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Simulated Nitrogen Loading from Corn, Sorghum, and Soybean Production in the Upper Mississippi Valley

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ABSTRACT

Nitrogen moving in runoff water and sediment from cropland in the Upper Mississippi River Valley is thought to be one of the contributors to hypoxia in the Gulf of Mexico. The effects of reducing nitrogen fertilizer on corn and sorghum in the Upper Mississippi River Valley to the point that the crop suffers nitrogen stress during five and ten percent of the growing season were simulated. Effects shown included possible changes in N fertilizer use, nitrate and organic N losses, soil erosion, crop yields, crop prices and production levels, and nitrate loadings in the major rivers of the Valley.

The ten percent stress level could reduce fertilizer by about 30% and N transport in the Upper Mississippi and Ohio rivers by about three percent while having only a modest impact on agricultural prices and income. The modest economic impact would be due to the net effect of reduced fertilizer expenditure and increased crop prices as crop yields are reduced. Farmers in the area could be grouped according to whether the policy increases or decreases individual profits. For the 10% stress level, aggregate profits could increase by $307 million for the gainers while the group with losses could experience a $314 million decrease. The impact of nitrogen stress induced reductions in crop growth may result in slight increases in soil erosion.

INTRODUCTION

Issues such as hypoxia in the Gulf of Mexico are so environmentally and economically complex that they may appear to be nearly impossible to address. Holistic analysis of this issue through measurement and monitoring would be prohibitively expensive. An alternative is to use combinations of environmental process models and regional/national economic models to simulate the impacts of alternative policies. A more limited set of measured impacts can be used to validate the reasonableness of the results. This analysis uses a combination of two process models, Erosion Productivity Impact Calculator (EPIC) (Williams et al. 1984) and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993; Srinivasan et al., 1995), to simulate the impact of field level management decisions on nutrient and sediment loadings at the large watershed scale.

The field scale model EPIC was originally developed to analyze the impacts of erosion on crop yields as part of the 1985 Resource Conservation Assessment. Since that time, it has had numerous additions and enhancements to improve its applicability to various natural resource and crop management issues. The input data used in simulation runs reflect independent, small and homogenous units of climate, soil, management practice, land use and topography, and the simulation results refer to the edge of field.

Most of the subroutines in the routing model SWAT are similar to the EPIC model, but it has additional modules to address hydrology, sediment, and nutrient transport at the large watershed scale. The SWAT model considers the interrelations of homogenous sub-regions of a watershed (*upstream - downstream effect*). These modules make it possible to simulate the complexity and diversity of large watersheds such as river basins and lakes. The hydraulic components of SWAT are designed to "collect" the water from land areas and route it through the natural and modified stream, lake, reservoir, and river system. Surface water runoff is combined with groundwater return flows from lateral flow through the root zone and from shallow groundwater aquifers. Typical stream flow velocities are estimated from slope, channel shape, and roughness characteristics. Typical groundwater return flow rates (lag times) are estimated from the analysis of recession hydrographs derived from representative stream gauge records. A generalized reservoir inflow-outflow relationship has been developed to simulate changes in lake and reservoir storage through time.

In addition, the Agricultural Sector Model (ASM) (McCarl et al. 2000) estimates price impacts of resulting crop production and land use changes on regional, national and international agricultural commodity markets. The ASM maximizes total economic surplus and simulates the market and trade equilibrium in agricultural markets of the U.S. and 28 major foreign trading partners subject to constraints from domestic and foreign supply and demand conditions, and resource endowments. The market equilibrium reveals commodity and factor prices, levels of domestic production, export and import quantities, agricultural welfare distribution, adoption of specific management alternatives, resource usage, and a wide variety of environmental impact indicators. The model portrays farmers' choices across 63 U.S. regions among a wide variety of detailed crop and livestock management options including tillage, fertilization, irrigation, and manure treatment alternatives.

The Upper Mississippi River drainage area encompasses most of the Corn Belt region of the United States. It has been suggested that a reduction in the application of nitrogen fertilizer in this area may considerably reduce the size of the hypoxic zone in the Gulf of Mexico. This simulation analyses examines reductions in N application that would

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result in small decreases in expected yield to determine both the potential reduction to nitrogen loading in the Mississippi River and the economic impacts for that region.

METHODOLOGY

The environmental analysis used EPIC model to simulate N movements at the edge of field under alternative tillage and nutrient management systems. Representative cropland soils were selected for each region of the ASM for 3 soil erodibility groups (severely erodible, moderately erodible, and low erodible) and wet soils. The primary crops grown in this region are corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.]. Grain sorghum [*Sorghum bicolor* (L.) Moench], oats (*Avena sativa* L.), wheat (*Triticum aestivum* L.), other close grown grains, hay and pasture account for the remainder of the managed farmland. This analysis was limited to corn, grain sorghum, and corn-soybean in rotation because these cropping systems accounted for most of the fertilizer use in these watersheds. EPIC simulated yields and nitrogen application rates with expected nitrogen stress 1% of the growing period are similar to those reported by the National Agricultural Statistics Service for the Corn Belt region.

The analysis was broken into the following steps:

1. Simulation of corn, grain sorghum and corn-soybean cropping system in the 15 ASM regions included within the states of Ohio, Indiana, Illinois, Iowa, Minnesota, Wisconsin, Nebraska, and Missouri on each soil group using conventional, conservation, and no-till tillage systems[1] in combination with 3 alternative nitrogen management systems. Grain sorghum was only simulated in the regions where it accounted for a large percentage of crop acreage.
2. An analysis of the statistical significance of tillage and nutrient management on nitrogen movement in surface runoff using Statistical Analysis System (SAS) regression analyses.
3. An analysis of the statistical significance of nitrogen management on crop yields using SAS regression analyses.
4. An analysis of the statistical significance of tillage and nutrient management systems on nutrients in sediment using SAS regression analyses.
5. The National Resources Inventory (www.nhq.nrcs.usda.gov/CCS/NRIrlse.html) database was analyzed to determine the statistically estimated total acreage planted in each crop to attach to each of EPIC simulation results to estimate total change in nutrient and sediment movement and crop yields.
6. The next step was to use this information as input into ASM to assess the potential impacts of these changes in production in the Upper Mississippi Valley area on crop prices, farm income, regional production shifts, and the resulting environmental impacts on other regions of the United States.
7. The final step was to use the SWAT model and the database developed by Hydrologic Unit Modeling of the United States (HUMUS) (Srinivasan et al., 1993) project to estimate downstream impacts.

EPIC Simulation Results

Approximately 1500 EPIC simulations were run to estimate the environmental and crop productivity impacts of the combinations of tillage and nutrient management systems. These data were summarized and analyzed using regression analyzes. The regression analyzes identify shifts in N in runoff and sediment, crop yield, and N application rates by soil group relative to conventional tillage, very low N stress management, on severely erodible soils through the use of dummy variables. The three nutrient management systems were based on the average percent of the growing season that the crop was estimated to have N stress. Very low N stress was defined as having only one 1% of the growing season with the crop suffering from N stress; low N stress allowed 5 percent; and moderate N stress allowed 10 percent. The results follow.

1. The corn and corn-soybean cropping systems had statistically significant simulated reductions in N in runoff at greater than a 99 % confidence level. The grain sorghum also had significant reductions; however, the low N stress reduction was significant only at a 90 % level.
2. Nitrogen runoff was also significantly reduced in the simulations for corn and corn-soybean but not for grain sorghum. The lack of significance on grain sorghum may be due to fewer regions being simulated and more homogeneity of soils or due to water stress overriding N stress since sorghum is grown in the more rainfall limited areas.
3. Tillage was not found to significantly impact N in runoff in these simulations.
4. Crop yields were reduced significantly with simulated moderate N stress management, but with less than 90 percent confidence at the low nitrogen stress level. Yields were significantly different for some but not all soil groups for corn, corn-soybean, and grain sorghum systems. Tillage was not found to significantly impact yields for these crops in this area.
5. Organic N movement with sediment was significantly reduced by no-till tillage for all combinations used in this simulation. Conservation tillage also reduced nutrient movement in sediment; however, the statistical confidence level of the simulation was usually lower.
6. Nitrogen application rates were statistically lower for all crops for both the low and moderate stress management systems used in this simulation.

Figures 1 through 3 indicate that 10 to 40% reductions in nitrogen in runoff might be attainable with less than 4% reductions in yield with the low N-stress management. However, the differences in crop yield were not statistically significant in most cases. The moderate N-stress management could have reductions of over 50% in some cases; however, yield reductions could be higher and significantly different.

[1]The definitions of conventional, conservation, and no-till operations are based on survey data collected as part of the Economic Research Services on Cropping Practices.

Nitrogen fertilizer application could be reduced by 18 and 25 pounds per acre on average for the 5 and 10% stress scenarios, respectively (Table 1). Crop rotation could have a large effect on potential pollution of water by nitrates. The percentage reductions of nitrate in runoff for continuous corn and grain sorghum could be more than double that for the corn-soybean rotation.

Extending the EPIC Results to the Regional Total

The EPIC per-acre results were multiplied by crop acreage estimate data from the 1992 National Resource Inventory (NRI) and Conservation Technology Information Center (CTIC) to produce the regional results. The NRI data includes the current crop, previous crop, soil group, and whether or not a conservation tillage system was used for each survey point. Since the NRI data did not show what type of conservation tillage was used, data from the CTIC survey was used to determine the proportions on zero tillage and other conservation tillage. Based on the NRI data, the corn and soybean rotations simulated with EPIC represented 81% of the corn and soybean acreage in the study area (Table 1).

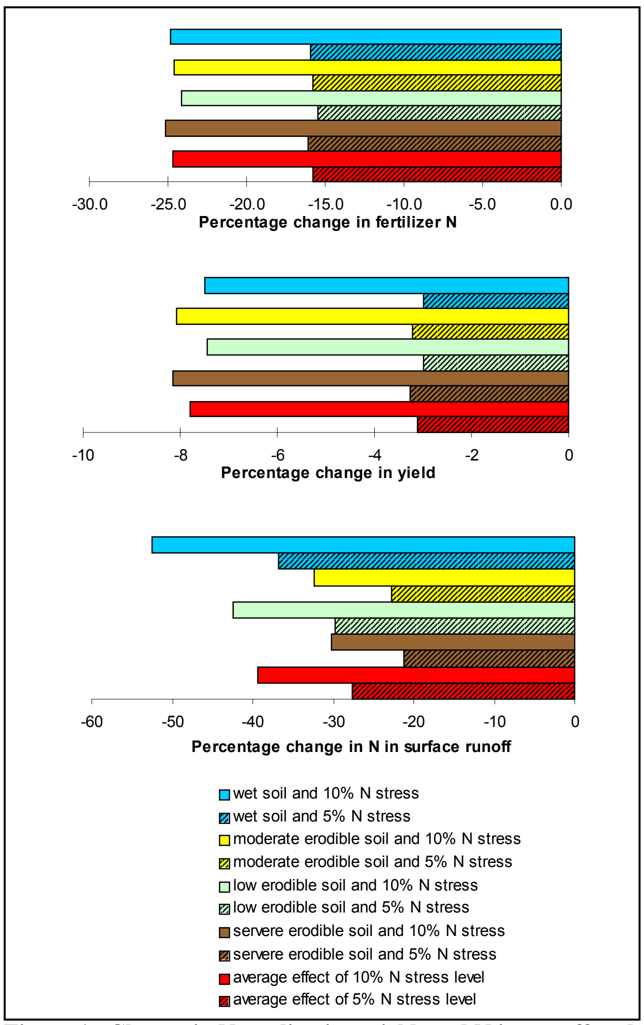

Figure 1. Change in N application, yield, and N in runoff under alternative N stress levels relative to1% N stress in continuous corn.

Estimated Agricultural Sector Impacts of the Nitrogen Reduction Scenarios.

The Agricultural Sector Model (ASM) was used to estimate economic impacts of the 5 and 10% stress scenarios. It was assumed that all the corn, soybean, and sorghum acreage in the study area grown in continuous corn, corn-soybean, and continuous sorghum rotations were affected by the nutrient use policy that encouraged nitrogen stress risk taking and so received reduced N fertilizer and suffered the yield losses estimated with EPIC. Within each sub-state production region, irrigation and alternative conservation production practices were simulated for each crop on each of four representative soils. For each production region and representative soil, acreage information from the NRI was used to calculate average changes in yields and fertilizer use for corn, soybeans, and sorghum based on the EPIC results. The ASM per-acre coefficient changes were smaller than the EPIC results since the ASM includes all production of corn and soybeans while only continuous corn and corn-soybean rotations were assumed affected by the policy.

Nitrogen stress scenarios could have only a small economic effect on corn producers for either the nation or for the Corn Belt. There are three main reasons for this:

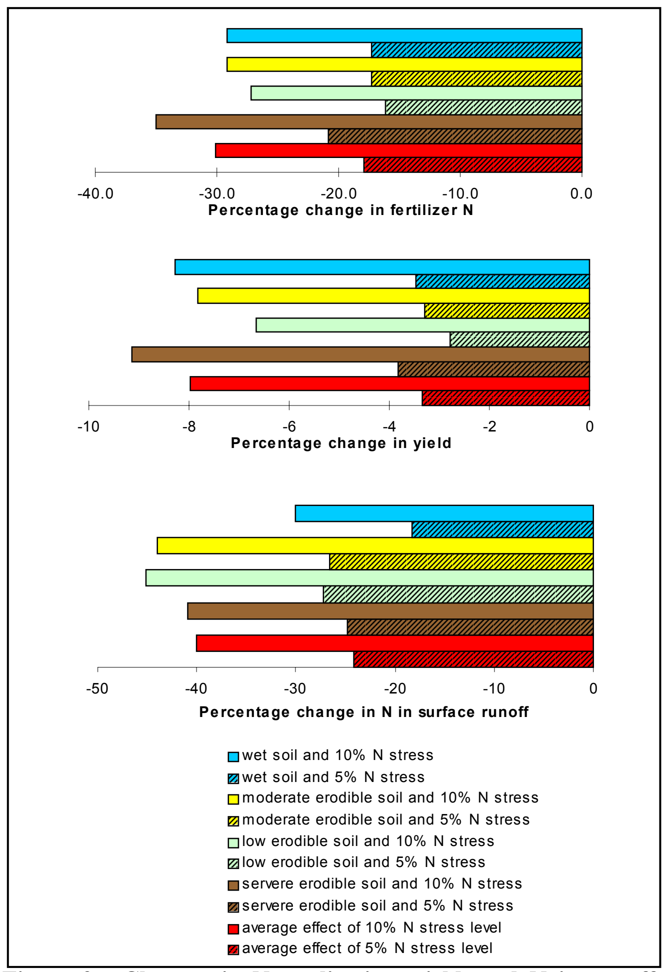

Figure 2. Changes in N application, yield, and N in runoff under alternative N stress levels relative to 1% N stress in continuous sorghum.

Table 1. Potential effects in the Upper Mississippi Valley of nitrogen in fertilizer reduction based on N-stress levels compared to 1%[a] N stress.

	5% stress level	10% stress level
Change in nitrogen applied	(percent)	
Continuous corn	-17	-27
Corn-soybean rotation	-30	-40
Continuous sorghum	-19	-32
Combined area weighted effect	-24	-34
Change in crop yield		
Continuous corn	-3.3	-8.8
Corn in corn-soybean rotation	-2.1	-4.3
Soybeans in corn-soybean rotation	-0.4	-0.4
Continuous sorghum	-3.5	-8.6
Change in nitrogen runoff from fields		
Continuous corn	-23	-34
Corn-soybean rotation	-10	-14
Sorghum	-25	-42
Combined area weighted effect	-14	-21
Change in sheet and rill erosion rates[b]	0.1	0.2
Overall change in crop producers' welfare in U.S.[c]	1.69	3.63
Change in crop producers' welfare in the study area	1.71	3.42
Percentage of farmers in study area who might benefit	44	59
Percentage of farmers in study area who might lose profits	56	41
Change in the portion of U.S. consumers' welfare associated with consumption of agriculture sector products	-0.04	-0.12

Note: Calculated on the assumption the 1992 crop acreage distribution remains constant for the scenarios.
[a]Percentage of time during growing season that crop is under nitrogen stress.
[b]Changes in erosion rates are caused by reduced crop residue.
[c]Due to fertilizer savings and crop price increases.

Table 2. Estimated changes in profit due to reduced nitrogen fertilizer.

	5% stress		10% stress	
	Acres	Profits	Acres	Profits
	(million)		(million)	
Negative	42.4	-$129.5	30.7	$-314.3
Positive	33.4	$113.1	45.1	$306.9
Net profits		-$16.4		-7.4
Total acres	75.8		75.8	

1. The demand for corn, soybeans, and sorghum is relatively inelastic so that as the yield reduction reduces delivery to the markets, the price response is nearly large enough that revenue is maintained.
2. The factors leading to the choice of the corn-soybean rotation are so large in the Corn Belt, that even a 4% reduction in the corn yield doesn't alter that choice.
3. The Corn Belt has such a large comparative advantage in corn and soybean production over other regions that the advantage is maintained even as higher prices stimulate production increases in other regions.

Estimated per Acre Profit Changes (required incentive payments)

Simulated profits accounted for changes in revenue and variable cost. Welfare estimates were changes in producer surplus for suppliers of the various land, water, and labor resources (Table 2). Also, producer surplus included the return to labor used in livestock production as well as the producer surplus associated with livestock supply functions. Consequently, the simulated welfare changes were not comparable to the profit changes (Table 2). Results were averaged for each crop rotation by sub-state region and by soil group.

The changes in profit shown in Table 2 were calculated as follows, and were positive in many situations (situations defined as specific sub-state area, cropland class, tillage method, and crop rotation):

(base price*base yield) – (scenario price*scenario yield) + nitrogen savings.

If the conditions shown in Table 2 were placed on U.S. crop producers, the long-term response elsewhere in the world could be to increase production because of higher prices. Consequently, the eventual effect for U.S. producers as compared to current conditions might be lower yields and production with constant prices, resulting in losses for most producers.

The 10% stress scenario could seemingly be less expensive to implement than the 5% stress scenario if it assumed that 100 % of the farmers participated fully (Table 2). This scenario would be less costly to farmers because crop prices increases and would more than offset crop yield losses.

Watershed Impacts of Changes in Nitrogen Management

Potential changes in nutrient concentrations and flows in local watersheds and in major rivers in the Corn Belt area were estimated with SWAT. Nutrient management analyses were based on N stress approach similar to the one used in the EPIC simulations. The results of the watershed analysis indicated that the reductions in NO_3-N from the corn, grain sorghum, and corn-soybean rotation fields may result in less than a 5% reduction in total N downstream (Figure 4). The 5% reduction was based on total N, which included organic N in sediment. The EPIC results indicated little change in sediment but significant change in NO_3-N in runoff. Nitrate-N is the form most available to aquatic plants. The percent change of NO_3-N in the water could exceed 10%.

These analyzes indicated that cropland agriculture is only one of a number of sources of N flowing into the Gulf of Mexico. Programs to encourage farmers in the Upper Mississippi Valley to apply less N and accept more risk of yield reduction may result in little if any loss of economic welfare. However, wide spread adoption of a reduced N application practice would be necessary to attain the price response necessary to offset reduced crop yields in some years. A public support program would likely be necessary to share short-term economic risks and to encourage the broad level of adoption necessary for this type of change in farm practices to be effective.

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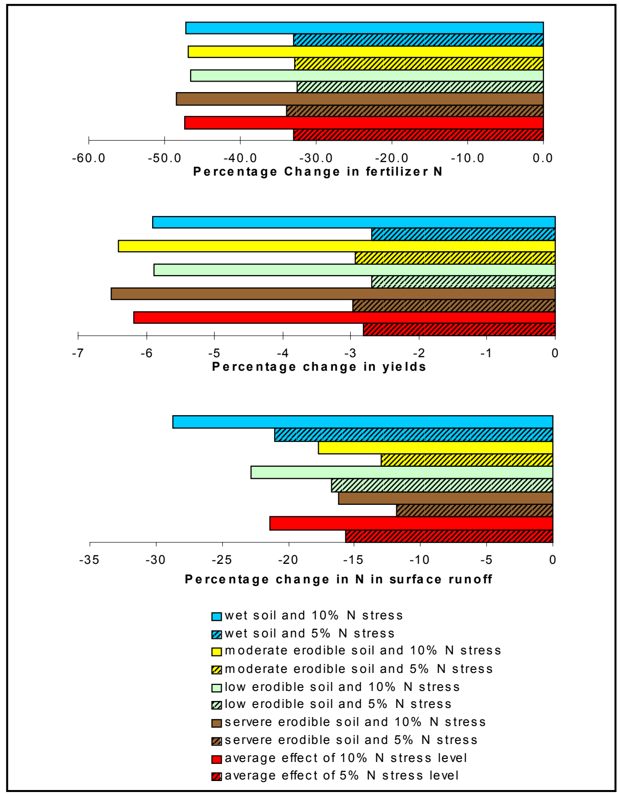

Figure 3. Changes in N application, yield, and N in runoff under alternative N stress levels relative to 1% N stress in corn-soybean rotation.

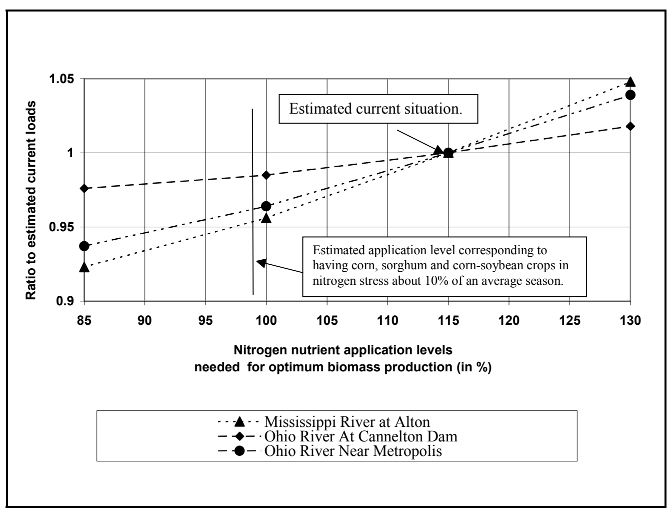

Figure 4. Changes in loads of nitrogen nutrients in downstream rivers to be expected by imposing changes in nitrogen fertilizer application rates.