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Cutting Nitrogen Applications for Improved Water Quality: Does the Farmer Lose?

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Abstract

The nitrate contamination issue caused us to reexamine the relationship between nitrogen applied and profits. Test plot data were used to estimate nitrogen-yield production functions for economic analysis. Results showed (1) why fertilizer may be overapplied, (2) nitrogen may be reduced 20 - 30 percent with little effect on profits, and (3) the test-plot implications are conservative when applied at the farm.

Introduction

The issues of nitrate contamination of groundwater and low-input, sustainable agriculture caused us to take a new look at the relationship between the amount of nitrogen applied and short run profits. In Arizona, where this study was focused, nitrogen applications increased from 140 pounds per acre in 1978 to 198 pounds per acre in 1986. A recent study indicates that some farmers may apply more nitrogen than needed to maximize crop yield. Some evidence of nitrate contamination of wells and public concern caused the Arizona legislature to pass The Environmental Quality Act of 1986. The Act is to reduce the threat of groundwater contamination through better management of nitrogen fertilizer and increased research and educational efforts. Nitrate contamination of groundwater is an issue in several western states, and is likely to become even more pronounced.

We wanted to answer the questions: (1) why might some growers over-apply fertilizer? and (2) what would happen to short run profits if nitrogen applications were reduced? After using test plot experiments to answer these questions, another important question was raised: (3) Are the implications based on experiment station tests valid for the farm?
We answered these questions using test plot data to estimate nitrogen-yield production functions and then do an economic analysis. The results are quite significant, we believe, for reducing nitrogen applications in Arizona.

**Methods and Data**

Ordinary least squares regression was used to estimate nitrogen-yield production functions for each of four crops. Some functions included both nitrogen and irrigation water levels because both inputs were varied in some of the experiments. Several forms of the functions (quadratic, square root and log) were estimated and the forms having the highest adjusted R-squared values used in the economic analysis.

The production functions were used to estimate yield and profit-maximizing levels of nitrogen, and the amount by which profits were diminished as nitrogen levels were reduced from yield maximizing levels. We gave attention to the yield maximizing level because many nitrogen recommendations are currently made on that basis and because there was evidence that some farmers apply at least enough nitrogen to maximize yield.

Data to estimate the functions were from test plot experiments for four of Arizona's most important crops - cotton, wheat, barley and lettuce. The experiments were conducted between 1983 and 1988 by University of Arizona scientists at University experiment stations. The experimental design was either a complete factorial with two to four replications or a central composite rotatable design.

Two nitrogen prices, $0.16 per pound (approximately the current level) and $0.32 per pound were used in a sensitivity analysis. Variable costs were from the 1988 Arizona Field Crop Budgets and the 1987 Arizona Vegetable Crop Budgets (Wade, et al.).

**Results - Production Functions**

Most estimated functions (Table 1) explained variations in yield very well. Most $R^2$ values were .85 or greater. All coefficients except one were statistically significant at the 10 percent level or better, and most were significant at the 1 percent level.

**Results - Why May Farmers Apply Too Much Nitrogen?**

We used the production functions to estimate short run profits as nitrogen was applied beyond the yield maximizing level. This was of interest because, as indicated previously, recent soil tests (Doerge, Farr, and Watson) indicate that in some fields residual nitrogen was high enough to maximize cotton yields the following year. Our analysis shows that applying nitrogen beyond the yield maximizing level, at least up to the point often observed on the farm, has little negative effect on profits. This is true because the production functions tended to be somewhat flat near the apex, and because because the relative cost of nitrogen is so low. For example, nitrogen costs are only about 6 percent of the variable cost of cotton production.

**Results - Nitrogen Reductions and Profits**

The effects of three different reductions in nitrogen applications (reductions of 10, 20 and 30 percent from the yield maximizing level) on yields and net returns (total revenue minus total variable cost) were examined.

**Barley**. Net returns on barley increased slightly as nitrogen applications were reduced by up to 30 percent. Even though yields were slightly reduced with less nitrogen applied, the
Table 1. Crop-Nitrogen Production Functions

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield Function</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>$Y_B, Y_M, S = -21.734 - .015N + .41N^5 - .604W + 7.605W^5$</td>
<td>.92</td>
</tr>
<tr>
<td>Cotton</td>
<td>$Y_C, Y_M, S, 1 = -2.12 + .0106N - .00002N^2 + 0.119W - .00026W^2 + .000044WN$</td>
<td>.95</td>
</tr>
<tr>
<td>Lettuce</td>
<td>$Y_L, Y_M, S = -734.454 + 11.572N - .018N^2$</td>
<td>.55</td>
</tr>
<tr>
<td>Wheat</td>
<td>$Y_W, Y_M, S = -20.349 - .024N + .78N^5 - .455W + 5.743W^5$</td>
<td>.77</td>
</tr>
<tr>
<td></td>
<td>$Y_W, M, SL, 85 = 3683.843 + 18.007N - .03N^2$</td>
<td>.85</td>
</tr>
<tr>
<td></td>
<td>$Y_W, M, CL, 87 = 3918.243 + 18.377N - .039N^2$</td>
<td>.95</td>
</tr>
<tr>
<td></td>
<td>$Y_W, M, CL, 86 = 2699.195 - 16.826N + 446.396N^5$</td>
<td>.96</td>
</tr>
</tbody>
</table>

Note:
- $Y_B, Y_M, S$ = barley yield at Yuma Mesa on sand in tons per acre.
- $Y_C, Y_M, S, 1$ = cotton yield at Yuma Mesa on sandy soil, variety 1, in bales (500 lbs) per acre.
- $Y_C, Y_M, S, 2$ = cotton yield at Yuma Mesa on sandy soil, variety 2, in bales (500 lbs) per acre.
- $Y_L, Y_M, S$ = lettuce yield at Yuma Mesa on sand in cartons of marketable lettuce per acre.
- $Y_W, Y_M, S$ = wheat yield at Yuma Mesa on sand in tons per acre.
- $Y_W, M, SL, 86$ = wheat yield at Maricopa on sandy loam in 1986 in tons per acre.
- $Y_W, M, SL, 85$ = wheat yield at Maricopa on sandy loam in 1985 in tons per acre.
- $Y_W, M, CL, 87$ = wheat yield at Maricopa on clay loam in 1987 in tons per acre.
- $Y_W, M, CL, 86$ = wheat yield at Maricopa on clay loam in 1986 in tons per acre.
- $W$ = water applied (w/ effective rainfall) from preplant to harvest, in inches.
- $N$ = actual nitrogen applied in pounds per acre.
- $WN = W \cdot N$
- $R^2$ = coefficient of determination adjusted for degrees of freedom.

- *** = coefficient is statistically significant at the one percent level.
- ** = coefficient is statistically significant at the five percent level.
- * = coefficient is statistically significant at the ten percent level.
lower costs of nitrogen fertilizer and associated harvest costs more than compensated for the decreased total revenue.

Cotton. Cotton yields were reduced 2 - 3 percent by reductions in nitrogen of up to 20 percent and even with a 30 percent reduction in nitrogen from the yield-maximizing level, yield was reduced by only 5 - 7 percent. With nitrogen costing $0.16 per pound, net revenues (total revenue minus total variable costs) were reduced 2 - 4 percent with a 20 percent reduction in nitrogen, and 7 - 11 percent with a 30 percent nitrogen reduction. With higher priced nitrogen ($0.32 per pound), the negative effect of lower nitrogen levels was less and even caused net revenues to increase in some cases.

Lettuce. Lettuce yields and net returns were more sharply affected by large reductions in applied nitrogen. Although a 10 percent reduction in nitrogen resulted in about a 2 percent reduction in yield and net returns, a 30 percent reduction in nitrogen caused yield to decline by almost 15 percent and net returns to decrease by over 22 percent. The price of nitrogen had little effect on the percentage decline in net returns, because the cost of fertilizer is such a small share (about 5 percent) of the total variable costs of growing lettuce.

Wheat. Wheat yields were reduced only marginally — 4.1 percent at most — as nitrogen was reduced up to 30 percent from the yield maximizing level. This small yield effect was true in all five wheat experiments. Net returns actually increased in nearly all the experiments and for nitrogen priced at both $0.16 and $0.32 per pound. The single exception was for the Yuma Mesa, sandy soil experiment — when nitrogen was reduced 30 percent, net returns were reduced 1.8 percent.

In general, though, reductions in nitrogen of up to 30 percent caused net returns to increase marginally when the price of nitrogen was $0.16 per pound, and caused net returns to increase by as much as 12.7 percent when the price of nitrogen was $0.32 per pound.

Test Plot vs Farm Level Implications

These results are based on test plot experiments conducted at university experimental farms. The results suggest that nitrogen can often be reduced by 20 - 30 percent from yield maximizing levels with little or no negative effect on short run profits. But what about at the farm level where conditions may differ from those at the experiment stations? The first reviewers of our results were concerned about differences in residual nitrogen in the soil, nitrogen occurring naturally in the irrigation water, timing of nitrogen applications and nitrogen application “efficiency.” Here we show why at the farm level our results are probably conservative: i.e. nitrogen can likely be reduced by even more than 20-30 percent (for cotton, barley and wheat) with little or no effect on profits.

Differences in Residual Soil and Water Nitrogen. Consider first the case of residual soil nitrogen and nitrogen occurring naturally in the water. There is strong reason to believe that the level of residual soil nitrogen was less at the experimental sites than on many farms. Many on-farm experiments conducted by University of Arizona extension agents have shown no yield response to nitrogen applications and attributed this lack of response to high residual soil nitrogen. Further, a 1986 study of 20 cotton fields in Maricopa County (Maricopa County is Arizona’s largest producer of cotton) found that many of the fields contained sufficient residual nitrate to produce maximum expected yields for a following crop of cotton (Doerge, Farr, and Watson).
Consider the production function \( Y(E) \) in Figure 1A, where \( Y(E) \) is the production function showing yield response to nitrogen at the experimental site with low residual soil nitrogen. The effect of a higher residual soil nitrogen (the farm) is to shift the production function exactly parallel and to the left, as shown by \( Y(F) \). The values of marginal product (VMPs) for these two production functions are parallel and shown at the bottom of panel A. For simplicity, assume the price of nitrogen \( (P_n) \) cuts the VMP(E) curve at \( W \) and is an amount 30 percent less than the yield maximizing amount \( OZ \). The 30 percent cut from the yield maximizing level is just enough to maximize short run profits for the experimental plot. What can be said about a 30 percent cut in nitrogen from the yield maximizing level on the farm where residual soil nitrogen is greater? Since VMP(F) is parallel to VMP(E), and the price line is horizontal, the reduction in applied nitrogen necessary to maximize short run profits on the farm is the same as at the experimental site; that is, \( JK \) is the same as \( WZ \). Since \( OK \) is less than \( OZ \), a 30 percent reduction from \( OK \) is less than \( JK \). Thus, cutting the farm applications of nitrogen by 30 percent from the yield maximizing level is not enough: profits would be increased by even further reductions!

**Differences in Timing of Application.** University scientists attempted to time fertilizer applications to best meet plant needs. In the case of cotton, petiole analysis was used to determine when nitrogen was needed. Most farmers do not currently apply nitrogen in such a timely fashion. How does this difference affect the implication that profits will not be harmed if nitrogen applications are reduced 20-30 percent from yield maximizing levels?

Consider panel B of Figure 1. If nitrogen is applied in a more timely fashion, we expect a higher yield for any level of nitrogen, at least within a reasonable range of nitrogen application. Further, we expect that the maximum yield will occur at a lower level of nitrogen if it is applied in a timely manner than if it is not. These assumptions, based on many years of observation and experience, are reflected in the production functions and associated MVPs. Again, for expository purposes, assume the price of nitrogen as indicated by \( P_n \). If nitrogen at the experimental site with a high level of timing accuracy is cut from the yield maximizing level \( OB \) to the profit maximizing level \( OA \), that is a percentage reduction in nitrogen of \( ab/ob \). How does this compare with cutting nitrogen from yield maximizing to profit maximizing at the farm with a lower level of timing accuracy? If \( ab/ob \) is less than \( cd/od \), then the implication that the farm can cut nitrogen by the percent \( ab/ob \) from the farm’s yield maximizing level is conservative. This is precisely the case. Consider that:

\[
\begin{align*}
(1) \quad og/ob &= ah/ab, \text{ so that } ab/ob = ah/og, \text{ and } \\
(2) \quad of/od &= ck/cd, \text{ so that } cd/od = ck/of, \text{ and } \\
(3) \quad ah &= ck. \\
(4) \quad \text{Since } ah &= ck, \text{ and since } og > of, \text{ then } \\
\quad ah/og &< ah/of, \text{ or } \\
\quad ah/og &< ck/of, \text{ and from (1), (2), and (4) above, } \\
(5) \quad ab/ob &< cd/od.
\end{align*}
\]

Therefore, the implication to cut farm applications by \( ab/ob \) is conservative.
Figure 1. Experiment Station vs. Farm Conditions

A
Different Residual Soil & Water Nitrogen

B
Different Timing of Application

C
Different Application Efficiency
Differences in Application Efficiency. University scientists tried to apply fertilizer in a physically efficient manner. That is, they attempted to avoid leaching the fertilizer beyond the root zone. Most farmers may not be as efficient in their fertilizer applications since their fields are much larger than experimental plots and water-run nitrogen fertilizer can be lost due to over irrigation or poor irrigation application efficiency. This situation is changing in Arizona as water has become more expensive to pump and many farmers have laser leveled their fields to attain greater field application efficiency of irrigation water. Still, it is likely that the physical application efficiency at the experiment stations was greater than on most farms. Under, this scenario, we expect a higher output for any particular level of nitrogen, up to a point, and that yield will be maximized at a lower level of nitrogen application if it is applied more “efficiently” than if less efficiently. The maximum yield may be the same, given that enough fertilizer is applied to overcome inefficient application. Panel C reflects these assumptions. Since the MVPs are essentially the same as the case just analyzed in panel B, our conclusion is the same. Again, our implication for reducing fertilizer without harming profits is conservative under most farm conditions.

Summary and Conclusion

Nitrogen contamination of groundwater is likely to become an even greater issue. There is considerable interest in reducing nitrogen applications in agriculture, both through regulation and through research and education. In our research, we utilized test plot experiments showing yield response to nitrogen to show why farmers may over-apply fertilizer and how profits are effected by reduced nitrogen levels. The results support the explanation that fertilizer is over-applied because it is inexpensive to do so — the added nitrogen is inexpensive and yields are not greatly affected. Thus farmers may inexpensively over-apply nitrogen to reduce the riskiness of not knowing what their yields would be at lower nitrogen levels. Our study should help reduce this risk. We also found that for three of Arizona’s most important crops, nitrogen applications could be reduced by at least 20-30 percent from yield maximizing levels with little or no negative effect on short run profits. Since supplemental evidence shows that many farmers apply at least enough fertilizer to maximize yield, this result seems quite significant. It suggests that education should have a significant effect in reducing applications.

Finally, our analysis addressed the issue of whether or not our implications based on experiment station test plots could be applied to the farm. In particular, we were concerned about how differences in residual soil and irrigation water nitrogen, differences in the timing of application, and differences in application efficiency, which likely exist between the experiment stations and farms, would effect the results. The test-plot implication that nitrogen could be reduced 20-30 percent with little effect on profits is shown to be conservative when applied to likely farm conditions.
References


Roth, Robert and Bryant Gardner, unpublished data from files, Yuma Mesa Experiment Station, The University of Arizona, Yuma, 1988.

