INCOME RISK AND WATER QUALITY, DAMAGE ABATEMENT AND PESTICIDE PRODUCTIVITY, AND ABATING SPATIAL EXTERNALITIES IN AGRICULTURE

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PREFACE

The body of this dissertation is composed of three separate essays. The first essay was written with a focus on the consideration of income risk in the formulation of policies which are designed to protect groundwater from intrusion of agricultural pesticides and fertilizers. The primary goal of this research was to examine the link between income risk and the effectiveness of these policies.

Bio-physical simulation is used to develop yield, leaching , and run-off for common cropping activities. A safety-first model of income risk is combined with an environmental impact measure to account for both economic and environmental impacts. Fragility of results from model specification as well as the failure to consider income risk is developed.

The second essay focuses on pesticide productivity in Upland cotton. Previous research has used aggregate time series data to estimate pesticide productivity. These estimates are likely to contain biases resulting from the nature of aggregate data as well as the functional specification. A damage abatement specification is used with specific chemical data to derive marginal productivity estimates of chemical components for a sample of Texas Upland cotton producers.

Essay three is an examination of policies which consider the inherent spatial nature of agricultural production and the relative efficiency of these policies. This research is intended to shed some light on different policies which are targeted towards controlling agricultural pollution efficiently.

A theoretical examination of policies which account for spatial differentiation in agriculture is developed. A discrete-time, stochastic dynamic-optimization problem is formulated and used to compare the polices of land use permits and spatially differentiated taxes which target nitrogen leachate for a sub-watershed in Western Oklahoma. Policies which consider spatial differences in agricultural production are more efficient than those which do not.

Each of these essays is meant to be read as a separate work and they are clearly divided in the dissertation. Each essay has an abstract which more fully describes the purpose and intent of each essay and should be used to fully understand the content of each essay and the complete dissertation.

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ESSAY I

INCOME RISK AND WATER QUALITY

INCOME RISK AND WATER QUALITY

Abstract

The sensitivity of environmental policy conclusions to programming methods is a seldom considered topic. Previous research has shown that producer decisions are not likely to be ignorant of risk and policy conclusions must be made with this in mind. The focus of this research is development of an efficient means of handling risk in the examination of environmental policy.

A safety-first farm level risk programming model is developed and for sensitivity compared with a commonly used linear programming approach Conclusions of groundwater quality policies based on these different programming approaches are examined. Both economic and environmental impacts are considered.

Stochastic net returns are generated using a bio-physical simulation program, EPIC-PST, (Erosion Productivity Impact Calculator, Pesticide Movement Subroutines). The EPIC-PST results were entered into a safety-first programming model. A multi-attribute index of environmental outcomes is used to develop measures of environmental risk under the alternate groundwater protection policies being compared.

The farm plan portfolios under the different groundwater policies differ between the risk programming and expected returns approach. The returns were decreased by a larger percentage for the risk programming solutions than for the expected returns

approach. The risk programming model revealed that the variability of returns for the respective portfolios increased under the nitrogen effluent tax and both increased and decreased under a ethyl-parathion, methyl parathion, atrazine restriction and pesticide effluent tax . It was concluded that pesticide leachate polices that were effective at lowering groundwater pollution were associated with decreased variability.

The environmental results imply that the actual impacts of groundwater protection policies under the risk programming approach may not match policy maker's expectations under the expected net returns approach. Empirical distributions of the environmental indexes show that environmental risk could increase under the chemical effluent tax. Likewise, the nitrogen limit ineffective for less risk averse producers. These results imply that failure to consider risk could result in erroneous policy formation.

Keywords:
Water - quality, safety-first, income risk.

INCOME RISK AND WATER QUALITY

Introduction

Federal, state, and local concerns in response to groundwater risk from agricultural pesticides and nutrients have risen in the past decade. These concerns reflect both the continued dependence of producers on agricultural chemicals and their intensity of use. For example, in 1986 producers used pesticides on approximately 57% and commercially made fertilizers on 75% of U.S. farms (Office of Technology Assessment). In 1994, 94% of all upland cotton received some type of herbicide and 71% received some insecticides (USDA-NASS). The presence of and potential for agricultural non-point source pollution (NPS) from these chemicals is well documented and as a result these federal, state, and local governments are considering policy alternatives to protect groundwater reserves (Abdalla and Libby).

Policies aimed at reducing non-point source pollution can reduce the producers' production capability and change income risk. Hence, the producers' production decisions in response to a non-point source pollution policy will determine if the intended policy is effective in reducing groundwater pollution. The consideration of producer response to this change in income risk for non-point source pollution policy formulation is extremely weak and in some cases non-existent (Milon). Conversely, researchers have typically modeled producer response with linear programming and maximization of expected net returns (Jacobs and Cassler; Mapp et al.; Johnson, Adams, and Perry).

While reducing the potential of NPS pollution might be possible with usage or limiting policies, the risk of actual groundwater contamination is very difficult to quantify since contamination may depend on a multitude of factors including weather, soil characteristics, and production practices. This research builds on previous studies that have used bioeconomic simulation to quantify impacts, both environmental and economic, in examining groundwater concerns. The overall objective of this study is to develop a framework for studying producer risk and the impacts of risk on the effectiveness of water quality policies.

A farm level programming model with stochastic net returns and a multi-attribute environmental index is used to compare the relative farm level economic and environmental outcomes of five groundwater policies. The stochastic net returns for the representative farm are generated using EPIC-PST, a bio-physical simulation program, and used to model producer income risk. A "safety-first" risk model is developed and solved under water quality policies aimed at controlling pollution from pesticides and nitrogen. Results from the risk model are compared to the risk neutral maximization of expected net return solutions. A number of policies that have been considered in previous research are examined here (Teague, Bernardo, and Map; Jacobs and Cassler).

The policies considered for nitrogen are a per-acre nitrogen restriction, a per pound tax on nitrogen, and an effluent tax based on a nitrogen environmental index. The chemical policies considered are a selected pesticide ban and an effluent tax based on a chemical environmental index. A multi-attribute stochastic environmental index based on

20-year distributions of environmental outcomes is used to give accurate measures of groundwater risk associated with the farm-plans selected. The indexes are an ordinal measurement based on percolation, runoff, toxicity, and persistence for different cropping systems, nitrogen levels, and pesticide strategies. Correctly identifying the extent of environmental impacts by using a multi-attribute measure rather than a single criterion of run-off or amount of chemical applied should improve the understanding of the impacts on water quality under risk.

Previous Research

Policy measures aimed at reducing groundwater contamination and their potential impacts have been discussed throughout the literature. Mapp et al. considered targeted polices versus broad policies for nitrogen on a regional basis. Their study used linear programming and maximized average net returns to determine optimal crop production and distributions of chemical losses generated by EPIC-PST to quantify probabilities of runoff . They compared reductions in regional net returns under alternative water quality policies. Anderson, Opaluch, and Sullivan considered reduction and targeted area policies to reduce aldicarb in a specific area of Rhode Island, while Jacobs and Casler have compared private and social costs of phosphorus reduction under uniform and effluent tax policy. Both studies used linear programming. Govindasamy, Cochran, and Buchberger compared per acre versus per ton Pigouvian Tax polices for poultry litter application in northwest Arkansas, also with linear programming. Teague, Bernardo, and Mapp examined expected income reductions under multi-attribute environmental index goals consistent with nitrogen and chemical restriction policies. Their study showed that best management strategies could reduce agricultural chemical threats to groundwater and thus offer alternatives to direct regulatory policies while maintaining expected returns.

Producer risk and chemical use has been studied by Olson and Eidman in a MOTAD (Minimum of Total Absolute Deviations) formulation with price and yield variation to analyze decisions on herbicide use. Current federal and potential changes in policy and their impacts on herbicide adoption are examined for a representative farm in Minnesota. Results show that reductions in income variability through herbicide use are preferable, at least to the representative producer, to higher expected net returns. Archer and Shogren have used a risk model to look at the inter and intra substitution of herbicides for weed control decisions. They predicted decreased herbicide and fertilizer use for increased probability of herbicide failure that resulted in lower levels of non-point pollution under herbicide restriction policies. Johnson, Adams, and Perry used bio-economic simulation to assess the on farm impacts of nitrate reduction. They studied best management practices to achieve lower levels of nitrate pollution with less income reduction.

While research has explicitly considered income risk and water quality separately, income risk and its linkages to environmental impacts have not been explored . No studies testing the linkage between potential environmental impacts and the consideration of income risk were found in the literature.

Safety First Risk

Safety-first constraints in income risk analysis have evolved from portfolio risk analysis. Safety-first (SF) rules are perceived by researchers as an alternate model of decision analysis for the firm. Patrick et al. and others have shown that Kataoka and Telser's safety-first rules are likely to be accurate representations of firm decisions. Alternately, risk models such as the expected utility model have come under scrutiny as a model of producer decision since it is recognized that the independence axiom underlying expected utility is often violated (Khaneman and Tversky).

Under SF rules, the decision maker is assumed to maximize income subject to achieving a disaster level of returns a required percentage of the time. As shown by Pyle and Turnovsky, the relationship between the expected utility hypothesis and a SF criterion is neither direct nor unique. They demonstrated however, that the choice of SF rule is important in determining possible correspondence. The SF criterion used in this study can be consistent with the expected utility maximization hypothesis, but will not always produce choice sets equal to those under expected utility maximization. Since it is not a true model of expected utility maximization, common criticisms of expected utility cannot be leveled. However, this model, as discussed below, maintains some appeal of the expected utility model.

Model Specification

Introduced by Charnes and Cooper, have been to model stochastic programming problems. Incorporated into safety-first risk programming, chance constraints offer alternatives to computationally tractable methods such as MOTAD and Target MOTAD (Hazell; Tauer). Safety-first allows for probabilistic interpretation of the results.

Because net returns are believed to approximate a normally distributed random variable and because of the large size of the environmental policy model, a variation of the computationally tractable method for linearizing chance constraints first used by Wicks and Guise is developed here. The model is modified to solve safety-first rules of income risk and utilizes the multi-attribute environmental index developed by Teague, Mapp, and Bernardo to account for environmental impacts.

Safety-First and Chance Constraints

Let the constraint being considered here be

$$\Pr[\sum_{j} n_j x_j \geq b] \geq 1-\alpha, \tag{1}$$

where α is the corresponding level of acceptable risk. Let n_j be a normally distributed random variable of net returns for the j'th activity, x_j, where x_j is the level of the j'th activity. The sum

$$\sum_{j} n_j x_j \tag{2}$$

is a normally distributed random variable with mean π_j and variance σ_j^2. By the assumption of normality of returns, constraints or objective functions as given in equation (1) can be formulated. Risk is defined in this model to be the probability of not achieving at least some "disaster" level of net returns b, α percent of the time. A model that maximizes expected net returns subject to a constraint as defined in equation (1) requires the decision maker to choose α, the desired level of risk, and the disaster level of income b. As proven by Pyle and Turnovsky, using a SF criterion of this type will always result in non-feasible expected utility choice sets and maintains little theoretical tractability. However, if it is assumed that no riskless cropping choices can be made, the model can be reconstructed to avoid this non-feasibility. The model is restructured so that for each risk level α, there is a unique disaster level of net returns and expected net returns. Using a variation of the model by Wicks and Guise, this chance constraint problem can be linearized in the following formulation:

(3) $$\text{Max } b = \sum_j (\pi_j x_j) - \beta_\alpha \hat{\sigma}_j$$

subject to:

(4) $$\sum_j (\pi_j - n_{jt}) x_j - D^-_{jt} \le 0 \qquad \forall\ t$$

(5) $$\hat{\sigma}_j = (2F^{1/2} / T) \sum_j D^-_{jt} \qquad \forall\ t$$

(6) $$\sum_j \pi_j x_j \ge 0$$

(7) $$\sum_j ic_{jt} x_{jt} \ge 0 \qquad \forall\ t$$

(8) $$\sum_j in_{jt} x_{jt} \ge 0 \qquad \forall\ t$$

(9) $$\sum_j a_{ij} x_j \le r_i$$

where D^-_{jt} is the negative net return deviations below expected net returns for activity j in the t'th period. Net return deviations are transformed into estimators of the standard deviation in equation (6) by F, Fisher's constant. This is defined as

(10) $$F = (PI)T / 2(T-1),$$

where T is the number of periods and PI is the mathematical constant 3.14159. These estimates of standard deviation are entered into the objective function via equation (4) (Hazell and Norton). β_α is the normal deviate for the desired risk preference level (RPL) α. Equations (7) and (8) are accounting rows for the i'th chemical and nitrogen indices and j'th activity respectively. Equation (9) is a normal resource constraint where a_{ij} is i'th resource requirement for activity j and r_i is the i'th restriction. Positivity constraints for each activity are included in the model but not listed here.

This model provides advantages over other safety-first specifications and risk programming models. By virtue of the model, estimates of standard deviation are minimized and expected returns are maximized as under the Expected Utility approach. Also, for a RPL of 50% ($\beta_\alpha = 0$), the special case of risk neutral Expected Utility maximization is implied or maximization of expected net returns. The level of expected net returns and estimate of standard deviation for each level of risk is a point on the expected utility maximization "opportunity locus" in the mean-standard deviation plane (Pyle and Turnovsky). This locus for each water quality policy traces out an efficiency frontier that can be compared in the mean-standard deviation plane. Also, for each RPL assumed, there is a unique disaster level of income associated with that level of expected net returns. This is the lowest level of net returns a producer would be willing to accept at that particular RPL level when choosing to maximize expected net returns, which makes correlation between producer risk perceptions and producer decisions easier. Further, the environmental outcome associated with the level of risk and the resulting farm plan chosen will be unique so that expected net-returns and environmental outcomes can be compared under alternate environmental or governmental restrictions.

Environmental Risk Indices

The multi-attribute environmental risk indices, equations (7) and (8), used in this model follow those developed by Teague, Mapp, and Bernardo. While other indices have been developed, these indices are comprehensive indices taking into account both surface and groundwater impacts of agricultural chemicals. The environmental index for pesticides is defined as:

$$EIC_{ij} = (CPERC_{ij} \times HA_i \times PP) + (CRUNOFF_{ij} \times LC_i \times RP)$$

where:

EIC_{ij} = the environmental index of chemical i for activity j

$CPERC_{ij}$ = the quantity of pesticide i lost in percolation for crop activity j in grams per acre.

$CRUNOFF_{ij}$ = The quantity of pesticide i lost in runoff for crop activity j in grams per acre.

$$HA_i = \begin{cases} 5 \text{ if } HAL_i \leq 10 \text{ or the EPA Carcinogenic Risk Category is A, B, B1, B2, or C} \\ 3 \text{ if } 10 < HAL_i \leq 200 \\ 1 \text{ if } HAL_i > 200 \end{cases}$$

HAL_i is the Lifetime Health Advisory Level set by EPA for the i`th chemical.

$$LC_i = \begin{cases} 5 \text{ if } LC_{50} < 1 \\ 3 \text{ if } 1 \leq LC_{50} \leq 10 \\ 1 \text{ if } LC_{50} > 10 \end{cases}$$

LC_{50} is the acute toxicity to fish for 96 hours of exposure. The indices are calculated for each chemical applied and summed over each activity. The index given in equation (7) is:

$$IC_j = \sum_{i=1}^{n} PIC_{ij}$$

where,

PEI_j is the Chemical Environmental Index for cropping activity j and n is the number of chemicals applied on cropping activity j. The nitrogen environmental index in equation (8) is defined as:

$$IN_j = (NPERC_j \times PP) + (NRUNOFF_j \times RP)$$

where,

NEI_j = Nitrate Environmental Index for cropping activity j

$NPERC_j$ = the quantity of nitrogen lost in percolation for cropping activity j in grams per acre

$NRUNOFF_j$ = the quantity of nitrogen lost in run-off for cropping activity j in grams per acre.

Percolation and runoff in both indices can be weighted by the parameters RP and PP to reflect the relative concern for either groundwater or surface water. In this study, percolation is weighted more heavily than runoff. PP is set to .75 and RP is set to .25 in both indicies. This reflects the emphasis on groundwater and the fact that the study area has very little surface water of concern.

Study Area, Data, and Methods

The area chosen for the representative farm used in this study is the Southern High Plains region of the Texas Panhandle. Because of the difficulty of developing an extensive set of data that can be utilized to examine farm level environmental impacts, this study uses an extension of the data from the 1995 Teague, Bernardo, and Mapp study. This data is pre-1996 Farm Bill which relaxed constraints on producer flexibility, however most believe that producer response to the increased flexibility will be small. Surveyed producers indicated that most would not flex out of 1995 crop mixes due to rotation and/or cultural concerns (FAPRI, Texas A&M). Further, since income risk and water quality rather management recommendations are the focus of this study, this data is not limiting in its policy assumptions.

The farm was chosen to include both irrigated and dryland production on a total of 1280 acres of predominantly Pullman Clay Loam soil. 570 acres are available for irrigated production with 250 acres of center pivot sprinkler systems and 320 acres of conventional gated pipe furrow systems. For the irrigated acres, continuous rotations of corn, wheat, cotton , and grain sorghum were chosen as possible cropping activities. A cotton-wheat kill rotation is included for the irrigated cropping situation; wheat is planted after harvesting cotton and chemically killed prior to planting cotton in the spring. Dryland cropping activities included wheat, wheat-fallow, wheat-grain-fallow, grain sorghum, and cotton.

EPIC-PST, a biophysical simulator combining EPIC and the pesticide subroutines from the GLEAMS model, simulated crop yields and chemical losses using 20 years of weather data for the region (Sabbagh et al.). This model has been applied and tested at multiple sites. The cropping situations for irrigated and dryland production included corn, cotton, wheat, and grain sorghum. Percolation and runoff from nitrogen, pesticides, and herbicides applied were used in the generation of the nitrogen and chemical indices and linked to the safety-first model through equations (7) and (8).

Over 4100 cropping activities were generated for a full range of irritation levels, nitrogen levels, pesticides, and herbicides applied. Those insecticides and herbicides included were based on survey data of area specialists and published chemical data (Teague, Bernardo, and Mapp). Because net returns are dependent on the effectiveness of fertilizers and pesticides, specific data on the impact of each input on yield is needed. EPIC-PST provides specific data on nitrogen inputs but not the yield impacts of insecticides or herbicides. A survey of state and area agronomists and entomologists was conducted to determine yield reductions from combinations of herbicides and insecticides. Those reduction estimates were applied to yields generated by EPIC-PST to give revised yield stimates for different cropping activities. These unique yields and resource requirements for each cropping activity were used to generate a 20 year stochastic net-return series. The stochastic element arises from yield, precipitation, and application of irrigation water, nitrogen, and phosphorus.

The model specified in equations (4) through (10) was solved using LINDO (Linear Interactive and Discrete, Optimizer) for nine levels of β_α corresponding to the normal deviate for the level of desired risk α. Risk is defined as the probability of not achieving at least some "disaster" level of net returns at least α percent of the time. Increasing risk preference implies that the producer is willing to accept a larger variation in income and thus the possibility of higher expected net returns. The levels of risk preferences chosen are 3%, 5%, 15%, 20%, 25%, 30%, 40%, and 50%. As noted, the α=50% corresponds to maximizing expected net returns or to a risk neutral Expected Utility approach. The model was solved for these nine risk preference levels under the groundwater protection policies of a nitrogen restriction of 150 lbs. applied per acre, a 30 percent per pound tax on the level of nitrogen applied, and an effluent tax based on the nitrogen environmental index. The pesticide policies considered are a restriction on Methyl-Parathion, Ethyl-Parathion, and Atrazine, and a chemical effluent tax based on the chemical environmental index. Atrazine poses a dangerous threat to groundwater and is being reviewed by the EPA. Ethyl and Methyl Parathion are used extensively and have been studied by the EPA due to NPS pollution concerns (Holloway; Criswell).

For a baseline, the safety-first model was solved with no groundwater polices for each RPL. Since each safety-first solution and resulting set of farm plans has an associated set of environmental outcomes for each risk preference level, nitrogen and pesticide environmental distributions for each policy at selected levels are compared with the unrestricted safety first solution using the Mann-Whitney non-parametric test. Since previous studies have used linear programming and expected net returns (ENR) to examine water-quality, policy sensitivity is developed with comparisons between safety-first solutions and the ENR solutions.

The Mann-Whitney (MW) is a ranks test which has reasonable asymptotic relative efficiency when compared to the parametric two sample t-test, its parametric counterpart, and is considered conservative (Conover). The MW tests whether or not each respective environmental distribution is equal to, greater, or less than the unrestricted safety-first environmental distributions under the RPL's of 3%,15%, 25%, and ENR. This comparison provides an indication of the relative effectiveness of changing the environmental distribution at alternate risk preference levels.

The mean-standard deviation efficiency frontier for each policy is traced out. Because solutions represent a point in the Expected Returns - Standard Deviation plane, a comparison between policies can determine those which yield farm plan portfolios preferred by producers for all risk levels.

Economic Considerations

Impacts Under Nitrogen Policies

A comparison of economic impacts under the safety-first solutions and an expected net returns (ENR) solution gives insight into the importance of producer risk in the formation of water quality policies. Table 1 outlines the expected net returns and disaster income levels for the ENR approach and selected safety-first risk preference levels for each of the nitrogen and pesticide water quality policies.

Table 1 shows that under ENR, the imposition of nitrogen groundwater policies translates into a decrease in expected returns of $35827 for the nitrogen limit, $3538 for the nitrogen tax, and $6459 for the nitrogen effluent tax. These are a 14.48%, 1.43%, and 2.82% decreases in returns respectively (Table 2). The solutions under safety-first show that when producer risk is considered, the resulting impacts from the groundwater policies could be greater than estimated under the ENR solutions. For the 25% ,15%, and 3% risk preference levels, the percentage decrease in returns is as great or greater for at least one of RPL's than under the ENR solution.

Of the policies considered, the nitrogen limit produces the largest percentage changes with 16.30%, 16.50%, and 15.49% decreases in net returns for the 25%, 15% and 3% RPL, respectively; all percentage decreases are greater than the ENR solution. At the 25% and 15% RPL's, the nitrogen effluent tax reduced expected net returns a maximum of 2.74%, which was less than the ENR approach. However, expected net returns actually increased by .07% for the 3% risk preference level. Similarly, the nitrogen tax decreased net returns by 1.65% at the 25% RPL, which is greater than the reduction under the expected net returns solution. The reductions were not larger than the ENR approach for the 15% and 3% RPL.

Table 1. Expected Net Returns and Disaster Income Levels for Unrestricted, Nitrogen, and Pesticide Groundwater Policies Under ENR, 25%, 15% and 3% Risk Preference Levels.

Risk Level	Policy	Expected Net Returns	Disaster Income Level	Risk Level	Policy	Expected Net Returns	Disaster Income Level
	Unrestricted				Nitrogen Limit		
ENR		247396	247396	ENR		211568	211568
25%		242694	214344	25%		203111	173276
15%		236300	200445	15%		197308	158163
3%		228159	172111	3%		192799	127475
	Nitrogen Tax				Nitrogen Effluent Tax		
ENR		243857	243857	ENR		240936	240936
25%		238670	210883	25%		236032	210433
15%		233055	197199	15%		231161	197701
3%		224998	168954	3%		228340	172001
	Chemical Restriction				Chemical Effluent Tax		
ENR		239698	239698	ENR		231390	231390
25%		233231	207688	25%		223635	197613
15%		230167	194799	15%		219210	184379
3%		223041	167193	3%		217426	156020

The range of disaster income levels for a given policy reflects the level of negative net return deviations below the mean, and hence the standard deviation of net returns, for the crop portfolio. The lower the level of disaster income, the larger the "confidence interval" for a given risk level. Comparing the 3% risk level across the policies, the lowest disaster income is associated with the 150 lb. nitrogen limit, and is $65,325 below the expected net returns of $192800 When compared with the unrestricted plan which has a difference of $56,047, an increase in the deviations of net returns is implied. Table 2 gives the dollar percentage change in estimated standard deviations under the alternate nitrogen policies. For the nitrogen limit, variability in returns is increased and the increase is greater under the ENR approach than under the safety-first solutions. Under the nitrogen effluent tax, variability of returns is decreased and the percentage decrease is greater for at least one of the safety-first solutions than under ENR. The nitrogen tax produces negligible changes in income variability under both ENR and safety first.

Table 2. Safety-First Solution Percentage Changes in Estimated Standard Deviations and Net Returns From Expected Net Returns Solutions for Nitrogen and Pesticide Water Quality Policies at Selected Risk Preference Levels.

Risk Level	Standard Deviation % Change	Expected Returns % Change
ENR		Nitrogen Effluent Tax
	-8.31	-2.82
25%	-9.70	-2.74
15%	-6.68	-2.17
3%	0.53	0.07
ENR		Nitrogen Limit
	19.82	-14.48
25%	5.23	-16.30
15%	9.16	-16.50
3%	16.56	-15.49
ENR		Nitrogen Tax
	-0.00	-1.43
25%	-1.98	-1.65
15%	-0.00	-1.37
3%	0.00	-1.38
ENR		Chemical Limit
	-4.06	-3.11
25%	-9.89	-3.89
15%	-1.35	-2.59
3%	-0.34	-2.24
ENR		Chemical Effluent Tax
	0.14	-6.46
25%	-8.20	-7.85
15%	-2.85	-7.23
3%	9.56	-4.70

The most restrictive policy, the nitrogen limit, is marked by large decreases in net returns and increases in variability. The percentage decrease in returns is greater when risk is considered then under ENR. If policy formulation is based on the ENR approach, then impacts to producers could be underestimated. The same could be said for the nitrogen tax. The nitrogen limit is sensitive to the model used, while the nitrogen tax is less sensitive, and nitrogen effluent tax, at the levels tested, did not display any sensitivity.

Economic Impacts Under Pesticide Policies

The economic impacts produced with the pesticide policies hold many of the same implications as the nitrogen polices. For the ENR approach, expected returns were decreased by $7697 and $16005 under the pesticide restriction and pesticide effluent tax respectively. These represent 3.11% and 6.46% decreases in expected returns (Table 1). Compared to the ENR, the percentage decrease is as great as or greater for at least one of the risk preference levels. For the pesticide restriction, expected returns were decreased by 3.89% at the 25% RPL. When compared to the ENR, net returns were decreased by a larger percentage at the 25% and 15% RPL's.

Changes in the variability of returns are mixed between the pesticide policies. Under the pesticide limit, percentage decreases in variability are less than the ENR solutions except for the 25% RPL. For the chemical effluent tax, standard deviations increase for ENR while falling at the 25% and 15% RPL. However, standard deviations increase considerably for safety-first at the 3% RPL.

As with the nitrogen polices, there are significant differences for both expected net returns and standard deviations under ENR and safety-first. Similarly then, the formulation of policy without consideration of risk implies that impacts to producers could be underestimated or misestimated.

Nitrogen Policies and Water Quality

150 lb. Nitrogen Restriction

A comparison of the farm plan portfolios under a 150 lb. nitrogen restriction over the different levels of income risk preferences and ENR shows that the cropping patterns change with respect to the cropping choices, irrigation strategy, level of nitrogen, and the pesticide regime. Increasing risk aversion implies decreased levels of corn acreage under irrigation which translates into lower levels of water applied to the marginal acres farmed under irrigation. The acreage devoted to wheat changes over the risk preference levels. Wheat-Grain acreage declines from 546 acres under the ENR solution to 67 acres under the 15% risk preference level (Appendix Table 2). The total on-farm nitrogen application declines from its highest level under the ENR portfolio to the lowest under the 15% RPL portfolio. Additionally, the pesticide and herbicide regimes change so that the fewest number of pesticides and herbicides are applied under the 15% RPL. These changes reflect the higher penalty associated with deviations below the disaster level of income.

Table 3 presents the Mann-Whitney tests of the effectiveness of the 150 lb. nitrogen restriction policy at decreasing the nitrogen and chemical distributions below those associated with the unrestricted farm-plan portfolios. Means and standard deviations for the nitrogen and chemical distributions are presented in Appendix Table 5. The 150 lb. nitrogen restriction policy was ineffective in reducing the 150 lb. nitrogen environmental distributions (NED) below the unrestricted NED for ENR solutions. For the safety-first solutions, there was no statistical difference at the 25% RPL. However the 150 lb. NED's were below the unrestricted NED's at the 15% and 3% RPL's. Changes in water quality under the 150 lb. nitrogen restriction did not occur except for more risk averse producers and there was no impact for the ENR producer.

Table 3. Mann-Whitney Test for Comparison of Nitrogen and Chemical Environmental Index Distributions under 150 lb. Nitrogen Restriction Policy.

Risk Level	Policy	Distribution	Mann-Whitney Statistic	Conclusion[1]
	150 lb. Nitrogen Limit	Nitrogen Environmental Distribution		
ENR			194	unrestricted distribution = nitrogen distribution
25%			208	unrestricted distribution = nitrogen distribution
15%			248[2]	unrestricted distribution > nitrogen distribution
3%			248[2]	unrestricted distribution > nitrogen distribution
	150 lb. Nitrogen Limit	Chemical Environmental Distribution		
ENR			308	unrestricted distribution > chemical distribution
25%			359	unrestricted distribution > chemical distribution
15%			373	unrestricted distribution > chemical distribution
3%			393	unrestricted distribution > chemical distribution

[1] Significant at the 95% confidence level unless otherwise indicated.
[2] Significant at the 90% confidence level.

The chemical environmental distributions (CED's) associated with the 150 lb. nitrogen restriction were below the unrestricted farm plan CED's at all risk preference levels tested and for the ENR solution. This result is due to decreased water application, pesticide and herbicide regime changes, and cropping changes.

Nitrogen Effluent Tax and 30% Nitrogen Tax

Table 4 presents the statistics and results of the Mann-Whitney Tests of nitrogen and pesticide environmental distributions associated with a nitrogen effluent tax and Table 5 presents the results of the Mann-Whitney Tests of the nitrogen and pesticide environmental distributions under a nitrogen tax. As with the nitrogen effluent tax, the 30% nitrogen tax was ineffective at decreasing the NED's and CED's below that of the unrestricted farm plan for both programming approaches. This reflects the relative price inelasticity and high marginal productivity of fertilizers.

Table 4. Mann-Whitney Test for Comparison of Nitrogen and Chemical Environmental Index Distributions under Nitrogen Effluent Tax Policy.

Risk Level	Policy	Distribution	Mann-Whitney Statistic	Conclusion[1]
	Nitrogen Effluent Tax	Nitrogen Environmental Distribution		
ENR			213	unrestricted distribution = nitrogen distribution
25%			215	unrestricted distribution = nitrogen distribution
15%			229	unrestricted distribution = nitrogen distribution
3%			186	unrestricted distribution = nitrogen distribution
	Nitrogen Effluent Tax	Chemical Environmental Distribution		
ENR			207	unrestricted distribution = chemical distribution
25%			198	unrestricted distribution = chemical distribution
15%			193	unrestricted distribution =chemical distribution
3%			208	unrestricted distribution = chemical distribution

[1] Significant at the 95% confidence level unless otherwise indicated.
[2] Significant at the 90% confidence level.

Table 5. Mann-Whitney Test for Comparison of Nitrogen and Chemical Environmental Index Distributions under 30% Nitrogen Tax Policy.

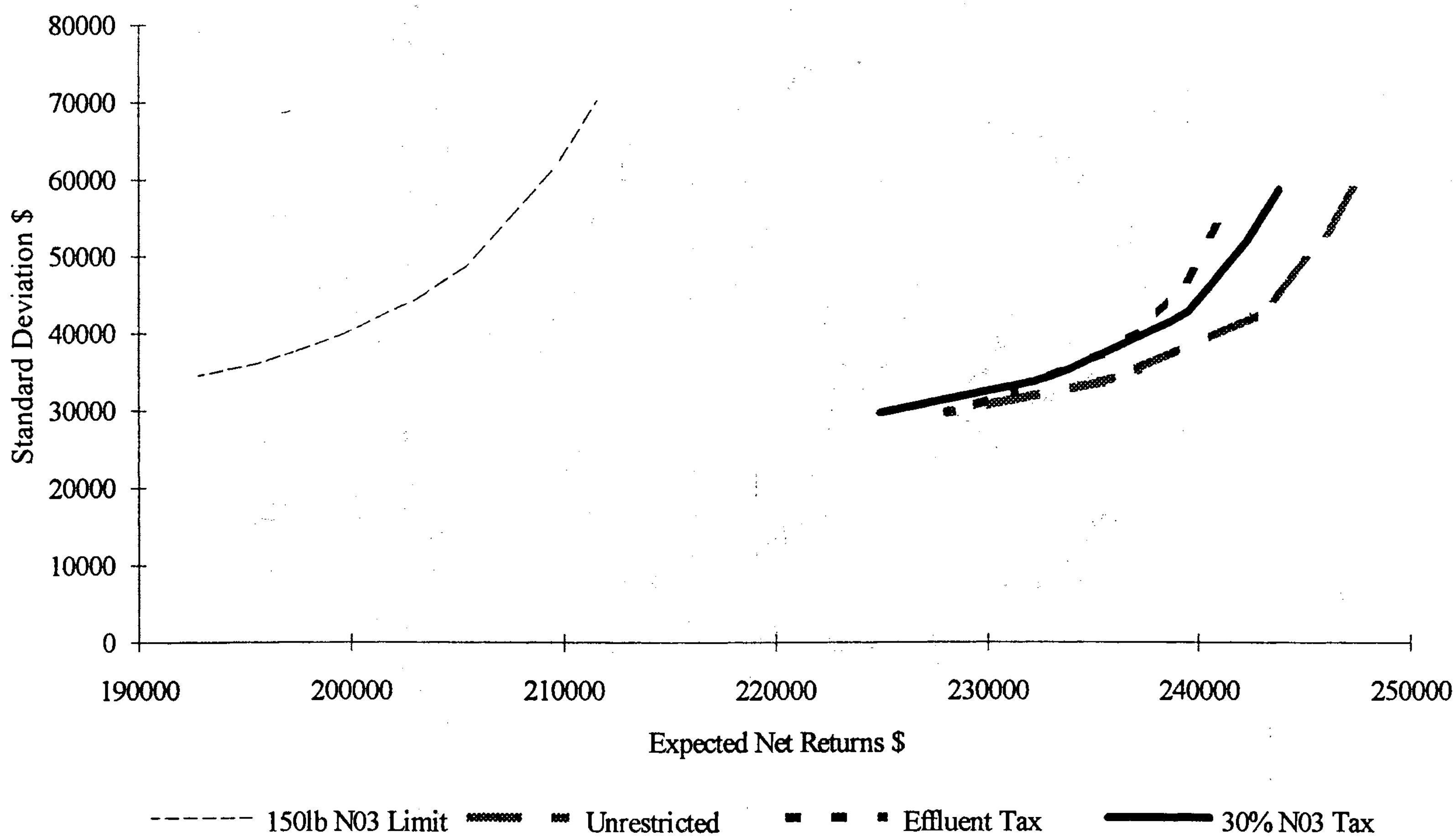
Risk Level	Policy	Distribution	Mann-Whitney Statistic	Conclusion[1]
	30% Nitrogen Tax	Nitrogen Environmental Distribution		
ENR			200	unrestricted distribution = nitrogen distribution
25%			201.5	unrestricted distribution = nitrogen distribution
15%			190	unrestricted distribution = nitrogen distribution
3%			190.5	unrestricted distribution = nitrogen distribution
	30% Nitrogen Tax	Chemical Environmental Distribution		
ENR			200	unrestricted distribution = chemical distribution
25%			210	unrestricted distribution = chemical distribution
15%			200	unrestricted distribution =chemical distribution
3%			200	unrestricted distribution = chemical distribution

[1] Significant at the 95% confidence level unless otherwise indicated.
[2] Significant at the 90% confidence level.

Portfolio Comparison

Figure 1 presents the mean-standard deviation frontiers from the farm plan portfolios associated with the nitrogen groundwater policies listed above and the unrestricted portfolio. The mean-standard deviation frontiers associated with the 30% nitrogen tax and the nitrogen effluent tax are close to the unrestricted frontier. The most restrictive policy is the 150 lb. nitrogen restriction as it lies to the far left of the unrestricted mean-standard deviation frontier. Expected net returns are far below the unrestricted, 30% tax, and effluent tax groundwater policies. Note that producers are heavily penalized even in the cases (ENR and 25% risk preference levels) where no change in groundwater quality has been achieved.

Figure 1. Nitrogen Groundwater Policies Mean-Standard Deviation Efficiency Frontiers.



Chemical Polices and Water Quality

Atrazine, Ethyl-Parathion, and Methyl-Parathion Restriction

The farm plan portfolios under the Atrazine, Ethyl-Parathion, and Methyl-Parathion Restrictions reveal that the acreage of cotton-wheat and corn remain the same over all RPL's considered (Appendix Table 3). The farm plan under the ENR solution is identical to the unrestricted farm plan. The level of water applied to furrow irrigated corn declines from 29 acre inches to 14 acre inches under the 15% RPL. The most significant acreage change over the RPL's is the change in the number of acres planted in wheat-grain-fallow under 25% and 15% levels. The total farm level of nitrogen under the 25% level is comparable to the unrestricted farm plan and is greater under the chemical limit than under the unrestricted farm plan at the 15% level (Appendix Table 3). For the risk programming solutions, the chemical regime changes significantly as the number of insecticides and herbicides applied increases over RPL's to reflect the relative aversion to risk, while the ENR farm plan reveals no changes in the number of pesticides applied.

As shown in Table 6, the Atrazine, Ethyl-Parathion, and Methyl-Parathion restriction is effective at reducing the chemical distributions below that of the unrestricted chemical distributions at all RPL's tested. The policy had no statistically significant impact on the nitrogen environmental distributions although total farm application of nitrogen decreased relative to the unrestricted solution at the 25% RPL and increased at the 15% RPL.

Table 6. Mann-Whitney Test for Comparison of Nitrogen and Chemical Environmental Index Distributions under Atrazine, Ethyl-Parathion, and Methy-Parathion Restriction.

Risk Level	Policy	Distribution	Mann-Whitney Statistic	Conclusion[1]
	Chemical Restriction	Nitrogen Environmental Distribution		
ENR			200.2	unrestricted distribution = nitrogen distribution
25%			185.5	unrestricted distribution = nitrogen distribution
15%			199.5	unrestricted distribution = nitrogen distribution
3%			188.5	unrestricted distribution = nitrogen distribution
	Chemical Restriction	Chemical Environmental Distribution		
ENR			325	unrestricted distribution > chemical distribution
25%			374	unrestricted distribution > chemical distribution
15%			385	unrestricted distribution > chemical distribution
3%			395	unrestricted distribution > chemical distribution

[1] Significant at the 95% confidence level unless otherwise indicated.
[2] Significant at the 90% confidence level.

Chemical Effluent Tax

A significant amount of acreage is devoted to furrow irrigated corn under the chemical effluent tax groundwater policy. Acreage of furrow corn is 282 under all risk preference levels considered and ENR. This implies that all available corn acreage is planted under a furrow irrigation system. The level of water applied to furrow corn is higher under the 15% level than under the 25% risk level. Under each RPL, the chemical regime changes The 15% RPL has the largest number of pesticides and herbicides applied. The total level of nitrogen applied is actually higher under the 15% RPL than the unrestricted farm plan under the chemical limit. Under the ENR solution, cotton-wheat is produced on 258 acres, which is lower than the unrestricted solution. This is due to the variability in income associated with the rotation. Total farm nitrogen is greater for the ENR solution than under the safety-first risk restricted and unrestricted solutions.

Table 7. Mann-Whitney Test for Comparison of Nitrogen and Chemical Environmental Index Distributions under Chemical Effluent Tax Policy.

Risk Level	Policy	Distribution	Mann-Whitney Statistic	Conclusion[1]
	Chemical Effluent Tax	Nitrogen Environmental Distribution		
ENR			151[2]	unrestricted distribution<nitrogen distribution
25%			176	unrestricted distribution = nitrogen distribution
15%			148[2]	unrestricted distribution<nitrogen distribution
3%			138	unrestricted distribution<nitrogen distribution
	Chemical Effluent Tax	Chemical Environmental Distribution		
ENR			253	unrestricted distribution = chemical distribution
25%			292	unrestricted distribution>chemical distribution
15%			337	unrestricted distribution>chemical distribution
3%			265	unrestricted distribution>chemical distribution

[1] Significant at the 95% confidence level unless otherwise indicated.
[2] Significant at the 90% confidence level.

The Mann-Whitney tests of the chemical effluent tax on the chemical and nitrogen distributions, as given in Table 7, show that the chemical effluent tax is ineffective at reducing the chemical distribution below the unrestricted distribution for the ENR solutions. However, it is effective at reducing the distributions for the risk programming solutions. Comparing the nitrogen distributions, they statistically greater for the ENR, and the 15% and 3% risk preference levels tested. There is no statistical difference in the restricted and unrestricted nitrogen distributions at the 25% RPL. In this case, the results of the Mann-Whitney distribution tests show that a chemical effluent tax policy under risk programming increases the threat to groundwater from nitrogen at higher risk preference levels, but is effective at decreasing the threat from chemicals. The ENR solution shows that the chemical effluent policy is effective for both nitrogen and chemical distributions.

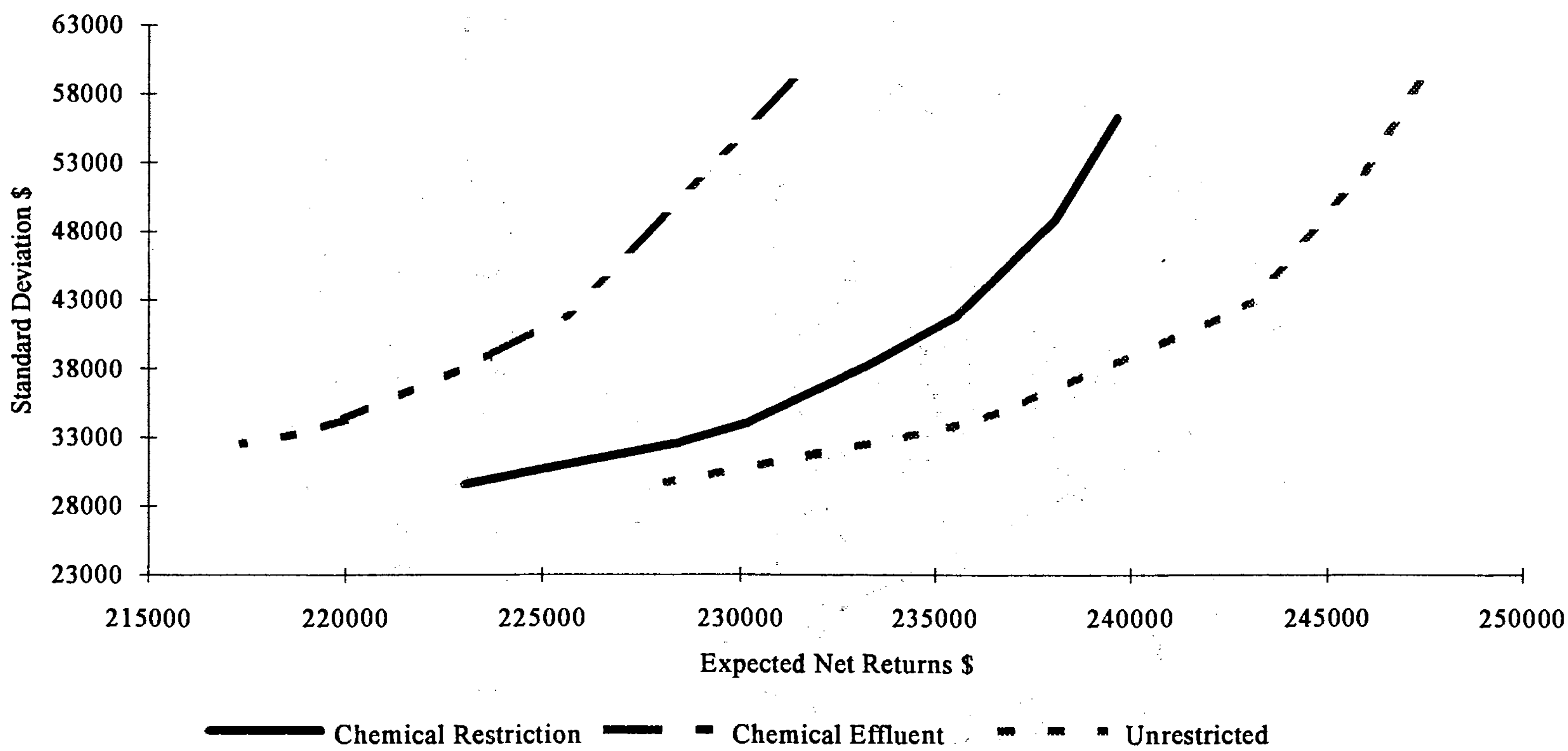
Portfolio Comparison

The mean-standard deviation frontiers associated with the chemical restriction and chemical effluent tax are given in Figure 2. The unrestricted portfolio is the most preferred followed by the chemical restriction and chemical effluent policy. The chemical restriction and chemical effluent tax provide similar standard deviation trade-offs but these deviation trade-offs are greater than under the unrestricted farm plans.

Policy Implications and Conclusions

Income risk at the farm-level is an aspect of environmental and water quality problems often overlooked in economic studies. This analysis builds on earlier research using results from a farm-level risk programming model, stochastic net returns, and a multi-attribute environmental index to compare against a typical maximization of expected net returns. The sensitivity of farm-level economic and environmental outcomes of several groundwater policies are compared for the ENR and risk programming solutions. The overall objective of this additional analysis is to develop an efficient means of examining income risk, water quality, and the sensitivity of policy formation for the expected returns approach versus a risk programming approach.

Figure 2. Chemical Groundwater Policies Mean-Standard Deviation Efficiency Frontiers.



A safety-first criterion of income risk is constructed so that a maximum disaster level of income and corresponding level of expected net returns can be found for multiple income risk preference levels. Impacts on expected net returns and water quality are compared for a range of levels. The policies considered for nitrogen are a per-acre nitrogen restriction, a per pound tax on nitrogen, and an effluent tax based on a nitrogen environmental index. The chemical policies are a selected ban on problematic pesticides and an effluent tax based on a chemical environmental index.

The comparison of the ENR and safety-first criterion produced several interesting economic results. The safety-first farm plans produced under the nitrogen and pesticide polices show that producers must be penalized heavily to induce changes in water-quality. This holds true under the ENR approach as well. However, when compared, the ENR approach tends to underestimate the costs to producers to comply with these policies. Income variation is impacted negatively under the nitrogen restriction, which is unaccounted for in the typical ENR approach, although under the pesticide restriction, income variability is actually decreased.

The environmental implications of this study point to the fact that producers who operate under a safety-first criterion may not be susceptible to nitrogen groundwater protection policies. Input substitution may negate any attempt at groundwater protection as the distributional tests from the 150 lb. nitrogen limit show.

The chemical policies considered produced similar results. Lower risk preference levels under the chemical restriction imply lower chemical environmental distributions. The chemical effluent tax was effective at reducing the chemical environmental distributions at higher risk preference levels, but actually increased the nitrogen distributions at some risk preference levels contrary to intuition. Contrasted to the ENR approach and the policy considered, policy formation could be erroneous. As under the chemical effluent tax, it was effective under the risk programming solutions, but not under the ENR solutions. The same implications hold for 150 lb. nitrogen limit.

These results imply that if producers operate under a similar rule such as the safety-first rule and risk is not considered, the actual impacts of ground water protection policies may not always be directly discernible and care must be taken in implementing water quality policies. These findings also have implications for regional or watershed analysis. Failure to consider risk preferences over numerous producers could invalidate findings or notions of policy effectiveness.

While these results may be specific to the farm and location studied, other sites and other agricultural areas should be modeled to determine the sensitivity of policy to income risk. Additional investigation into the connection between the economic and environmental impacts of water quality policies under income risk should provide needed insight for policy makers considering agricultural non-point source groundwater protection policies for ground and surface water.

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APPENDIX

Appendix Table 1. Safety-First and Expected Net Returns Unrestricted Farm Plans for Alternate Risk Preference Levels.

Crop	Acres	Irrigation Strategy	Water Applied[a]	Nitrogen[b]	Phosphorus[b]	Number of Insecticides	Number of Herbicides
ENR							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	1
Corn	32	Furrow	29	223	53	2	1
Wheat	317	None		26	26	1	1
Wheat-Grain-Fallow	392	None		28	20	3	2
Total N03 [c]				107.23			
25% Risk							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	1
Corn	32	Furrow	29	223	53	2	1
Sorghum	138	None		31	17	2	1
Wheat	348	None		26	26	1	1
Wheat-Fallow	150	None		27	27		1
Wheat-Grain-Fallow	72	None		28	20	2	2
Total N03 [c]				105.40			
15% Risk							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	1
Corn	32	Furrow	14	223	53	2	1
Wheat	321	None		26	26	1	1
Wheat-Fallow	228	None		13	13		
Wheat-Grain-Fallow	72	None		28	20	2	2
Total N03 [c]				98.35			

[a] Inches of water applied.
[b] Pounds per acre applied.
[c] Total nitrogen applied in thousand pounds .

Appendix Table 2. Safety-First and Expected Net Return Farm Plans for 150 lb. Nitrogen Limit Groundwater Policy Under Alternate Risk Preference Levels.

Crop	Acres	Irrigation Strategy	Water Applied[a]	Nitrogen[b]	Phosphorus[b]	Number of Pesticides	Number of Herbicides
ENR							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	179	Sprinkler	12	119	53	2	1
Wheat	70	Sprinkler	16	110	53	1	1
Wheat	32	Furrow	19	110	53	1	1
Wheat	163	None		26	26	1	1
Wheat-Grain-Fallow	546	None		28	20	3	2
Total N03[c]				82.39			
25% Risk							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	221	Sprinkler	12	129	53	2	1
Corn	32	Furrow	14	147	53	2	1
Sorghum	57	None		31	17	2	1
Wheat	28	Sprinkler	16	110	53	1	1
Wheat-Fallow	312	None		13	13		1
Wheat-Grain-Fallow	115	None		28	20	3	2
Total N03[c]				79.87			
15% Risk							
Cotton-Wheat	280	Furrow	17	97	26	2	4
Corn	165	Sprinkler	12	129	53	2	1
Corn	32	Furrow	14	147	53	2	1
Wheat	84	Sprinkler	16	110	53	1	1
Wheat	325	None		26	26	1	1
Wheat-Fallow	30	None		7	7		1
Wheat-Grain-Fallow	67	None		28	20	2	2
Total N03[c]				74.38			

[a] Inches of water applied.
[b] Pounds per acre applied.
[c] Total nitrogen applied in thousand pounds .

Appendix Table 3. Safety-First and Expected Net Return Farm Plans Under Atrazine, Ethyl-Parathion, and Methyl-Parathion, Pesticide Restriction for Alternate Risk Preference Levels.

Crop	Acres	Irrigation Strategy	Water Applied[a]	Nitrogen[b]	Phosphorus[b]	Number of Pesticides	Number of Herbicides
ENR							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	1
Corn	32	Furrow	29	223	53	2	1
Wheat	317	None		26	26	1	1
Wheat-Grain-Fallow	392	None		28	20	3	2
Total N03 [c]				107.23			
25% Risk							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	2
Corn	32	Furrow	29	223	53	2	2
Wheat	215	None		26	26	1	1
Wheat-Fallow	405	None		6	6		1
Wheat-Grain-Fallow	88	None		28	20	2	
Total N03 [c]				98.67			
15% Risk							
Cotton-Wheat	288	Furrow	17	97	26	2	4
Corn	250	Sprinkler	27	209	53	2	1
Corn	32	Furrow	14	223	53	2	2
Wheat	322	None		26	26	1	1
Wheat-Fallow	219	None		6	6		1
Wheat-Grain-Fallow	48	None		28	20	2	
Total N03 [c]				98.47			

[a] Inches of water applied.
[b] Pounds per acre applied.
[c] Total nitrogen applied in thousand pounds .

Appendix Table 4. Safety-First and Expected Net Return Farm Plans Under A Chemical Effluent Tax and Alternate Risk Preference Levels.

Crop	Acres	Irrigation Strategy	Water Applied[a]	Nitrogen[b]	Phosphorus[b]	Number of Pesticides	Number of Herbicides
ENR							
Cotton-Wheat	258	Sprinkler	15	88	26	2	2
Cotton-Wheat	38	Furrow	17	97	26	2	2
Corn	282	furrow	29	223	53	2	1
Wheat	317	None		26	26	1	1
Wheat-Grain-Fallow	292	None		28	20	3	2
Total N03[c]				108.30			
25% Risk							
Cotton-Wheat	258	Sprinkler	15	88	26	2	2
Cotton-Wheat	38	Furrow	17	97	26	2	2
Corn	282	Furrow	27	205	53	2	1
Wheat	230	None		26	26	1	1
Wheat-Fallow	345	None		6	6		1
Wheat-Grain-Fallow	133	None		28	20	2	2
Total N03[c]				95.97			
15% Risk							
Cotton-Wheat	250	Sprinkler	15	88	26	2	2
Cotton-Wheat	32	Furrow	17	97	26	2	2
Cotton	5	Furrow	21	70	26	2	1
Corn	282	Furrow	29	223	53	2	2
Wheat	293	None		26	26	1	1
Wheat-Fallow	279	None		6	6		
Wheat-Grain-Fallow	43	None		28	20	2	2
Total N03[c]				98.95			

[a] Inches of water applied.
[b] Pounds per acre applied.
[c] Total nitrogen applied in thousand pounds.

Appendix Table 5. Means and Standard Deviations for Nitrogen and Chemical Environmental Distributions for Alternate Risk Preference Levels and Groundwater Policies.

Policy / Distribution		RPL[a] 50%	RPL 25%	RPL 15%	RPL 3%
Unrestricted /NED[b]	Mean	9378.80	9033.12	8842.60	8121.75
	Std. Dev[d]	4761.70	4595.78	4510.14	4166.44
Unrestricted / CED[c]	Mean	6791.92	4921.31	4585.37	4371.84
	Std. Dev	6225.42	3003.38	2862.31	2786.98
Nitrogen Effluent Tax / NED	Mean	8834.52	8482.91	7741.61	8598.03
	Std. Dev	4256.97	4163.78	3718.13	4487.72
Nitrogen Effluent Tax / CED	Mean	6671.77	5003.45	4747.70	4251.69
	Std. Dev	6171.06	3105.42	2940.62	2610.46
Nitrogen Limit / NED	Mean	9562.66	8666.53	7965.54	9812.68
	Std. Dev	4565.33	4394.74	3729.91	5068.27
Nitrogen Limit / CED	Mean	4225.19	1552.38	1107.10	823.15
	Std. Dev	7383.34	1752.15	1125.61	536.40
Nitrogen Tax / NED	Mean	9378.80	8951.72	8842.60	8121.82
	Std. Dev	4761.79	4526.35	4510.14	4166.47
Nitrogen Tax / CED	Mean	6791.92	4894.73	4585.37	4371.84
	Std. Dev	6225.42	2986.94	2862.31	2786.98
Chemical Restriction / NED	Mean	9378.80	9552.96	8833.65	8294.98
	Std. Dev	4761.79	5082.38	4499.29	4257.29
Chemical Restriction / CED	Mean	2972.81	1120.87	899.33	635.72
	Std. Dev	5260.22	1288.94	807.89	491.24
Chemical Effluent Tax / NED	Mean	14466.68	12430.94	14013.36	13758.81
	Std. Dev	13397.86	11929.04	12942.47	12853.04
Chemical Effluent Tax / CED	Mean	5245.017	2960.85	1910.36	2838.81
	Std. Dev	5977.775	2694.78	1112.63	1289.73

[a] Risk preference level.
[b] Nitrogen environmental distribution.
[c] Chemical environmental distribution.
[d] Standard deviation.

ESSAY II

PESTICIDE PRODUCTIVITY IN UPLAND COTTON

PESTICIDE PRODUCTIVITY IN UPLAND COTTON

Abstract

A yield response function with a damage abatement specification was estimated for Texas Upland cotton using data from the USDA, 1994 cropping practices survey. The damage abatement specification recognizes the potential bias that can result from aggregate data and seeks to provide insights into individual chemical productivity. Damage abatement sources included were individual chemical components for all herbicides and insecticides applied in the 1994 production season.

Using commonly applied representative products, cost per pound of active ingredient was derived for each of the components and used to compare economic efficiency. Marginal productivity estimates for insecticides ranged from 619 to -174.10 pounds of cotton lint per acre. These estimates pointed to the fact that some of the commonly applied insecticide chemicals dramatically increase yields. For these components, when compared with the price at which they are just economically efficient (net of application costs), it was found that although marginal productivities were high corresponding economic efficiency results were not necessarily so. Further, there were many components which were economically effective with low unit costs and high marginal productivities which gives credence to producer dependence on insecticides.

Herbicide marginal productivity did not truly provide clear answers to producer choice as well as insecticides because economic efficiency is determined by exogenous elements besides increases in yield such as ginning costs, trash discounts, and cultivation costs. Many of the herbicides had, on average, low marginal productivities. Most associated prices at which marginal value product equaled marginal costs were greater than $10.00 and as high as $293.00, which implies poor producer decision. However, some marginal productivity estimates pointed to economically efficient application and may be better choices for producers depending on the targeted pest.

Keywords:

Pesticide productivity, damage abatement, upland cotton.

PESTICIDE PRODUCTIVITY IN UPLAND COTTON

Introduction

Agricultural producers, governmental agencies, and the public are concerned about the increased use of agricultural chemicals. In 1986, there were approximately 600 active ingredients used in some 55 thousand pesticide products, and this trend has continued upward (U.S. General Accounting Office). The concern over their extensive use and their value to agricultural production are important problems that need to be addressed. Arguably, the ability of some agricultural chemicals, such as nitrogen-fertilizer, to economically increase output is high, however there is some question as to the economic productivity of other chemicals, especially pesticides (Horowitz and Lichtenburg). There are some indications that economic productivity of pesticides may be decreasing (Teague and Brorsen).

Most current and past estimates of pesticide productivity are econometric estimates of the contribution of pesticides to the dollar value of output. Headly's seminal paper on insecticide productivity used a Cobb-Douglass specification to derive marginal productivity of insecticides for aggregate production data. He concluded that the marginal value of contributions were well above their marginal costs. Carlson used the Cobb-Douglas specification but included pest abundance to address biological resistance and falling marginal productivity of insecticides. The importance of the dynamics of agricultural pests and the ability to adapt is addressed. Lichtenberg and Zilberman have studied production functions with damage abatement model specification and have shown that functional form misspecification can bias productivity estimates upward. Their paper extends the weibull, pareto, logistic, and exponential forms as general forms of damage control. Carrasco-Tauber and Moffitt have estimated a Cobb-Douglas production function and the weibull, logistic, and exponential damage control functions with aggregate data and compared the resulting marginal productivities.

While the existing insecticide productivity research has given important insights into model specification and gross productivity, most have not addressed specific chemical productivity and all have used aggregate data which, as Lichtenberg and Zilberman note, is a potential source of bias. The most recent and only example that uses specific chemical data in a pesticide productivity study is Babcock, Lichtenberg, and Zilberman. Babcock, Lichtenberg, and Zilberman address quality and quantity damage control with specific chemical and production practices data for apple production. However, because insecticides are primarily not applied to increase yields but to control quality in apple production , their analysis did not include insecticide productivity estimates in increasing output.

Productivity estimates can be used to derive marginal productivity of pesticides. If the estimates of productivity are accurate, and the conclusion is that the marginal cost of pesticides exceed the marginal value of production, there are important implications. First, the potential overuse of agricultural chemicals could imply environmental damage that is both unnecessary and inefficient. Secondly, the producer is using inputs in a non-optimal manner. Existing studies give producers no indication of economic efficiency of individual insecticide use. The use of specific chemical data in an analysis of insecticide productivity could provide accurate measures of productivity and useful information for management decisions.

The purpose of this paper is twofold. The primary goal is to develop measures of pesticide productivity with a damage abatement specification for commonly used pesticides in upland cotton. With the estimates of chemical productivity, questions of economic efficiency can be answered. Secondly, this research seeks to provide producers with insights into chemical productivity for pest management decisions.

Production Function and Damage Control Specification

Following Lichtenberg and Zilberman, consider a production function of the form

$$Y = f(\mathbf{X},\ A(\mathbf{P})), \qquad (1)$$

where $\mathbf{X}$ is a vector of direct inputs, $\mathbf{P}$ is a vector of damage abatement instruments, and $A(\mathbf{P})$ is a damage control function which gives the proportion of the destructive capacity of a damaging agent eliminated by applying a level of damage control agent $\mathbf{P}$. Assume that $A(\mathbf{P})$ can be represented by a cumulative distribution function bounded at zero and one with the following characteristics: $A(0) \geq 0$ since natural elements can act as damage abatement functions, $A(\mathbf{P}) = 0$ implies no abatement, and $A(\mathbf{P}) = 1$ implies complete abatement.

A specific technology can be represented by a model of the form:

$$Y = \alpha I_j^{\beta_j}\left[A(\mathbf{P})\right]^{\delta}, \qquad (2)$$

where $I_j^{\beta_j}$ is one of j possible direct inputs and β_j is the corresponding coefficient. Babcock, Lichtenberg, and Zilberman used the exponential form damage abatement because of its fit and ease of estimation. However not all functional forms are amenable to estimation of pesticide abatement functions. If the levels of all pesticides used are bounded at zero, then abatement function forms such as the exponential or weibull are not workable. A form which is tractable is the logistic function because zero bounded values of pesticide do not result in functional errors (Evans, Hastings, and Peacock). Because of the possibility of zero bounded values, the logistic abatement function will be used in this research.

It follows then, if A(**P**) is logistic, the abatement function can be written as:

(3)
$$\frac{1}{\left[1+\exp(\mu-\sum_n b_n p_n)\right]}$$

where b_n is the n'th coefficient associated with the p_n element of the vector **P**.

There has been no statistical research which has addressed specific chemical use and abatement functional form specification. However, in the study by Carrasco-Tauber and Moffitt which utilized aggregate data from the Carlson research, they found that the exponential form of the abatement function produced the lowest estimates of marginal pesticide productivity while the Weibull and logistic distributions produced higher estimates of marginal productivity and were comparable to the Cobb-Douglass specification. The Akaike criterion, a statistical measure used to compare functional specifications, gave no strong theoretical or econometric reason to choose one of these damage control specifications over another.

Data Description and Procedure

Primary data on chemical usage was obtained from the "USDA, 1994 Cropping Practices Survey, Unofficial data files", Economic Research Service, U.S. Department of Agriculture, Washington D.C. This data set is a comprehensive research database developed to analyze production inputs, tillage practices, and chemical application associated with production crops in major producing states. Data on chemical application, production practices are drawn from surveyed producers to provide information on on-farm and off-farm environmental issues associated with agricultural chemical use (USDA-NASS). Specifically, the data set includes such items as yields, fertilizers applied, machinery complements, and chemical inputs. Chemical inputs are given both as label names and major active components of the label names. For cotton production, it contains sample information on the major upland cotton producing states of Arizona, Arkansas, California, Louisiana, Missouri, and Texas.

U.S. cotton production is marked by intensive use of both fertilizers and chemicals. Modern production requires application of both herbicides and insecticides to obtain high yields. In 1994, 94% of all upland cotton received some type of herbicide and 71% received some insecticide.

For this study, a subset of Texas upland cotton producers was chosen because Texas plants over 50% of upland cotton in the United States. Herbicides and insecticides were applied to over 96% and 50% respectively of upland cotton acreage in Texas in 1994 (NASS-USDA). Data from 1994 was chosen because the 1995 cotton producing season was marked by relatively high applications of insecticides due to large infestations of army beetworms throughout the state and would not provide reliable estimates (1996 Proceedings Beltwide Cotton Conferences). Data for the 1996 production season were not available at the time this research was conducted. Information on a total of 507 producers throughout the state was available in the production practice survey. Further, since production practices, planting dates, insecticide application, types of pesticides applied, insect types, and insect populations vary from state to state, and possibly region to region, inclusion of all cross sectional data from all states could increase econometric problems and thus reliability of the estimates.

Tables 1 and 2 give major insecticide and herbicide brand names, ingredients, variable names, and number of times the component appeared in the Texas sample. These components correspond to primary ingredients of all major insecticide and herbicide products applied in the 1994 Texas production season and are the elements of a insecticide damage abatement vector, say **P,** as above, and a herbicide damage abatement vector, say **H**. The only insecticide not included in this study was Bacillus - Thuringiensic (Bt.), which is a commonly used biological insecticide. Numerous reporting errors would not allow its inclusion.

Because agricultural producers may apply chemical components more than once per season to maintain control of insects and weeds, especially in cotton production, chemical quantities were summed by component for each sample after conversion to equal units (i.e. pounds per acre). The variables p1-p28 and h1-h17 reflect total pounds per acre of primary insecticide and herbicide ingredients applied in the 1994 season. Table 1 reveals that the three most frequently used insecticides are azinphos-methyl, methyl-parathion, and aldicarb, while trifluralin, prometryn, and glyphosate are the three most frequently used herbicides.

Table 1. Product Name, Active Ingredient, Variable Name, and Frequency of Use for Insecticides in the Texas Sample.

Representative Product[a]	Active Ingredient	Variable Name	Frequency[b,c]
Dimethoate 4EC	Dimethoate	p2	6
Bidrin 8	Dicrotophos	p3	43
Methyl Parathion 4EC	Methyl-Parathion	p4	46
PCNB 2E	PCNB	p5	5
Sevin XLR Plus (4E)	Carbyrl	p6	7
Thimet 20-G	Phorate	p7	28
Cytion ULV (9.33)	Malathion	p8	10
Guthion 2L	Azinphos-Methyl	p9	56
Thiodat 3EC	Endosulfan	p10	10
Terraclor Super X	Etridiazole	p11	4
Lannate LV (2.4)	Methomyl	p12	5
Furadan 4F	Carbofuan	p13	35
Comite (6.55EC)	Propargite	p14	5
Temic 15-G	Aldicarb	p15	45
Orthene 90S	Acephate	p16	25
Vydate C-LV (3.77)	Oxamyl	p17	39
Counter 20CR	Terbufos	p18	3
Dimlin 2F	Diflubenzuron	p19	9
Asana XL (.66EC)	Esfenvalerate	p20	11
Ammo 2.5 EC	Cypermethrin	p21	19
Curacron 8E	Profenofos	p22	18
Larvin 3.2	Thidocarb	p23	9
Scout X-TRA (.9 l EC)	Tralomethrin	p24	14
Capture 2EC	Bifenthrin	p25	6
Baythroid 2 (EC)	Cyflutrin	p26	6
Karate (1EC)	Lambda-Cyhalothrin	p27	43
Fury 1.5 EC	Zeta-Cypermetrin	p28	5

[a] Product names correspond with the product for which prices were solicited and used to estimate unit cost per pound in 1994 prices.
[b] Number of times ingredient was applied at least once by a producer.
[c] 507 producers in survey.

Table 2. Product Name, Active Ingredient, Variable Name, and Frequency of Use for Herbicides in the Texas Sample.

Representative Product[a]	Active Ingredient	Variable Name	Frequency[b,c]
MSMA 6.6 Plus H.C.	MSMA	h1	18
Banvel 4L	Dicamba	h2	4
Weedar MCPA Concentrate (4E)	MCPA	h3	2
Cotoran 4L	Fluometuron	h4	25
Direx 4L	Diuron	h5	41
Linex 4l	Linuron	h6	10
Treflan EC	Trifluralin	h7	311
Caparol 4L	Prometryn	h8	108
Bladex 4L	Cyanazine	h9	10
Roundup Ultra	Glyphospate	h10	98
Solicam DF 80%	Norflurazon	h11	13
Prowl 3.3 EC	Pendamenthalin	h12	74
Poast Plus (1EC)	Sethoxydim	h13	2
Fusilade DX	Fluaxifop-P-butyl	h14	19
Command 4EC	Clomazone	h15	17
Fusion	Fenaxaprop-ethyl	h16	4
Assurre II	Quizalofop-ethyl	h17	3

[a] Product names correspond with the product for which prices were solicited and used to estimate unit costs.
[b] Number of times ingredient was applied at least once by a producer.
[c] 507 producers in survey.

The summary statistics for insecticides ingredients, herbicides ingredients, and direct inputs are given in Tables 3, 4, and 5 respectively. Note that all the chemicals considered have a minimal value of zero.

Table 3. Summary Statistics for Insecticide Ingredients Used on Texas Upland Cotton.

Active Ingredient[a]	Mean[b]	Maximum[b]	Standard Deviation[b]
BT	-	-	-
Dimethoate	.0034	0.50	.0323
Dicrotophos	.0412	1.50	.1526
Methyl-Parathion	.1918	4.21	.6718
PCNB	.0053	1.00	.0527
Carbyrl	.0018	0.75	.0369
Phorate	.0394	0.80	.1519
Malathion	.1056	5.83	.7308
Azinphos-Methy	.0665	2.22	.2127
Endosulfan	.0100	0.60	.0650
Etridiazole	.0007	0.07	.0073
Methomyl	.0057	0.60	.0544
Carbofuan	.0265	0.75	.1104
Propargite	.0029	1.22	.0605
Aldicarb	.0619	1.35	.2058
Acephate	.0250	0.90	.1228
Oxamyl	.0469	2.82	.2146
Terbufos	.0034	0.60	.0431
Diflubenzuron	.0001	0.06	.3079
Esfenvalerate	.0010	0.08	.0068
Cypermethrin	.0009	0.11	.0067
Profenofos	.0819	4.00	.5004
Thidocarb	.0142	1.00	.1058
Tralomethrin	.0010	0.06	.0065
Bifenthrin	.0010	0.08	.0088
Cyflutrin	.0006	0.07	.0055
Lambda-Cyhalothrin	.0056	0.12	.0194
Zeta-Cypermetrin	.0004	0.04	.0043

[a] All ingredients had a minimum value of zero.
[b] Reported in pounds of active ingredients used per acre.

Table 4. Summary Statistics for Herbicides Used on Texas Upland Cotton.

Active Ingredient[a]	Mean[b]	Maximum[b]	Standard Deviation[b]
MSMA	0.0667	4.50	0.4216
Dicamba	0.0030	0.12	0.0065
MCPA	0.0048	1.00	0.0695
Fluometuron	0.0914	7.50	0.6566
Diuron	0.0473	2.40	0.1854
Linuron	0.0006	0.25	0.0123
Trifluralin	0.5779	2.25	0.4146
Prometryn	0.1963	2.00	0.3711
Cyanazine	0.0185	4.00	0.2060
Glyphosate	0.1554	2.88	0.3644
Norflurazon	0.0137	0.80	0.0878
Pendamenthalin	0.1272	2.00	0.2979
Sethoxydim	0.0009	0.18	0.0130
Fluaxifop-P-Butyl	0.0063	0.59	0.0390
Clomazone	0.0167	1.20	0.1002
Fenaxaprop-ethyl	0.0034	0.07	0.0048
Quizalofop-ethyl	0.0036	0.05	0.0042

[a] All ingredients had a minimum value of zero.
[b] Reported in pounds of active ingredients used per acre.

Table 5. Summary Statistics for Direct Inputs and Yield , 1994 Texas Upland Cotton.

Direct Input	Variable	Mean	Maximum	Minimum	Standard Deviation
Yield[a]	χ_1	490.83	2665.70	18.04	358.15
Nitrogen[b]	χ_2	56.42	441.00	0.00	62.52
Phosphorus[c]	χ_3	25.05	118.00	0.00	26.08
Potassium[d]	χ_4	6.14	81.00	0.00	13.24
Irrigation[e]	χ_5	-	2.71	1.00	-

[a] Pounds of lint per acre.
[b] Pounds of actual nitrogen per acre.
[c] Pounds of actual phosphorus per acre.
[d] Pounds of actual potassium per acre.
[e] Defined as a binary variable: 2.718 = use of irrigation, 1 = no irrigation.

Equations (2) and (3) provide a production function technology that incorporates damage abatement. This specification does not consider different sources of damage and alternate damage abatement for these sources. An example of this would be the sources of damage from insects and weeds. A first order logarithmic approximation of equation (2) with damage abatement functions for both herbicides and insecticides gives,

$$y = a + \sum_j \beta_j \chi_j + \delta \ln[G(\mathbf{P},\mathbf{H})] + \varepsilon \tag{4}$$

where there are j direct inputs, y, a and χ represent the natural logs of Y,α and X respectively and ε is assumed to be a $N(0,\sigma^2\mathbf{I})$ error term. The function $G(\mathbf{P},\mathbf{H})$ is:

$$\left[\frac{1}{1+\exp(\mu_1 - \sum_n b_n p_n)}\right] \cdot \left[\frac{1}{1+\exp(\mu_2 - \sum_m q_m h_m)}\right], \tag{5}$$

which implicitly requires the assumption of independence between control of damage from insects and weeds. The variables b_n and p_n are as defined earlier but apply to n insecticides and similarly, the variables q_m and h_m apply to m herbicides. The variable δ is the proportional relation between yield and damage abatement.

For identification, the restriction $\delta = 1$ is imposed on equation (4). This assumption requires that abatement be proportional to potential output (Carrasco-Tauber, Catalina, and Moffit). Equation (4) is nonlinear in the abatement function and necessitates estimation by a non-linear method.

Accuracy of estimates in nonlinear least squares is dependent on the classical assumptions of normality of the error terms and homoskedasticity. These null hypotheses are tested using the Jarque-Bera test for normality and procedures recommended by McGuirk, Driscoll, and Alwang for testing the hypothesis of homoskedasticity (McGuirk, Driscoll, and

Alwang; White). Fragility of results resulting from a local solution with a nonlinear least squares algorithm was minimized by using multiple starting values and comparing the estimates against other starting values that achieved convergence. All estimation and pretesting was done with the SHAZAM econometrics software package (White).

Carlson, and Moffitt and Farnsworth have considered insecticide productivity in relation to insect resistance. While insecticide productivity and resistance are linked, insecticide resistance is not considered in this study. Interactions between insecticide components and the order in which the components are applied are assumed to be non-significant. This assumption relies on the fact that producers are often aware of the implications of applying more effective chemicals such as pyrethrins early in the season and the possibility of a decrease in effectiveness due to increased resistance in later pest populations (J.C. Banks). Additionally, it is assumed that expensive chemicals which are considered to be more effective, are not applied until pest populations are either uncontrollable (or perceived as uncontrollable) with less expensive insecticides or as a "last ditch effort". Resistance to herbicides is not a concern since this is a cross-sectional sample and herbicide resistance by weeds is a considered a longer term problem (Archer and Shogren).

The marginal productivities for the n'th insecticide or m'th herbicide can be found by the partial derivative of equation (4) with respect to each chemical component. These can be written as:

$$(6)\quad \frac{\partial y}{\partial p_n} = \left[\frac{-b_n \cdot \exp(\mu_1 - \sum_n b_n p_n) - b_n \cdot \exp(\mu_1 + \mu_2 - \sum_n b_n p_n - \sum_m q_m h_m)}{1 + \exp(\mu_1 - \sum_n b_n p_n) + \exp(\mu_2 - \sum_m q_n h_m) + \exp(\mu_1 + \mu_2 - \sum_n b_n p_n - \sum_m q_m h_m)} \right]$$

for insecticides, and

$$(7)\quad \frac{\partial y}{\partial h_n} = \left[\frac{-q_m \cdot \exp(m_2 - \sum_m q_m h_m) - q_m \cdot \exp(m_1 + m_2 - \sum_n b_n p_n - \sum_m q_m h_m)}{1 + \exp(m_1 - \sum_n b_n p_n) + \exp(m_2 - \sum_m q_n h_m) + \exp(m_1 + m_2 - \sum_n b_n p_n - \sum_m q_m h_m)} \right]$$

for herbicides. If unit prices of the n insecticides and m herbicides along with the unit price of yield are known, a marginal value of production can be obtained and compared with the marginal cost associated with the pesticide inputs.

Results

Estimation

Nonlinear least squares estimation converged in approximately 200 iterations for all starting values and the differences in estimated coefficients were small. Since convergence did not produce identical estimated coefficients, the starting value that gave the largest log likelihood value was chosen.

For the starting value chosen, the Jarque-Bera test failed to reject the hypothesis of normal error terms at the significance level of α=.005 with a test statistic $\chi^2_2 \sim 8.37$. The reset test for homoskedasticity rejected the null of homoskedasticity at the significance level of α=.01 with a test statistic $t \sim 3.792$. The null hypothesis of zero coefficients was easily rejected using the Likelihood Ratio Test with a test statistic of LR = 435.35 and α=.005 (Judge et al.).

Since apriori no specific form of heteroskedasticity was known, the finding of heteroskedasticity was accommodated by correcting the covariance matrix using procedures recommended by White. The covariance matrix estimated is:

(8) $$(\mathbf{X}'\Omega\mathbf{X}) = \left[\sum_{t=1}^{N} e_t^2 X_t X_t'\right],$$

where X_t is a vector of instrumental variables and e_t is the error term for the t'th observation estimated using two stage least squares. The instrumental variables used in X_t are all the direct and damage abating inputs (White).

Insecticide Coefficients

Non-linear least squares estimates and asymptotic t-statistics for the insecticide coefficients specified in (4) are given in Tables 6. Seventeen of the variables were found to be significantly greater than zero starting with the significance level of α=.20. Eight of the seventeen were found to be highly significant at the level of α=.05. Dimethoate, propargite, and cyflutrin had large estimated coefficients with respect to the other chemicals considered. However, only dimethoate was found to be statistically significant. The signs for most of the coefficients conform to expected sign since the coefficients are required to be negative for a positive marginal productivity. Six of the coefficients had positive coefficients.

The cause of positive coefficients cannot be determined. However, positive coefficients, and thus negative chemical productivity estimates, may result from the failure to completely control a pest population or from an increase in pressure from secondary pests caused by decreased beneficial populations (J.C. Banks). Because pest populations are not known, it is assumed here that producers are applying the insecticides at or before pest populations are uncontrollable. Failure to do so by the producer does not invalidate the productivity estimates however, because empirically, damage is not being abated by these chemicals indicating that on average some other insecticide should have been utilized.

Table 6. Nonlinear Least Squares Insecticide Damage Abatement Coefficients and Asymptotic Students t-Statistics.

Variable	Coefficient	Asymptotic t-Statistic
Constant	-.23	-1.33*
Dimethoate	-148.21	-2.09***
Dicrotophos	-6.20	-1.47*
Methyl-Parathion	-.64	-.97
PCNB	-110.73	-2.59***
Carbyrl	-54.18	-2.59***
Phorate	-.12	-.24
Malathion	-.06	.26
Azinphos-Methyl	-1.64	-1.56*
Endosulfan	-72.05	-1.49*
Etridiazole	-29.33	-2.56***
Methomyl	-1.39	-.41
Carbofuan	-11.10	-1.83**
Propargite	-97.90	-.95
Aldicarb	.50	1.86**
Acephate	-4.14	-.71
Oxamyl	-28.18	-1.81**
Terbufos	-32.35	-2.31***
Diflubenzuron	-10.48	-2.27***
Esfenvalerate	-10.25	-.39
Cypermethrin	3.42	.34
Profenofos	2.08	5.21***
Thidocarb	.49	.23
Tralomethrin	-26.16	-.53
Bifenthrin	52.30	1.61*
Cyflutrin	-119.53	-.46
Lambda-Cyhalothrin	-29.73	-1.31*
Zeta-Cypermetrin	41.63	2.46***

*** Significant at the α=.05 level.
** Significant at the α=.10 level.
* Significant at the α=.20 level.

Herbicide Coefficients

The estimated coefficients for the herbicides are listed in Table 7. Eight of the estimated coefficients were significant atleast at the level of α=.20 with five of the eight significant at the level of α=.05. Interestingly, the signs of the coefficients do not necessarily conform to the expected. Ten of the seventeen herbicide components considered are positive, which results in negative marginal productivity. The explanation for this arises out of the producers need to control weed predator populations to increase yield as well as to keep cotton plants free of weeds (Communication with producers; Tom Green, Concho, and Runnels County, Texas). Failure to control weed populations could result in high ginning costs as well as lowered quality of cotton and thus price received. Hence, producers may be willing to trade some cotton yield for weed control. The existence of negative marginal productivity does not necessarily translate into inefficient input choices.

Table 7. Nonlinear Least Squares Herbicide Damage Abatement Coefficients and Asymptotic Students t-Statistics.

Variable	Coefficient	Asymptotic t-Statistic
Constant	-1.14	-2.17***
MSMA	1.51	2.42***
Dicamba	-5.21	-.21
MCPA	.94	1.08
Fluometuron	-50.29	-1.97***
Diuron	.56	.94
Linuron	4.23	1.31*
Trifluralin	-.67	-.16
Prometryn	.82	1.96***
Cyanazine	.27	1.32*
Glyphosate	.62	3.28***
Norflurazon	.43	.28
Pendamenthalin	-1.36	-1.03
Sethoxydim	3.37	.49
Fluaxifop-P-Butyl	-.52	-.14
Clomazone	-7.63	-.50
Fenaxaprop-ethyl	20.05	1.63*
Quizalofop-ethyl	-331.74	-1.07

*** Significant at the α=.05 level.
** Significant at the α=.10 level.
* Significant at the α=.20 level.

Direct Inputs

The estimates for the direct inputs are listed in Table 8. All signs are positive as expected and the estimated coefficients are statistically significant. Note that each of the coefficients is scaled. Nitrogen is estimated so that each unit is 50 pounds, Phosphorus and Potassium are in 10 pound units. Also, cotton lint yield is in 500 pound units and all are on a per acre basis.

Table 8. Nonlinear Least Squares Direct Input Coefficients, Asymptotic Students t-Statistics, and Log Likelihood Value.

Variable	Coefficient	Asymptotic t-Statistic
Constant	.17431	1.71**
Nitrogen[a]	.06931	3.34***
Phosphorus[b]	.05597	2.92***
Potassium[c]	.04116	1.74**
Irrigation[d]	.88170	15.14***
Log Likelihood	-275.91	

[a] Increase in 500 lbs. of lint increase per 50 lb. increase in actual nitrogen applied.
[b] Increase in 500 lbs. of lint increase per 10 lb. increase in actual phosphorus applied.
[c] Increase in 500 lbs. of lint increase per 10 lb. increase in actual potassium applied.
[d] Increase in 500 lbs. of lint increase for use of irrigation.

Pesticide Productivity

Insecticides

Marginal productivity estimates for insecticides range from a high of 619.79 pounds of lint per acre for dimethoate to a low of -174.10 for zeta-cypermetrin indicating the ability of insecticides to marginally impact yields positively as well as the inability of insecticides to control pest populations (Table 9). Of the three most frequently used insecticides, the marginal productivity estimates are either low, negative, or the coefficients were not significant. Estimated marginal productivity for azinphos-methyl is only 6.87 pounds of lint per acre for each pound of active ingredient applied while methyl-Parathion, although insignificant, has a marginal productivity of 2.68 pounds of lint per acre. aldicarb, the most frequently applied insecticide ingredient, did not have a positive marginal productivity. Dicrotophos and lambda-cyhalothrin, both heavily applied, had marginal productivities of 25.96 and 174.10 respectively.

Using cost per pound of active ingredient and estimated marginal productivity, the price per pound of cotton lint at which marginal value product and marginal cost is equal are estimated for the insecticide components (denoted as a break even price) and listed in Table 9. Note that these prices do not include application costs because application costs can vary from \$1.50 to \$5.00 per acre depending on the type of application. Inclusion of application costs would increase break even prices for all products considered. Thus pesticides with break even prices close to or at market price would not likely be economically efficient.

For the sixteen insecticides that had significant coefficients, ten had break even prices below \$.65 per pound of lint, or below U.S. market average price for 1994 (UDSA-NASS). For those with high marginal productive and low unit prices, such as dimethoate, PCNB, and carbaryl, the break even price is less than 3 cents (\$ .03) per pound which indicates relatively high economic efficiency. Conversely, three of the insecticides with significant coefficients, azinphos-methyl, lambda-cyhalothrin, and diflubenzuron have break even prices greater than \$2.00 which exceeds average market prices by greater than 200%. Insecticides such as phorate, malathion, and esfenvalerate, which were not found to be statistically significant in changing lint yield, had break even prices exceeding \$4.00 and as high as \$18.00. Note that esfenvalerate increased yields by greater than 40 lbs of lint per acre, but high marginal costs ($209/lb) make application inefficient at that level of productivity.

Table 9. Marginal Productivity Estimates for Insecticides and Break Even Prices for Texas Upland Cotton, 1994.

Active Ingredient	Marginal Productivity[a]	Cost Per Pound[b]	Break Even Price[c]
Dimethoate	619.79*	$ 7.56	$.01
Dicrotophos	25.96***	$ 11.13	$.42
Methyl-Parathion	2.68	$ 6.25	$ 2.33
PCNB	463.06***	$ 9.37	$.02
Carbaryl	226.58***	$ 6.29	$.02
Phorate	.51	$ 9.65	$ 18.79
Malathion	.26	$ 2.70	$ 10.07
Azinphos-Methyl	6.87*	$ 16.65	$ 2.42
Endosulfan	301.33*	$ 12.33	$.04
Etridiazole	122.69***	$ 34.97	$.28
Methomyl	5.825	$ 20.16	$ 3.46
Carbofuan	46.44**	$ 16.50	$.35
Propargite	409.4	$ 8.85	$.02
Aldicarb	-2.10**	$ 21.00	-
Acephate	17.32	$ 11.11	$.64
Oxamyl	117.80**	$ 16.63	$.14
Terbufos	135.30***	$ 12.00	$.08
Diflubenzuron	43.85***	$ 97.50	$ 2.01
Esfenvalerate	42.87	$ 209.09	$ 4.87
Cypermethrin	-14.30	$ 96.80	-
Profenofos	-8.72***	$ 13.62	-
Thidocarb	-2.08	$ 16.75	-
Tralomethrin	109.40	$ 331.11	$ 3.02
Bifenthrin	-218.70*	$ 246.00	-
Cyflutrin	499.88	$ 231.00	$.46
Lambda-Cyhalothrin	124.32*	$ 258.00	$ 2.07
Zeta-Cypermetrin	-174.10***	$ 200.66	-

[a] Marginal productivity in pounds of lint per acre per pound of active ingredient.
[b] Derived from products reported in Table 1 and in 1994 prices.
[c] Dollars per pound of lint at which MC=MVP; does not include application costs.
*** Corresponding estimated coefficient significant at the α=.05 level.
** Corresponding estimated coefficient significant at the α=.10 level.
* Corresponding estimated coefficient significant at the α=.20 level.

Herbicides

A significant number of herbicide coefficients, as noted, are positive and thus have negative estimated marginal productivity. However, these negative marginal productivities are small and range from -7.72 to -.30 pounds of lint per acre, or $5.01 to $.46 in lost lint value if cotton lint is valued at $.65 per pound (Table 10). In terms of economic efficiency, this may be a small tradeoff for costs associated with a low grade cotton, which could be discounted as much as 7.8 cents per pound (Plains Cotton Cooperative Association). For the herbicides with significant coefficients, estimated marginal productivities are as high as 127.71 pounds of lint per acre to a low of .20 pounds of lint. Of these, fluometuron and quizalofop-ethyl have break even prices below the $.65 average lint price, while others have break even prices that are as great as $293.08. trifluralin, the most often applied herbicide had a break even price of $28.05. As with insecticides, these break even prices do not include application costs. Although the break even prices are high for some of the herbicides, positive statements about the economic efficiency. Break even price does not encompass the loss associated with poor quality cotton with higher weed populations or increased cultivation costs. If cultivation costs are on average valued at $5.00 per acre per trip, then the economic implications may be different if the number of cultivation trips are decreased by as few as two. However, it is not likely that costs savings and increased value will ever equate to a break even price of $293.08 such as that for fluaxifop-p-butyl.

Table 10. Marginal Productivity Estimates for Herbicides and Break Even Prices for Texas Upland Cotton, 1994.

Active Ingredient	Marginal Productivity[a]	Cost Per Pound[b]	Break Even Price[c]
MSMA	-.58***	$ 3.03	-
Dicamba	2.00	$ 29.50	$ 14.68
MCPA	-.36	$ 3.75	-
Fluometuron	19.36***	$ 5.70	$ .29
Diuron	-.21	$ 5.75	-
Linuron	-1.62*	$ 22.00	-
Trifluralin	.25	$ 7.25	$ 28.05
Prometryn	-.31***	$ 8.10	-
Cyanazine	-.10*	$ 7.38	-
Glyphosate	-.24***	$ 12.95	-
Norflurazon	-.16	$ 12.80	-
Pendamenthalin	.52	$ 7.81	$ 14.88
Sethoxydim	-1.30	$ 50.65	-
Fluaxifop-P-butyl	.20	$ 59.35	$ 293.08
Clomazone	2.39	$ 20.50	$ 8.56
Fenaxaprop-ethyl	-7.72*	$ 65.00	-
Quizalofop-ethyl	127.71	$ 59.35	$ .46

[a] Marginal productivity in pounds of lint per acre per pound of active ingredient.
[b] Derived from products reported in Table 2.
[c] Dollars per pound of lint at which MC=MVP; does not include application costs.
*** Corresponding estimated coefficient significant at the α=.05 level.
** Corresponding estimated coefficient significant at the α=.10 level.
* Corresponding estimated coefficient significant at the α=.20 level.

Discussion

The marginal productivity estimates obtained from the yield response function and damage abatement specification show the appeal of chemical input use to producers . The ability to increase yields in excess of 500 pounds of lint per acre, or approximately one bale, as with dimethoate, makes obvious why cotton producers heavily apply insecticides. Interestingly however, is that those chemicals applied most frequently were most likely to have small marginal productivities relative to the costs per unit of active ingredient, which results in marginal costs greatly exceeding marginal value product. Examples include esfenvalerate, lambda-cyhalothrin, and zeta-cypermethrin. Conversely, there are a number of insecticides that have low unit costs and high marginal productivities such as cyfluthrin, etridiazole, and endosulfan, and may be a better economic alternative for producers.

While similar statements can be made about herbicides, it is difficult to draw firm conclusions about producer decisions except to say that there are those chemicals that are not likely to be economically efficient. Components such as fluaxifop-p-butyl that cost $59.35 per unit but only increase yields by .20 pounds per acre are unlikely to be a wise producer choice. Chemicals like trifluralin in popular pre-emergent herbicides like Treflan do not have a significant impact directly on yield. However, the economic incentives exist because of increased weed control, lowered cultivation costs, and better lint quality. These incentives are difficult to quantify with the marginal value product and marginal cost measures.

Conclusions

A yield response function with a damage abatement specification was estimated for Texas Upland cotton producers. Damage abatement sources included were herbicides and insecticides. The overall objective of this study was to develop estimates of marginal productivity of pesticide components and investigate the economic efficiency of producer pesticide choice.

The productivity estimates for insecticides pointed to the fact that some of the commonly applied chemical components did not economically reduce pest populations, although the marginal productivities were high. There were however, many components which were economically effective with low break even prices, thereby making producer choice of insecticide application clear.

Herbicide marginal productivity did not provide clear answers to producer choice as do insecticides. Economic efficiency is determined by elements beside increases in yield such as ginning costs, trash discounts, and cultivation costs. Most associated break even prices were greater than $10.00 and as high as $293.00 which could mean poor producer decision. However, some marginal productivity estimates implied economically efficient application and may be better choices for producers.

In contrast to previous research in pesticide productivity, the conclusion is that no clear answers as to the overall productivity of pesticides can be drawn. This stems from the fact that past publications have not recognized individual component productivity or the potential bias that could result from using aggregate data. This research concludes that producers are choosing many chemical components that are economically efficient, some that are not likely to be so, and that there is room for producers to make better pesticide decisions. While previous studies present an easily interpreted and potentially biased answer, like many economic questions the answers to pesticide productivity are never truly simple.

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ESSAY III

ABATING SPATIAL EXTERNALITIES IN AGRICULTURE

ABATING SPATIAL EXTERNALITIES IN AGRICULTURE

Abstract

Previous research has pointed towards the fact that spatial characteristics are important in the formation of policies aimed at abating non-point source pollution from agriculture. An initial theoretical examination is built which develops an understanding of the spatial nature of agriculture and its importance in development of policy. Several different policies are considered. The analysis focuses on a system of land use permits and on spatially differentiated taxes. Relative weaknesses and strengths of each policy are discussed. A system of land use permits suffers from the common criticisms of command and control approaches while spatially differentiated taxes maintain the appeal of a market oriented approach. Because the comparative efficiency of these policies becomes an empirical question, an analytical framework is developed to examine the importance and efficiency of considering spatial differences.

A GIS system and a stochastic dynamic optimization model are used to examine the relative impacts for a sub-watershed in Western Oklahoma. Soils and soil acreage are identified using GIS and impacts of controlling nitrate leachate on these soils are examined using the dynamic model. Relative leachability and soil productivity determine the costs of controlling leachate. Under the system of land use permits, the importance of considering spatial variability was reflected in the differing cropping levels. Similarly, under spatially

differentiated taxes, tax levels required to achieve emissions levels were different for most soils. These results also highlight the importance of considering spatial differences.

Efficiency in meeting emissions levels for the sub-watershed are also considered. The tax system is much more efficient in meeting a 10 lb. per acre nitrate leachate restriction since producers are able to control inputs and outputs so that marginal costs are equated to marginal value product. The difficulty with the land use permit system is obvious because administrators can really only control crop acreage to meet emission levels. The tax system is twice as efficient in terms of decreases in net returns. Wealth transfers under spatially differentiated taxes are less than under a land permit system.

Net returns and total leachate levels for the spatially differentiated tax system are compared with returns and leachate levels under a uniform tax. While decreases in net returns are less under the uniform tax, emission standards are not met. Thus, uniform taxes that do not consider spatial differences may not effective.

Keywords:

Non-point pollution, agricultural emissions, spatial externalities, dynamic optimization.

ABATING SPATIAL EXTERNALITIES IN AGRICULTURE

Introduction

Externalities from agricultural production exist in the form of non-point source pollution resulting from application of agricultural chemicals and fertilizers. The concern over control of the environmental impact of these chemicals and fertilizers is reflected in the quantity of research that has been dedicated to this subject (Jacobs and Casseler; Mapp et al; Teague, Bernardo, and Mapp; Milon; Thomas; Johnson, Adams, and Perry; Kim, Sandreto, and Hostetler; Kim and Hostetler; Kim, Hostetler, and Amacher). The most common theme of these studies is the impact on groundwater quality and economic control and alleviation of these impacts. It could be inferred that this quantity of research is a indication of both the complexity and importance of this issue to producer and public welfare.

Central to these issues, especially to issues of water quality, is the means by which non-point source pollution can be minimized via incentives or controls extended to the economic agents responsible for pollution. Likewise, the economic efficiency of these controls is at question and new and innovative approaches to controlling non-point source pollution are being explored (EPA).

Griffin and Bromley have addressed efficiency and the inherent spatial nature of agricultural non-point pollution. They focus on agricultural run-off as an externality and develop a theory of non-point pollution. Their conclusion is that decision makers must be cognizant of both economic and environmental impacts arising from non-point pollution and its control. Policies may not be effective unless the impacts on the environment are fully realized. Additionally, there exists the possibility to conceal actual impacts, both economic and environmental, via economic models taht do not reflect the differing productive capabilities and resource constraints of different farms, productive regions, or productive units.

Others such as Mapp et al. and Geleta et al. have addressed spatial concerns in reference to ground water quality. Geleta et al stress the importance of soil and cropping systems in the analysis of regional water quality. Cropping systems and major soils for the high plains region are examined for differences in leachate and run-off resulting from differences in soil and cropping patterns as well as alternate management practices.

Implicitly, this and other research reveals the importance of spatial characteristics and their relevance in the analysis of non-point source pollution in agriculture. Policies that view agricultural pollution as a spatial problem as well as a function of input choices are likely to be more efficient in handling non-point source pollution (Griffin and Bromley). For example, in the study by Huang and LeBlanc, a residual nitrogen tax is developed as a means of controlling percolation due to excess application of nitrogen fertilizers. They note that for a residual nitrogen tax to be efficient, tax rates must vary by region or soil. Blanket ad valorem nitrogen taxes fail by penalizing producers who use land that is not vulnerable to leaching. Huang and LeBlanc, however, do not consider different soils in their study.

Spatial variability and its importance have been examined outside of the agricultural context by Forsund. Forsund examines the impact of environmental pollution due to the generation of residuals in a general equilibrium context. The dynamic problems associated with stocks of accumulated residuals and degradation are not considered. Forsund concludes that residuals must be distributed in such a way that social damage is equal at the margin for all loaded recipients which implies that distinction between loading capabilities of the environment must be made. Alternately, Tietenburg examines the efficiency and legality of spatially differentiated air pollution emissions charges. Tietenberg shows that spatially differentiated charges are much more efficient than uniform emissions charges. There are many ways to build spatial variability into a taxing system; form individual taxing jurisdictions or taxing districts to tax different emitters at different rates, or increase the number of geographically distinct taxing authorities where each authority has control over its tax rate.

An alternate means of controlling agricultural non-point source pollution has been forwarded by Pan and Hodge. Pan and Hodge suggest that land use monitoring is much more tractable than monitoring input use. They extended a regional analysis of land use permits and compared their efficiency with ad valorem taxes. However, the authors fail to utilize spatial differentiation even though they believe that an analysis that incorporates unique spatial characteristics would be preferable.

The direct assessment of policies that view externalities in agriculture as a spatial problem, while hinted in the literature, has not been addressed. This paper has several goals and reflects these deficiencies. The first part of the paper develops a theoretical examination of several policies which take spatial differences into account. A general theoretical discussion of policies aimed at controlling non-point source pollution in agriculture is forwarded and policies are compared. The development centers on land use permits and spatially differentiated taxes.

The second part of this manuscript compares the efficiency of these spatially sensitive policies for controlling agricultural non-point source groundwater pollution resulting from nitrate percolate for soils within a sub-watershed in Western Oklahoma. A Geographic Information System (GIS), Arc-View, is used to determine soil acreage which is developed for irrigated and dryland cropping in the Cobb-Fastrunner sub-watershed located in Caddo, Washita, and Custer counties. A discrete time stochastic optimal control model is developed for each of the distinct soils using simulation data from EPIC-5300, a biophysical simulation program (USDA-ARS). The optimization model accounts for the carry-over resulting from application of nitrogen fertilizers to produce different crops in continuous and rotation systems. Using this model , the relative efficiency of land use permits and a spatially differentiated ad valorem nitrogen tax are tested and compared in meeting emission standards for nitrogen leached. This comparison is made for each soil and for the sub-watershed.

Theory

The argument for developing efficient emission schemes has been framed in terms of market oriented policies versus "command and control" policies (Tietenburg; Baumol and Oates; Taylor). Market oriented policies such as emission permits, input taxes, and output taxes, have been shown to achieve a given emission level most efficiently within the parameters of specific assumptions. Emission permits have the characteristic that any arbitrary assignment of permits will efficiently achieve a level of emissions chosen by a regulator if trading of these pollution permits is allowed and the market for these permits is efficient (Montgomery) However, oligopolistic behavior is possible implying rent seeking by firms and failure to control pollution (Gibbons).

With market solutions, such as emission permits and an input tax, agents will seek to equate the marginal costs of emission in terms of the licenses that must be purchased and the price of outputs, while uniform input taxes (Coasian taxes) seek to impose costs to the agent producing the externality such that full social costs of the externality are realized (Pearce and Turner; Tietenberg).

These methods abstract from pollution externalities imposed in an agricultural context. The control of agricultural non-point source pollution is complicated by the difficulty associated with numerous agents, a heterogeneous set of inputs for like outputs, the stochastic influence of weather, and hydrologic relationships. Policies implemented to control emissions that account for these spatial differences in agricultural production seem plausible and may be more efficient.

To provide a framework for this analysis, a mathematical structure developed by Montgomery is presented. The efficiency of achieving efficient emissions with tradeable effluent permits, uniform controls, land use permits, and spatial taxes is discussed. Within this framework, the control of agricultural pollution and the potential success of these methods are compared.

Theoretical Comparison

Following Montgomery consider a general pollution control problem faced by a policy maker. Define a set of integers $I = \{1, 2, \ldots, n\}$ describing n possible units which are to be monitored for pollution emissions at m different monitoring locations. The term unit is meant to be as general as possible to abstract from the idea of the firm, however it could refer to a farm level analysis or to a homogenous soil on which agricultural production occurs. Let the emissions vector for the n units be denoted as $E = \{e_1, e_2, \ldots, e_n\}$. The vector describing the desired level of emissions at all m locations can be described by $Q^* = \{q_1^*, q_2^*, \ldots, q_m^*\}$. Let H be an m x n matrix that describes the diffusion of emissions by the i'th unit at measurement location j, or $H = \begin{pmatrix} . & . & . \\ . & h_{ij} & . \\ . & . & . \end{pmatrix}$. This does not exclude the case where H is diagonal and emissions for the i'th unit impact only on the corresponding m'th location such as in the case of agricultural chemical percolation into a specific soil. Alternately, the case where H is not diagonal might be a case of agricultural run-off within a watershed where pollution is measured at m points in the watershed outlet. The above implies that $E \cdot H = Q$ and for an emissions level Q* the condition is that $E \cdot H \le Q^*$. Let the i'th unit face the convex cost function $G_i(y_{i1}, y_{i2}, \ldots, y_{ir}, e_i)$ which describes the minimum cost of producing outputs with emissions e_i, where $(y_{i1}, y_{i2}, \ldots, y_{ir})$ is the set of outputs for the unit. Then, the profit function can be defined by,

$$\pi_i = \sum_r p_r y_r - G_i(y_{i1}, y_{i2}, \ldots, y_{ir}, e_i) \tag{1.1}$$

which is convex by virtue of the convex cost function. An important construction by Montgomery is

$$\max_{\bar{y}_{ir}, \bar{e}_i} \pi_i [\bullet] = \sum_r p_r \bar{y}_r - G_i(\bar{y}_{i1}, \bar{y}_{i2}, \ldots, \bar{y}_{ir}, \bar{e}_i), \tag{1.2}$$

and

$$\max_{\tilde{y}_{ir}} \pi_i [\bullet] = \sum_r p_r \tilde{y}_r - G_i(\tilde{y}_{i1}, \tilde{y}_{i2}, \ldots, \tilde{y}_{ir}, e_i); \tag{1.3}$$

where e_i is some level of effluent and $\bar{e}_i$ is the level of effluent associated with the production set the firm would choose under no restrictions; it is assumed that $\bar{e}_i \geq e_i$.

The cost to the unit for a given emissions level is

$$F(e_i) = \sum_r p_r(\bar{y}_r - \tilde{y}_r) - [G_i(\tilde{y}_{i1}, \bar{y}_{i2}, \ldots, \bar{y}_{ir}, \bar{e}_i) - G_i(\tilde{y}_{i1}, \tilde{y}_{i2}, \ldots, \tilde{y}_{ir}, e_i)], \quad (1.4)$$

and the administrator's problem is:

$$\min_{e_i} \sum_i F(e_i) \text{ s.t } E \geq 0 \text{ and } E \cdot H \leq Q^*. \quad (1.5)$$

The Karousch-Kuhn-Tucker (KKT) conditions for the saddle point of a Lagrangean require that:

$$F_i'(e_i) + \sum_j u_j h_{ij} \quad , \quad \sum_i [e_i (F_i'(e_i) + \sum_j u_j h_{ij})] = 0 \quad (1.6)$$

$$q^*_i - \sum_i h_{ij} e_i \quad , \quad \sum_j [h_{ij}(q_i^* - \sum_i h_{ij} e_i)] = 0, \quad (1.7)$$

where $F_i'(e_i) = \dfrac{\partial F_i(e_i)}{\partial e_i}$. It can be shown that that there exists a solution vector $U^{**} \geq 0$ and $E^{**} \geq 0$, a vector of Lagrange multipliers and emissions respectively, which solve the cost minimization problem (Montgomery).

Spatially Insensitive Solutions

Uniform Charges

To examine the effectiveness of a uniform charge, for example a uniform tax, consider two units i and k (or possibly two different soils for which leaching probability is different) by taking the ratio of the KKT conditions to show that a necessary condition would be:

(1.6a)
$$\frac{F_i'(e_i)}{F_k'(e_k)} = \frac{\sum_l u_l h_{ij}}{\sum_l u_l h_{kj}}.$$

A uniform tax requires that $\sum_l u_l h_{ij} = \sum_l u_l h_{kj}$ since the first order necessary conditions require that $F_i'(e_i) = F_k'(e_k)$. Interpreted, the shadow price of diffusion for the i'th and k'th unit must be equated. If this problem is framed in terms of a set of agricultural producers or heterogeneous soils over a basin or watershed level analysis, the inherent difficulty of making 1.6a true becomes obvious and negates the effectiveness of a uniform charge.

If efficiency is addressed, begin by noting that there are no restrictions on h_{ij} or h_{kj}. A uniform charge fails to levy appropriate charges in relation to the emissions of a particular firm or a particular soil. Appropriate weights, i.e. the H matrix, are not considered. Hence uniform emissions charges cannot be efficient (Tietenburg). Take for example, a case in which the H matrix is diagonal and represents different soils with different rates of percolation. If the rates of diffusion are equal, then a uniform tax on an input which is considered to contribute to non-point pollution is efficient, however the likelihood for percolation rates to be equal across soils is small (Folley; Fleming and Adams).

Emissions Permits

For efficiency, the existence of emission controls by a set of emission permits is accepted without rigorous treatment. As Montgomery proves, there exists an efficient cost minimizing emissions vector, denoted E^*, which can be achieved via a system of emission permits, regardless of the initial allocation of permits if the market is efficient. The solution implies that for the i'th unit, there exists $F_i(e_i^*) = F_i(e_i^{**})$, an efficient market permit equilibrium equal to the regulator's problem which is also a competitive equilibrium. This treatment is a significant set of theorems and proofs which will be accepted here without restatement. An important point is that the existence of such an emissions vector and a corresponding set of licenses held by each decision unit relies heavily on the fact that for a given allocation, all units can achieve the license portfolio via trades with other units. A failure for say the i'th unit to purchase a needed license will result in disequilibria.

The attributes of agricultural production may imply controlling agricultural emissions via market processes to be difficult or impossible because license trades become difficult. Comparisons to agricultural production and typical industrial firms have been made resulting in the conclusion that agricultural firms differ greatly from industrial firms.

These differences can be described under the guises of spatial intensity (Olson). Define spatial intensity here to describe the units of land required to produce an output or vector of outputs. In terms of the marginal production value per unit of land, agricultural production is small compared to industry which produces its products on fewer units of land. The spatial intensity of agriculture makes organization and communication difficult between agricultural producers (Olson). Spatial intensity significantly impacts the regulation of non-point emissions from agriculture. If the key to an efficient market is cheap and abundant information, then the problem is obvious. An argument against pollution permits in agriculture can be levied on these merits. If trades fail to take place, then an initial allocation of permits may be the equilibrium or close to the market equilibrium which may exacerbate the pollution problem by concentrating emissions. Failure of trades to be made has distributional considerations. There is therefore, no guarantee that the market equilibrium will efficiently achieve the level of emissions desired.

Precisely, define $A_i = (a_{i1},\ldots,a_{ik)})$ where a_{ik} is the number of licenses of type k held by the i'th unit. If H_i is the i'th row of the H matrix, then let the emissions be a function $\Gamma(H_i, A_i)$ so that the problem is to

$$\text{(1.8)} \qquad \text{minimize}\, F_i(e_i) + \sum_k p_k(l_{ik} - l_{ik}^0) \text{ s.t. } e_i \le \Gamma(H_i, A_i)$$

where l_{ik}^0 is the initial allocation of licenses. Montgomery defines the market equilibrium as the non-negative prices P^* where the efficient emissions vector and license vector are such that the market clearing conditions below hold:

$$\text{(1.9)} \qquad \sum_i (l_{ik}^* - l_{ik}^0) \le 0 \qquad \sum_k p_k^*[\sum_i (l_{ik}^* - l_{ik}^0)] = 0.$$

The above statements imply that spatial intensity of agriculture translates to $\sum_k p_k^*[\sum_i (l_{ik}^* - l_{ik}^0)] \ne 0$.

An additional criticism to the use of emission permits in agriculture results from the difficulty associated with monitoring emissions. Because non-point pollution by definition is difficult to monitor, effluent emission standards make little sense in an agricultural context. Determining the number of emission permits needed and input use required under the level of emissions would be difficult if not impossible for a large number of producers because of implementation and enforecement costs (Griffin and Bromley).

Spatially Sensitive Policies

Land Use Permits

Land permits, initially discussed by Pan and Hodge, could imply an efficient distribution of emissions by agricultural producers. As will be shown below, there exists an allocation of land use permits that matches the cost minimizing competitive equilibrium solution achieved with emission permits in the presence of perfect information. Land use permits could escape two essential problems noted with alternate emissions control. The extension of land use permits could be easily monitored. Land use has been monitored to confirm producers' compliance with government programs. Secondly, land use permits do not require perfect information be communicated between producers and do not suffer from the problems of spatial intensity of agriculture. General trends for soils and agricultural practices can be easily observed and permits extended based on those observations (Pan and Hodge).

Although land use permits seem appealing in an applied format, no theoretical treatment of land use permits has been extended. I will use the mathematical system stated above to prove that there exists an efficient allocation of land use permits which achieves a required level of emissions that is equal to the market equilibrium efficient emissions achieved with a system of tradable emissions licenses.

Assume that $F_i(e_i)$ is convex if and only if $G_i(e_i)$ is convex. Further, if $G_i(e_i)$ is strictly convex, then E^{**} and by implication E^{*} are unique (Montgomery). Define a land use permit for the i'th production unit as $L_i = (\hat{m}_{i1}, \hat{m}_{i2}, \ldots, \hat{m}_{ir})$, which describes a possible production set of $\hat{m}$ outputs for unit i. If the regulator imposes a land use permit which achieves a level of emissions, $\hat{e}_i$, then agents in the i'th unit face the problem,

$$(1.11) \qquad \max_{m_{ir}} \pi_i = \sum_r p_r m_{ir} - G_i(m_{i1}, m_{i2}, \ldots, m_{ir}, \hat{e}_i) \quad \text{s.t. } (m_{i1}, m_{i2} \ldots m_{ir}) \cdot I \leq L_i .$$

Let $m_{ir}, L_i \subseteq \Omega$, where Ω is the set of all possible output values. The parameter space of the output is restricted by the land use permit. The cost of the given land use permit is defined as

$$(1.12)\quad F(\hat{e}_i) = \sum_r p_r(\bar{y}_{ir} - m_{ir}) - [G_i(\bar{y}_{i1}, \bar{y}_{i2}, \ldots, \bar{y}_{ir}, \bar{e}_i) - G_i(m_{i1}, m_{i2}, \ldots, m_{ir}, \hat{e}_i)].$$

The above gives way to the following proposition:

proposition 1.0: there exists an emissions $\hat{E}$ *achieved by the assignment of land use permits which is efficient.*

proof: given that there exists a solution to the regulators problem of minimizing costs or

$\min_{e_i} \sum_i F(e_i)$ s.t $E \geq 0$ and $E \cdot H \leq Q^*$, which achieves the efficient vector E^{**}. Since by

definition, $m_{ir} \subseteq \Omega$, this $\Rightarrow$ that $\exists\ m_{ir} = \tilde{y}_{ir}$ so that for the i'th production unit

$F_i(\hat{e}_i) = F_i(e_i^{**})$. $\square$

This leads to the following collary:

Corollary: if there exists L_i *such that* $F_i(\hat{e}_i) = F_i(e_i^{**})$, *then there exists a land use permit equivalent to any market license determined efficient emissions equilibrium.*

proof: this proof is trivial since from proposition 1.0 there $\exists\ F_i(\hat{e}_i) = F_i(e_i^{**})$ and

since $\sum_i F_i(e_i^{**}) = \sum_i F_i(e_i^{*})$, the corollary holds. $\square$

By the previous statement, correct assignment of land use permits could achieve the same solution as that obtained under the efficient market equilibrium and by implication, land use permits could be an efficient cost minimizing solution to agricultural emissions.

However, the efficiency of land use permits relies heavily on the correct assignment of permits. This is a potential problem if complete knowledge of the cropping systems and cultural practices is not known. Standard arguments that apply to command and control approaches to regulating emissions are applicable to land use permits (Baumol and Oates; Kneese and Bower).

Spatially Differentiated Taxes

The argument for spatially differentiated taxes follows from the argument given against uniform charges. As noted, the uniform charge requires that shadow prices of diffusion be equated between units, which is inherently cost ineffective if the rates of diffusion are not similar. The imposition of a spatially differentiated tax could equate to perfect tax discrimination for each unit of analysis. Optimality no longer requires $F_i'(e_i) = F_k'(e_k)$. The differences in efficiency between spatially differentiated taxes and uniform taxes hinge on the rates of diffusion. In agriculture, this might be determined by the differences in soils, soil leachate, and run-off probabilities. If the unit of analysis is at the firm level, it may be a function of management practices, such as irrigation techniques or, in cases where manure is applied for fertilizer, spreading equipment (Mapp et al.; Rauschkolb and Hornsby). Following from the previous discussion, taxes levied based on differing soil productivity could result in minimum cost control of agricultural non-point source pollution.

Land Use Permits and Spatial Taxes Compared

While both spatially differentiated taxes and land use permits have individual merit, efficiencies and success of each method differ. If agricultural non-point pollution results from inputs or overuse of inputs, both land use permits and taxes offer potential solutions. A tax could be constructed so that the full cost of using the input would be realized by the producer. Similarly, a system of land use permits could be implemented to control production of those crops for which excess levels of the input are required to produce profitable yields. The question of which policy is most efficient hinges on the spatial variability of the area of production as well as the possible production choices. As noted, land use permits may suffer from problems typical of the command and control approach to controlling emissions. The relative efficiency of these policies becomes an empirical question.

If agricultural pollution arises from production choices rather than inputs, ad valorem taxes which target inputs, no matter how spatially differentiated, are going to be neither effective nor efficient. For example, legumes that fix their own nitrogen can often be a significant source of nitrogen leachate even though nitrogen fertilizer is not heavily applied and would not be impacted under an ad valorem tax on nitrogen fertilizer (*Folley*).

Empirical Application

Because questions of efficiency are dependent on the spatial variability, it is useful to develop an empirical comparison of the spatial policies of land use permits and spatially differentiated taxes. The implication that control of agricultural non-point emissions may be achieved efficiently by the extension of land use permits depends largely on the ability to distribute permits in a spatially optimal way. That is, such that marginal costs to producers in terms of foregone production are minimized while meeting leachate constraints. Similarly, for spatially differentiated taxes, the potential environmental damage, or the components of the H matrix above, must be known or estimated to develop taxes that fully reflect spatial differences in the separate units of production. With this knowledge, efficiency of these two policies can be examined and comparisons made.

One of the most investigated and serious problems in agriculture is leachate from commercially applied nitrogen fertilizers into groundwater (Johnson, Adams, and Perry; Kim and Hostetler; Nielsen and Lee). The differences in the two policies described above are investigated for their efficiency in controlling leachate from agricultural nitrogen application for a sub-watershed in Western Oklahoma. This area was chosen because of its spatial differentiability as well as the potential problems that nitrogen percolation poses for the area. For this study, the logical unit of spatial differentiation is chosen to be soils since soils play a significant role in determining the probability of leachate (Raschkolb and Hornsby; Mapp et al.). Using land used data provided by OSU Department of Agronomy, a GIS (Geographic Information System) is used to determine the soils and acreage of soils that are developed for dryland and irrigated cropping in the sub-watershed (Mark Gregory). A biophysical model which incorporates nitrogen carry-over is developed to reflect the cropping patterns and potential carry-over effects of these cropping patterns. Using this model, optimal land use and spatially differentiated taxes are compared for their efficiency for the associated soils and over the sub-watershed.

Area of Study

The area chosen to study is the Cobb-Fastrunner sub-watershed in Western Oklahoma. Most of this sub-watershed lies in the hydrologic sub-region Red-Washita river basin with a small percentage in the Lower Canadian River Basin and with approximate center degree coordinates of 98’30° longitude and 35’15° latitude. This sub-watershed comprises an area of over 240,000 acres. Land use is primarily agricultural with 168,907 acres in dryland cropping or improved range coverage. A total area of 31,683 acres is developed for irrigated production. The sub-watershed overlies areas of Caddo, Washita, and Custer counties. On a percentage basis, 71% overlies Caddo county, 26% in Washita county, and 2% in Custer county (Land Use Data, Mark Gregory).

The source of irrigation water is the Rush Springs Aquifer. The Rush Springs Aquifer is an alluvial aquifer described as a poorly cemented, reddish brown, fine-grained sandstone that locally is silty or argillaceous, and contains several thin but persistent beds of gypsum or anhydrite and dolomite, which produces high quality water that is generally potable. Well yields range from 20 to 600 gallons per minute but some producing wells exceed 1200 gallons per minute. Saturated thickness ranges from 0 to 394 ft in the study area. Data from 1990 statistics show that upwards of 55 million gallons per day were withdrawn from the Rush Springs Aquifer (Becker). Of that total, 78% (42.8 mil gal/d) was devoted to irrigated agriculture. (Becker)

GIS data reveal there are extensive differentiation in the soils in the production area with 53 different soils ranging from clay loams to fine sandy loams identified. A large number of these soils are susceptible to high rates of percolation (Soil Surveys, Caddo, Washita, and Custer Counties). A 1994 study by the USGS identified 91 test wells that exceeded the maximum contaminant level for nitrogen in the study area. This is approximately 30% of all the wells tested throughout the Rush Springs Aquifer. Many of these are in the north central portion of Caddo, eastern regions of Washita, and south-eastern portions of Custer county and within the boundaries of the Cobb-Fastrunner sub-watershed.

Agricultural Production and Cultural Practices

Agricultural crop production in Caddo, Washita, and Custer counties is mainly wheat, peanuts, grain sorghum, and cotton. Caddo county ranks first in peanut production for the state with 31,500 acres of peanuts planted in 1995 with an average yield of 2490 lbs. per acre. Planted acreages of cotton, wheat, and sorghum for 1995 are

14,600, 230,000, and 8,600 with average yields of 163 lbs. of lint, 25.6 bu. per acre, and 58 bu. per acre respectively (Oklahoma Agricultural Statistics 1995).

Washita county produces mostly wheat with 250,000 planted acres in 1995 and an average yield of 24.3 bu per acre. Planted cotton acreage for 1995 was greater than 40,000 acres and had an average yield of 175 pounds of lint per acre. Washita had only 700 acres of planted peanuts in 1995 and 3500 acres of grain sorghum (Oklahoma Agricultural Statistics 1995). However, peanut production was in the eastern part of the county and likely to be in the area of the Cobb-Fastrunner sub-watershed where the soils are favorable for peanut production (Ron Sholar).

Producers in Custer county planted 260,000 acres of wheat in 1995 with an average yield of 23.1 bu. per acre and no peanuts were planted. Total planted acreage of cotton was 6400 with an average yield of 134 lbs. of lint per acre. Producers planted 5000 acres of grain sorghum in 1995 with an average yield of 46.6 bushels per acre (Oklahoma Agricultural Statistics 1995).

For soils in which peanut production is feasible, including sands, loams, and fine sandy loams, common production practices are to rotate with either cotton, sorghum, or wheat to minimize pesticide requirements. However this practice depends on rainfall, pests, and prices of alternate crops (Ramming; Sholar). Peanuts are intensively farmed with 90% of producers applying on average 35 lbs. of nitrogen per acre (Brooks and Ali). Irrigated peanuts are watered heavily to insure proper growth even though average rainfall exceeds 35 inches per year (Ramming).

Sorghum, cotton, and wheat are less intensively farmed. Fertilizer is commonly applied to all crops and levels vary with soil nutrient requirements. Nitrogen is applied to

96% of all winter wheat at an average of 72 pounds of actual nitrogen per acre (Oklahoma Agricultural Statistics, 1995).

Biophysical Model

Numerous studies which incorporate biophysical relationships and outcomes have been developed to examine impacts from non-point source pollution on groundwater and the environment. Examples of static models (single period stochastic and non-stochastic optimization models) can be found in Teague, Bernardo and Mapp and Pan and Hodge. In these static models, relationship coefficients are often estimated and used as fixed coefficients in programming models. The models are used to find optimal outcomes subject to a restricted parameter space as defined by the estimated biological relationships. Leaching or runoff relationships are the most often studied problem (Connor, Perry and Adams; Sun, Houston, and Bergstrom; Thomas and Boisvert).

While static models are often used because of their mathematical tractability, the inherent dynamics of biological systems mean that dynamic analysis should offer more robust results. Development of models which incorporate all biological relationships would be impossible (Bouzaher et al). However, biological models can be used to examine general trade-offs and risks associated with physical actions. While the results will not predict actual outcomes, they will describe impacts, directions of impacts, and rank outcomes (Johnson, Adams, and Perry).

Studies conducted using dynamic biological relationships can be found in Kim and Hostetler; Kim, Sandretto, and Hostettler; Segarra et al; Johnson, Adams and Perry; and Conrad. Previous research dictates that for efficient analysis, dynamic relationships should be incorporated into the model. A dynamic model of nitrogen leachate can be developed which incorporates biophysical processes of nitrogen from site specific agricultural production practices. Solutions to this model will imply optimal spatial cropping subject to meeting leachate restrictions and resource constraints.

Optimal use of nitrogen fertilizers has been studied by Segarra et al; Taylor; Thomas and Boisvert; and Kennedy. Crop management and crop rotations are often used to supplement nutrients for those crops which require additional nutrients, especially nitrogen to obtain profitable yields (*Folley*). Total nitrogen available to the plant is a function of nitrogen applied, nitrogen that has been carried over from previous nutrient application, and nitrogen that has been produced naturally (either fixed , mineralized, or exogenous sources such as rainfall) as well as precipitation, irrigation water applied, crop rooting depth, and unique soil characteristics. Such characteristics as soil uniformity and depth may determine nitrogen availability and utilization. These factors in turn are important to the potential of nitrogen leachate as it is a function of soil properties, crop management, and nitrogen inputs (Rauschkolb and Hornsby). All of these factors have the potential to positively and negatively impact yields and thus profits. Therefore, these relationships must be incorporated into the dynamic model.

The dynamic optimization model below derives optimal levels of nitrogen, irrigation water, and land produced under each crop over the decision period for each set of unique soil parameters in the study area. This model follows that developed by Segarra et al., which used available nitrogen as a transition variable, and Thomas and Boisvert which included multiple crop rotations. To account for the stochastic nature of precipitation, rainfall is included using a gaussian-quadrature approach (Preckel and DeVuyst).

Gaussian-quadrature approximates expectations using probability mass and points. The points and weights are chosen so that the moments for the discrete approximation to the distribution match to moments of the true distribution for the 0'th through some fixed order (Preckle and DeVuyst). Here, precipitation is assumed to follow a binomial distribution because the binomial has a flexible form and has been used in previous work (Dai, Fletcher, and Lee; Thomas and Boisvert)

The dynamic optimization model for the q'th soil is :

(2.0)

$$\max_{(\lambda_{it}, n_{it}, w_{it})} NR_q = \sum_{t=1}^{T} \rho^t \left[\sum_i \sum_j pr_j \left[r_{it} \cdot y_{it}(na_{it}, w_{it}, s_j) - pn_{it} \cdot n_{it} - pw_{it} \cdot w_{it} \right] \right] \cdot \lambda_{it}$$

subject to:

(2.1) $$na_{it} = \sum_j pr_j \cdot \left(f(n_{it}, nm_{it}, w_{it}, s_j, nr_{it}, nf_{it}) \right)$$

(2.2) $$nm_{it} = \sum_j pr_j \cdot \left(f\left(n_{it}, w_{it}, s_j\right) \right)$$

(2.3) $$l_{it} = \sum_j pr_j \cdot \left(f(w_{it}, na_{it}, s_j) \right)$$

(2.4) $$\sum_i l_{it} \cdot \lambda_{it} \leq L_B$$

(2.5) $$\lambda_{1t} \leq \lambda_{1(t-1)}$$

(2.6) $$\lambda_{2t} \leq \lambda_{2(t-1)}$$

(2.7) $$\lambda_{3t} \leq \lambda_{2(t-1)} + \lambda_{7(t-1)}$$

(2.8) $$\lambda_{6t} + \lambda_{7t} + \lambda_{8t} \leq \lambda_{5(t-1)}$$

(2.9) $$\sum_i \lambda_{it} \le 1$$

(2.10) $$nr_{1t} = \frac{\lambda_{1t}}{\lambda_{1(t-1)} + \lambda_{6(t-1)}} \cdot (na_{1(t-1)}) + \frac{\lambda_{1t}}{\lambda_{1(t-1)} + \lambda_{6(t-1)}} \cdot (na_{6(t-1)})$$

(2.11) $$nr_{2t} = \frac{\lambda_{2t}}{\lambda_{2(t-1)} + \lambda_{7(t-1)}} \cdot (na_{2(t-1)}) + \frac{\lambda_{7t}}{\lambda_{2(t-1)} + \lambda_{7(t-1)}} \cdot (na_{7(t-1)})$$

(2.12) $$nr_{3t} = \frac{\lambda_{3t}}{\lambda_{2(t-1)} + \lambda_{7(t-1)}} \cdot (na_{2(t-1)}) + \frac{\lambda_{3t}}{\lambda_{2(t-1)} + \lambda_{7(t-1)}} \cdot (na_{7(t-1)})$$

(2.13) $$nr_{4t} = \frac{\lambda_{4t}}{\lambda_{4(t-1)}} \cdot (na_{4(t-1)})$$

(2.14) $$nr_{6t} = \frac{\lambda_{6t}}{\lambda_{5(t-1)}} \cdot (na_{5(t-1)})$$

(2.15) $$nr_{7t} = \frac{\lambda_{7t}}{\lambda_{5(t-1)}} \cdot (na_{5(t-1)})$$

(2.16) $$nr_{8t} = \frac{\lambda_{8t}}{\lambda_{5(t-1)}} \cdot (na_{5(t-1)})$$

(2.17) $$\lambda_{it}, n_{it}, w_{it}, nm_{it}, na_{it}, nr_{it} \ge 0$$

(2.18) $$\lambda_{i0}, n_{i0} w_{i0}, na_{i0}, nm_{i0}, and\ nf_0 \text{ given,}$$

where NR_q is the per acre present value of expected returns to land, irrigation water, nitrogen applied, and cropping choice for the q'th soil. For the readers convenience, a complete list of notation for equations 2.0 - 2.18 is given in Table 1.

Table 1. Notation Summary for Bioeconomic Model.

Subscripts:	
Crops	$i=1,2,\ldots,8$
	1=irrigated cotton following irrigated cotton
	2=dryland cotton following dryland cotton
	3=sorghum following dryland cotton
	4=wheat following wheat
	5=peanuts
	6=irrigated cotton following peanuts
	7=dryland cotton following peanuts
	8=sorghum following peanuts
Year	$t=1,2,\ldots,T$
Soils	$q=1,2,\ldots,Q$
Variables:	
na_{it}	nitrogen available to the i'th crop in year t.
w_{it}	acre inches of irrigation water applied to the i'th crop year t.
λ_{it}	percentage of acre devoted to the i'th crop in year t.
n_{it}	nitrogen applied to the i'th crop in year t.
Parameters:	
pr_j	probability mass associated with the j'th gaussian-quadrature point for random precipitation.
s_j	probability mass associated with the j'th gaussian-quadrature point for random precipitation.
y_{it}	yield response to water, nitrogen available, and precipitation for the i'th crop year t.
r_{it}	unit return net of nitrogen fertilizer and irrigation water in year t for the i'th crop.
l_{it}	expected leachate from the i'th crop in year t.
nm_{it}	expected nitrogen mineralized by the i'th crop in year t.
nf_{it}	nitrogen fixed by the i'th crop in year t.
Standards:	
L_b	total expected leachate restriction for one acre of production.

Equation 2.0 is the objective function to be maximized in nitrogen fertilizer, irrigation water, and percentage of land devoted to crop i, or n_{it}, w_{it}, and λ_{it} respectively. The parameters ρ^t, r_{it}, pn_{it}, and pw_{it} are the discount parameter, return to crop i in the t'th year net of nitrogen applied and water applied, price of nitrogen applied in year t, and price of water applied in year t respectively. The parameter y_{it} is the yield response

function for the i'th crop as a function of nitrogen available in the root zone, irrigation water applied, and stochastic precipitation s_j with associated gaussian-quadrature probability pr_j. Equation 2.1 is the carry-over equation for expected available nitrogen for the i'th crop in year t as a function of nitrogen fertilizer applied, nitrogen mineralized, irrigation water applied, stochastic precipitation, residual nitrogen available for period t, and nitrogen fixed in t. Equation 2.2 is the expected level of nitrogen mineralized for crop i in period t as a function of nitrogen applied, irrigation water applied, and precipitation. Equation 2.3 is expected leachate as a function of irrigation water, nitrogen available in the root-zone, and precipitation. Total expected leachate for an acre is limited by equation 2.4 where L_b is the upper bound on leachate. Equations 2.5 - 2.8 are rotation restrictions for irrigated cotton, dryland cotton, sorghum following dryland cotton, and irrigated cotton, dryland cotton, and sorghum following peanuts. As will be discussed below, this model assumes that peanuts are always grown in rotation to minimize chemical requirements and maximize soil fertility (Elder; Ramming). Equations 2.9 - 2.15 are the transition equations for residual nitrogen in the root-zone available to each respective crop and equations 2.16 and 2.17 are positivity constraints and initial conditions respectively.

Data, Methods, and Procedures

Simulation Data

The relationships that exist among biological systems are rarely observable. Thus, researchers often use biophysical simulation models to represent biological systems (Mapp et al). Further, statistically fitting equations to these estimated relationship offers a way of summarizing and managing these data (Bouzaher et al). EPIC-5300 (Environmental Policy Integrated Climate) was used to estimate the parameters for the bio-physical model above. Nitrogen levels and irrigation levels were parameterized to develop 1000 years of simulation data to create the yield response, nitrogen mineralization response, nitrogen leachate response, and total nitrogen available response functions for each of the cropping systems listed in Table 1. This was done for each of the cropped soils identified for the study area using weather parameters from the weather station located in Weatherford, Oklahoma.

Previous research gives no clear indication of functional specification for the biological relationships. Yield response to nitrogen availability has been estimated using the Mitscherlich-Spillman functional form (Rauschkolb and Hornsby). More typical is a quadratic approach which captures negative marginal returns to available nutrients (Segarra et al). Alternate functional forms were tried, but a quadratic functional form was chosen because it provided the best overall statistical fit for the soils in the study area. Additionally, the range of functional forms was limited both by the number of soils used in this study as well as the stipulation that non-convexities in the response functions must be limited. Because of the number of soils developed in this study, separate functional forms for each soil, while ideal, were not feasible. The functional form chosen for the yield response is:

(3.1)

$$y_{it} = \beta_0 + \beta_1 na_{it} + \beta_2 w_{it} + \beta_3 s_t + \beta_4 na_{it} w_{it} + \beta_5 na_{it} s_t + \beta_6 na_{it}^2 + \beta_7 w_{it}^2 + \beta_8 s_t^2 + \beta_9 s_t w_{it} + e_t$$

where the parameter notation is the same as given in Table 1. General statistical fit was good with measures of linear correlation (corrected R^2) ranging from .30 to .70 depending on the cropping system and soil estimated. The signs of the coefficients were as expected with the squared terms negative and linear terms positive. Cross product terms varied in sign depending on the crop. Statistical significance of the coefficients also varied, but they were often significant at the 90% confidence level.

Nitrogen mineralization response was specified as a linear function of nitrogen fertilizer applied, irrigation water applied, and random precipitation. The functional form is:

$$nm_{it} = \beta_0 + \beta_1 n_{ij} + \beta_2 w_{it} + \beta_3 s_t + e_t. \tag{3.2}$$

This functional form reflects Broadbent's research on nitrogen mineralization (*Management of Nitrogen in Irrigated Agriculture* pg. 120-125). Levels of nitrogen mineralization are correlated with nitrogen fertilizer as well as available water. Statistical fit was good with R^2 averaging .8 to .9 and coefficient statistical significance at the 90 percent confidence level.

For available nitrogen, a linear specification is used to account for the available nitrogen sources as well as nitrogen carry-over from previous crops. The function is specified as:

$$na_{it} = \beta_0 + \beta_1 n_{it} + \beta_2 nm_{it} + \beta_3 w_{it} + \beta_4 s_t + \beta_5 nr_{it} + \beta_6 nf_{it} + e_t. \tag{3.3}$$

Coefficient signs were as expected, with available nitrogen decreasing in water applied and increasing in nitrogen fixed, nitrogen applied, and nitrogen mineralized. Linear correlation varied by crop and by soil.

Finally, leachate was modeled as a linear function in irrigation water, precipitation, and total nitrogen available to the plant. Total nitrogen is assumed to be nitrogen mineralized, average nitrogen fixed, and nitrogen fertilizer applied. The function form is:

$$l_{it} = \beta_1 w_{it} + \beta_2 na_{it} + \beta_3 s_t + e_t. \tag{3.4}$$

The functional fit was deemed superior to others both statistically as well as in its simplicity. Measures of linear correlation corrected for the intercept restriction were all greater than .8 and coefficients for all soils and cropping rotations were highly significant.

Return and Cropping Assumptions

The cropping rotations assumed for this study are outlined in Table 1. Cost, chemical, price, and yield assumptions used in deriving net returns for each of the crops are given in Table 2. Oklahoma enterprise budgets were used to determine fixed costs and discussion with chemical specialists helped determine common chemicals used (Jim Criswell, personal correspondence). The chemical regimes assume intensive cropping.

Table 2. Cost, Chemical, Price, Yield, and Net Return Assumptions for Cotton, Wheat, Sorghum and Peanuts.

Crop	Fixed[a] Costs	Chemical[a] Costs	Chemicals Applied	Average[a] Yield	Price[b]	Net[c] Return
Dryland Cotton	75.57	5.33	Bidrin, Ethyl-Parathion, Cypermethin	392	.66	.4536
Irrigated Cotton	141.37	17.66	Treflan, Bidrin, Ethl-Parathion, Cypermethin, Dimethoate	507	.66	.3463
Wheat	64.23	14.75	2,4-D, Glean, Dimethoate, Methyl-Parathion, Lorsban	33.2	3.78	1.88[d]
Sorghum	46.62	7.70	Ethyl-Parathion, Atrazine	38.1	2.58	1.15
Irrigated Peanuts	215.26	142.36	Vernam, Balan, Dual, Bugle, Bravo, Orthene, Nemacur	3134	.2875	.17

[a] On a per acre basis in 1996 prices.
[b] Ten year averages for Caddo county.
[c] Units are per pound of lint for cotton, per bushel for wheat and sorghum, and per pound for peanuts.
[d] Includes a $16.00 per acre imputed value for winter wheat pasture.

Ten year average yields were derived from USDA county level data. Because the largest area of study overlies Caddo County, average yields from Caddo were used. Price assumptions are 1996 estimates taken from Food and Agricultural Policy Research Institute publications while cost data is on a 1995 basis. Return assumptions for the crops were found by dividing net returns by the average yield to get a unit return net of fertilizer costs and irrigation water costs. To account for the value of winter wheat pasture, an imputed value of $16.00 per acre was included in the wheat return assumptions (Doye and Kletke). The nitrogen fertilizer price assumption was 13 cents per pound of actual nitrogen and irrigation water was assumed to cost $3.20 per acre inch.

Cropping rotations were developed from discussion with area conservation specialists, soil scientists, and from agricultural statistics (Brad Elder and Phil Perryman, personal correspondence). Cropping distribution among soils is essential to this analysis. Additional discussion with area specialists helped determine soils on which peanut production is common and most productive. Peanuts are seldom dryland cropped and are the major irrigated crop in north Caddo county. A list of major cropped soils used in this study is given in Table 3. The irrigated soils are Cobb fine sandy loam, Dougherty and Eufala complex, Shellabarger, Grant loam, Pond Creek fine sandy loam, Port silt loam, and Mclain. Peanuts are feasible and grown on all of these irrigated soils except for Mclain. It is assumed that all irrigated acres are irrigated with center pivot sprinkler systems. For the dryland soils, major crops are small grains and cotton. As noted, small grains, specifically winter wheat, are the most common dryland crop. Rainfall patterns and common cultural practices dictate that although cotton can be a profitable crop, producers do not plant it as often. It is assumed that no more than 30 percent of any one soil is cropped in dryland cotton. Small grains and cotton are commonly grown on all the soils in this study except for the Woodward, Lucien, and Hardeman series. It is assumed that only winter wheat is cropped on these soils (Soil Surveys, Caddo, Custer, and Washita Counties).

Table 3. Land Acreage and Percent of Sub-Watershed.

Soil Series	Acres	Percent of Area
Pulaski	1275.28	.64
Cobb fine sandy loam	7097.94	3.56
Cobb fine sandy loam [a]	355.88	.17
Reinach silt loam	771.08	.38
Shellabarger	168.05	.08
Shellabarger [a]	889.71	.44
Dougherty loamy fine sand	4834.10	2.42
Dougherty & Eufala	2076.001	1.04
Dougherty & Eufala complex [a]	1482.85	.74
Eufala fine sand	1690.45	.84
Gracemont	355.88	.17
Hardeman	2471.43	1.24
Grant loam	6900.23	3.46
Grant loam [a]	4122.34	2.06
Woodward silt loam	148.28	.74
Konowa loamy fine sand	1008.34	.50
Lucien Dill fine sandy loam	731.54	.36
Noble fine sandy loam	1235.71	.62
Noble fine sandy loam [a]	573.37	.28
Pond Creek fine sandy loam	132537.90	66.51
Pond Creek fine sandy loam [a]	23933.33	12.01
Minco very fine sand	128.51	.06
Port silt loam	2847.08	1.42
Port silt loam [a]	1166.51	.58
McLain [a]	444.85	.22

[a] Denotes irrigated soils.

Soils Data

Since a goal of this analysis is to develop the relationship between spatial variability and agricultural emissions, every effort was extended to develop accurate soils data for input into the EPIC biophysical simulation model. All soils which were cropped in areas greater than 100 acres were identified using Arc-View and digital land use data provide by OSU Department of Agronomy (Mark Gregory). The soils and acreage of each soil are listed in Table 3. The most prevalent soil in the sub-watershed is the Pond Creek series, however the Cobb and Dougherty series are also extensive. Soils parameter input data was collected from the Soils V soils database for Oklahoma developed by the USDA. For comparison, data from the MUUF v2.14 program available from the Grasslands Research Center was also collected. Initial investigations revealed that MUUF data was not as accurate since soil parameters were not necessarily based on soil samples from Caddo, Custer, or Washita counties while the Soils V soils database is based on county specific soil samples. Moreover, EPIC output, especially nitrogen leachate estimates, are sensitive to a number of these soil parameters, especially pH (EPIC Model Documentation). Also, yield estimates using the Soils V data were deemed to be closer to county averages. Soils used and their primary surface textures are given in Table 4.

Most of the soils cropped contain significant amounts of sand which increases permeability. The permeability classification for the soils identified ranges from slowly permeable to moderately rapid with most classified as moderately permeable. Note that most of the soils have shallow surface horizons which are generally less than twelve inches deep with Reinach and Port series the exception.

Table 4. Initial Soil Horizon Textures by Soil Series for Major Cropped Soils in the Cobb-Fastrunner Sub-watershed.

Soil Series	Horizon[a]	% Silt[b]	% Sand[b]	Bulk Density	pH	Saturated Conductivity	Permeability Classification
Pulaski	0 - 10	36	58	1.525	6.45	4	moderately rapid
Cobb fine sandy loam	0 - 8	30	64	1.45	6.95	4	moderately permeable
Reinach silt loam	0 - 32	65	31	1.425	7.25	1.3	moderately permeable
Shellabarger	0 - 9	34	51	1.45	6.45	1.3	moderately permeable
Dougherty loamy fine sand	0 - 7	15	75	1.55	5.8	4	moderately permeable
Dougherty & Eufala	0 - 7	15	75	1.55	5.8	4	moderately permeable
Dougherty & Eufala complex	0 - 7	15	75	1.55	5.8	4	moderately permeable
Eufala fine sand	0 - 8	5	77	1.575	6.2	4	rapidly permeable
Hardeman	0 - 10	30	40	1.45	7.9	4	moderately rapid
Hollister silt loam	0 - 11	75	15	1.45	7.5	.4	slowly permeable
Grant loam	0 - 9	65	31	1.4	6.95	1.3	moderately permeable
Woodward silt loam	0 - 10	65	31	1.45	7.5	1.3	moderately permeable
Konowa loamy fine sand	0 - 7	15	75	1.55	5.8	4	moderately permeable
Lucien Dill fine sandy loam	0 - 7	36	44	1.425	6.45	4	moderately rapid
Noble fine sandy loam	0 - 9	36	58	1.45	6.45	4	moderately permeable
Pond Creek fine sandy loam	0 - 13	36	58	1.45	6.2	4	moderately permeable
Minco very fine sand	0 - 12	65	31	1.475	6.45	1.3	moderately permeable
Port silt loam	0 - 22	65	31	1.425	6.7	1.3	moderately permeable
McLain	0 - 14	80	16	1.45	7	.4	moderately slow

[a] Corresponds to the surface horizon in inches.
[b] Percentage by weight.
[c] Same soil characteristics as Dougherty and Eufala.

The soils series of Dougherty loamy fine sand, Dougherty and Eufala, and Dougherty and Eufala complex are assumed to have the same soil characteristics. Soils V data on each of these soil series were compared and all were similar except for surface horizon depth which differed very little.

Solution Procedure

The optimal allocation of land use permits depends on finding $m_{ir} \subseteq \Omega$ for a given e_i over t periods. Since the regulator is concerned with Q different soils, the problem can be solved by finding $L_i = (\hat{m}_{i1}, \hat{m}_{i2}, \ldots, \hat{m}_{ir})$ for all soils which maximize producer profit and minimizes the producers cost of meeting the emission level. Solving the biophysical model defined in equations 2.0 - 2.18 with no leachate restriction gives a steady state solution for the resulting optimal levels of nitrogen, irrigation water applied, cropping percentages, and the resulting emissions. To find optimal cropping percentages and the implied land use permit, nitrogen and irrigation water application are fixed at the optimal levels and solved with a leachate restriction imposed. The final output is the land use levels required to achieve the level of leachate set by the regulator. The underlying assumption is that producers always apply the optimal levels of inputs for each crop. Note however, this method abstracts from the proof given in the theoretical section because the minimum cost may not be reached with changing output mix but also with input mix contrary to what is assumed above. This method reflects the way in which land use permits would have to be imposed because an administrator, unless omnipotent, would be unable to efficiently monitor input levels. Because leachate levels and optimal input levels will differ by soil, spatial variability is recognized by solving the model for each soil and distinct set of soil parameters.

To find the optimal tax level, the biophysical model was solved over parameterized values of nitrogen prices scaled to reflect the imposition of a tax. Like solutions used to find land use permits, steady state levels are taken to be optimal input choices under each tax level. As with the land use permits, spatial variability is recognized via solutions over the different soils and the corresponding productivity of the inputs.

For insight into the productivity of each soil and the costs associated with emissions abatements, the biophysical model is solved over the leachate bounds of 20 and 10 pounds of nitrogen leachate per acre. When compared to the unrestricted solution, costs of abatement and net return sensitivity to emissions restrictions can be developed. This is an indirect measure of the parameters in the diffusion matrix H.

The biophysical model was coded and solved with GAMS, a FORTRAN based interface for the non-linear optimization routine MINOS (Brooke). The difficulty associated with non-linear intertemporal models is the possibility of convergence to a stationary point that is not a global optimum (Bryson and Ho). With this in mind, great care was taken to develop accurate starting values. Preliminary experiments showed that steady states were found before five iterations if average simulation values of nitrogen, irrigation water, and available nitrogen, which were different for each soil, were used as starting values. Sensitivity analysis showed that steady state values were usually unaffected by the starting values other than the length of time required to achieve a steady state. Scaling did not seem to be a problem. To minimize computational costs, a ten year time period was chosen for this study.

Comparing Policies that Reduce Nitrogen Leachate

Baseline

The model was solved initially with no leachate restrictions to establish a baseline for comparison. The cropping percentages, expected leachate, and expected returns are presented in Table 5. All soil series for which cotton and winter wheat are commonly cropped, except for the Minco series, solve to the upper bounds of 30% in dryland cotton and 70% in winter wheat. This reflects the upper bound imposed on dryland cotton acreage. While seemingly arbitrary, this reflects both cultural concerns as well as common agricultural practices. Minco very fine sand is the only soil series on which grain sorghum after dryland cotton is grown. The .73 cent per bushel price difference between grain sorghum and winter wheat makes grain sorghum less feasible except at higher grain sorghum yields or lower winter wheat yields or some combination. Ten year discounted expected returns range from a low of $296.96 per acre on the Konowa series to a high of $595.67 on the Pulaski series. The low returns on the Konowa series reflect the low native fertility as well as the fact that it is a highly eroded soil (Soil Survey, Caddo County). The range of returns represents the differences in the productivity of the soil series in this study. Expected yields and nitrogen input levels for Baseline solutions are given in Table 6. Nitrogen input levels for dryland cotton are 15 to 20 lbs. of actual nitrogen. Again, the Konowa series has the lowest yield for dryland cotton. On some series such as on Reinach, the biophysical model solves to low nitrogen input levels and it could be inferred that additional nutrient application for dryland is not profitable.

For dryland wheat cropping, steady state yields range from 17 bushels per acre to 35 bushels per acre. On soils on which wheat profitably responds to nitrogen fertilizer, the optimal level of nitrogen fertilizer applied is 35 to 86 lbs of actual nitrogen. For grain sorghum which is cropped only on the Minco series, 33 lbs of nitrogen fertilizer is required for a yield of 35 bushels per acre. This lower level of nitrogen applied to grain sorghum when compared to average nitrogen applied to wheat reflects the fertilizer credits derived from the cotton-grain sorghum rotation.

Steady state levels of expected nitrogen leachate for each of the soil series are given in Table 5. Leachate levels, when compared with levels of nitrogen applied, agree with expectations. Soils which are highly permeable have higher rates of diffusion than less permeable soils. True validation of levels of leachate is difficult, however nitrogen budgets reveal that 60 to 80% of actual nitrogen applied to winter wheat is used by the plant with the remaining percentage either leached or removed by natural processes. Levels of leachate vary with weather and soil characteristics (*Management of Nitrogen in Irrigated Agriculture*; Rauschkolb and Hornsby). For example, on the Lucien series, 44.38 lbs of nitrogen is applied and 15.1 lbs or 34% is leached below the root-zone. The highest leachate is on the Reinach series followed by the Minco series.

Irrigated acres solve to the upper bounds imposed on peanut and cotton rotations. Irrigated acres are cropped in either irrigated cotton or peanuts for all soils except the Dougherty and Eufala complex series which is cropped in irrigated peanuts and dryland cotton.

Table 5. Cropping Percentages, Expected Leachate, and Expected Returns for Base Solutions.

Soil Series	I/I[a]	D/D[b]	D/S[c]	W/W[d]	P/P[e]	P/I[f]	P/D[g]	Expected Leachate[h] lbs / acre	Net Returns[i] $ / acre
Pulaski		.3		.7				19.5	595.67
Cobb Fine sandy loam		.3		.7				20.1	533.75
Cobb Fine sandy loam[j]					.5	.5		6.69	1577.72
Reinach Silt Loam		.3		.7				25.4	494.79
Shellabarger		.3		.7				17.0	421.94
Shellabarger[j]					.5	.5		8.65	1359.42
Dougherty loamy fine sand		.3		.7				14.65	438.28
Dougherty & Eufala		.3		.7				14.65	438.28
Dougherty & Eufala complex[j]					.5		.5	7.9	1644.88
Eufala fine sand		.3		.7				21.20	408.10
Hardeman				1				12.2	314.88
Grant loam		.3		.5				17.9	638.32
Grant loam[j]					.5	.5		6.5	2262.65
Woodward silt loam				1				17.10	235.94
Konowa loamy fine sand		.3		.7				15.70	296.96
Lucien Dill fine sandy loam				1				15.1	223.75
Noble Fine sandy loam		.3		.7				16.3	395.30
Noble Fine sandy loam[j]					.5	.5		9.50	1585.29
Pond Creek fine sandy loam		.3		.7				18.20	555.34
Pond Creek fine sandy loam[j]					.5	.5		15.71	2011.04
Minco very fine sand		.3	.3	.4				25.10	431.13
Port Silt loam		.3		.7				15.3	566.71
Port Silt loam[j]					.5	.5		5.3	1877.46
McLain	.3	.3		.4				6.6	924.00

[a] Continuous irrigated cotton; [b] Continuous dryland cotton; [c] Sorghum after dryland cotton; [d] Continuous wheat;
[e] Peanuts; [f] Irrigated cotton after peanuts; [g] Dryland cotton after Peanuts.
[h] Steady state levels for one acre .
[i] Expected ten year discounted net returns.
[j] Denotes Irrigated Soils.

Table 6. Expected Yields and Levels of Nitrogen Applied by Crop and by Soil for Base Solutions*.

Soil Series	c_1 [a]	c_2 [a]	c_3 [a]	c_4 [a]	c_5 [a]	c_6 [a]	c_7 [a]	n_1 [a]	n_2 [a]	n_3 [a]	n_4 [a]	n_5 [a]	n_6 [a]	n_7 [a]
Pulaski		321		27					20.76		67.17			
Cobb fine sandy loam		258		31					23.36		69.32			
Cobb fine sandy loam [b]					2439	613						28.00	11.74	
Reinach silt loam		213		32					2.32		56.12			
Shellabarger		203		25					8.14		65.08			
Shellabarger [b]					2406	517						0	8.43	
Dougherty loamy fine sand		247		22					20.47		65.71			
Dougherty & Eufala complex [b]					2606		258					24.10		3.82
Dougherty and Eufala		247		22					20.47		65.71			
Eufala fine sand		202		24					10.33		59.54			
Hardeman				29							35.16			
Grant loam		353		32					17.49		64.00			
Grant loam [b]					2693	926						21.00	45.02	
Woodward silt loam				19							57.16			
Konowa loamy fine sand		153		17					7.48		55.59			
Lucien Dill fine sandy loam				22							44.38			
Noble fine sandy loam		209		21					15.65		61.40			
Noble fine sandy loam [b]					2267	767						22.23	2.83	
Pond Creek fine sandy loam		262		32					4.79		57.99			
Pond Creek fine sandy loam [b]					2724	757						26.25	63.28	
Minco very fine sand		244	35	23					21.91	33.16	86.48			
Port silt Loam		262		35					0		62.86			
Port silt Loam [b]					2585	558						17	0	
McLain [b]	567	163		25				58.94	0	0				

* Variables as defined in Table 1.
[a] Steady state levels for one acre .
[b] Denotes Irrigated Soils.

This cropping pattern reflects the amount of water required to maintain profitable cotton yields on this soil series. The average amount of nitrogen applied to peanuts is less than 30 lbs of nitrogen and agrees with the common practice of applying starter nitrogen (Sholar; Brooks).

Net returns are naturally higher for irrigated acreage. This reflects the relative profitability of peanuts and irrigated cotton. Grant loam soils have the highest discounted net returns due in part to the high yields on cotton. Pond creek soils follow with ten year discounted net returns of $2011.04.

On most of the irrigated soils, nitrogen is applied to irrigated cotton with the largest amount of nitrogen applied on the Pond Creek series. Leachate is greater on Pond Creek irrigated soils than on any other irrigated soil. Average levels of irrigation water applied to peanuts were 20 to 30 acre inches per acre of water, while irrigated cotton received an average of 18 to 22 acre inches per acre of water. Leachate is less for most of the irrigated soils than for dryland soils. This is due to the differences in both cropping practices and the timing of rainfall. Since a large percentage of dryland acres are devoted to winter wheat and high levels of nitrogen are applied, higher levels of leachate result from increased rainfall in the period of September to June (National Climactic Data Center). Note that under the baseline solutions no grain sorghum is cropped for any of the soil series.

Peanut and cotton yields are within acceptable ranges although peanuts yields are on average lower than expected with the high input levels. Since differences between the soil series are preserved, no adjustments were made to the yields. This discrepancy should not affect the analysis. Cotton yields are considered representative.

Soil Characteristics and Cost of Abatement

As has been discussed, unique spatial characteristics will determine the cost of controlling emissions. In this study, soil characteristics for each series will determine those soils which require higher levels of nutrients and/or those soils which have the highest probability of leaching. The minimum cost of meeting emission standards would arise where input levels as well as cropping amounts could be controlled to arrive at the chosen emission standard. The difference between net returns from the baseline solutions and this minimum cost solution would give an indication of abatement costs as well as insight into relative soil productivity.

The difference in net returns between base solutions and solutions for a system of land use permits would be larger since inputs are fixed and the optimal levels of land percentages change. This difference does not give as much insight into the relative productivity of each soil and highlights a relative weakness of land use permits. If a policy fails to fully consider the differences in each soil, then the policy cannot be as cost efficient in achieving an emission standard as policies which can fully recognize differences in soils.

Using baseline solutions from the biophysical model and solutions with a maximum leachate levels imposed, cost of abatement for each series has been derived. Table 7 outlines the abatement costs for each soil for leachate levels of 20 and 10 lbs per acre respectively. Abatement costs are estimated as the difference in net returns between the baseline solutions and solutions with an emission standard imposed. Note that solutions with emission standards imposed are achieved by changing both input and output levels. Since leachate for most soils does not greatly exceed 20 pounds per acre, abatement cost is less than ten dollars per acre. However, the costs of abatement increase greatly if the emission level is set at 10 lbs per acre.

Table 7. Cost of Abatement and Tax Levels Required to Achieve 20 and 10 Pounds of Nitrogen Leachate Per Acre by Soil Series.

Soil Series	CA 20 lbs	CA 10 lbs	Tax for 20 lbs	Tax for 10 lbs
Pulaski	0	17.35	0	400%
Cobb fine sandy loam	0	30.73	0	700%
Cobb fine sandy loam[b]	0	0	0	0
Reinach silt loam	9.46	46.91	300%	500%
Shellabarger	0	13.59	0	400%
Shellabarger[b]	0	0	0	0
Dougherty loamy fine sand	0	5.43	0	200%
Dougherty & Eufala	0	5.43	0	200%
Dougherty & Eufala complex[b]	0	0	0	0
Eufala fine sand	3.33	21.09	50%	400%
Hardeman	0	5.436	0	25%
Grant loam	0	18.57	0	400%
Grant loam[b]	0	0	0	0
Woodward silt loam	0	21.88	0	400%
Konowa loamy fine sand	0	7.88	0	300%
Lucien Dill fine sandy loam	0	117.40	0	150%
Noble fine sandy loam	0	7.08	0	300%
Noble fine sandy loam[b]	0	0	0	0
Pond Creek fine sandy loam	0	23.38	0	550%
Pond Creek fine sandy loam[b]	0	185.22	0	700%
Minco very fine sand	8.64	75.97	300%	700%
Port silt loam	0	20.49	0	400%
Port silt loam[b]	0	0	0	0
McLain	0	0	0	0

[a] Cost of abatement estimated as difference between base solution expected net returns and solution with emission level imposed.

[b] Denotes irrigated acres.

Lucien and irrigated Pond Creek series have costs which exceed $100.00 per acre and reflect the relative importance of nutrients in maintaining yields as well as the leachability of the soil. The Minco series also has high abatement costs. Note that Reinach, which has the highest level of leachate, does not have as large abatement costs as some of the other soils. This implies that the marginal productivity of nutrients is not as great for Reinach as for the Lucien or Pond Creek series. Comparatively, however, costs of abatement are still large. The lowest abatement costs are for the Hardeman and Dougherty series with a $5.43 difference between unrestricted expected net returns and returns with the emission level imposed.

Finally, these abatement cost are implicitly the lower bound on the per acre ten year cost of achieving a given emission level. These estimates could be used as a measure of total investment needed to induce agents who produce on the specific soil series to follow nitrogen and input recommendations or as a baseline in a cost benefit analysis of different policies aimed at reducing leachate.

Spatially Differentiated Tax Levels

Like the abatement costs estimated above, tax levels required to achieve emission levels are also representative of the relative productivity of each soil. The method described in the procedures section was used to derive input tax levels required to achieve 20 and 10 lbs of leachate per acre for each of the soil series and are listed in Table 7. The relative tax levels between the 20 and 10 pound leachate levels reflects the same relationships found between the abatement costs for higher and lower emission standards. Moving from 20 to 10 lbs of leachate requires higher input tax levels. Relatively, soils for which nutrient marginal productivity is high require higher tax levels at both the 20 and 10 lbs levels.

The tax levels required to achieve the leachate levels are high. The 400, 500, and 700% levels required to achieve a 10 pound emissions level are obviously a reflection of nutrient productivity and price inelasticity of nitrogen. However, these levels are comparable to levels found in other studies. Pan and Hodge needed a tax of 790% to reduce nitrate leachate by 50%. These estimates closely match the reduction implied under the 10 pound emission level. Similarly, Johnson, Adams and Perry found that a 100% tax on nitrogen fertilizer was needed for a 33% decrease in leachate. These estimates will vary depending on the production response for each soil.

The differences in tax rates for the different soil series obviates the inherent problem of a blanket ad valorem tax on nitrogen fertilizer and the need for a spatially differentiated tax. The impositions of a fixed nitrogen tax could not be effective or efficient since no one single tax rate could achieve an emissions standard.

For example, if a regulator chooses to impose a single tax rate, the question of what tax level to impose arises. If the most prevalent soil in the administrative region is targeted, such as the Pond Creek series in this case, agents producing on other soil series would be over taxed since Pond Creek requires the highest tax level to achieve the standard. Or, if the most common tax rate is chosen, 400%, then emission standards would not be met on all the soils.

Land Use Permits

Using the method described in the procedure section, optimal land use required to meet an emission standard of 10 pounds of nitrate leachate per acre was found. Looking at the cropping percentages presented in Table 8, the land use imposed by land use permits shows that on dryland acres the optimal mix requires decreased cropping of winter wheat and a change from continuous dryland cotton to dryland cotton and grain sorghum rotation. For those soils in which dryland cotton was grown, winter wheat is decreased from the upper bound of 70% of land to less than 50% of an acre and on most soils total wheat acreage is less than 25%. The spatial variability is reflected in the percentages of winter wheat cropped for each soil. Note that for the soils which have the most leachate, winter wheat acreage is scaled back considerably. For example, wheat acreage on the Reinach series declines from 70% to less than 10% under land use permits. Implicitly, land retirement is required on some of the soil series since total percentages do not sum to one. On those acreages for which winter wheat was the only crop, less than 60% of the land is used.

On the irrigated soils, the only soil impacted is the Pond Creek series. The cropping change implied by the land use permit is a decrease in irrigated cotton and an increase in dryland cotton reflecting the increased potential for nitrate leachate under irrigation. Cropping does not change for the other irrigated soils since nitrate leaching was not a problem on these soils.

Corresponding to the land use and resulting land retirement, the net returns are decreased under the land use permits. Percentage changes in net returns from base line solutions are given in Table 8. On some soils, net returns are diminished by as much as 75% below baseline solutions as on the Lucien series. Decreases in net returns average 15 percent below baseline. It is obvious that decreases in net returns would be much greater if the differences between soil productivity were not recognized under the permit system. Similar to the uniform tax level, requiring all soils to decrease winter wheat acreage by 62% as with the Reinach series would be extremely costly and inefficient.

Table 8. Land Use Required for 10 lb. Per Acre of Nitrogen Leachate.

Soil Series	I/I[a]	D/D[b]	D/S[c]	W/W[d]	P/P[e]	P/I[f]	P/D[g]	Expected Leachate[h] lbs / acre	Net Returns[i] $ / acre	Net Returns % Change from Base Solutions
Pulaski		.3	.3	.11				10.0	464.86	-21.9
Cobb Fine sandy loam		.3	.3	.23				10.0	451.24	-15
Cobb Fine sandy loam[j]					.5	.5		6.69	1577.72	0
Reinach silt loam		.3	.3	.08				10.0	317.40	-35
Shellabarger		.3	.3	.26				10.0	350.29	-16
Shellabarger[j]					.5	.5		8.6	1359.42	0
Dougherty loamy fine sand		.3	.3	.21				9.98	399.85	-8
Dougherty and Eufala		.3	.3	.21				9.98	399.85	-8
Dougherty & Eufala complex[j]					.5	.5		7.9	1644.88	-22
Eufala fine sand		.3	.3	.24				10.0	317.61	-36.5
Hardeman				.78				10.0	199.94	-15
Grant loam		.3	.3	.23				10.0	536.69	0
Grant loam[j]					.5	.5		6.5	2262.95	0
Woodward silt loam				.55				10.0	128.48	-45
Konowa loamy fine sand		.3	.3	.36				10.0	275.44	-7
Lucien Dill fine sandy loam				.59				8.7	54.3	-75
Noble Fine sandy loam		.3	.3	.33				10.0	368.34	-6
Noble Fine sandy loam[j]					.5	.5		9.5	1585.29	-0
Pond Creek fine sandy loam		.3	.3	.27				10.0	478.32	-13
Pond Creek fine sandy loam[j]					.5	.11	.39	10.0	1762.53	-12
Minco very fine sand		.3	.3	.05				10.0	341.76	-20
Port Silt Loam		.3	.3	.38				10.0	482.70	-14
Port Silt Loam[j]					.5	.5		5.3	1816.15	-3
McLain[j]	.3	.3		.4				6.6	924.90	0

[a] Continuous irrigated cotton; [b] Continuous dryland cotton; [c] Sorghum after dryland cotton; [d] Continuous wheat;
[e] Peanuts; [f] Irrigated cotton after peanuts; [g] Dryland cotton after peanuts.
[h] Steady state levels for one acre .
[i] Expected ten year discounted net returns.
[j] Denotes Irrigated Soils.

The cropping percentages point to the inherent weakness in command and control approaches to controlling emissions. Because the only control a regulator exerts in this case with land use permits is essentially what is cropped, inefficiency results. While theoretically it is possible for an omnipotent regulator to choose both input levels as well as cropping choices as was shown in the theoretical section, this is not a practical solution to controlling emissions. For areas in which significant leachate problems exist, these results may point to some combination of policies to control emissions such as a uniform restriction on nitrogen application imposed in conjunction with a system of land use permits.

Sub -Watershed Analysis

The importance of recognizing the unique spatial characteristics in formulating environmental policy is clear. Using the analysis above, the impacts of each of these two policies can be compared for their efficiency at controlling emissions on the sub-watershed scale. Table 9 presents the differences between the two policies and compares them to a uniform tax imposed on all soils.

A comparison of total returns for each of the soil series shows that the spatially differentiated tax is much more efficient than the system of land use permits. While both policies meet the emission standard, the total returns for the differentiated tax policy, except for a few cases, are much higher than the system of land use permits. Grant loam is the only series for which land permits produce a greater net return than the differentiated tax system. For some series, such as Hardeman, the difference is as great as 46%. For the Pond Creek series, which is the most prevalent soil series in the study area, the difference in the dryland returns is 5.5% while the irrigated cropping returns difference is

7.7%. These relative differences hold when compared to the base solutions with the differentiated tax polices being the most efficient. When total returns over all the soil series are compared, differentiated taxes decrease total net returns by 6.75% from the baseline while the system of land use permits decreases total net returns by 12%.While both policies are set to meet the emission standard of 10 lbs. of nitrate leachate per acre, there is a difference in the total level of leachate. Total levels of leachate are greater under the system of land use permits than that under the system of differentiated taxes. However, the percentage difference is less than 3% with both decreasing total leachate by more than 40% below base line levels.

For comparison , Table 9 also lists the impacts the imposition of a uniform tax on each of the soil series. A tax level of 400% was chosen since this was the level required most frequently to achieve the 10 pound emission standard (Table 7). When compared to the other two policies the inefficiency of this policy is obvious. Note that on the soils for which higher tax levels are required, the producer is penalized and the emission standard is not met for that soil. For example, under the uniform tax the dryland Pond series returns are decreased by 7% but since a tax level of 550% is needed to achieve the emission standard the level of leachate will exceed the standard. Since Pond Creek is the most prevalent series, total leachate is greatly increased. Total leachate under the uniform tax is 33% below the baseline but since it is 14% greater than total leachate under the system of land use permits emission standards are obviously not met.

Table 9. Cobb-Fast Runner Sub-Watershed Net Returns Under Land Use Permits, Differentiated Taxes, Uniform Standard, and Base Solution Policies.

Soil Series	Land Use[a] Permits	Differentiated[a] Taxes	Uniform[a] Tax	Base[a] Solution
Pulaski	592.82	683.60	686.60	759.63
Cobb fine sandy loam	3202.88	3227.72	3503.75	3788.53
Cobb fine sandy loam[b]	561.49	561.51	545.69	561.49
Reinach silt loam	244.74	333.66	339.42	381.53
Shellabarger	58.87	62.82	62.82	70.91
Shellabarger[b]	1209.50	1209.50	1235.15	1209.50
Dougherty loamy fine sand	1932.92	2035.21	1949.69	2118.70
Dougherty & Eufala	830.09	874.02	837.29	909.87
Dougherty & Eufala complex[b]	2439.12	2439.12	2439.12	2439.12
Eufala fine sand	536.91	593.20	593.19	689.88
Gracemont	113.03	124.88	124.88	145.24
Hardeman	494.14	726.35	614.44	778.20
Grant Loam	3703.29	4021.25	4021.44	4404.56
Grant Loam[b]	9328.66	9325.78	9040.26	9327.43
Woodward silt loam	19.05	27.05	27.05	34.99
Konowa loamy fine sand	277.74	270.00	259.42	299.44
Lucien Dill fine sandy loam	39.72	120.49	118.35	163.68
Noble fine sandy loam	455.16	447.22	433.624	488.48
Noble fine sandy loam[b]	908.96	908.96	911.25	908.96
Pond Creek fine sandy loam	63395.51	67134.40	68201.33	73603.58
Pond Creek fine sandy loam[b]	42183.21	45743.30	47755.00	48130.89
Minco very fine sand	43.92	47.31	50.51	55.41
Port silt loam	1374.29	1468.24	1468.24	1613.47
Port silt loam[b]	2118.57	2190.09	1967.29	2190.09
McLain[b]	411.45	411.05	269.83	411.05
Total Returns	136476.04	144986.73	147152.55	155484.59
% Decrease from Base Returns	12.2%	6.75%	5.3%	0
Total Leachate[c]	1964.13	1872.89	2296.58	3435.34
% Change from Base Leachate	-.428	-.454	-.331	0

[a] Expected ten year discounted net returns in 1000's of dollars.
[b] Denotes irrigated soils.
[c] Units are 1000's of pounds of nitrate leachate.

Costs and Transfers

For the two policies considered, there are considerable differences in total costs. Wealth transfers from producers occur from both the diminished value of production and diminished land values. An upper bound on the decrease in land values is the difference between net returns under the land use permits and the baseline polices. Differences in net returns are high (Table 8). Under the system of land use permits, land values are likely to be lower than those under a spatially differentiated tax because producers can still make production choices in favor of crops which require less nitrogen while the same cannot be said for the land use permits. Further, the tax system produces revenues which further lowers the net social costs of implementing a tax. Ten year discounted revenues collected from the tax on nitrate would equate to $12,166,895. Assuming that all tax revenues are returned to the producer, it is estimated that the net difference in the spatially differentiated tax system is only 5.9% which enforces the case for using a spatially differentiated tax.

Conclusions and Policy Implications

The main purpose of this research has been to investigate the impacts of considering spatial characteristics in the formation of policies which abate agricultural non-point source pollution. The initial theoretical examination seeks to develop an understanding that the spatial nature of agriculture must be incorporated into policies. The inefficiency of uniform input taxes and infeasibility of marketable emission permits are explained. Spatially sensitive policies of land use permits and spatially differentiated taxes are examined. The existence of an allocation of land use permits which results in a cost minimizing emissions level is proved. If the relative weaknesses of the land use permit systems are considered, the permit system suffers from the same criticisms as those extended to most command and control approaches and the ability to control emissions depends on the spatial variation. Spatially differentiated input taxes do not have these weaknesses and maintain the appeal of market oriented policies.

Because the comparative efficiency of these policies becomes an empirical question, an analytical framework is developed to examine the importance of considering spatial differences and the relative efficiency of these two policies in controlling nitrate leachate for a sub-watershed in Western Oklahoma. Control of leachate from the application of fertilizers is an important and often studied problem. The framework is comprised of a geographic information system and a biophysical model. The biophysical model accounts for differences in cropping rotations and nutrient carryover. Because leachate is dependent on stochastic rainfall patterns, the biophysical model incorporates rainfall using a gaussian-quadrature approach. Arc-View GIS is used to identify soils, acreage, and land use for the Cobb-Fastrunner sub-watershed and the biophysical model is used to identify optimal cropping and nutrient application for each soil. Parameters for the bio-physical model are obtained using site specific soil parameters input into EPIC-5300, a biophysical simulation program.

This framework is adapted to compare and contrast the efficiency of both a system of land use permits and spatially differentiated nitrogen input taxes for each soil and the whole sub-watershed. The analysis makes clear the importance of recognizing differences in soils. A baseline is established by solving the model without an emissions goal and deviations of net returns from this baseline under the polices aimed at achieving a emissions level are used to estimate costs of abating nitrate leachate.

Relative leachability and soil productivity determine the cost of abatement The costs of achieving 10 pounds of nitrate per acre were as high as $117 and as low as $5.00. Similarly, the levels of input taxes required to achieve the desired emissions level reflect the spatial variability of the soils. Failure to consider these differences could result in inefficient policies and this is examined in the whole sub-watershed analysis.

Under the system of land use permits, weaknesses of command and control approaches are borne out. The difficulty in controlling both input levels and cropping choices is clear. When compared to the system of spatially differentiated taxes, the theoretical appeal of market oriented approaches holds. For the Cobb-Fastrunner sub-watershed, a 10 pound emissions target under spatially differentiated taxes decreased net returns from the baseline by only 6% while land use permits decreased total net returns by more than 12%. Thus, one of the major conclusions of this study is that market oriented approaches are likely to be more efficient than command and control approaches. Further, a market oriented approach which considers spatial characteristics is superior. A uniform tax fails to recognize differences in soils and soil productivities is not effective at achieving the emissions standard efficiently.

An additional difference between the system of land use permits and spatially differentiated taxes is that no additional revenue is created. Input taxes can create additional revenue which lowers the net social cost of the polices and increases the difference in net costs of the two policies. These revenues could be used to defray both administration of the policy as well as the cost to the producers in terms of net revenue and diminished land values.

Policy Implications

Extrapolation of the results obtained from the analysis on the Cobb-Fastrunner sub-watershed shows that policy makers interested in developing efficient policies must take spatial characteristics of agricultural production into account. Total returns were decreased by more under the command and control approach of land use permits than under the spatiality differentiated tax on nitrogen. However, total net returns would be less if individual productivity and leachability of the soils were not considered. Similarly, the spatially differentiated tax is much more efficient than a uniform standard because it accounts for spatial differences. These results suggest that federal agencies seeking new and innovative approaches to controlling non-point pollution in agriculture should consider policies such as the spatially differentiated tax.

Finally, while every effort was made to develop correct soil parameters and accurate simulation data for this analysis, the author makes no policy recommendations for the Cobb-Fastrunner sub-watershed. Additional validation of yields and nitrate leachate should be conducted to establish accuracy. Also, the biophysical model should be expanded to reflect more cropping choices since producers may abandon common cultural practices with the new cropping flexibility established by 1996 Farm Bill legislation. While these implications would not change the conclusions of the above analysis, they do represent future directions for this research.

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APPENDIX

Example Optimization Program Coded in Gams

```
************************************************************************
*Optimal Control Progam with Stochastic Rainfall Using Gaussian Points *
************************************************************************

$OFFSYMLIST OFFSYMXREF

Sets
     T time periods /0*10/
     J Gauss points /1*5/
     O leach levels /1*4/
     Q ntax level   /1*6/

     I Crops
       / c1    ict_ict
         c2    dct_dct
         c3    dct_srg
         c4    wht_wht
         c5    pnt_pnt
         c6    pnt_ict
         c7    pnt_dct
         c8    pnt_srg
                      /
     N Yield
      /  b1    intercep
         b2    precip
         b3    irga
         b4    fl
         b5    pr2
         b6    i2
         b7    irpr
         b8    flpr
         b9    flir
         b10   fl2 /

     L Leachate
     /   l1    precip
         l2    irga
         l3    no3 avail
         l4    yield   /
```

```
A available nitrogen
/   a1   intercept
    a2   precip
    a3   fno3
    a4   nitrogen minearalized
    a5   no3 carry
    a6   nitrogen fixed
    a7   intercept        /

M  nitrogen mineralized
/   m1   fno3
    m2   prcp
    m3   irga           /;

Table yld(I,N)  Yield Response Parameters

          b1          b2          b3          b4          b5
   c1  251.9326    -8.6759      0.0000     -0.6378      0.3143
   c2   50.7568     3.6780      0.0000      1.2394      0.1575
   c3   31.2146    -0.1235      0.0000      0.2353      0.0011
   c4   24.8001    -0.1235      0.0000      0.2353      0.0011
   c5  239.2635    32.2467     51.9649     27.1320     -0.0011
   c6  248.3606     8.1517    -18.5868     46.7750     -0.1348
   c7  -14.4339    13.6044      0.0000      0.5588     -0.0592
   c8   31.2146    -0.1235      0.0000      0.2353      0.0011

   +      b6          b7          b8          b9          b10
   c1  0.0000      0.0000      0.0058      0.0000      0.0014
   c2  0.0000      0.0000     -0.0803      0.0000      0.0010
   c3  0.0000      0.0000      0.0028      0.0000     -0.0018
   c4  0.0000      0.0000      0.0028      0.0000     -0.0018
   c5 -0.5135     -0.3315     -0.9544     -0.2598     -0.0553
   c6  0.3144     -0.0033     -0.2029      0.2547     -0.9997
   c7  0.0000      0.0000     -0.1431      0.0000      0.0143
   c8  0.0000      0.0000      0.0028      0.0000     -0.0018

 Table lch(I,L)  Leachate Response Parameters

            l1          l2          l3          l4
   c1  1.2497     -0.6023      0.1018      0.00
   c2 -0.1684      0.0000      0.3798      0.00
   c3  0.4902      0.0000      0.1083      0.00
   c4 -0.1365      0.0000      0.1856      0.00
   c5  0.1723      1.0177      0.0324      0.00
   c6  0.1729      0.0521      0.2358      0.00
   c7  0.2437      0.0000      0.0292      0.00
   c8  0.2053      0.0000      0.0195      0.00
                                                ;
```

```
Table an(I,A)  Available Nitrogen Response Parameters

          a1           a2           a3           a4           a5
 c1 -3.3671       0.0000       0.8845       1.7242       0.5659
 c2 -2.2572       0.0000       0.6996       1.3834       0.5121
 c3 -1.5959       0.0000       0.5162       0.8857       0.4203
 c4 -0.5783       0.0000       0.9152       0.1590       0.2518
 c5 -0.5410      -0.3467       0.0000       0.5772      -0.2465
 c6  0.0253      -0.0824       0.0879       0.2555      -0.3922
 c7 -0.1086       0.0000       1.1940       0.1845      -0.3625
 c8 -0.3086       0.0000       0.1282       0.7054      -0.7915

+      a6           a7
 c1  0.0000       0.0000
 c2  0.0000       0.0000
 c3  0.0000       0.0000
 c4  0.0000       0.0000
 c5  0.0188       0.0000
 c6  0.0000       0.0000
 c7  0.0000       0.0000
 c8  0.0000       0.0000
                                         ;

Table mn(I,M)  mineralized nitrogen response parameters

          m1           m2           m3
 c1  0.1399       1.8235       0.0000
 c2  0.4183       1.7325       0.0000
 c3  0.1726       1.9098       0.0000
 c4  0.8761       1.8137       0.0000
 c5  0.6415       1.3457       0.6453
 c6  0.0209       0.8444       0.9254
 c7  0.4323       1.7072       0.0000
 c8  0.5292       1.4867       0.0000
                                         ;

Parameters
********************************************
*          n03 fixed                       *
********************************************

nfix(i) / c1    0.000
          c2    0.000
          c3    0.000
          c4    0.000
          c5   94.654
          c6    0.000
          c7    0.000
          c8    0.000
                       /
```

```
r(j)
         /1 3.1953
          2 11.012
          3 21.512
          4 32.093
          5 40.166 /

p(j)    /1  .064855
         2  .263788
         3  .351760
         4  .239989
         5  .064855 /

************************************************************************
*                             net returns                              *
************************************************************************

nr(i)  / c1 .3363
         c2 .4436
         c3 1.15
         c4 1.880
         c5 .1722
         c6 .3363
         c7 .4436
         c8 1.15
                   /

rd(I) /
         c1  1
         c2  1
         c3  1
         c4  1
         c5  1
         c6  1
         c7  1
         c8  1
                   /

pnt(Q) /
         1 .1625
         2 .195
         3 .2275
         4 .26
         5 .39
         6 .52
                  /

ml(O) /
          1 1000
          2 50
          3 20
          4 10
                /;
```

```
**************************************************************************
*                      miscellaneous parameters                          *
**************************************************************************

parameter mtm sum total leachate;
mtm= (1000000);

scalar delta discount rate  /.05/;
scalar disc discount;
disc = 1/(1+delta);
parameter rho(T) discount factor;
rho(T)= Disc**(ORD(T));

parameter pn price of nitrogen per actual lb of no3;
pn=.13;

parameter pw price of water per acre inch;
pw=3.20;

parameter totlech(O);
totlech(O)=1;


**************************************************************************
*                             variables                                  *
**************************************************************************
variables

         n3(I,T)     nitrogen fertilizer applied to the i'th crop
         G(I,T)      land fraction for the ith crop
         w(I,T)      irrigaton water applied to the i'th crop
         netret      net revenue
         lc(I,T)     leachate variable
         lc2(I,T)    2cd leachate varaible
         tyLd(I,T)   yield variable
         rzn(I,T)    root zone nitrogen
         min(I,T)    nitrogen minearlized
         mmm         rhs on the leach constraint;
positive variables n3,G,w,rzn,min;

**************************************************************************
*                             equations                                  *
**************************************************************************

equations

netrev1            net revenue for lechate restriction
crryc1(T)         carryover equation for available nitrogen
crryc2(T)         carryover equation for available nitrogen
crryc3(T)         carryover equation for available nitrogen
crryc4(T)         carryover equation for available nitrogen
crryc5(T)         carryover equation for available nitrogen
crryc6(T)         carryover equation for available nitrogen
crryc7(T)         carryover equation for available nitrogen
crryc8(T)         carryover equation for available nitrogen
```

```
leach(I,T)          leachate equation
leach2(I,T)         second leachate equation
minliz(I,T)         nitrogen minearlized
yield(I,T)          yield response function
landrestc1(T)       land restriction
landrestc4(T)       land restriction
landrestc3(T)       land restriction
landrestc2(T)       land restriction
mleach1(T)          sumtotal leach
totland(T)          total land percent less than 1

netrev1.. sum(T  $(ORD(T) GT 1),(rho(T)*
(
sum(I,rd(I)*(nr(I)*sum(J,
(
p(j)*(yld(I,'b1')
+yld(I,'b2')*r(j)
+w(I,T)*yld(I,'b3')+
(rzn(I,T))*yld(I,'b4')+
(yld(I,'b5')*r(j)**2)+
(yld(I,'b6')*w(I,T)**2)+
yld(I,'b7')*r(j)*w(I,T)+
yld(I,'b8')*(rzn(I,T))*r(j)+
yld(I,'b9')*(rzn(I,T))*w(I,T)+
(rzn(I,T)**2)*yld(I,'b10')
)
))-w(I,T)*pw-n3(I,T)*pn)*G(I,T)))))=E=netret;

yield(I,T)..rd(I)*sum(J,p(j)*
(((
yld(I,'b1')+
yld(I,'b2')*(r(j))+
yld(I,'b3')*w(I,T)+
yld(I,'b4')*((rzn(I,T)))+
yld(I,'b5')*((r(j))*(r(j)))+
yld(I,'b6')*(w(I,T)**2)+
yld(I,'b7')*(r(j))*w(I,T)+
yld(I,'b8')*((rzn(I,T))*(r(j)))+
yld(I,'b9')*((rzn(I,T))*w(I,T))+
yld(I,'b10')*((rzn(I,T))*(rzn(I,T)))
))))=E=tyld(I,T);

crryc1(T+1)..sum(J,p(j)*(
r(J)*an('c1','a1')+w('c1',T+1)*an('c1','a2')
+n3('c1',T+1)*an('c1','a3')+min('c1',T+1)*an('c1','a4')
+((G('c1',T+1)/(G('c1',T)+G('c6',T)))*rzn('c1',T)
+(G('c6',T+1)/(G('c1',T)+G('c6',T)))*rzn('c6',T))*an('c1','a5')
))=E=rzn('c1',T+1);
```

```
crryc2(T+1)..sum(J,p(j)*(
r(J)*an('c2','a1')+w('c2',T+1)*an('c2','a2')
+n3('c2',T+1)*an('c2','a3')+min('c2',T+1)*an('c2','a4')
+((G('c2',T+1)/(G('c2',T)+G('c7',T)))*rzn('c2',T)
+(G('c7',T+1)/(G('c2',T)+G('c7',T)))*rzn('c7',T))*an('c2','a5')
))=E=rzn('c2',T+1);

crryc3(T+1)..sum(J,p(j)*(
r(J)*an('c3','a1')+w('c3',T+1)*an('c3','a2')
+n3('c3',T+1)*an('c3','a3')+min('c3',T+1)*an('c3','a4')
+(G('c2',T+1)/(G('c3',T)+G('c2',T)))*
(rzn('c2',T))*an('c3','a5')
+(G('c3',T+1)/(G('c3',T)+G('c2',T)))*
(rzn('c2',T))*an('c3','a5')
))=E=rzn('c3',T+1);

crryc4(T+1)..sum(J,p(j)*(
r(J)*an('c4','a1')+w('c4',T+1)*an('c4','a2')
+n3('c4',T+1)*an('c4','a3')+min('c4',T+1)*an('c4','a4')
+(G('c4',T+1)/(G('c4',T)+G('c8',T)))*
((rzn('c4',T)))*an('c4','a5')
))=E=rzn('c4',T+1);

crryc5(T+1)..sum(J,p(j)*(
r(J)*an('c5','a1')+w('c5',T+1)*an('c5','a2')
+n3('c5',T+1)*an('c5','a3')+min('c5',T+1)*an('c5','a4')
+nfix('c5')*an('c5','a6')))
=E=rzn('c5',T+1);

crryc6(T+1)..sum(J,p(j)*(
r(J)*an('c6','a1')+w('c6',T+1)*an('c6','a2')
+n3('c6',T+1)*an('c6','a3')+min('c6',T+1)*an('c6','a4')
+((G('c6',T+1)/(G('c5',T)))*rzn('c5',T))*an('c6','a5')
))=E=rzn('c6',T+1);

crryc7(T+1)..sum(J,p(j)*(
r(J)*an('c7','a1')+w('c7',T+1)*an('c7','a2')
+n3('c7',T+1)*an('c7','a3')+min('c7',T+1)*an('c7','a4')
+((G('c7',T+1)/(G('c5',T)))*rzn('c5',T))*an('c7','a5')
))=E=rzn('c7',T+1);

crryc8(T+1)..sum(J,p(j)*(
r(J)*an('c8','a1')+w('c8',T+1)*an('c8','a2')
+n3('c8',T+1)*an('c8','a3')+min('c8',T+1)*an('c8','a4')
+((G('c8',T+1)/(G('c5',T)))*rzn('c5',T))*an('c8','a5')
))=E=rzn('c8',T+1);

minliz(I,T)..
min(I,T)=E=(sum(J,p(j)*(r(J)*mn(I,'m2')+
n3(I,T)*mn(I,'m1')+w(I,T)*mn(I,'m3'))));

leach(I,T)..
lc(I,T)=E=((sum(J,p(j)*(r(J)*lch(I,'l1')
+(rzn(I,T)+n3(I,T)+min(I,T)+nfix(I))*lch(I,'l3')+
tyld(I,T)*lch(I,'l4')+w(I,T)*lch(I,'l2')))));
```

```
leach2(I,T)..
lc2(I,T)=E=((sum(J,p(j)*((r(J)*lch(I,'l1')
+(rzn(I,T)+n3(I,T)+min(I,T)+nfix(I))*lch(I,'l3')+
tyld(I,T)*lch(I,'l4')+w(I,T)*lch(I,'l2')))))*G(I,T));

************************************************************************
*                              restrictions                            *
************************************************************************

mleach1(T)..
sum(I,lc(I,T)*G(I,T)) =L= mmm;

landrestc2(T+1).. G('c2',T+1) =L=G('c2',T)+G('c7',T);

landrestc1(T+1).. G('c1',T+1) =L=G('c1',T)+G('c6',T);

landrestc4(T+1).. G('c4',T+1) =L= G('c4',T);

landrestc3(T+1).. G('c3',T+1)=L=G('c2',T)+G('c7',T);

totland(T).. sum(I,G(I,T)) =L= 1;

************************************************************************
*                            lower land limits                         *
************************************************************************
G.LO('C1',T) = .0001;
G.LO('C2',T) = .0001;
G.LO('C3',T) = .0001;
G.LO('C4',T) = .0001;
G.LO('C5',T) = .0001;
G.LO('C6',T) = .0001;
G.LO('C7',T) = .0001;
G.LO('C8',T) = .0001;

************************************************************************
*                           initial conditions                         *
************************************************************************
G.l('C1','1') = .0001;
G.l('C2','1') = .002;
G.l('C3','1') = .002;
G.l('C4','1') = .01;
G.l('C5','1') = .5;
G.l('C6','1') = .01;
G.l('C7','1') = .2;
G.l('C8','1') = .2;

n3.l('C1','1') = 0;
n3.l('C2','1') = 0;
n3.l('C3','1') = 0;
n3.l('C4','1') = 0;
n3.l('C5','1') = 0;
n3.l('C6','1') = 0;
n3.l('C7','1') = 0;
n3.l('C8','1') = 0;
```

```
w.l('c1','1') = 0;
w.l('c2','1') = 0;
w.l('c3','1') = 0;
w.l('c4','1') = 0;
w.l('c5','1') = 0;
w.l('c6','1') = 0;
w.l('c7','1') = 0;
w.l('c8','1') = 0;

rzn.l('c1','1') = 66.219 ;
rzn.l('c2','1') = 66.967 ;
rzn.l('c3','1') = 60.848 ;
rzn.l('c4','1') = 52.523 ;
rzn.l('c5','1') = 92.017 ;
rzn.l('c6','1') = 78.235 ;
rzn.l('c7','1') = 30.392 ;
rzn.l('c8','1') = 48.090 ;

min.l('c1','1') =121.743 ;
min.l('c2','1') = 61.708 ;
min.l('c3','1') = 75.303 ;
min.l('c4','1') = 53.133 ;
min.l('c5','1') = 14.487 ;
min.l('c6','1') =  8.389 ;
min.l('c7','1') = 36.863 ;
min.l('c8','1') = 29.382 ;

tyld.l('c1','1') = 239.023;
tyld.l('c2','1') = 238.471;
tyld.l('c3','1') =  21.823;
tyld.l('c4','1') =  36.463;
tyld.l('c5','1') = 795.456;
tyld.l('c6','1') = 437.985;
tyld.l('c7','1') = 216.644;
tyld.l('c8','1') =  19.797;

G.UP('C1',T) $(ORD (T) GT 1)=.0001;
G.UP('C2',T) $(ORD (T) GT 1)=.3;
G.UP('C3',T) $(ORD (T) GT 1)=1;
G.UP('C4',T) $(ORD (T) GT 1)=1;
g.UP('C5',T) $(ORD (T) GT 1)=.0001;
G.UP('C6',T) $(ORD (T) GT 1)=.0001;
G.UP('C7',T) $(ORD (T) GT 1)=.0001;
G.UP('C8',T) $(ORD (T) GT 1)=.0001;

n3.UP('C1',T) $(ORD (T) GT 1)= 200;
n3.UP('C2',T) $(ORD (T) GT 1)= 200;
n3.UP('C3',T) $(ORD (T) GT 1)= 200;
n3.UP('C4',T) $(ORD (T) GT 1)= 200;
n3.UP('C5',T) $(ORD (T) GT 1)= 30;
n3.UP('C6',T) $(ORD (T) GT 1)= 200;
n3.UP('C7',T) $(ORD (T) GT 1)= 200;
n3.UP('C8',T) $(ORD (T) GT 1)= 200;
```

```
w.up('C1',T) $(ORD (T) GT 1)= 20;
w.UP('C2',T) $(ORD (T) GT 1)= 0;
w.UP('C3',T) $(ORD (T) GT 1)= 0;
w.UP('C4',T) $(ORD (T) GT 1)= 0;
w.UP('C5',T) $(ORD (T) GT 1)= 40;
w.UP('C6',T) $(ORD (T) GT 1)= 30;
w.UP('C7',T) $(ORD (T) GT 1)= 0;
w.UP('c8',T) $(ORD (T) GT 1)= 0;

rzn.UP('C1',T) $(ORD (T) GT 1)= 86.219 ;
rzn.UP('C2',T) $(ORD (T) GT 1)= 86.967 ;
rzn.UP('C3',T) $(ORD (T) GT 1)=160.848 ;
rzn.UP('C4',T) $(ORD (T) GT 1)=520.523 ;
rzn.UP('C5',T) $(ORD (T) GT 1)=292.017 ;
rzn.UP('C6',T) $(ORD (T) GT 1)= 98.235 ;
rzn.UP('C7',T) $(ORD (T) GT 1)= 80.392 ;
rzn.UP('C8',T) $(ORD (T) GT 1)=148.090 ;

**************************************************************************
*                              model statements                          *
**************************************************************************

model farml /all/;

option iterlim=20000;
option limrow=0;
option limcol=0;
option reslim=5000;

file a1 /lNR.out/;
file a2 /lC1.out/;
file a3 /lC2.out/;
file a4 /lC3.out/;
file a5 /lC4.out/;
file a6 /lC5.out/;
file a7 /lC6.out/;
file a8 /lC7.out/;
file a9 /lC8.out/;

*loop(Q,
*pn.fx = pnt(Q);
*solve farml using nlp maximizing netret;
*totlech('1')=sum(T $(ord (T) GT 1), sum(I,lc.l(I,T)*G.l(I,T)));
*put a1;
*put /;
*put netret.l:7:2, totlech('1'):7:2,

loop(O,
mmm.fx = ml(O);
solve farml using nlp maximizing netret;
totlech(O)=sum(T $(ord (T) GT 1), sum(I,lc.l(I,T)*G.l(I,T)));
put a1;
put /;
put netret.l:7:2, totlech(O):7:2,
```

```
put a2;
put/;
loop(T,
put a2;
put /;
put tyld.l('c1',T):7:2,
put n3.l('c1',T):7:2,
put rzn.l('c1',T):7:2,
put w.l('c1',T):7:2,
put g.l('c1',T):7:2,
put lc.l('c1',T):7:2,
lc2.l('c1',T):7:2,
);

put a3;
put/;
loop(T,
put a3;
put /;
put tyld.l('c2',T):7:2,
put n3.l('c2',T):7:2,
put rzn.l('c2',T):7:2,
put w.l('c2',T):7:2,
put g.l('c2',T):7:2,
put lc.l('c2',T):7:2,
lc2.l('c2',T):7:2,
);

put a4;
put/;
loop(T,
put a4;
put /;
put tyld.l('c3',T):7:2,
put n3.l('c3',T):7:2,
put rzn.l('c3',T):7:2,
put w.l('c3',T):7:2,
put g.l('c3',T):7:2,
put lc.l('c3',T):7:2,
lc2.l('c3',T):7:2,
);

put a5;
put/;
loop(T,
put a5;
put /;
put tyld.l('c4',T):7:2,
put n3.l('c4',T):7:2,
put rzn.l('c4',T):7:2,
put w.l('c4',T):7:2,
put g.l('c4',T):7:2,
put lc.l('c4',T):7:2,
lc2.l('c4',T):7:2,
);
```

```
put a6;
put/;
loop(T,
put a6;
put /;
put tyld.l('c5',T):7:2,
put n3.l('c5',T):7:2,
put rzn.l('c5',T):7:2,
put w.l('c5',T):7:2,
put g.l('c5',T):7:2,
put lc.l('c5',T):7:2,
lc2.l('c5',T):7:2,
);

put a7;
put/;
loop(T,
put a7;
put /;
put tyld.l('c6',T):7:2,
put n3.l('c6',T):7:2,
put rzn.l('c6',T):7:2,
put w.l('c6',T):7:2,
put g.l('c6',T):7:2,
put lc.l('c6',T):7:2,
lc2.l('c6',T):7:2,
);

put a8;
put/;
loop(T,
put a8;
put /;
put tyld.l('c7',T):7:2,
put n3.l('c7',T):7:2,
put rzn.l('c7',T):7:2,
put w.l('c7',T):7:2,
put g.l('c7',T):7:2,
put lc.l('c7',T):7:2,
lc2.l('c7',T):7:2,
);
put a9;
put/;
loop(T,
put a9;
put /;
put tyld.l('c8',T):7:2,
put n3.l('c8',T):7:2,
put rzn.l('c8',T):7:2,
put w.l('c8',T):7:2,
put g.l('c8',T):7:2,
put lc.l('c8',T):7:2,
lc2.l('c8',T):7:2,
);
);
```

2

VITA

John a. Lehr

Candidate for the Degree of

Doctor of Philosophy

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