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Water Quality Impacts of Best Management Practices under Environmental and Equity Constraints in the Mississippi Watershed

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Background

Modern agricultural systems depend on the use of natural resources and a wide range of industrial inputs such as fertilizers and pesticides. Agricultural cultivation, combined with use of chemical inputs, can impose significant damages to environmental quality in the form of soil erosion, waterways sedimentation, and chemical runoff.

To lessen the environmental problems associated with agricultural production, a number of programs have been introduced to directly limit environmental degradation, including the Conservation Reserve Program (CRP) that offers annual rental payments and cost-share assistance to farmers in an exchange for setting aside some portion of land (USDA, 1998). Recently, Total Maximum Daily Load environmental standards (TMDL) have come under consideration to reduce environmental runoff of nutrients, chemicals and sediment. Best management practices including crop rotations and alternative tillage practices (no-till and conservation tillage) may help farmers comply with TMDL rules. Levels of BMPs adoption will ultimately depend on the impact of such conservation practices on farm profitability.

A number of studies have been conducted to investigate runoff reduction and profitability associated with alternative practices, using either experimental plot data or simulation models. To analyze profitability of different fixed rotation and input combinations, Funk et al. (1999) used 8 input combinations of commercial fertilizer, insecticides, and herbicides on a research plot utilizing corn, soybean, and a corn/soybean crop rotation in the Brazos River Bottom Research Farm of Texas. They found that input combinations that do not fully utilize levels of fertilizer, pesticides and herbicides (e.g., fertilizer-insecticide-no herbicide, fertilizer-no insecticide-herbicide, fertilizer-no insecticide-no herbicide) consistently ranked among the highest of expected net returns and were the preferred input strategy for corn-soybean rotation systems. In a similar fashion, Helmers et al. (1986) used experimental test plots on thirteen cropping systems in East Central Nebraska, and found that row crop rotations had higher returns than continuously grown crops, and a corn-soybean rotation system was more stable, in terms of net returns, than continuous corn or soybeans. Using experimental data on 3 pest management systems and 2 tillage practices for 3 cropping systems, Zavaleta et al. (1984) found that corn/soybean rotations had higher yields and higher net returns than either continuous corn or soybeans. In addition to crop rotations, no-till practices have been shown to reduce soil erosion, while causing no significant reduction in crop yields. (Phillips et al. 1993).

To reduce environmental damages resulting from traditional agricultural cultivation, conservation practice, including minimum and no-till operations, have been adopted by some farmers. No-till operations have the potential to reduce erosion by up to 90% and conserve 2-4" of soil moisture for dryer periods (USDA). Despite the benefits of conservation tillage practices, they have not been widely adopted by farmers. It is hypothesized that adjustment costs associated with equipment replacement and risk aversion regarding yield uncertainty under this technology could play significant roles in low adoption rates. Krause and Black (1995) examined the factors affecting no-tillage technology adoption of representative farmers in Michigan, and found that risk averse farmers would wait until their current conventional planters had aged many years before adopting no-tillage technology, mean yields constant across the two technologies. For profitmaximizing representative farmers, adoption is quicker if it is assumed that there is no learning curve. Ultimately, acceptance and optimal implementation by farmers will depend on the effect of conservation tillage on farm profits.

In addition to minimizing loss in net return due to an implementation of environmental restrictions, the equity impact of such policies should be considered. Changes in net return bought on by environmental restriction may vary from farm to farm, depending on soil characteristics, topography, etc. To investigate watershed level impacts of such policies, in our optimization model, the equity constraint of equal per acre profit for each farm will be simultaneously imposed with environmental restrictions.

To evaluate the full scope of economic and environmental impacts of BMPs, analysis at both farm and watershed levels must be addressed. At the farm level, BMPs will allow farmers to reduce soil, nutrient and chemical losses, which may provide benefits to farmers in the terms of improved soil productivity. However, farmers may perceive that conservation practices would also result in reduced crop yields and/or increased costs. Thus, benefits from avoided environmental degradation might be countered by potential reduction in net returns, rendering BMPs unattractive to individual farmers. At the watershed level, societal benefits may accrue from reductions in runoff that can degrade offsite water quality and ecosystems. Furthermore, it must be recognized that in order to be successful, BMP implementation in a watershed will require cooperative effort among farmers since the method will only be effective if all producers participate. Proper incentives for participation such as increased profits and equity must be considered. Economic impacts at the farm level must be evaluated to understand the magnitude of gains and losses to individual farmers through the use of conservation practices. In the meantime, the different magnitude of gains and losses among farms must be considered and the equity constraints must be taken into accounted.

In our research, full economic and environmental effects of conservation and no-till practices of continuous and crop rotation practices under environmental and equity constraints, as compared to conventional practices at the farm level, will be estimated, using simulation models that allow us to generate a large number of expected environmental and economic outcomes under various cropping practices. Water quality, as well as the economic impacts of BMPs in comparison with conventional practices will be examined at the watershed level. To complete our analysis, profit maximization subject to environmental restrictions and equity constraints will be evaluated, which can be used to establish policies that promote BMP adoption and in turn improve water quality. Equity constraints will be imposed to examine the optimal environmental and economic aspects under restricted environmental measures and equality of farms' per acre net returns.

Data and Methods

Data

The experimental watershed in the Mississippi Delta Management Systems Evaluation Areas (MDMSEA), Deep Hollow, located in LeFlore County, MS is our focus. The Deep Hollow watershed is located on oxbow lakes in a heavily agricultural areas of the Mississippi Delta. The watershed is approximately 400 acres, surrounding a 20-acre lake, with nearly 250 acres under row crop cultivation. Both structural and cultural BMPs, as well as conventional practices, have been used in the farming system, and the primary crops are cotton and soybeans. The watershed consists of 10 fields in which the primary crops grown have been cotton and soybeans. Within the watershed, there are 6 different soil types: Alligator, Arents, Arkabutla, Dubbs, Dundee and Tensas. In each field is a combination consisting of 2 to 3 soil types resulting in 22 subfields of unique soils (Table 1).

Bioeconomic Model

The impacts of alternative crop management practices will be estimated using a bioeconomic simulation model, the Agricultural Policy Environmental Extender or APEX (Blackland Research Center, 1999; Williams et al., 2000). APEX was developed to model small watersheds by the US Department of Agriculture's Agricultural Research Service (ARS), Soil Conservation Service (SCS), and Economic Research Service (ERS) in the early 1980's (Sharply and Williams 1990 (a and b)). APEX is designed to simulate biophysical processes and the interaction of cropping systems with management practices, soils and climates over long time periods.

APEX is a relatively recent extension to the Erosion-Productivity Impact Calculator (EPIC), and has been demonstrated as a tool for predicting changes in NPP from global warming (Williams et al, 1998). Although few studies exist using APEX, there is a wide body of literature using EPIC to measure edge of field environmental and economic impacts. For example, Smith et al. (1998) used EPIC to demonstrate the reductions of edge of field runoff of nutrients and sediment and the expected changes in profit under conventional and no-till practices, and Forster et al. (1998) compared edge of field predictions from EPIC with actual water quality in two Lake Erie watersheds. Chapman (1998) used data from the Ohio MSEA site near Piketon, Ohio and EPIC to demonstrate the impact of nitrogen taxes on the economic well being of farmers.

A bioeconomic model is useful to demonstrate novel ways farmers can manage crops manage crops to optimize profits as well as contribute to improvements in environmental quality. Because actual experience with BMP implementation will be correlated with exogenous factors, such as weather, a number of years' experience will be needed to demonstrate the expected outcome on farm profits and environmental quality. By using simulation models, we are able to generate a number of expected economic and environmental outcomes under various assumptions about BMP implementation.

APEX captures timing of planting and harvesting and the use of cultural BMPs, and produces environmental parameters where water flows through small watersheds as surface, channelized and subsurface flow. APEX has flexibility in allowing for model calibration with existing data. In this study, we are interested in calibrating our model to correspond with onsite empirical measures of environmental parameters.

The model merges physical data and biological data to analyze various management decisions and to simultaneously determine optimal management in terms of profit and environmental quality. Site information such as cropping practices, soil types, topography and meteorological data has been collected over a number of years in the project, but in this paper, we focus on the years 1998 and 1999 as the basis for our analyses. In 1998, crop BMPs were used in this watershed, and in 1999, conservation tillage practices were used.

Traditional farm models assume that a farmer's production decisions are constrained by various factors such as amount of land, labor and other available inputs. An extension of the traditional model that we use in our analysis is a bioeconomic model. In the bioeconomic model we develop here, environmental quality becomes an additional consideration, and BMPs are included as inputs into the production process. Our model is developed for the Deep Hollow watershed, and we extrapolate the model results over a 25-year time period. The underlying physical simulation model incorporates local weather conditions in the watershed, nutrient uptake and the timing of planting and harvesting of crops, as well as conservation tillage practices.

A number of inputs are needed for APEX simulation include weather, soil type, soil erodibility factors, topography (as measured by average slope length and steepness), distance from fields to watercourses, relative geographic location of fields within the watershed, crop rotation, tillage practices and fertilizer and chemical use. As part of the MDMSEA project, the soils and topography of these fields have been measured to a high degree of accuracy, and onsite meteorological monitoring provides weather data for several years (Rebich 2000). In addition, as part of the project, onsite monitoring of runoff of nitrogen and sediment provide some limited historical data that are used to calibrate the APEX model.

We have simulated scenarios under a number of assumptions in order to find out how BMPs can affect yields and environmental outputs over a 25-year time period. The specific scenarios include crop-tillage combinations under conventional tillage, conservation tillage and notill. The crops considered are continuous cotton, continuous soybeans, and a cotton/soybean rotation. After calibrating model to the known watershed parameters, we then run simulation models using different crop combinations, and cultural practices in order to obtain expected long-run annual environmental impacts and crop yields. The APEX model is used as an input to the economic optimization model described in the next section.

Optimization model

Before adopting any conservation practices, the agricultural producer will consider the profitability of their use. An input-saving technology will have the effect of reducing marginal cost. At the market level, competition will pass the cost of reduction along to consumers in lower prices, which will then stimulate output demand. The net impact of these two changes on producer revenue could be positive or negative. If revenue increased, and if the increase were large enough, the total use of the input could rise, even though usage at the intensive margin (per unit of output) would fall (Abler and Shortle 1992).

To investigate the impact of various practices in the watershed on profit and environmental quality, we develop a series of mathematical models in which we find the maximum watershed profit under a number of constraints. MDMSEA personnel have collected 5 years of budget and operation data (1996-2000) for the watershed, and these data provide important inputs for the economic model. That is, from the budget and operation data, we are able to derive input and output prices, labor and machinery costs, and so on. The model is run using a number of different constraints, including acreage, labor and, in some cases, environmental standards. We use this model to investigate economic and environmental impacts under decreasing levels of restriction on cropping and increasing levels of restrictions on nonpoint pollution. For example, we examine three cases in which continuous cotton is the sole crop, and we vary the cultural practice to include conventional till, conservation till and no till. In a different scenario, we allow the model to be optimized over combinations of continuous cotton, continuous soybeans and a cotton/soybean rotation, while imposing constraints upon the amount of N or sediment allowed as runoff.

The outputs of the economic optimization model include total expected watershed profit, optimal cropping (i.e. crop acreage and practices to be used in each subfield), and gross expected N, P and sediment runoff in the watershed. Thus the model can tell us, for a given scenario, which crops should be planted in which field under which practice in order to obtain the maximum profit while still achieving a certain environmental goal.

Simulation Results

We attempt to maximize net returns across the different tillage practices (conventional, conservation and no-till), cropping practices (cotton, soybeans, cotton/soybeans), soil types, and effluents (nutrient and sediment runoff), using GAMS (General Algebraic Modeling Systems). As compared to the baseline scenario, imposing a 25% reduction in nitrogen runoff could result in a reduction in net returns by 5.4%, from $18,529 to $17,526 (Tables 2 and 3). Under this scenario, phosphorus and sediment loss reduced of 23.17%, and 3.19%, respectively (from 95.65 lbs and 206.76 tons to 73.49 lbs and 200.16 tons-Tables 2 and 3).

The shadow price represents the expected value of a change in a given resource, i.e. net returns with respect to changes in constraints, which in this case are limits to sediment and nitrate runoff. Therefore, the shadow prices for sediment and nitrate indicate net returns forfeited in order to induce a unit reduction in sediment and nitrate runoff, respectively. Under a 25% reduction in nitrate runoff and sediment, the shadow price of nitrogen is $1.42 per pound, while the shadow price of sediment is $99.73 per net ton. To reduce nitrate runoff by 25%, some cropland had to be taken out off production, which consequently helps reduce nitrate and phosphorus runoff. The results indicate a reduction of phosphorus runoff and sediment are 23.17% and 3.19%, respectively (reduction from 95.65 lbs to 73.69 lbs, and from 206.76 net tons to 200.16 net tons-Tables 2 and 3).

Comparing the second scenario with the baseline, a 25% reduction in sediment under the equality of per acre profit constraint could lead to decreases in nitrate and phosphorus runoff by 43.00% and 40.73%, respectively (Tables 2 and 3).

Concluding Remarks

We have examined the environmental and economic impacts of various cropping practices with different tillage under the environmental and equity constraints, as compared to conventional tillage of continuous cropping. Using mathematical programming, we have estimated optimal profits under environmental and equity restrictions on sediment and nitrate runoff. We found that conventional tillage is the optimal tillage practice for both nitrogen and sediment standard scenarios. However, the optimal cropping practices shift from continuous cotton to cotton/soybean rotation (Table 3).

Considering the two policy scenarios, sediment reductions are more likely to negatively affect income, as compared to restrictions on nitrate runoff. Considering the entire Deep Hollow watershed, a sediment reduction policy could cause a 24.26% reduction in net returns, as compared to 5.41% reduced net returns under a nitrate constraint, suggesting that implementing a nitrogen standard would be significantly less costly than a sediment standard.

Marginal or per unit costs of nitrate reduction are less than those for sediment reduction. With respect to the shadow price of sediment and nitrogen, the whole watershed is more susceptible to soil erosion. It would forego more income in order to reduce soil erosion, in comparison with nitrate runoff. Thus, shadow prices may be important in establishing environmental standards.

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Table 1. Composition of Subfields in Deep Hollow Watershed, MS

Field ID	*Acres*	*Soil*	*% Soil*
XP3A	24.8	Dubbs	7.75
XP3A		Tensas	3.11
XP3B	12.0	Dubbs	2.25
XP3B		Tensas	1.55
XP3B		Dundee	1.04
XP3C	12.4	Dubbs	0.66
XP3C		Dundee	1.04
XP10	37.1	Tensas	6.99
XP10		Dundee	8.30
XP10		Dubbs	1.80
XP1	17.2	Arkabutla	12.27
XP2W	29.5	Tensas	14.09
XP2W		Alligator	3.18
XP2W		Arkabutla	1.24
XP2E	29.5	Tensas	14.50
XP2E		Alligator	3.28
XP2E		Arkabutla	1.24
XP8	9.0	Alligator	2.36
XP9A	12.6	Arkabutla	6.04
XP9A		Arents	2.10
XP9B	10.6	Arents	1.57
XP9B		Arkabutla	3.64

Table 2. Optimization Model Base Case Scenarios—No Environmental Constraint

	Conventional Tillage		*Conservation Till*	
Field No.	*Planted Acreage—Continuous Cotton*	*Returns Per Field*	*Planted Acreage—Continuous Cotton*	*Returns Per Field*
XP3A	21.14	$2,118.94	21.14	$1,833.21
XP3B	9.42	917.75	9.42	788.80
XP3C	3.31	329.82	3.31	285.30
XP10	33.27	3,130.17	33.27	2,662.36
XP1	23.89	2,192.80	23.89	1,863.92
XP2W	36.04	3,287.42	36.04	2,801.32
XP2E	37.03	3,356.55	37.03	2,875.65
XP8	4.60	455.57	4.60	392.31
XP9A	15.85	1,656.18	15.85	1,441.21
XP9B	10.14	1,084.01	10.14	948.93
Total Watershed Profit $18,529.20			Total Watershed Profit $15,886.16	
Environmental Outcomes			*Environmental Outcomes*	
Nitrogen Runoff (lbs)		2,676.26	Nitrogen Runoff (lbs)	2,822.31
Phosphorous Runoff (lbs)		95.65	Phosphorous Runoff (lbs)	94.33
Sediment Loss (net tons)		206.76	Sediment Loss (net tons)	192.85

Table 2 (Continued): Optimization Model Base Case Scenarios—No Environmental Constraint

No-Till			
Field No.	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Cotton/ Soybean*	*Returns Per Field*
XP3A	21.14		$1,499.36
XP3B	9.42		636.47
XP3C	3.31		236.30
XP10	33.27		2,119.68
XP1	11.95	11.95	1,513.60
XP2W	36.04		2,280.24
XP2E	37.03		2,327.15
XP8	4.60		326.84
XP9A	15.85		1,203.52
XP9B	10.14		785.88
Total Watershed Profit			$12,929.05
Environmental Outcomes			
Nitrogen Runoff (lbs)			2,723.44
Phosphorous Runoff (lbs)			14.24
Sediment Loss (net tons)			64.36

Table 3. Optimization Model with Environmental and Equity Constraints—N-Standard

		25% N-Reduction Regulation		
Field No.	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Cotton/ Soybean*	*Conventional Tillage Acreage*	*Returns Per Field*
XP3A		20.44	20.44	$1,903.34
XP3B		9.10	9.10	848.27
XP3C		3.17	3.17	297.95
XP10	7.64	25.62	33.26	2,995.22
XP1		23.73	23.73	2,150.46
XP2W	26.05	9.98	36.03	3,244.09
XP2E	34.52	2.51	37.03	3,333.48
XP8		4.33	4.33	413.62
XP9A		14.60	14.60	1,426.63
XP9B	2.45	7.69	10.14	913.11
Profit per acre		$90.02		
Total Watershed Profit		$17,526.17		
Marginal Cost of Nitrogen Runoff ($/lb)		$1.42		
		Environmental Outcomes		
Nitrogen Runoff (lbs)		2,007.19		
Phosphorous Runoff (lbs)		73.49		
Sediment Loss (net tons)		200.16		

Table 3 (Continued): Optimization Model with Environmental and Equity Constraint—S-Standard

25% S-Reduction Regulation

Field No.	*Planted Acreage Continuous Cotton*	*Planted Acreage—Cotton/ Soybean*	*Conventional Tillage Acreage*	*Returns Per Field*
XP3A		16.37	16.37	$1,524.04
XP3B		7.26	7.26	679.22
XP3C		2.52	2.52	238.57
XP10	25.50		25.50	2,398.33
XP1		19.00	19.00	1,721.92
XP2W		29.90	29.90	2,597.61
XP2E		32.77	32.77	2,669.18
XP8	3.34		3.34	331.19
XP9A	10.93		10.93	1,142.33
XP9B	6.84		6.84	731.15

Profit per acre	$72.08
Total Watershed Profit	$14,033.54
Marginal Cost of Nitrogen Runoff ($/lb)	$99.73

Environmental Outcomes

Nitrogen Runoff (lbs)	1,522.68
Phosphorous Runoff (lbs)	56.69
Sediment Loss (net tons)	155.07

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