	46	-3	-3	-4	-7	300	-25	-1	-4	-10
15	49	-4	-4	-18	-9	347	-28	-2	-7	-33
25	59	-8	-8	-31	-10	390	-32	-5	-12	-57
North:										
5	13	-1	-1	-4	-10	130	-20	-1	-6	-2
15	35	-7	-7	-6	-41	286	-42	-3	-12	-24
25	53	-16	-16	-10	-69	340	-49	-8	-20	-39

partly to sprinkler irrigation due to lower nitrogen losses under sprinkler irrigation.

*Nitrogen and Irrigation Water Taxes*

Results of implementing nitrogen and irrigation water taxes to reduce N losses by five percent, 15 percent, and 25 percent are summarized in Tables 2 and 3. Very high input taxes are required to produce desirable environmental outcomes. For example, a 5-percent reduction in total nitrogen losses requires a 130 percent nitrogen use tax or an 85-percent irrigation water use tax in the north. The required tax rates are 300 percent and 313 percent in the south. Nitrogen applications are very inelastic with respect to changes in nitrogen or water prices. These results are consistent with findings in other recent empirical studies on nitrate pollution control policies (Taylor, Adams, and Miller; Johnson, Adams, and Perry).

Producers' responses to the nitrogen use and water use taxes are to reduce nitrogen and water use per acre. Production of the more water and nitrogen intensive crops, such as corn and grain sorghum, are reduced in both sub-regions, and farm income is reduced substantially under either tax policy. For example, a 5-percent reduction in N losses in the north reduces farm income by 20 percent under the nitrogen use tax and by 22 percent under the irrigation water tax; in the south, farm income is reduced by 25 percent and 35 percent under the two input taxes. Achieving 15-percent and 25-percent reductions in N losses would require even greater reductions in farm income.

Comparisons with the first policy reveal that farm income is reduced less under a nitrogen use restriction than under a nitrogen use tax or an irrigation water tax when the policies are used to achieve the same reduction in total nitrogen losses. However, when a nitrogen use tax is used to achieve the 25-percent reduction in N losses, farm income is reduced by 49 percent in the north and 32 percent in the south. Based on these differences in farm income, it appears that farmers would prefer the nitrogen use restriction to the nitrogen use tax.

From society's point of view, however, a

**Table 3.** Changes Relative to Baseline for Irrigation Water Tax and Reducing Furrow Irrigation to Reduce N Losses by 5%, 15%, and 25%

Reduction In N Losses (percent)	Irrigation Water Tax				Reducing Furrow Irrigation				
	Irrigation Water Tax (percent)	Farm Income (\$)	Farm Income +Taxes (\$)	Losses Leaching (lbs.)	Reduction In Furrow Irrigation (percent)	Farm Income (\$)	Farm Income +Taxes (\$)	Nitrate Runoff (lbs.)	Losses Leaching (lbs.)
South:									
5	313	-35	-5	-9	30	-	-1	-8	0
15	400	-42	-10	-16	75	-	-2	-22	0
25	460	-47	-16	-14	-	-	-	-	-
North:									
5	85	-22	-2	-26	20	-	-1	-4	-9
15	123	-30	-3	-47	60	-	-3	-12	-26
25	152	-36	-7	-65	85	-	-4	-21	-38

nitrogen use tax may be more desirable than a nitrogen use restriction because the reduction in social welfare is smaller under the tax than under the restriction. For example, when a nitrogen use restriction is used to reduce total nitrogen losses by 15 percent, farm income plus government tax revenue is reduced by seven percent in the north and by four percent in the south. However, when a nitrogen use tax is used to achieve the same goal, farm income is reduced by three percent in the north and by two percent in the south.

#### Reducing Furrow Irrigation

Results of the policy to reduce N losses by reducing furrow irrigation are presented in Table 3. The analysis indicates that incentives to convert furrow systems to sprinkler or LEPA systems outperform all other policies in both subregions. For example, when this policy is used to produce total nitrogen losses by 25 percent, farm income plus tax revenue is reduced by only four percent in the north. To achieve the same reduction in total nitrogen losses, farm income plus tax revenue is reduced by 16 percent under a nitrogen use restriction, by eight percent under a nitrogen use tax, and by seven percent under an irrigation water tax. This result indicates that a large amount of nitrogen lost in runoff and leaching is from furrow-irrigated production. Partly due to the increased water application efficiency, returns above operating costs increase when furrow-irrigation systems are converted to sprinkler or LEPA systems. Even if producers adsorb all of the irrigation investment costs, their income decreases only slightly. When furrow-irrigated acreage is small, however, this policy may not achieve large reductions in nitrogen losses. The 25-percent reduction goal is not achievable with this policy in the south.

Other regional studies using similar research methods—including those by Randhir and Lee, Thomas and Boisvert, and Helfand and House—have found similar results. However, it is difficult to draw definitive conclusions from other studies because the number is limited and they address different contami-

nants and water-quality protection policies. Also, most studies have focused on a single source of environmental damage, particularly nitrate pollution. Few have considered nitrogen and pesticides within a framework that allows tradeoffs among sources of contamination or environmental effects.

### **Farm-Level Analysis of Water-Quality Policies**

The farm-level analysis compares management-based and regulatory means of protecting environmental quality in a framework that considers pollution from nitrates and pesticides (Teague, Bernardo, and Mapp 1995a). Also, the relative efficiency of water-quality policies is compared based on differences in distributions of environmental outcomes achieved under regulatory and management-based policies. A cost-benefit framework is used to compare income lost versus amounts of pollution reduction achieved. A per-acre nitrogen use restriction and a chemical ban are compared to a management-based protection strategy.

### **Environmental Target MOTAD Model**

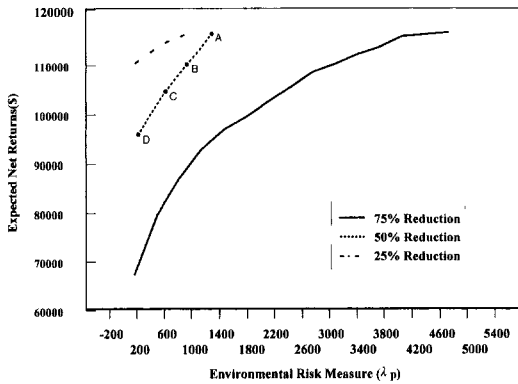
In this analysis, the Target MOTAD formulation developed by Tauer is modified to incorporate the effect of environmental risk (Teague, Bernardo, and Mapp 1995a). An Environmental Target MOTAD model is developed to identify farm plans that maximize net returns, but maintain environmental risk below a critical level or target. Targets are identified for two environmental risk indices, one for pesticides and one for nitrates. The nitrate environmental index (NEI) considers the quantity of nitrate lost in percolation and runoff for each crop activity. The pesticide environmental index (PEI) considers the quantity of pesticide lost in percolation and runoff, the lifetime Health Advisory Level (HAL) set by EPA, the EPA Carcinogenic Risk Category, and the acute toxicity to fish for 96 hours of exposure ( $LC_{50}$ ). The pesticide's lifetime HAL is used as a proxy for threats to human health through groundwater and  $LC_{50}$  is used as a

proxy for threats to aquatic life in surface water. Index values are determined for each activity and state of nature, and deviations above the targets are measured for each index. Surface water and groundwater are assigned equal weights in the estimation of both environmental risk indices. The pesticide and nitrate environmental indices for each production activity are calculated from chemical loading estimates generated by the crop yield and chemical movement model, EPIC-PST.

The Environmental Target MOTAD model can assess tradeoffs between net returns and environmental risk. For each index, both target levels and levels of compliance are set. One way to establish target levels is to solve the model without constraints on the environmental risk indices. These solutions identify the maximum levels of the nitrate and pesticide risk indices over the states of nature. Target levels are then established by reducing these values by 25 percent, 50 percent, and 75 percent. Finally, a net return-environmental risk tradeoff frontier is derived for each target by parametrically varying the average deviation above the target. Solving the Environmental Target MOTAD model produces farm plans that maximize income subject to achieving satisfactory levels of compliance with the target levels of chemical and nitrate environmental risk specified in the analysis. Risk is measured in terms of annual average deviations of the environmental indices above the specified targets.

### **Farm Situation and Data Requirements**

The model is applied to a representative farm in the Oklahoma Panhandle. The farm consists of 1440 acres, 285 in irrigated production and 1155 in dryland production on Richfield clay loam and Dalhart fine sandy loam soils. Irrigated crops include corn, wheat, and grain sorghum; dryland crops are wheat and grain sorghum produced continuously and in wheat-fallow and wheat-grain sorghum-fallow rotations. About 5000 activities are included for each crop to account for differences in soils, fertilizers, pesticides, and irrigation levels. At least six herbicides and six insecticides are included for each crop to represent varia-



**Figure 1.** Tradeoff between environmental risk and expected net returns for targets corresponding to 25%, 50%, and 75% reductions below maximum Nitrate Environmental Index

tions in toxicity, soil half-life, mobility, and effectiveness. Results are presented to compare restrictions on the nitrate environmental risk index, the pesticide environmental risk index, and both indices.

**Restrictions on Nitrate Environmental Risk**

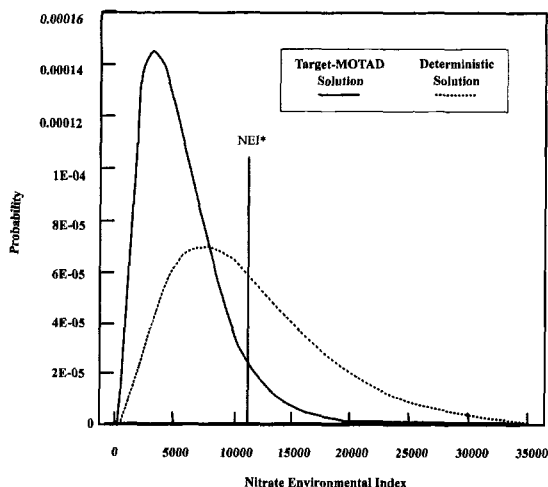
The tradeoff curves for targets corresponding to 25-percent, 50-percent, and 75-percent reductions below the maximum nitrate environmental index from the profit maximizing farm plan are shown in Figure 1. Points A through D correspond to optimal farm plans generated using the 50-percent target level of compliance. Alternative  $\lambda_n$  values represent average deviations above the target. For  $\lambda_n$  values greater than 1200, the Target MOTAD solution is equivalent to the profit maximizing solution (point A) which has expected returns above operating costs of about \$117,000. Expected net returns are relatively sensitive to both the level of the NEI target and the tolerance level of exceeding the target. For  $\lambda_n$  of 800, the profit maximizing plan remains feasible under the 25-percent target level and expected returns total \$117,000. For the 50-percent and 75-percent targets, net returns are reduced to \$111,000 and \$86,000. The slope of the frontier reflects the sensitivity of expected net returns to changes in the tolerance of exceeding the target NEI. At

the 50-percent level, expected returns fall by \$21,000 as  $\lambda_n$  is reduced from 1200 to zero. This sensitivity reflects the frequency and magnitude of annual nitrate loadings in the area. As the environmental target is tightened and  $\lambda_n$  decreases, important crop changes occur. For example, wheat is substituted for sorghum on irrigated acres and irrigated corn shifts from sandy loam to clay loam soils to reduce nitrate loadings.

**Distributions of Environmental Risk**

Most studies have used deterministic measures of environmental risk. To illustrate the importance of considering distributions of environmental risk, we compare solutions from the Target MOTAD model with those derived using deterministic measures of environmental risk. The model is reformulated using the 20-year averages of the indices to represent environmental risk. Two rows of the Environmental Target MOTAD model are replaced with the constraint that the expected NEI index value be equal to or less than a specified limit. In this case, the NEI limit equals the 75-percent reduction ( $NEI^* = 11,627$ ). Based on the optimal farm plan and annual NEI estimates, a 20-year distribution of farm-level NEI outcomes is estimated for the deterministic solution. The 20-year distributions of NEI values for the deterministic and Target MOTAD ( $\lambda_n = 400$ ) solutions are approximated as gamma distributions (Figure 2). Although the deterministic solution produces an expected value of NEI that is below  $NEI^*$ , the probability that a NEI outcome will exceed the target level is nearly 40 percent. In contrast, less than 10 percent of the area under the distribution derived using the Environmental Target MOTAD model lies to the right of  $NEI^*$ . Thus, if water-quality protection policies are based on expected values of environmental damage, without considering the stochastic nature of environmental risk, the probability of environmental damage may be much higher than is suggested by the results. In this analysis, the probability of environmental damage is four times greater under the deterministic risk measure.



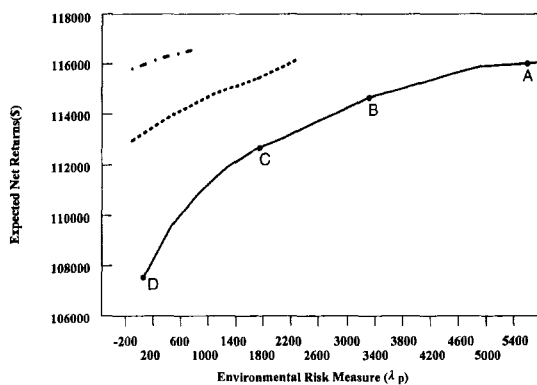


**Figure 2.** Probability distribution of NEI outcomes under deterministic and Target-MOTAD solutions, target NEI = level corresponding to 75% reduction scenario

**Restrictions on Pesticide Environmental Risk**

Tradeoffs between expected net returns and environmental risk from pesticides are shown in Figure 3. Frontiers are presented for targets 25 percent, 50 percent, and 75 percent below the maximum PEI under the profit maximizing plan. Many of the adjustments in farm plans along the frontiers are similar to those under the nitrate restriction. However, substitutions of herbicides and insecticides are also used in meeting reductions in the level of tolerance for the PEI target ( $\lambda_p$ ). Pesticides included in the profit maximizing solution generally have the lowest yield reductions. Several of these pesticides have low HAL or LC<sub>50</sub> values, implying that their runoff and percolation loadings are heavily weighted in calculating the environmental index. As  $\lambda_p$  is reduced, pesticides with less harmful effects enter the optimal farm plan.

A comparison of Figures 1 and 3 indicates that greater opportunity exists to reduce environmental risk from pesticides than from nitrates. Under the 25-percent and 50-percent targets, net returns are reduced by less than \$3500 when going from the profit maximizing solution to a zero tolerance of exceeding the



**Figure 3.** Tradeoff between environmental risk and expected net returns for targets corresponding to 25%, 50%, 75% reductions below the maximum Pesticide Environmental Index

PEI target. Even when the target is reduced to 75 percent, the tolerance limit may be reduced significantly with a small reduction in income. Expected net returns decrease by less than 7 percent in attaining a 75-percent PEI reduction with zero tolerance.

When nitrate and pesticide environmental risk are considered simultaneously by varying  $\lambda_n$  and  $\lambda_p$  from the NEI and PEI targets, the frontiers are similar to those presented in Figure 1. However, they are below the nitrate environmental risk and net returns frontiers due to the increased cost of meeting both pesticide and nitrate restrictions.

**Summary and Conclusions**

The regional analysis indicates that producers would make a variety of adjustments in response to the water-quality protection policies, including reducing nitrogen and water use, making crop substitutions, removing land from crop production, and converting from irrigated to dryland production. These adjustments are closely tied to the unique production setting (e.g., soil, climate, and irrigation system) facing producers. These differences make it difficult to generalize results of this analysis to other regions of the country. However, the results illustrate the importance of representing a wide array of production adjustments

and a diverse set of possible producer responses in water-quality policy analyses.

The farm-level analysis emphasized the importance of considering environmental risk as a stochastic process. Deterministic measures of environmental risk may not indicate a problem, even though a relatively high probability exists that the environmental standard will be exceeded. The farm-level model derives farm plans that limit the expected values of environmental indices and restrict the probability that a specified target will be exceeded. The importance of considering the stochastic nature of environmental outcomes is illustrated by the sensitivity of income to changes in tolerance limits on the nitrate and pesticide environmental indices.

In many ways these analyses represent beginnings rather than final solutions to water-quality protection problems involving agricultural production. In most cases it appears that there will be tradeoffs between water quality improvements and farm income. In many cases water quality can be maintained with little sacrifice in farm income. However, as water quality goals are increased, improvements will likely result in greater reductions in farm income. Public concern over pesticides in ground water can be addressed only by increasing the emphasis on pesticides in future research. Multi-objective analysis that considers nitrates and pesticides and allows tradeoffs among environmental goals should be a high priority. Analysis of site specific management practices to improve net returns should be given high priority for additional funding. Such analyses should consider the stochastic nature of environmental risk, as well as tradeoffs among net return and environmental goals.

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