Determination of Least Cost Phosphorus Abatement Practices in a Watershed Under Stochastic Conditions

Arthur Stoecker, Davis S. Marumo, Stella Machooka, Sierra Howry, Daniel Storm and Michael White

Arthur Stoecker, Department of Agricultural Economics, Oklahoma State University
312 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-6165, Fax: 405-744-8210
E-mail: art.stoecker@okstate.edu

Davis S. Marumo, Department of Agricultural Economics, Oklahoma State University
555 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-9969, Fax: 405-744-8210
E-mail: marumods@yahoo.com

Stella Machooka, Department of Agricultural Economics, Oklahoma State University
557 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-9799, Fax: 405-744-8210
E-mail: machookaste@yahoo.com

Sierra Howry, Department of Agricultural Economics, Oklahoma State University
316 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-6172, Fax: 405-744-8210
E-mail:hsierra@okstate.edu

Daniel Storm, Department of Agricultural Economics, Oklahoma State University
121 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-8422, Fax: 405-744-6059
E-mail: dan.storm@okstate.edu

Mike White, Department of Agricultural Economics, Oklahoma State University
120 Ag. Hall, Stillwater, OK 74078;Tel: 405-744-5288, Fax: 405-744-8210
E-mail: mike.white@okstate.edu

Selected Paper Prepared for Presentation at the American Agricultural Economics Association Annual Meeting, Portland, OR, July 29-August 1, 2007

Determination of Least Cost Phosphorus Abatement Practices in a Watershed Under Stochastic Conditions

Arthur Stoecker, Davis S. Marumo, Stella Machooka, Sierra Howry, Daniel Storm and Michael White

The U.S. Environmental Protection Agency implements the Total Maximum Daily Load (TMDL) program with the objective of attaining ambient water quality standards by controlling both point and nonpoint sources of pollution. The TMDLs are being implemented to prevent eutrophication of public water supplies by phosphorus runoff from manure applications in many watersheds (USEPA 2003). This article determines the least cost mix, location, and magnitude of management practices to meet maximum average annual phosphorus loads entering watershed lakes within specified margins of safety. Possible practices included pasture management, converting poultry litter to energy, adding alum to poultry litter, and hauling litter from the Eucha-Spavinaw watershed in Oklahoma. This watershed is of interest because there is very little cropland in the watershed, most of the non-point pollution comes from fertilized pastures and because eutrophication threatens a metropolitan water supply. The Geographical Information System (GIS) - based Soil Water Assessment Tool (SWAT) was calibrated and used to evaluate non-point source sediment and nutrient loading into Lakes under alternative land management practices. SWAT simulations generated site-specific

production, sediment yield, nitrogen and phosphorus runoff coefficients that were used in a Target MOTAD programming model to select a specific management practice for each site in the watershed. The objective was to maximize net agricultural and electrical returns from the watershed less litter transportation costs subject to maximum annual nutrient loads with limits on average annual deviations above the limits.

Agricultural pollution attributed to excessive land application of poultry manure as fertilizer is a serious environmental problem for surface water quality in the Eucha-Spavinaw watershed situated on the border of the states of Oklahoma and Arkansas . The Eucha-Spavinaw watershed is of interest because Lake Eucha and Spavinaw Lake are currently on the Environmental Protection Agency (EPA) 303(d) Impaired Water List due to low dissolved oxygen and excessive phosphorus from municipal point source discharges, agriculture, and other unknown sources (ODEQ, 2004). The Oklahoma Water Quality Standard specifies the designated beneficial uses of Lake Eucha and Spavinaw Lake as including public and private water supply, aquatic community, agricultural irrigation, recreation and aesthetics, and sensitive drinking water supply (OWRB 2004; 2006). There is rapid urban expansion in adjacent watershed, rapid expansion of poultry production and very little cropland within the Eucha-Spavinaw watershed. The rate at which poultry litter is currently being produced and land applied is most likely to exceed the assimilative capacity of the limited cropland available in the watershed. Most of the non-point nutrient pollution comes from poultry manure fertilized pastures (OWRB 2002; Storm et al 2003).

Eutrophication threatens the Tulsa metropolitan water supply. Excessive levels of phosphorus and algal growth impair the designated aesthetics, recreational and drinking water beneficial uses of Lakes Eucha and Spavinaw by causing undesirable taste and bad odor. Municipal water treatment facilities that treat the water to achieve established drinking water standards find it difficult and prohibitively expensive to remove the bad taste and odor in drinking water. The City of Tulsa reported additional water treatment costs due to excessive algae exceeding $72.78 per million gallons. Should their current treatment system be unable to eliminate the taste and odor problems, the City of Tulsa will have to either increase water treatment costs or abandon lake Eucha and Spavinaw lake as a water supply entirely and look for alternative drinking water supply such as Lake Hudson. The additional costs of using Lake Hudson water was estimated to exceed $7,000 per day whereas the cost of abandoning lakes Eucha and Spavinaw as a water supply and using Lake Hudson was estimated to exceed $250 million (City of Tulsa 2006; OWRB 2006).

There is need for regulations and nutrient management plans to reduce both point and nonpoint source nutrient pollution in the Eucha-Spavinaw watershed, especially that coming from agriculture. Therefore best management practices (BMPs) to reduce phosphorus loading in the watershed are of high interest, not only to poultry integrators and farmers using poultry manure, but also to municipal authorities, recreation managers, regulators, policy makers and the general public. Although several studies have analyzed nitrogen and phosphorus loading in the watershed, few studies have analyzed the role of

grazing management systems as a profitable economic enterprise and a phosphorus reduction strategy under stochastic conditions from a watershed where large quantities of litter were available for use as fertilizer on pastures to achieve the established phosphorus total maximum daily loads (TMDL) for the watershed at minimum cost to society. The research presented in this article addresses the question, "What is the most efficient set of litter and grazing management practices that can be used to maximize net agricultural income while meeting the phosphorus TMDL for the Eucha-Spavinaw watershed within specified margins of safety?" To answer this question we develop an integrated biophysical - economic optimization model for cost efficient non-point source pollution abatement in the Eucha - Spavinaw watershed to determine the least cost mix, location, and magnitude of grazing management practices to reduce phosphorus loading under various phosphorus loading targets and margins of safety for the Eucha-Spavinaw watershed. We determine the optimal transportation pattern for poultry litter under various phosphorus loading targets and margins of safety for the watershed as well as evaluate the efficiency of changes in pasture management practices in reducing phosphorus runoff relative to the use in a possible litter-to-energy power plant under various phosphorus loading targets and margins of safety for the Eucha-Spavinaw watershed with and without the alum-treated poultry litter option.

Conceptual Framework

The water quality problem resulting from excessive emissions of nutrients (e.g. phosphorus and nitrogen) into Lakes Eucha and Spavinaw is viewed in this article as a

case of market failure. The water pollution problem exists because property rights for clean water in the area are not clearly defined. Polluters, especially agricultural producers using inputs that have adverse effects on the environment such as pesticides and fertilizers (especially poultry manure) do not internalize the social costs associated with the use of such inputs in their private cost calculations. The negative environmental externality for which polluters do not account causes a divergence between private and social costs that gives them an incentive to use the inputs (e.g. poultry litter) in quantities exceeding socially optimal levels.

This article approaches the problem of phosphorus pollution in the Eucha-Spavinaw watershed from a social perspective, a point of view that calls for choosing a level of phosphorus control that maximizes total net benefits to the society. The conceptual framework for determining optimal abatement levels, as noted by Freeman, Haveman and Kneese (1973), is based on the concept of minimizing the sum of total pollution abatement cost and total environmental damage cost. This concept assumes that there exists a social welfare function with which to work. The general social welfare function can be maximized by minimizing the sum of total pollution abatement cost and total environmental damage cost as demonstrated in Tietenberg (2003). This article is based on the same concept and assumes existence of a social welfare function to be maximized from consumption of market or economic output and environmental services in the Eucha-Spavinaw watershed. This relationship can be mathematically expressed as:

(1) $W = M + E$

Where W is the social welfare function; M is the value of the market goods and services consumed by society and E is the value of environmental service consumed by society. If we let E* be maximum potential value of environmental services from pristine environment, D be costs of environmental damages from production and consumption of market goods and services, M* be maximum value of market goods and services with no pollution treatment, and T be costs associated with treating pollution, then we may state the actual values of market goods and services and environmental services as follows:

(2) $M = M^* - T$

(3) $E = E^* - D$

Substituting equations (2) and (3) into equation (1) redefines total social welfare function as:

(4) $W = (M^* - T) + (E^* - D) = M^* + E^* - (T + D)$

Given that M* and T* are fixed, equation (4) shows that we can maximize total welfare function by minimizing (T + D), the sum of pollution treatment costs and environmental damage costs. If we assume that both T and D are functions of a given pollutant (p), equation (4) may be recast to show that total welfare function will also be a function of pollutant (p) as follows:

(5) $W(p) = M^* + E^* - (T(p) + D(p))$

Maximizing total social welfare function in this form requires differentiating equation (5) with respect to p and setting the derivative equal to zero:

(6) $$\frac{\partial W}{\partial p} = -\frac{\partial T}{\partial p} - \frac{\partial D}{\partial p} = 0$$

(7) $$\Rightarrow -\frac{\partial T}{\partial p} = \frac{\partial D}{\partial p}$$

Where $\partial T/\partial p$ is the marginal treatment cost, the change in total treatment costs from an additional unit of pollutant treated; and $\partial D/\partial p$ is the marginal environmental damage costs, the change in total environmental cost due to an additional untreated unit of pollutant emitted into the environment. The result in equation (7) implies that total social welfare is maximum when marginal treatment costs are equal to marginal environmental damage costs.

The second order conditions with respect to p are:

(8) $$\frac{\partial^2 W}{\partial p^2} = -\frac{\partial^2 T}{\partial p^2} - \frac{\partial^2 D}{\partial p^2} \leq 0$$

Equation (8) shows that the second order derivative is non-positive and thus consistent with the requirement for the point of maximum of the social welfare function. The implicit assumption here is that both $\partial^2 T/\partial p^2$ and $\partial^2 D/\partial p^2$ are non-negative at the optimal point in order for the second order derivative to be non-positive. Equation (8) implies that the treatment cost function should be increasing at a non-decreasing rate as the amount of pollution treatment increases. On the other hand, the environmental damage cost function should be increasing at a non-decreasing rate as the amount of pollution treatment decreases. In the case of water pollution as in the Eucha-Spavinaw watershed, the damage cost function represents the cost to the environment (such as dead fish, reduced recreational values, increased downstream water treatment costs) if various amounts of

the pollutant (phosphorus) enters into the water supply. The treatment cost function represents all the costs incurred in the process of removing and / or preventing the pollutant (phosphorus) from entering the water course (Lakes Eucha and Spavinaw). The total damage and treatment cost curve (usually U-shaped) is obtained by vertical summation of the damage and treatment cost curves. The optimal level of pollution and treatment occurs at the minimum point of the total damage and treatment cost curve, a point at which the marginal treatment cost equals the marginal damage cost (Tietenberg 2003).

Methodology

The main purpose of this article was to determine optimal poultry litter and pasture management practices within the Eucha-Spavinaw watershed that will effectively control phosphorus, nitrogen, and sediment runoff in a way that is least costly to society. We employed a two-step modeling approach that combined Geographical Information Systems (GIS) data-based biophysical simulations with mathematical programming to estimate the change in pasture management practices and producer income from the implementation of different environmental pollution standards or Total Maximum Daily Loads (TMDL) and policy instruments in the Eucha-Spavinaw watershed.

Simulation of Pasture Management Practices in the Watershed

A calibrated GIS-based Soil Water Assessment Tool (SWAT) model (Storm et al. 2003) was used to simulate hydrological and biophysical characteristics, production, and

sediment, nitrogen and phosphorus runoff for feasible alternative pasture management practices in the Eucha-Spavinaw watershed. We used daily weather records for temperature and rainfall for the period 1950 to 2004, from which three sets of 23 years of daily weather (rainfall and temperature) were selected for use in all simulations performed in this study. The first three years in each set comprised of daily weather data for the period 1993-95 and were used for warm-up and the base run of the simulation model. The other twenty years in each of the three weather data sets consisted of randomly selected sequence of years between 1950 and 2004. GIS data for topography, soils, land cover and streams required by SWAT model were obtained from various sources including public agencies (especially USGS, NRCS, and NOAA), extension offices, and via personal communication. The SWAT model delineated the Eucha-Spavinaw watershed into 90 subbasins with a total of 2416 hydraulic response units (HRUs) and 27 major soil types. Clarksville is the dominant soil type, covering about 44 percent of the watershed area, followed by Nixa which accounts for approximately 14 percent. Captina and Doniphan cover approximately 7 percent of the watershed area each. The soil types Razort and Tonti account for about 6 and 4 percent of the area, respectively. The other 21 soil types collectively account for about 18 percent of the Eucha-Spavinaw watershed area.

A series of simulation runs were performed for a total of one hundred and five feasible pasture management practices in each hydraulic response unit (HRU) in the Eucha-Spavinaw watershed. Potential alternative pasture management practices were simulated

using different combinations of land use/land cover, rate of poultry litter application, commercial nitrogen, minimum biomass retained during grazing, and stocking rates shown in Table 1 below. The land uses modeled are low-biomass pasture (LPAS), medium-biomass pasture (MPAS), high-biomass pasture (HPAS), litter low-biomass pasture (LLPA), litter medium-biomass pasture (LMPA), and litter high-biomass pasture (LHPA), winter wheat (WWHT), green beans (GRBN), rangeland (RNGB) and forests (FRST). It was assumed that poultry litter is applied only to pastures and row crops in the management simulations. The results of each simulation were then used to generate HRU specific coefficients for production, phosphorus runoff, nitrogen runoff and sediment runoff for each pasture management practice in each HRU. The respective coefficients obtained from the SWAT model were then used to develop an environmental target MOTAD risk programming model that was later used to select the most efficient pasture management practice for each HRU in the watershed.

Table 1. Levels of Management Practice Variables Used

Land Use /Land Cover	Litter Applied (kg/ha)	Nitrogen Applied (kg/ha)	Minimum Plant Biomass for Grazing (kg/ha)	Stocking Rate (AU/ acre)
AGRL	0	0	1100	0.63
HPAS	1765	50	1600	1.00
LHPA	2000	100	2000	1.26
LLPA	3529	150		
LMPA	4000	200		
LPAS	5294			
MPAS	6000			
RNGB				
FRST				

Table 1shows levels of each management practice variable simulated. There are

eight types of land use / land cover, seven levels of litter application rate, five levels of nitrogen application rate, three levels of minimum plant biomass maintained during grazing, and three levels that represented a low, medium and high stocking rate. A management scenario that maintained minimum plant biomass during grazing of 1100, 1600 and 2000 kg/ha was considered to represent a poor, fair, or good pasture, respectively. The SCS-curve numbers (CN2) were adjusted according to the pasture condition and hydrologic group (A, B, C, or D) assigned to each soil type.

The row crops, winter wheat and green beans were modeled as a graze-out wheat-and-green bean rotation (green beans followed by winter wheat). All other pasture management scenarios were modeled as tall fescue pasture management systems. It is assumed that poultry litter is applied only to pastures and row crops in the management simulations. Phosphorus applied on cropland was assumed to come solely from poultry litter. A metric ton of poultry litter was assumed to contain 14kg of phosphorus and 30kg of nitrogen. The model assumes a choice of nitrogen replacement by commercial fertilizer at litter application rates less than the base application rate to maintain the current total nitrogen rate and forage production. For application rates exceeding the base rate, the nitrogen applied on the grasses is assumed to come from the poultry litter. Both litter and nitrogen application rates are based on fertilization recommendations. The length of the grazing period was set at 270 days for all pastures.

Using Aluminum Sulfate (Alum) to Reduce Phosphorus Loading

Given elevated phosphorus levels in runoff from agricultural land on which poultry manure is used, there is need to determine alternative methods for controlling either available phosphorus content of the poultry litter or the phosphorus holding capacity of the soil. Our model allows for treatment of poultry litter with alum. A study has found that adding aluminum sulfate to poultry litter provides benefits for both the farmer and the environment. The presence of alum in the poultry litter allows it to trap nitrogen in the fertilizer and reduce nitrogen losses through ammonia volatilization (Cestti, Srivastava and Jung 2003). This increases the level of nitrogen available to plants. Based on the previous studies by Moore (1999), it is assumed that farmers using alum-treated poultry litter on their cropland produce runoff with less than 75 percent phosphorus content.

Development of Transportation Matrices

Based on the work done by Storm and White (2003), we assumed that there are 1053 broiler houses in the Eucha-Spavinaw watershed with an estimated output of approximately 89,500 tons of litter per year. Three hundred chicken farms were assigned into twenty four groups ensuring that no chicken farm was located more than two miles from a group centroid. Four distance calculations were performed. The average distance from each chicken farm to the centroid of the group to which it was assigned was determined using ArcView Version 3.3; the distance from each

chicken farm centroid to a point on the nearest road was estimated using the nearest feature algorithm; the distance from the point on the road nearest each chicken farm to a point on the road nearest each sub-basin centroid was estimated using a multi-path script; and lastly the nearest feature algorithm was used to determine the distance from the road to the sub-basin centroid. We used the same process to create a transportation matrix from each chicken farm centroid to Jay, Oklahoma for location of a possible litter-to-energy processing plant. This approach resulted in a matrix with 2208 possible transportation activities constituted from each of the 24 chicken farm centroids supplying litter to each of the 92 sub-basin centroids. Cost estimates for transporting litter from chicken farm centroids to subbasin centroids were based on information supplied by BMPs Inc. The cost for loading and coordinating a haul ranged from $7.50 to $8.00 per ton. The cost of hauling ranged from $3.25 to $3.50 per loading mile per truckload. Each truck averaged 23 tons per load. The loaded mileage is a one-way distance. No direct cost for spreading, but BMPs, Inc. would coordinate spreading at an average of $6 per short ton (BMPs, Inc 2006).

The Value of Biomass Consumed During Grazing

The value of hay and pasture consumed during grazing was derived based on a 100 cow unit size cow-calf enterprise budget obtained from Oklahoma State University Cooperative Extension Service. We assumed that part of the calf crop were kept beyond weaning and sold later as stockers. Table xxx below shows the modified OSU 100 herd

cow-calf enterprise budget with the net value of consumed grass estimated at $53.05 per metric ton.

Table 2. 100 Herd Cow Calf Enterprise Budget

Production	Weight	Unit	Price / Cwt	Qty	Revenue
Steer Calves	470	Lbs./hd	$107.42	18.91	$9,547
Heifer Calves	470	Lbs./hd	$100.04	7.49	$3,522
Cull Cows	1150	Lbs./hd	$44.27	12	$6,109
Cull Replacement	825	Lbs./hd	$84.34	12	$8,350
Cull Bulls	1750	Lbs./hd	$58.58	1	$1,025
Stockers	623	Lbs./hd	$112.00	40	$27,910
Total Receipts					$56,463
Protein Supp. $ Salt	1	hd.	$44.40	1.1	$4,884
Minerals	1	hd.	$14.07	1.1	$1,548
Vet Services	1	hd.	$7.14	1.1	$785
Vet Supplies	1	hd.	$1.16	1.1	$128
Marketing	1	hd.	$6.91	1	$691
Mach. Fuel,Oil, Repairs	1	hd.	$24.09	1.1	$2,650
Machinery labor	1	hrs.	$9.25	2.65	$2,451
Other labor	1	hrs.	$9.25	3	$2,775
Other expense	1	hd.	-	1.1	
Annual Oper. Capital		Dollars	0.0825	184.62	$1,523
Total Operating Costs					$17,435
Other Fixed Costs					$12,926
Net Return to Hay and Pasture					$26,102
		lbs/day	days/yr	lbs/yr	kg/yr
Cow		25	365	9125	4139
Bull		25	365	365	166

Replacement Heifer	18	365	788	358
Stocker	14	100	560	254
Hay and Pasture Required Per Cow Unit				4916
Net Revenue per Mg Biomass Consumed ($26,102/100hd/4.92)				$53.05

The Stochastic Optimization Model for the Watershed

Based on the works of Tauer (1983), Teague, Bernardo and Mapp (1995) and Qiu, Prato and Kaylen (1998), this article employs a modified environmental Target MOTAD risk programming model to determine the optimal spatial allocation of the alternative pasture management practices and a pattern of litter shipments within and outside the watershed that maximizes producer income subject to not exceeding maximum allowable total annual phosphorus runoff for the Eucha-Spavinaw watershed within a specified margin of safety. The optimization model may be mathematically expressed as:

(9) $$\max_{X_{ij},\, T_{kb}} \; E(z) = \sum_{i=1}^{2416}\sum_{j=1}^{105} R_{ij} X_{ij} - \sum_{k=1}^{24}\sum_{b=1}^{92} T_{kb} C_{kb}$$

(10) $$\sum_{j=1}^{105} X_{ij} = Area_i \,, \quad \forall_j$$

(11) $$PH_{\max} - \sum_{i=1}^{2416}\sum_{j=1}^{105} PH_{ij} X_{ij} + \delta_{PHr} \geq 0, \quad \forall\, i, j, r$$

(12) $$\sum_{r=1}^{s} p_r \delta_{PHr} \leq \lambda_{PH}, \quad \forall r \qquad\qquad \lambda_{PH} = M \rightarrow 0$$

(13) $$\sum_{b=1}^{92} T_{kb} = S_k \ , \quad \forall k$$

(14) $$\sum_{b=1}^{92} \sum_{j=1}^{105} Q_{jb} X_{jb} = \sum_{k=1}^{24} T_{kb} \ , \ \forall b, j, k$$

(15) $$X_{ij} \geq 0 \ , \ T_{kb} \geq 0$$

where E(z) is the expected net agricultural income for the watershed; R_{ij} is the net income from the jth management practice in the ith HRU; X_{ij} represents amount of land allocated for the jth management practice in the ith HRU; T_{kb} is the quantity of litter transported from the kth chicken farm centroid to the bth subbasin centroid; C_{kb} is the cost of transporting poultry litter from the kth chicken farm centroid to the bth subbasin centroid; $Area_i$ represents the amount of available land resource in each HRU that can be allocated for use under any feasible pasture management system; $PH_{max,}$ is the maximum allowable total annual phosphorus loading for the watershed; PH_{ij} represents the amount of phosphorus runoff from the ith HRU under the jth pasture management system and δp_{Hr} is the phosphorus runoff deviation above the maximum allowable total phosphorus load for the watershed under each state of nature r; p_r is probability that state of nature r will occur; λ_{PH} represents an environmental risk measure, the expected value of positive deviations above the annual phosphorus loading target for the watershed parameterized from a large number M to 0; S_k is the quantity of litter supplied at the kth chicken farm centroid; Q_{jb} is the quantity of litter required by the jth management practice in the bth subbasin; and X_{jb} is the amount of land allocated to the jth management practice in the bth

subbasin. Thus, this model maximizes net returns from grazing less transportation and treatment costs for poultry litter subject to a limit on phosphorus loading from the entire watershed within a specified tolerance level.

Phosphorus Pollution Abatement Costs

In the case of water pollution from phosphorus emissions as is the case in the Eucha-Spavinaw watershed, the treatment or abatement cost function represents all the costs incurred in the process of removing and / or preventing the pollutant (phosphorus) from entering the water course (Lakes Eucha and Spavinaw). However, for purposes of this study, we determined total abatement costs in terms of reduction in producer income from crops, pasture and range. Total abatement costs were estimated as the difference in the value of the objective function (representing total agricultural net returns for the watershed) of the Target MOTAD programming model (specified above) subject to the estimated current level of phosphorus loading for the Eucha-Spavinaw watershed (40 tons per year) and the value of the objective function at each of the alternative annual phosphorus loading targets (that is, at 35, 30, 25, and 20 tons per year) and a specified phosphorus deviation limit above a given phosphorus loading target. The upper limit on the phosphorus runoff deviation above annual phosphorus loading was varied from 10 tons to 2 tons per year. The marginal phosphorus treatment/abatement cost may be defined as the change in total phosphorus pollution abatement costs from an additional unit of phosphorus treated/abated. Optimal pollution abatement requires that the marginal

abatement costs in production be set equal to the marginal benefit of the abatements as measured by a reduction in environmental damage (Tietenberg 2003; Sterner 2003). For purposes of this study, we determined the marginal phosphorus pollution abatement cost using the shadow price on the binding average annual phosphorus runoff constraint obtained from the solution of the economic model specified above. This shadow price may be interpreted in economic terms to represent the amount by which the value of the objective function (or the total agricultural net return for the Eucha-Spavinaw watershed) is reduced as the maximum allowable annual phosphorus runoff is restricted by an additional unit per year. The intersection of the curves for the marginal costs of pollution damage and the marginal costs of pollution abatement determines the optimal levels of pollution emissions and their shadow cost (Steiner 2003; Tietenberg 2003).

Mixed Linear Model Specification

A general mixed linear econometric model was specified to determine the relationship between phosphorus runoff in the current period and soil type, RKLS-factor, curve number (CurV), minimum biomass maintained during grazing (BmMin), stocking rate (StkRate), amount of litter/phosphorus applied (Papl), amount of commercial nitrogen applied (Napl) and the litter/phosphorus applied (Napl) and phosphorus runoff in the previous period (LagPloss). The general econometric model may be mathematically specified as:

$$(16) \qquad P_{it} = \sum_{k=1}^{K} X_{itk} \beta_k + u_{it} \qquad i = 1,\ldots,N; \quad t = 1,\ldots,T$$

$$u_{it} = v_i + e_t + \varepsilon_{it} \quad (17)$$

Where P_{it} represent expected phosphorus runoff in the current period, X_{it} represent the independent variables outlined above, β_k are parameters to be estimated, v_i is a cross-section specific residual, e_t is a time-series specific residual, ε_{it} is a classical error term with zero mean and a homoskedastic covariance matrix, N is the number of cross-sections, T is the length of the time series for each cross section, and K is the number of explanatory variables included in the model.

Results

A total of 105 feasible grazing management practices were simulated and tested in each of the agricultural HRUs in the Eucha-Spavinaw watershed. However, not all of them were in the feasible solution set when the optimization model was solved for each of the possible mean annual phosphorus runoff targets and phosphorus runoff deviation limits above target for the Eucha-Spavinaw watershed.

Hauling Without Alum-Treated Litter Option

In this option we examined the effects of limiting total phosphorus runoff for the Eucha-Spavinaw watershed to 40, 35, 30, 25, and 20 tons per year on optimal litter and pasture management systems when the available method of litter allocation is hauling within the watershed and to a possible litter-to-energy power plant located at Jay, Oklahoma.

Table 2 below show a wide range of grazing management practices the optimization model identified for optimal level of phosphorus abatement in the Eucha-Spavinaw watershed at different phosphorus loading targets and deviation limits. Optimal phosphorus abatement for the watershed was achieved through a combination of various site-specific grazing management practices at each mean annual phosphorus loading target and phosphorus runoff deviation limit tested in this study. Table 3 to table 5 below show the optimal grazing management practices selected by the economic optimization model and amount of land allocated for each selected management practice when the mean annual total phosphorus runoff for the Eucha-Spavinaw watershed was limited to 40 Mg, 30Mg, 25Mg and 20Mg per year, respectively, with phosphorus deviation limits above target varied from 10 Mg to 2 Mg per year. Table xxx below shows that when mean annual phosphorus load for the Eucha-Spavinaw watershed is limited to 40 Mg per year with an upper limit on phosphorus deviation above mean load of not more than 10 Mg per year, BMP 2022 received the largest land allocation of about 16,000 hectares of pastureland. Under this grazing management practice, the pasture received 4 tons of poultry litter per hectare and no commercial nitrogen fertilizer was applied at all.

Table 2 Selected Optimal Grazing Management Practices for the Watershed

BMP Code	Poultry Litter Applied (tons/ha)	Elemental Nitrogen Applied (kg/ha)	Minimum Biomass Maintained During Grazing (tons/ha)	Stocking Rate (AU/ha)
0011	0	0	1.1	0.63
0012	0	0	1.1	1.00
0013	0	0	1.1	1.26
0221	0	100	1.6	0.63
0222	0	100	1.6	1.00
0223	0	100	1.6	1.26
0331	0	150	2.0	0.63
0332	0	150	2.0	1.00
0333	0	150	2.0	1.26
0111	0	50	1.1	0.63
0112	0	50	1.1	1.00
0113	0	50	1.1	1.26
1011	2	0	1.1	0.63
1012	2	0	1.1	1.00
1013	2	0	1.1	1.26
1231	2	100	2.0	0.63
1232	2	100	2.0	1.00
1233	2	100	2.0	1.26
1121	2	50	1.6	0.63
1122	2	50	1.6	1.00
1123	2	50	1.6	1.26
2021	4	0	1.6	0.63
2022	4	0	1.6	1.00
2023	4	0	1.6	1.26
3031	6	0	2.0	0.63
3032	6	0	2.0	1.00
3033	6	0	2.0	1.26
3231	6	100	2.0	0.63
3431	6	200	2.0	0.63
3432	6	200	2.0	1.00
3433	6	200	2.0	1.26

Table 3. Land Allocation (ha) by BMP When Phosphorus Target is 40 Mg / year.

Assigned BMP*	Mean Annual Total Phosphorus Load : Deviation Limit Above Mean (tons/yr)				
	40:10	40:08	40:06	40:04	40:02
0011	1753.1	1922.7	962.6	694.4	126.0
0012	6607.7	7397.4	6947.1	6335.3	6896.1
0013	3932.8	3792.8	3005.1	2470.3	1085.8
0221	0.5	1.6	1.9	163.9	336.9
0222	0.0	0.2	1.3	644.8	2432.2
0223	0.6	1.1	1.1	3.2	129.3
0331	0.9	2.5	0.0	55.5	882.8
0332	0.5	0.0	0.0	112.4	83.4
0333	0.0	0.09	1.0	126.9	327.0
0111	1.0	1.9	55.3	23.4	511.7
0112	1401.4	1100.3	4217.0	5776.7	4375.1
0113	1.0	1.4	2.4	2.1	1.4
1011	3.6	32.3	123.0	15.3	22.5
1012	4541.0	4293.6	2852.7	1186.3	115.4
1013	1.7	2.0	1.1	0.2	4.3
1231	1.8	0.9	0.4	3.9	2.6
1232	0.4	0.9	0.0	0.0	0.4
1233	0.6	1.4	0.0	0.0	0.0
1121	0.6	1.0	1.9	0.7	0.3
1122	1.7	221.7	362.0	65.5	0.0
1123	0.2	0.3	0.4	1.0	0.5
2021	1758.8	1939.1	2288.4	3820.8	5778.1
2022	15987.8	13962.4	12675.9	10694.2	6373.3
2023	0.3	1.3	0.4	46.7	1707.4
3031	0.8	1065.2	1597.4	2423.6	2652.4
3032	1.2	1.4	4.3	2.7	1.7
3033	0.6	0.5	1.0	0.5	1.5
3231	170.9	309.3	938.2	1353.0	1854.8
3431	0.9	0.3	0.3	3.7	118.1
3432	0.2	1.1	1.3	48.8	133.0
3433	2.5	5.8	5.7	43.6	646.1

However, producers maintained minimum biomass of 1600 kilograms per hectare during grazing at a stocking rate of 1.00 AU per hectare. As the upper limit on phosphorus deviation above mean load was reduced from 10 Mg to 2 Mg per year, more land was transferred from BMP 2022, BMP 1012, and BMP 0013 and put under BMP 2021, BMP

0112, BMP 0222 and BMP 0012. The amount of pastureland that received no poultry litter at all increased from about 14000 to 17000 ha whereas the amount of land that received 4 tons of poultry litter per hectare declined from about 18000 to 14000 ha. The amount of land that received from 50-150 kg/ha of commercial nitrogen fertilizer increased from approximately 1400 to 11000 hectares. However, the amount of pastureland on which a minimum biomass of 1100 kg/ha was maintained during grazing declined from 18000 to 13000 hectares whereas the land on which a minimum biomass of 1600 kg/ha and above was maintained during grazing increased from about 18000 to 27000 hectares. The amount of land that was stocked at a rate of 1.00 AU/ha and above declined from approximately 33000 to 24000 hectares while that which was stocked at a lower rate of 0.63 AU/ha increased from 4000 to 12000 hectares. Table 4 below shows the optimal grazing management practices selected by the economic optimization model and amount of land allocated for each selected management practice when the mean annual total phosphorus runoff for the Eucha-Spavinaw watershed was reduced from 40 Mg to 30 Mg per year, with phosphorus deviation limits above target varied from not more than 10 Mg to 2 Mg per year. The area allocated for BMP 2021 drastically increased from 1800 to 9000 hectares, the largest share of total area under pasture. Under this grazing management practice, the pasture received 4 tons of poultry litter per hectare and no commercial nitrogen fertilizer was applied at all. However, producers maintained minimum biomass of 1600 kilograms per hectare during grazing at a stocking rate of 0.63 AU per hectare. BMP 2022 and BMP 0012 are second, each of them allocated about

6000 ha. The grazing management practices BMP 0011 and BMP 3031 were each allocated about 3000 hectares of land.

Table 4 Land Allocation (Ha) by BMP When Phosphorus Target is 30 Mg / year.

Assigned BMP*	Mean Annual Total Phosphorus Load : Deviation Limit Above Mean (tons/yr)				
	30:10	30:08	30:06	30:04	30:02
0011	3469.3	3470.0	3470.2	1605.9	1568.0
0012	5953.5	5924.8	5902.6	6602.7	5349.1
0013	837.6	837.6	831.3	822.0	1.7
0221	360.1	360.1	364.9	97.8	989.5
0222	2575.2	2643.4	2446.6	3957.3	3870.0
0223	189.1	188.9	167.9	188.1	1735.6
0331	55.6	55.6	58.9	10.1	728.6
0332	13.4	13.2	14.3	42.4	498.5
0333	68.6	68.5	221.3	1213.5	4009.0
0111	1.4	1.3	123.9	0.8	7.2
0112	2717.4	2715.6	2896.5	2631.4	1782.3
0113	0.0	0.5	1.8	1.1	1.1
1011	4.1	4.2	7.7	6.5	7.0
1012	108.7	113.1	100.1	11.4	4.9
1013	2.1	2.7	2.5	1.8	1.1
1231	0.0	0.0	0.9	0.4	1.3
1232	0.2	0.2	0.0	0.0	0.0
1233	0.2	0.2	0.0	0.0	0.0
1121	0.1	0.5	0.9	0.4	0.0
1122	1.4	1.9	2.4	1.6	2.0
1123	0.0	0.5	0.0	0.0	0.0
2021	8910.9	8825.5	8115.3	6781.7	5939.2
2022	6090.8	6113.9	6463.3	5100.6	910.0
2023	1244.5	1245.9	939.1	1139.8	632.3
3031	3040.8	3113.9	3503.5	3805.1	4902.5
3032	2.4	2.6	6.8	3.7	1.0
3033	0.2	0.7	0.5	0.2	0.2
3231	378.9	378.5	423.8	1853.4	2431.7
3431	0.2	0.2	0.4	78.2	191.0
3432	0.5	0.6	0.8	59.7	199.1
3433	0.7	1.6	4.1	31.0	502.1

Table 5 below shows the optimal grazing management practices selected by the economic optimization model and amount of land allocated for each selected management practice

when the mean annual total phosphorus runoff for the Eucha-Spavinaw watershed was reduced from 40 Mg to 25 Mg and 20 Mg per year, with phosphorus deviation limits above target varied from not more than 10 Mg to 4 Mg per year. When the mean annual phosphorus runoff was limited to 25 Mg per year, the area allocated for BMP 2021 declined slightly, but it remained the largest share of total area under pasture followed by BMP 3031 and BMP 0011. The amount of land allocated for BMP 0011, BMP 0222, BMP 0333, and BMP 3031 increased. However, when the mean annual phosphorus runoff was further limited to 20 Mg per year, the area allocated for BMP 0333 drastically increased to about 9000 hectares, receiving the largest share of total area under pasture. The amount of land allocated for BMP 2021 declined to about 5000 hectares, but ranked second to BMP 0333. Land allocated for BMP 3031 declined while that allocated for BMP 0222 remained relatively the same. The amount of land allocated for BMP 0221 increased significantly. When the mean annual total phosphorus runoff for the Eucha-Spavinaw watershed was reduced from 40 Mg to 20 Mg per year, the amount of pastureland that received no poultry litter at all increased from about 14000 to 26000 hectares whereas the amount of land that received 4 tons of poultry litter per hectare declined from about 18000 to 5000 hectares. The amount of land that received no commercial nitrogen fertilizer dropped from approximately 35,000 to 14000 hectares whereas the land that received from 100-150 kg/ha of commercial nitrogen fertilizer increased from approximately 5 to 22000 hectares. However, the amount of pastureland on which a minimum biomass of 1100 kg/ha was maintained during grazing declined from 18000 to 4000 hectares whereas the land on which a minimum biomass of 1600

kg/ha and above was maintained during grazing increased from about 18000 to 32000 hectares. The amount of land that was stocked at a rate of 1.00 AU/ha and above declined from approximately 33000 to 19000 hectares while that which was stocked at a lower rate of 0.63 AU/ha increased drastically from 4000 to 16000 hectares.

Table 5. Land Size (ha) by BMP When Phosphorus Target is 25/20 Mg / year

	Mean Annual Total Phosphorus Load : Deviation Limit Above Mean (tons/yr)							
BMP	25:10	25:08	25:06	25:04	20:10	20:08	20:6	20:04
0011	4355.6	4356.4	4354.3	2916.9	1771.6	1771.0	1770.6	1774.8
0012	3081.2	3081.4	3095.9	4441.1	1965.9	1965.9	1967.0	1978.3
0013	1.4	0.6	2.2	2.5	1.6	1.5	1.1	3.7
0221	1107.3	1165.9	1079.6	1185.1	4129.2	4236.9	4132.7	4157.8
0222	3925.9	3739.8	3813.0	3604.8	3286.6	3247.0	3324.7	3368.8
0223	823.6	820.6	828.2	993.5	3123.9	3123.9	3116.0	3144.5
0331	1.2	1.2	1.2	15.2	1.2	1.2	1.2	8.1
0332	575.9	575.9	572.7	541.7	1884.1	1887.4	1886.2	1872.0
0333	3366.7	3596.9	3599.9	3948.7	8881.0	8869.5	8869.4	8878.8
0111	1.6	0.9	0.9	1.3	7.2	8.5	8.6	7.1
0112	1007.4	1012.5	1019.8	1069.9	554.1	545.4	553.2	568.8
0113	1.0	0.2	0.0	1.3	0.4	0.4	1.0	3.1
1011	2.1	2.1	2.9	9.7	2.8	2.9	2.6	9.0
1012	6.5	7.2	8.3	6.4	5.7	5.7	6.6	6.5
1013	2.0	2.2	2.9	1.2	2.2	2.5	3.1	3.9
1231	0.1		0.6	0.0	0.0	0.0	0.5	0.6
1232	0.2	0.2	0.2	0.0	0.3	0.2	0.2	0.9
1233	0.1	0.2	0.1	0.0	0.8	0.8	1.0	0.0
1121	0.4	0.1	0.1	0.4	0.1	0.1	0.9	1.0
1122	2.6	3.4	2.1	2.2	3.8	5.0	3.5	4.7
1123	0.0	0.1	0.4	0.7	0.1	0.1	0.1	0.6
2021	8173.5	8154.2	8337.7	7655.1	5277.7	5265.5	5327.6	5078.9
2022	1619.9	1620.7	1613.1	1304.3	12.9	13.4	12.4	150.2
2023	1678.8	1678.8	1670.6	1218.2	144.2	147.3	146.8	163.5
3031	6581.7	6620.2	6579.2	5576.0	4673.6	4595.2	4614.2	4381.7
3032	4.1	3.6	3.7	2.0	2.6	2.0	4.3	2.7
3033	0.9	1.1	1.3	18.0	0.8	0.8	1.1	1.4
3231	441.1	440.7	441.1	1658.3	300.8	300.9	300.2	367.9
3431	26.8	26.7	26.4	112.0	31.3	31.3	31.3	31.0
3432	0.3	0.5	0.7	37.1	24.8	25.1	25.2	26.0
3433	1.1	1.3	2.0	5.9	1.2	0.9	1.4	3.6

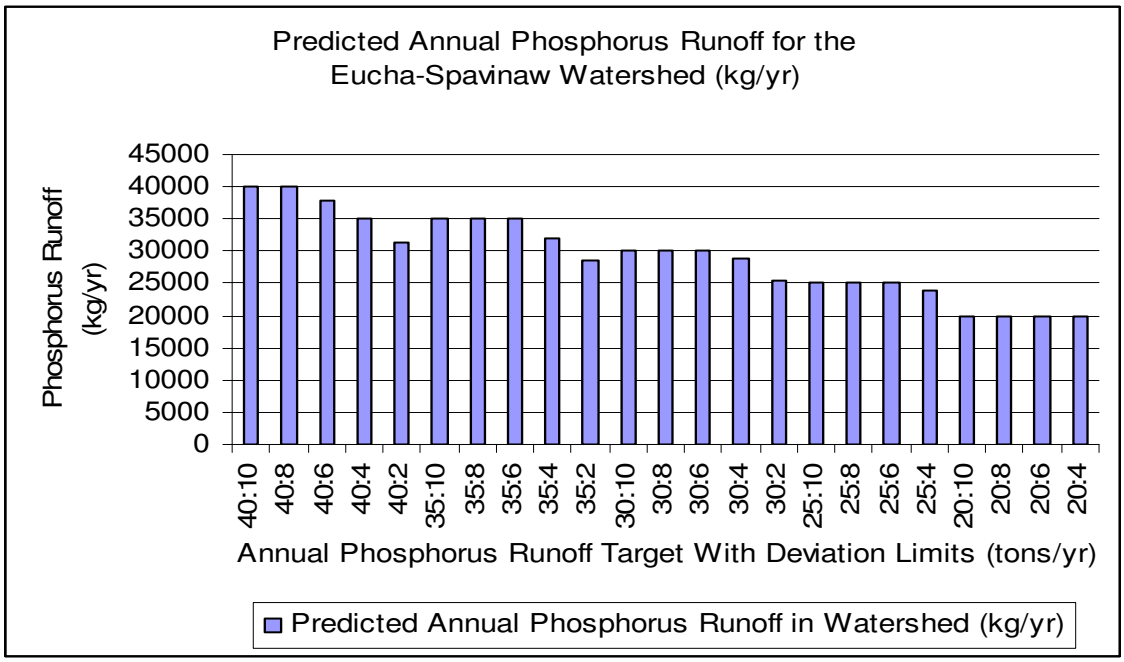

Figure 1. Predicted annual phosphorus runoff for the Eucha-Spavinaw watershed

Figure 1 shows the effect of alternative phosphorus runoff targets and deviation limits above target on predicted mean total annual phosphorus runoff from pastureland in the Eucha-Spavinaw Watershed. The estimated total annual phosphorus runoff from pastures declined from 40 to 20 tons per year as the annual phosphorus runoff target was reduced from 40 to 20 tons per year, respectively. The phosphorus deviation limit above the set annual phosphorus runoff target was varied in reductions of 2 tons from 10 to 2 tons per year. Lower phosphorus deviation limits above target appear to be effective in reducing phosphorus pollution when the total annual phosphorus load for the watershed was limited to 40 and 35 tons per year. However, the phosphorus deviation limits did not affect predicted phosphorus runoff when the maximum allowable phosphorus load was limited to 20 tons per year. Figure 9 below shows the effect of alternative annual

phosphorus runoff targets and phosphorus deviation limits above target on optimal poultry litter use in the Eucha-Spavinaw watershed. As the maximum allowable total annual phosphorus loading for the entire watershed was reduced from 40 to 20 tons per year without imposing an upper limit on the phosphorus deviation above target, the amount of poultry litter applied on pastures in the entire watershed declined from about 43000 to 11000 tons per year (approximately 76 percent reduction in litter applied as fertilizer). The imposition of an upper limit on phosphorus deviation above the set phosphorus loading target for the watershed resulted in further reduction of the optimal amount of poultry litter applied in the entire watershed at all phosphorus load levels. A phosphorus deviation limit above target of not more than 4 tons per year reduced the amount of litter applied as fertilizer to about 2 tons per year.

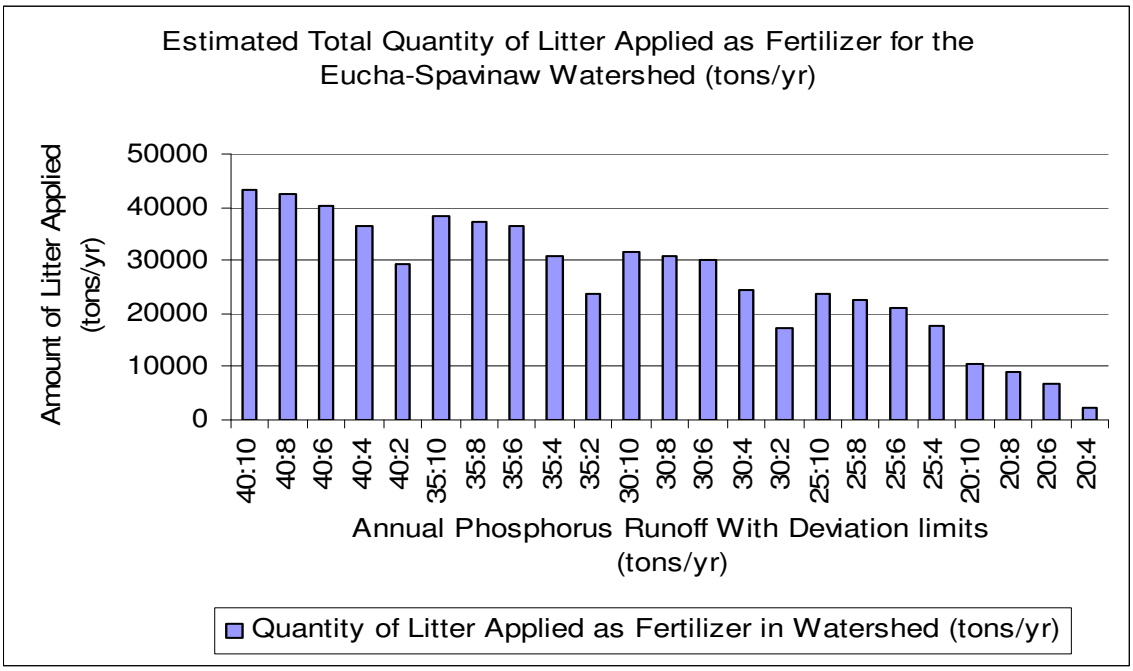

Figure 2 Estimated quantity of litter applied in the Eucha-Spavinaw watershed

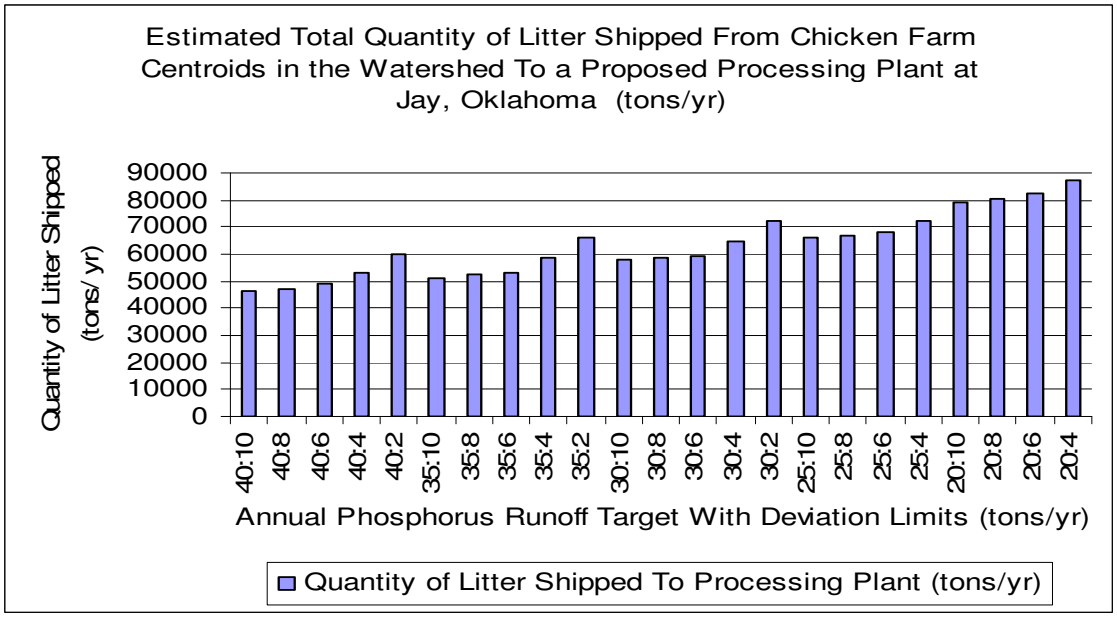

Figure 3 Litter shipments to litter-to-energy power plant at Jay, Oklahoma

Figure 3 above shows the effect of alternative annual phosphorus runoff targets and phosphorus deviation limits above target on optimal litter shipments from chicken farm centroids in the watershed to the possible litter-to-energy processing plant with and without upper phosphorus deviation limits above target. As the allowable total annual phosphorus loading for the entire watershed was reduced from 40 to 20 tons per year, the optimal amount of poultry litter shipped to the litter-to-energy processing plant (located at Jay, Oklahoma) increase from 46 to 79 tons per year. Reducing the phosphorus loading target from 40 to 20 tons per year without imposing an upper limit on the phosphorus deviation increased the optimal amount of poultry litter shipped to the litter-to-energy processing plant from 46 to 79 tons per year. The imposition of an upper limit on phosphorus deviation of not more than 4 tons per year above the phosphorus loading

target of 20 tons per year for the watershed resulted in further increases of the optimal amount of poultry litter shipped to the processing plant to about 87 tons per year.

Optimal Litter Application Rates on Selected Major Soils

For discussion purposes, we selected some major soils to highlight the variation between the amounts of litter that can be applied to and amount of predicted phosphorus runoff from different soil types given alternative phosphorus runoff targets and phosphorus runoff deviations above the specified targets. Figure xxx and xxx show the effect of limiting annual phosphorus runoff target on the amount of litter applied on soils Tonti and Nixa, respectively. Tonti received much higher levels of litter compared to Nixa, but the overall quantity of litter applied on Tonti declined drastically as the phosphorus runoff target was reduced from 40 to 20 tons per year. A 50 percent reduction in the annual phosphorus runoff target resulted in complete cessation of litter applications on both soils. However, in the case of soils such as Doniphan and Newtonia shown in figure 6 and figure 7 respectively, the amount of litter applied on these soils remained relatively high as the annual phosphorus load levels were reduced from 40 to 20 tons per year. These two sets of soils demonstrate that the degree and response pattern to reductions of the phosphorus runoff target is different for different soils. This result suggests that uniform phosphorus reduction policies and programs in the case of these major soil types in the Eucha-Spavinaw watershed are not effective and efficient in achieving the desired phosphorus reduction goals to ensure clean water in the lakes.

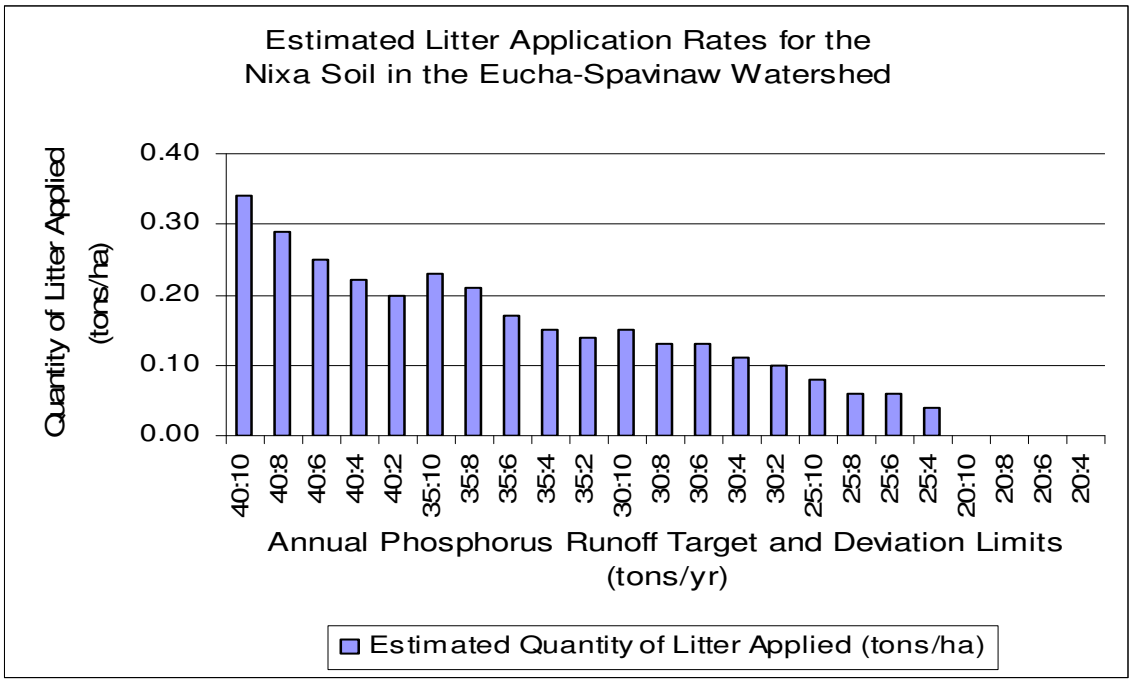

Figure 4 Estimated litter application rates for soil Nixa

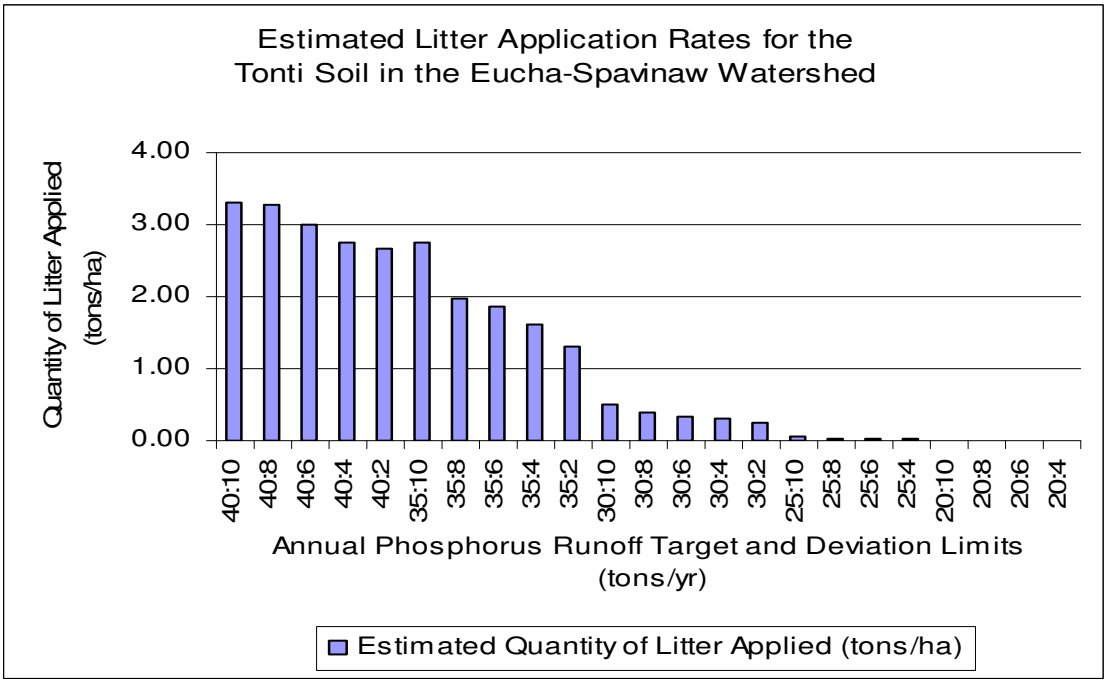

Figure 5 Estimated litter application rates for soil Tonti

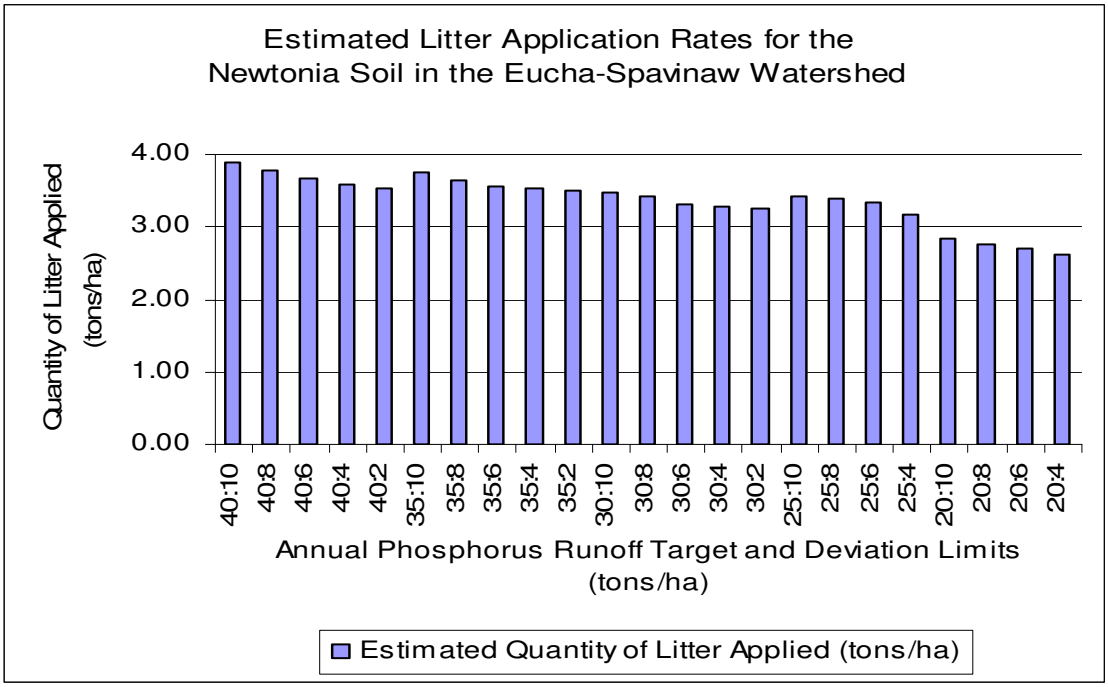

Figure 6 Estimated litter application rates for Newtonia

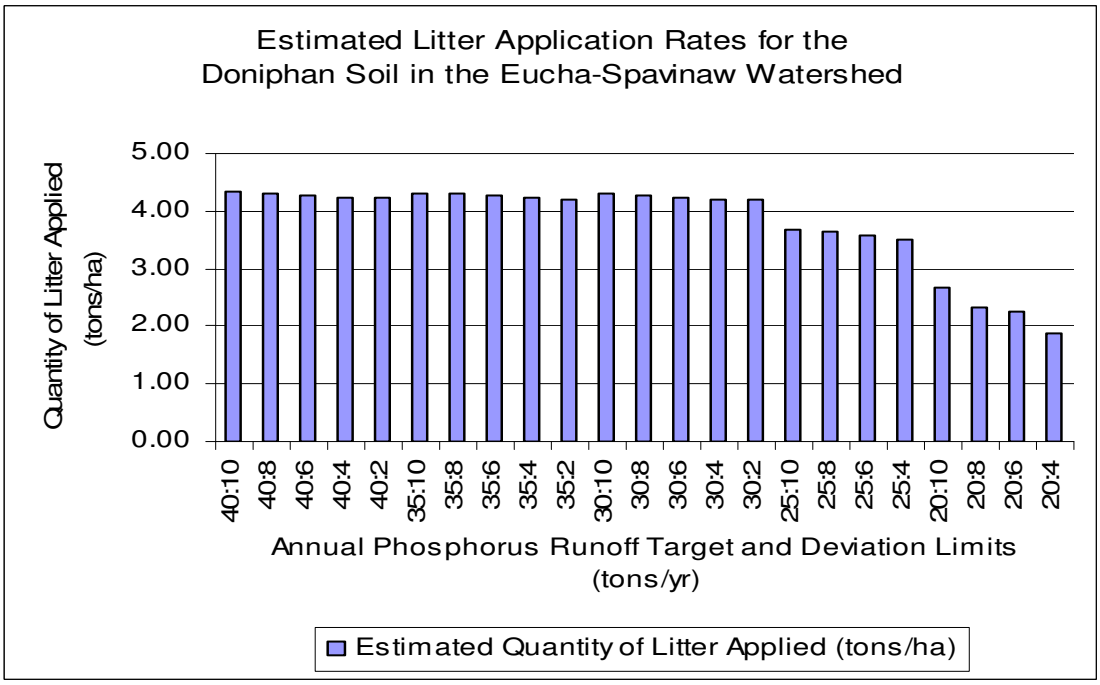

Figure 7 Estimated litter application rates for Doniphan

Hauling With Alum-Treated Litter Option

In this option we examined the effects of limiting total phosphorus runoff for the Eucha-Spavinaw watershed to 40, 35, 30, 25, and 20 tons per year on optimal litter and pasture management systems with an option to use alum-treated litter on pastures as well as hauling litter within the watershed and to a possible litter-to-energy power plant located at Jay, Oklahoma. Table 6 below shows the codes and description of management activities that entered the solution set at different levels of phosphorus runoff. The addition of the possibility to use alum-treated litter on pastures reduced the number of optimal management practices in the solution set at all levels of phosphorus runoff.

Table 6 Optimal Management Activities Given Alum-Treated Litter Option

BMP Code	Poultry Litter Applied (tons/ha)	Elemental Nitrogen Applied (kg/ha)	Minimum Biomass Maintained During Grazing (tons/ha)	Stocking Rate (AU/ha)
46	4	0	1.6	1.26
56	6	0	2.0	1.26
61	1.765	0	1.1	0.63
66	1.765	0	1.1	1.00
76	3.529	0	1.6	0.63
81	3.529	0	1.6	1.00
86	3.529	0	1.6	1.26
91	5.294	0	2.0	0.63
96	5.294	0	2.0	1.00
101	5.294	0	2.0	1.26

No commercial nitrogen was applied to pastures in this scenario. Poultry litter was applied to pastures at levels consistent with meeting the nitrogen requirement of the crop. There are only 2 pasture management systems in the solution set (codes 46 and 56) that do not involve the use of alum-treated poultry litter. Table 7, table 8, and table 9 show the range of pasture management practices that entered the solution when the annual phosphorus runoff was limited to 40, 30, and 20 tons per year, with phosphorus deviation limits above target varied from 10 to 2 tons per year. When the phosphorus runoff is limited to 40 tons per year, 21000 ha of land is allocated to pasture that receives 4 tons of untreated litter per ha, stocked at 1.26 AU/ha and the biomass maintained during grazing is 1600kg/ha. Approximately 15000 ha of pasture will be allocated to management 96. This BMP recommends application of alum-treated poultry litter at the rate of about 5 tons per ha, with cattle put on pasture at the stocking rate of 1.00 AU/ha. Biomass maintained during grazing is estimated at 2000kg/ha. However, as the phosphorus runoff limit is reduced to 20 tons per year, more land is moved out of management 46 and 56 (both use untreated litter) and allocated largely to management systems 96, 81 and 66 in that order. All these three management systems that come into the solution set recommend the use of alum-treated litter, maintaining at least 1600kg/ha of biomass during grazing and a stocking rate of 1.00 AU/ha. The option of using alum-treated poultry litter on pastures lead to complete cessation of litter shipments from the watershed to the possible litter-to-energy power plant in Jay, Oklahoma.

Table 7 Land Allocation (ha) By BMP When Phosphorus Limit is 40 Mg Per Year

	Annual Phosphorus Runoff and Deviation Limits Above Target				
Assigned BMP	40:10	40:08	40:06	40:04	40:02
46	20774	18873	14027	12009	4583
56	5473	6173	4954	3020	1025
61					
66					58
76					350
81				1303	11715
86					53
91			316	1174	21029
96	15208	16797	22833	23951	21029
101	1647	1611	1689	1445	3394

Table 8 Land Allocation (ha) By BMP When Phosphorus Limit is 30 Mg Per Year

	Annual Phosphorus Runoff and Deviation Limits Above Target				
Assigned BMP	30:10	30:08	30:06	30:04	30:02
46	14724	14724	10012	7314	71
56	1284	1284	1821	720	176
61					350
66					1433
76				125	797
81	36	36	34	1468	21696
86				32	1799
91			316	1050	226
96	24270	24270	27862	29607	16291
101	2739	2739	3144	2908	108

Table 9 Land Allocation (ha) By BMP When Phosphorus Limit is 20 Mg Per Year

Assigned BMP	20:10	20:08	20:06	20:04	20:02
46	1676	1676	1676	402	
56	375	375	375	283	
61	7	7	7	7	
66				58	20679
76	176	176	176	125	
81	9258	9258	9258	10396	17852
86	848	848	848	1702	
91	647	647	647	1277	
96	29682	29682	29682	28191	4605
101	252	252	252	595	

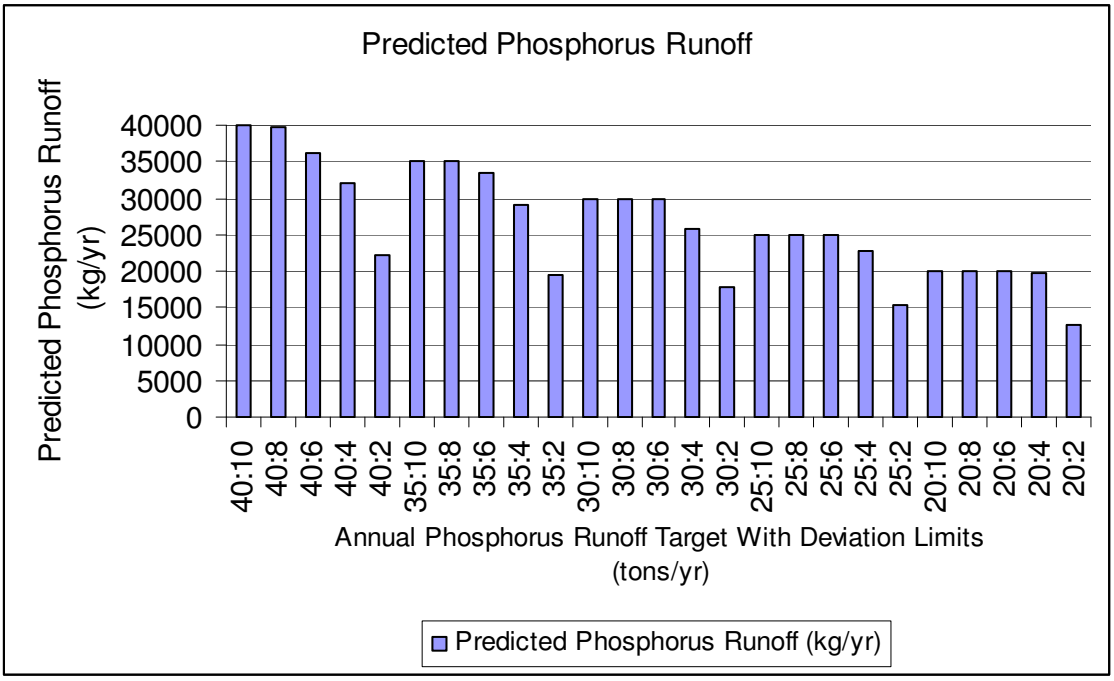

Figure 8 Predicted annual phosphorus runoff from pastures

Figure 8 shows that phosphorus pollution in the watershed can be reduced to levels below the set annual phosphorus runoff when the alum-treated poultry litter option is considered. Significant reductions in phosphorus runoff were achieved by varying expected phosphorus deviation above target at each phosphorus level without reducing the annual phosphorus runoff target. As the phosphorus load limit was reduced from 40 to 20 tons per year, predicted phosphorus runoff from pastures declined from 40 to 12.5 tons per year. Phosphorus runoff levels well below the expected annual phosphorus runoff target were obtained by varying only the phosphorus deviation limits above the specified target. Phosphorus runoff levels from all soil types in the watershed significantly declined when alum-treated litter was used on pastures. Tonti and Nixa still produced the least amount of phosphorus runoff whereas levels from Doniphan and Clarksville soils remained relatively higher.

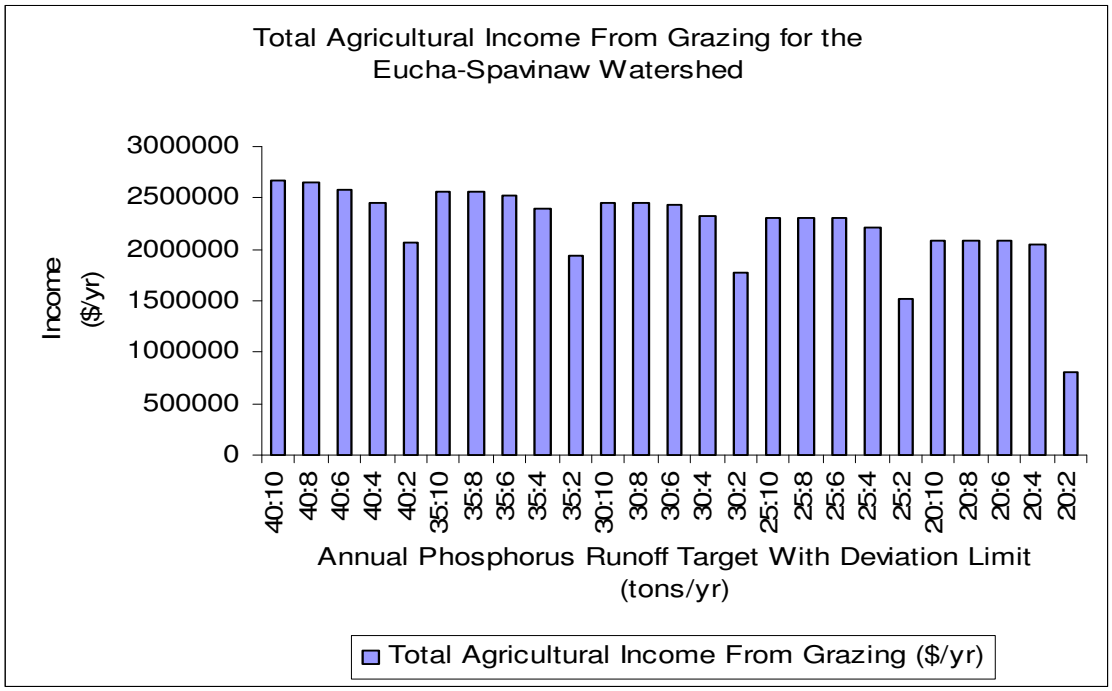

Figure 9 Estimated total producer income from grazing in the watershed

The total annual producer income from pasture management systems in the solution set when the annual phosphorus runoff was limited to 40 tons per year was estimated at about $2.7 million. A 25 percent reduction in the phosphorus runoff limit lowered producer income to about $1.7 million. A further reduction of the phosphorus limit to 20 tons per year yielded an annual producer income from grazing of about $700,000. Figure xxx below shows the respective reductions in agricultural income from grazing at each phosphorus runoff target and deviation limit. These reductions in producer income represent estimated total phosphorus pollution abatement costs for the watershed. Figure xxx indicates the estimated cost of abating an additional ton of phosphorus pollution per year in the watershed. Marginal abatement costs are shown to increase at an increasing rate as the annual phosphorus target and deviation limits are reduced.

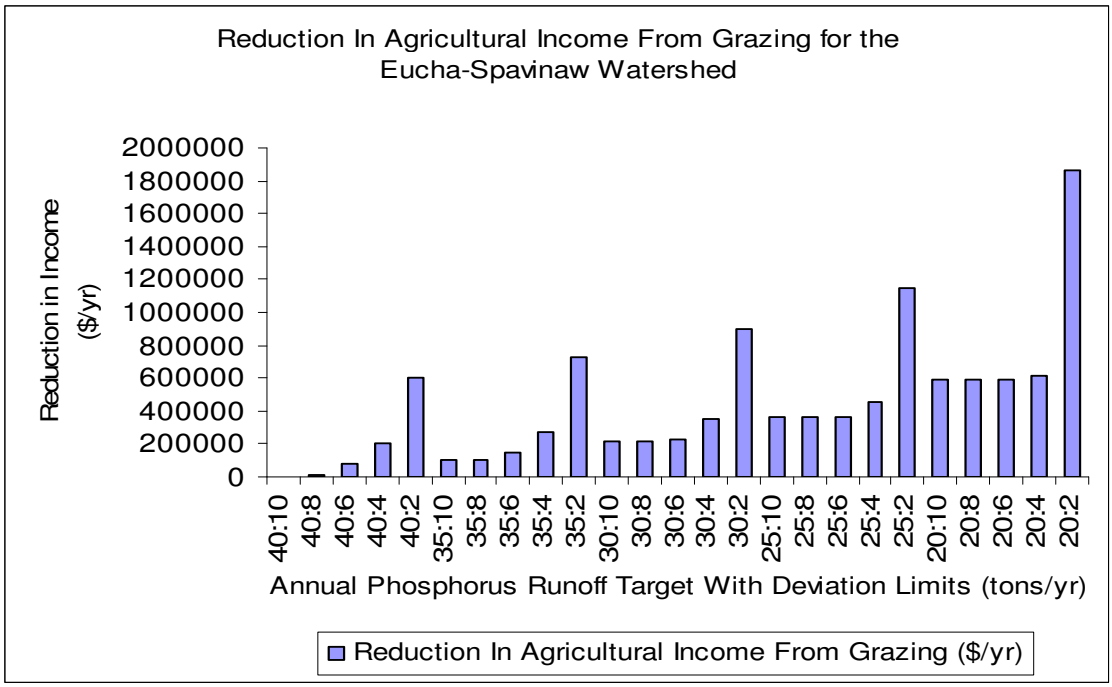

Figure 10 Estimated total phosphorus pollution abatement costs

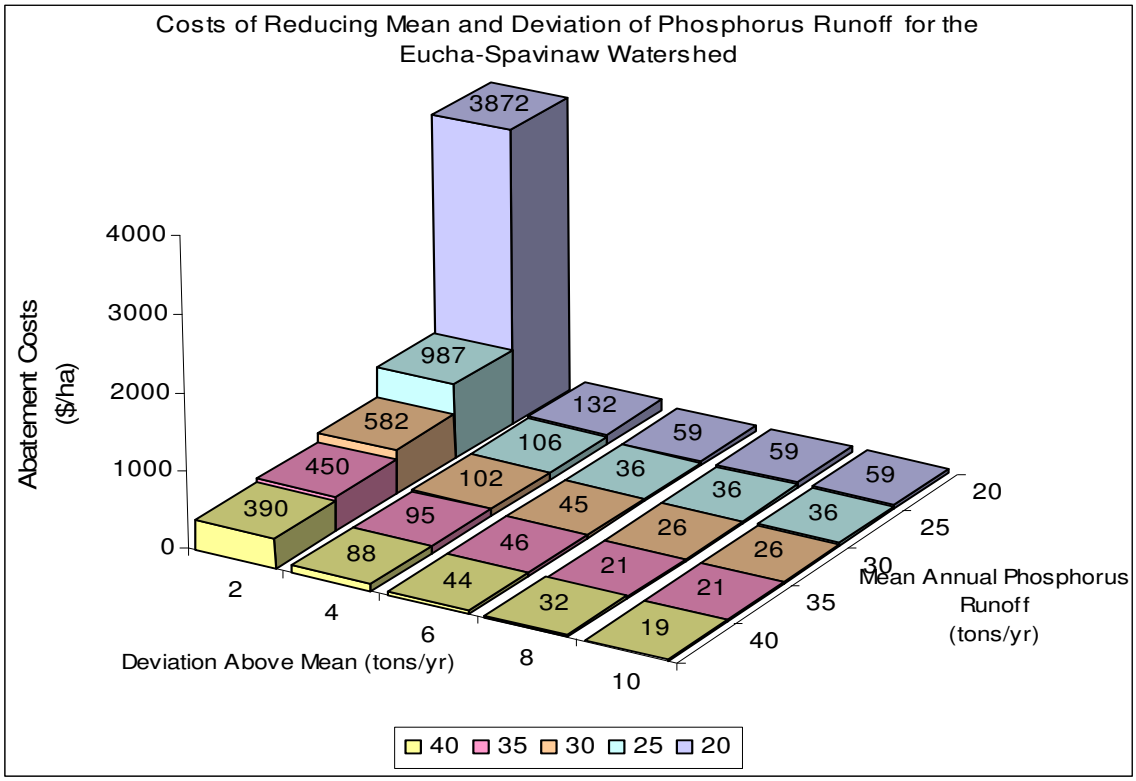

Figure 11 Estimated marginal phosphorus pollution abatement costs

Table10 below presents the estimates of fixed effects parameters of the mixed linear model fitted to the panel data considered in this article. The parameter estimates have been sorted in descending order to show to relative contribution of each explanatory variable to phosphorus runoff in the Eucha-Spavinaw watershed. All the "effects" shown in italics have regression coefficients that are significantly different from zero at the 5% significance level. This means a change in any of these variables will have a statistically significant impact on the amount of phosphorus loss from pastures in the watershed. Only 13 of the 24 soil types have a statistically significant effect on phosphorus runoff in the watershed. Britwater, Razort, Clarksville, Captina, Secesh and Healing contribute more to phosphorus pollution. It is estimated that putting one more hectare of Britwater under

pasture will increase phosphorus loss by 3 kg per hectare. When the stocking rate increases by 1AU / ha, phosphorus runoff will increase by about 24kg/ha.

Table 10. Fixed Effects Parameters of the Mixed Linear Model

Effect	Estimate	Standard Error	t Value	Pr>|t|
Intercept	-47.8379	5.0665	-9.44	<.0001
Britwater	3.0772	1.3424	2.29	0.0219
Razort	2.3981	1.1362	2.11	0.0348
Clarksville	2.0253	0.9638	2.10	0.0356
Captina	1.6864	0.4134	4.08	<.0001
Secesh	1.4292	0.7230	1.98	0.0481
Healing	1.4078	0.4822	2.92	0.0035
Cherokee	1.3653	0.7232	1.89	0.0590
Noark	1.3210	0.6886	1.92	0.0551
Nixa	1.0697	0.6202	1.72	0.0846
Macedonia	0.9691	0.3104	3.12	0.0018
Peridge	0.8471	0.2761	3.07	0.0022
Tonti	0.7468	0.4137	1.81	0.0711
Stigler	0.6987	0.1757	3.98	<.0001
Doniphan	0.2024	0.1395	1.45	0.1467
Jay	0.1896	0.2092	0.91	0.3648
Eldorado	0.1441	0.0202	7.15	<.0001
Taloka	0.1133	0.1100	1.03	0.3033
Elsah	0.0615	0.1052	0.58	0.5590
Hector	-0.1190	0.4494	-0.26	0.7912
Newtonia	-0.2618	0.1368	-1.89	0.0593
Linker	-0.6358	0.2075	-3.06	0.0022
Carytown	-1.4204	0.3809	-3.73	0.0020
Mountainburg	-2.0916	0.7242	-2.89	0.0039
Waben	0.0000	.	.	.
StkRate	24.3077	0.0599	405.54	<.0001
LagPloss	0.1355	0.0026	52.74	<.0001
CurV	0.0294	0.0018	16.05	<.0001
BmMin	0.0216	0.0026	8.27	<.0001
RKLS	-0.0745	0.0344	-2.16	0.0305
Papl	-0.0751	0.0138	-5.44	<.0001
Napl	-0.1101	0.0050	-21.85	<.0001

Conclusion

This article demonstrates that integrated environmental-economic modeling approach, that combines the use of the SWAT model and mathematical programming can be used to assess the impact of current and alternative farming practices on water quality in the Eucha-Spavinaw watershed. This decision-support tool can be used to assist policymakers in their strategic phosphorus loss reduction and water quality improvement decisions and in setting realistic and efficient Total Maximum Daily Loads (TMDLs). There is no single management practice that dominates in all parts of the watershed. The economic optimization model assigned various site-specific pasture management systems and litter allocations on the basis of relevant environmental and economic factors in that part of the watershed. The environmental-economic optimization model shows that least cost abatement policies may differ significantly from and be much less costly than the imposition of uniform restrictions. The econometric model determined that only about half of the soil types in the Eucha-Spavinaw watershed contribute significantly to the phosphorus runoff and water quality problem in the area. Britwater, Razort, Clarksville, Captina, Secesh and Healing contribute more to phosphorus pollution than any other soil found in the area. The phosphorus runoff problem gets even worse when pastures on these soils are heavily grazed at stocking rates exceeding 1 AU/ha and the plant biomass maintained during grazing is lower than 1600kg/ha. The use of alum-treated poultry litter

appears to be a very effective phosphorus runoff reduction strategy even at high phosphorus loss limits for the watershed. As the phosphorus loss limits were reduced, the pasture management practices that were adopted included those that encourage the use of alum-treated litter to meet the nitrogen requirement for the crop as well as lowering stocking rates on the pastures and retained higher levels of biomass during grazing.

The other soils that do not significantly contribute to phosphorus runoff received higher optimal litter application rates compared to the set of soils specified above. On the other hand, complete elimination of all fertilizer was found to actually increase total phosphorus loss on some soils because of increased erosion and sediment bound phosphorus. These results show that optimal poultry litter application rates can vary from one soil type to another within the watershed. This implies that it may be more cost effective to develop phosphorus reduction programs that target specific soil types within the watershed rather than continue with the current uniform policy of limiting litter application rates strictly by soil test phosphorus. The possible litter-to-energy plant does not appear to be a viable option when producers have an incentive to use alum-treated poultry as fertilizer. However, when the alum-treatment option is removed from the model, the litter-to-energy power plant located at Jay, Oklahoma becomes a more cost effective method of reducing both the level and the variability of phosphorus runoff as pollution limits for the Eucha-Spavinaw watershed are reduced.

References

Cestti, R., J. Srivastava and S. Jung. "Agriculture Non-Point Source Pollution Control: Good Management Practices- The Chesapeake Bay Experience." World Bank Working Paper No. 7, World Bank, Washington DC, 2003.

Freeman, A.M., R.M. Haveman, and A.V. Kneese. "The Economics of Environmental Policy", New york: Wiley Publishers, 1973.

Moore, P. A., T.C. Daniel and D. R. Edwards."Reducing Phosphorus Runoff and improving Poultry Production with Alum." Poultry Science, 78(1999):692-698.

Oklahoma Water Resources Board (OWRB). "Water Quality Evaluation of the Eucha / Spavinaw Lake System- Final Report." Oklahoma City, Oklahoma, 2002.

Oklahoma Department of Environmental Quality (ODEQ). "Water Quality Assessment Integrated Report", Oklahoma City, Oklahoma, 2004.

Oklahoma Water Resources Board (OWRB) and City of Tulsa. "Justification For Total Phosphorus Criteria to Protect Public and Private Water Supply Beneficial Use and Aesthetics Use of Lake Eucha and Spavinaw Lake", Oklahoma City, Oklahoma, 2006.

Qui, Z., T. Prato, and M. Kaylen. "Watershed-Scale Economic and Environmental Tradeoffs Incorporating Risks: A Target MOTAD Approach." *Agricultural and Resource Economics Review* 27 (1998): 231-240.

Sterner, T. "Policy Instruments for Environmental and Natural Resource Management",Resources for the Future. Washington, D. C., 2003

Storm, D.E., A.L. Stoecker, T. Ancev, and M.J. White. "Evaluating Cost effectiveTechnologies to Reduce Phosphorus Loading to Surface Waters for the Ozark Region." *Final* R*eport to Water Resources Institute*, Oklahoma State University and United State Geological Survey, June 2003.

Teague, M. L., Bernardo, D.J. and Mapp, H.P. "Farm-Level Economic Analysis Incorporating Stochastic Environmental Risk Assessment, *American Journal of Agricultural Economics* 77 (1995): 8-19

Tietenberg, T. "Environmental and Natural Resource Economics." 5th Ed., Addison Wesley, New York, NY, 2000.

United States Environmental Protection Agency (USEPA), Office of Water Quality. "*Water Quality Trading Policy.*" Washington DC, 2003.