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An Integrated Model of Surface and Ground Water Quality

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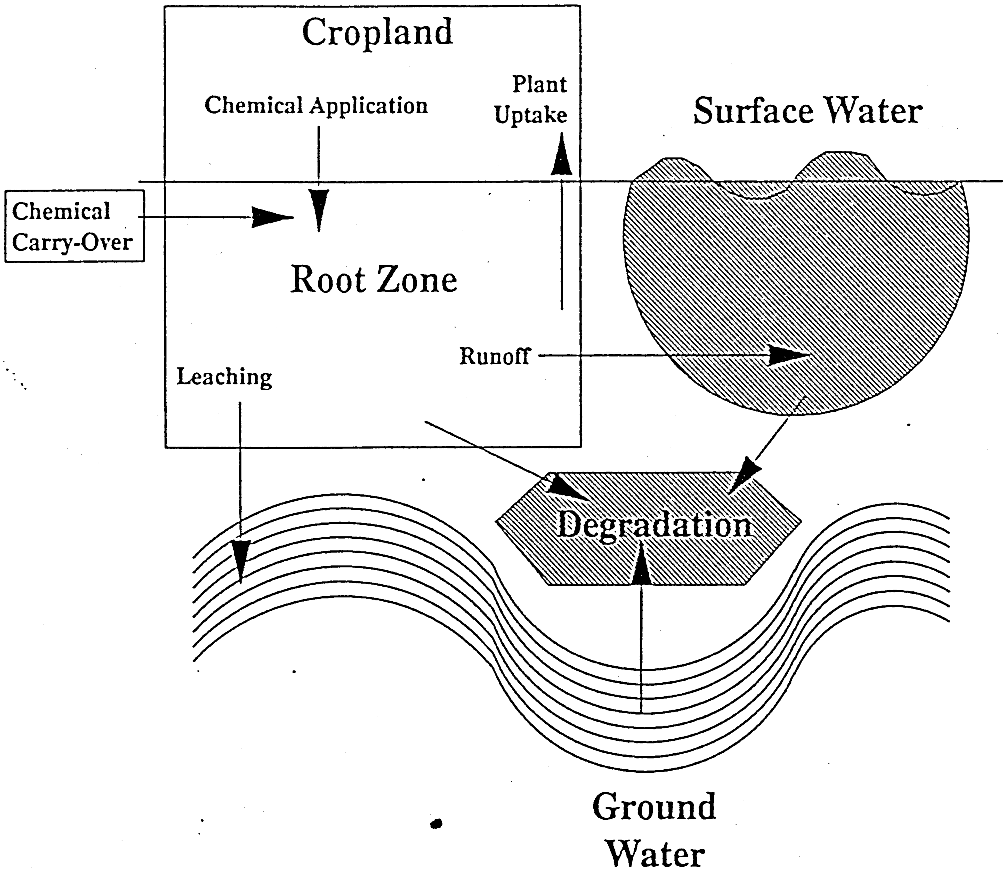
Abstract

The offsite impacts of agricultural chemicals and soil erosion on surface and ground waters are incorporated in an integrated model of agricultural production. The interdependencies of ground and surface water quality are highlighted. The effectiveness of chemical use and soil erosion restrictions in protecting water quality are compared and contrasted.

Fate and Transport of Agricultural Chemical Residuals



1. Introduction

The impact of agricultural production on water quality has figured prominently in the agro-environmental policy debate in recent years. The recent policy emphasis on controlling these externalities has been fueled by increasing concern about the presence of agricultural chemicals in groundwater and the increasing emphasis on reducing agricultural nonpoint source pollution of surface water (Soil Conservation Service 1986, Clark, et. al., 1985, US EPA 1986, Nielsen and Lee 1987). Renewed attention has been placed on the relationships between decisions made by farmers regarding agricultural chemical and the on- and off-farm degradation of water quality from sediment, nutrients, and pesticides.

This paper presents a simplified model of the relationship between agricultural production and the resulting impacts on water quality. We develop a model to explain the linkages between crop production, input use, soil loss, surface water quality and groundwater quality. The model is used to explore the economic and environmental implications of soil conservation and pesticide regulation programs.

2. Background

Economists have long recognized a fundamental externality: agricultural inputs that cause off-farm environmental degradation (particularly chemicals and eroded soils) are not fully priced in the market to reflect the economic costs of their use. (See Griffin and Bromley (1982), for example.) Agricultural chemicals and sediment flow via soil erosion to surface waters. These residuals and sediment degrade the quality of the receiving water. The economic costs of impaired water quality to users of lakes, streams and reservoirs are not fully reflected in the producers' costs of the agricultural inputs. Agricultural chemicals may also leach through the soil profile into groundwater, causing at least the potential for a variety of adverse effects on the health of humans and livestock who use contaminated groundwater.

A key feature of the model developed here is that it explicitly considers the tradeoff between protecting surface water from eroding soils and farm chemicals in runoff and protecting groundwater from leaching chemicals applied to cropland. Surface water and groundwater quality are not really separable issues: efforts to restrict transport of agricultural chemical residuals in one medium (soil, groundwater, surface water, or air) may increase residual flows in other media.

For the most part previous economic analyses of soil erosion, agricultural externalities, and water quality have examined one resource issue: surface water, ground water, or the on-farm productivity effects of eroding soils. McConnell (1983) analyzes soil productivity as a function of soil depth and soil loss without explicit consideration of the off-farm costs of soil loss. Later works have incorporate the economic costs of surface water quality degradation in models of soil conservation (See Shortle and Dunn (1986), Shortle and Miranowski (1987), Braden et. al. (1987) among others). Other researchers have developed models to incorporate the effects of agricultural chemicals leaching into ground water (Anderson, Opaluch and Sullivan (1985), Raucher (1986a, 1986b), Baker (1988), and Conrad (1988)). To date, few studies have considered the dual objectives of protecting both surface and ground water from agricultural externalities.[1]

3. A Model of Agricultural Residual Fate and Transport

Let the unit of time t correspond to one growing season. At time t, the farmer applies agricultural chemicals to his/her cropland. Considered the fate of the chemicals from a mass-balance perspective: the total amount C of chemicals applied to cropland during this time must either be consumed by the plant, transformed into other metabolites, displaced into other media (other parts of the soil profile, air, or water), or remain in the soil as carry-over to the next period. Let C_t be the amount of chemicals applied to the cropland in time t and R_t the amount of residual chemicals leftover in the soil from the previous period. Thus total nutrient availability at the beginning of the growing season is $C_t + R_t$.

At time t+1, then, the net residual of chemicals remaining in the soil equals application plus the previous period's carry over, less uptake, runoff, degradation, less leaching:

$$R_{t+1} - C_t + R_t - \mathrm{UPTAKE}_t - \mathrm{DEGRADATION}_t - \mathrm{RUNOFF}_t - \mathrm{LEACHING}_t \tag{1}$$

Between t and t+1, some portion of the chemicals are taken up by the plants. Assume a simple linear uptake function: total plant use of the chemicals is proportional to their availability in the soil.

$$\mathrm{UPTAKE} - \alpha \cdot (C_t + R_t) \tag{2}$$

where α is the fraction of chemicals absorbed by the plant.

Some fraction of the chemicals may break down into benign compounds:

$$\mathrm{DEGRADATION} - \beta \cdot (C_t + R_t) \tag{3}$$

where β is the fraction of chemicals that degrade into harmless metabolites during a time period.

Some of the chemicals in the soil are dissolved in runoff or attached to sediment transported off cropland via soil erosion. We assume that a fraction of the chemicals in the soil are dissolved in runoff, while another fraction of chemicals present in the soil will be lost to surface waters due to soil erosion at a rate proportional to the rate of soil loss:

$$\mathrm{RUNOFF} = \gamma \cdot (C_t + R_t) + \delta \cdot (C_t + R_t) \cdot S \tag{4}$$

where S_t is the rate of soil loss at time t, γ is the proportion of chemicals that are dissolved in runoff, and δ is the proportion of chemicals that are attached to eroding soils.

Finally, some of the chemicals may leach below the root zone into ground water:

$$\mathrm{LEACHING} = \epsilon \cdot (C_t + R_t) \tag{5}$$

where ϵ is the proportion of chemicals that leach into ground water over one time period.

When (2) - (5) are substituted into (1) we get the transition equation which describes the change in chemical availability in the soil from one period to the next:

$$R_{t+1} = (R_t + C_t) \cdot [1 - \alpha - \beta - \gamma - \delta \cdot S - \epsilon] \tag{6}$$

Groundwater is subject to contamination as chemical residuals leach through the soil profile and eventually end up in aquifers. As the chemicals move through the soil and after they reach the underground water resource, they are also subject to a certain about of natural decay and degradation. Thus groundwater quality at time t+1 will depend on previous levels of residuals in the overlying soil, and on previous levels of groundwater quality. For simplicity, we assume that this is a first-order process, that is:

$$G_{t+1} = (1 - \beta) \cdot G_t + \epsilon \cdot (C_t + R_t) \tag{7}$$

where G_t is the concentration of chemicals in the ground water, and β is the degradation coefficient described above.

Surface water quality, on the other hand, will depend on levels of runoff and chemical transport. Surface water quality at time t will depend on the surface water quality during the previous period, and the amount of chemicals transported off cropland (either dissolved in runoff or attached to eroding soils):

$$Q_{t+1} = (1 - \beta) \cdot Q_t + \gamma \cdot (C_t + R_t) + \delta \cdot (C_t + R_t) \cdot S \tag{8}$$

Soil loss will, of course, decrease the depth of the remaining soil on the farm. The transition equation for soil depth is:

$$Z_{t+1} = Z_t - S_t \tag{9}$$

where Z_t is the soil depth at time t.

Equations (6), (7), (8), and (9) describe a system whereby agricultural chemicals applied to cropland are distributed between on-farm (plant uptake, carry-over) and off-farm (ground or surface water) fates. The next task is to link this system into the economic model of farm production.

4. The On-Farm Maximization Problem

In the absence of any explicit consideration of the off-farm consequences of water quality problems related to agricultural chemical use the decision process for the individual farmer reduces to maximization of the present value of future net returns to farming. To begin with, we specify a production function. Let the per-acre production be a function of soil depth, agricultural chemicals, capital, and labor:

$$Y - f(C,Z,K,L) \tag{10}$$

Where Y is the output of the agricultural commodity in time period t, K is capital, and L is labor.

It is assumed that the production function is increasing in all its inputs. In order to distinguish between those inputs which are environmentally benign and those which have an externality associated with their use, we make the further simplifying assumption that Y is separable between (K,L) and (C,S). We then re-cast the production functions to consider only agricultural chemicals and soil depth.

$$Y - Y(C,Z) \tag{11}$$

We assume that the farmer is a price-taking, profit maximizer. To solve the system for optimal levels of chemical use and soil loss, we specify an objective function:

$$\text{Maximize } V(R_t,Z_t) - P \cdot Y(C,Z) - w \cdot C + V(R_{t+1},Z_{t+1}) \tag{12}$$

where P is the output price, w is the unit cost of agricultural chemicals, and V(R,Z) is the net present value function of residual level R and soil depth Z. V(R,Z) is maximized subject to (6) and (9), the transition equations for chemical residuals and soil depth.[2]

The first order conditions for an interior maximum are:

$$p \cdot Y_C(C,Z) - w + V_R(R_{t+1},Z_{t+1}) \cdot (1-\alpha-\beta-\gamma-\delta \cdot S_t-\epsilon) - 0 \tag{13}$$

and

$$V_R(R_{t+},Z_{t+1}) \cdot (R_t+C_t) \cdot (-\delta) - V_Z(R_{t+},Z_{t+1}) = 0 \qquad (14)$$

Condition (13) implies that marginal revenue of additional chemical less the marginal cost of chemicals must equal the marginal changes in value of available chemicals in the next period. Condition (14) implies the marginal change in the value of available chemicals in the next period (from an increase in soil loss) must equal the value of lost soil productivity.[3]

5. Protecting Water Quality via Input Use or Soil Erosion Constraints

5.1 Input Restrictions

Suppose that a decision is made to protect ground water from the infiltration of agricultural chemicals by imposing a chemical use constraint. That is, we require that in each period C be less than or equal to some value $\overline{C}$. Assume for simplicity that this constraint is initially binding in all periods under consideration:

$$C_t \leq \overline{C} \qquad (15)$$

The first order conditions then reduce to:[4]

$$V_R(R_{t+1},Z_{t+1}) \cdot (R_t+\overline{C}) \cdot (-\delta) - V_Z(R_{t+1},Z_{t+1}) = 0 \qquad (16)$$

Equation (16) is (14) evaluated at $\overline{C}$. That is, the net present value of future income streams is maximized with respect to soil loss given chemical level $\overline{C}$. Note that with a binding chemical use constraint that:

$$R_{t+1} = (R_t+\overline{C}) \cdot [1-\alpha-\beta-\gamma-\delta \cdot S-\epsilon] \qquad (17)$$

5.2 Soil Erosion Restrictions

Suppose instead of an input use constraint we require the farmer to reduce soil erosion to some predetermined level $\overline{S}$. Thus:[5]

During the periods that the soil erosion constraint is binding the first order conditions reduce to:

$$p \cdot Y_C(C,Z) - c + V_R(R_{t+1},Z_{t+1}) \cdot (1-\alpha-\beta-\gamma-\delta \cdot \overline{S}-\epsilon) = 0 \qquad (19)$$

Equation (19) is (13) evaluated at $\overline{S}$. The net present value function is maximized with respect to agrichemical use give soil loss of $\overline{S}$.

Here,

$$R_{t+1} = (R_t + C_t) \cdot [1-\alpha-\beta-\gamma-\delta \cdot \overline{S}-\epsilon] \qquad (20)$$

and

$$Z_{t+1} = Z_t - \overline{S} \qquad (21)$$

6. Protecting Ground Water Quality

The on farm solution, of course, does not take into account the negative externality of contamination of surface and ground water resources. To show how incorporating these externalities alters the allocation of resources, consider the simplest case of a quality constraint imposed on ground water. Suppose the regulatory authorities impose a rule that ground water must not contain chemicals in excess of a given concentration level. Let this concentration level be given by $\overline{G}$. This imposes an additional constraint on the objective function:

$$G_t \leq \overline{G} \qquad (22)$$

During a period in which the ground water constraint is binding, $G_{t+1} = G_t = \overline{G}$, which implies:

$$\beta \cdot \overline{G} - \epsilon \cdot (C_t + R_t) = 0 \qquad (23)$$

In addition to (23) the first order conditions for a maximum are similar to (13) and (14); the shadow price of the constraint must be appended to (13).

7. Protecting Surface Water Quality

Alternatively, a decision may be made to protect surface water quality. We do this by constraining surface water quality to some arbitrary value $\overline{Q}$:

$$Q_t \leq \overline{Q} \qquad (24)$$

During a period in which the surface water constraint is binding $Q_{t+1} = Q_t = \bar{Q}$, which implies:

$$\beta \cdot \bar{Q} - (\gamma + \delta \cdot S_t) \cdot (C_t + R_t) = 0 \tag{25}$$

In addition to (24) the first order conditions for a maximum are again slightly modified versions of (13) and (14). The shadow price of the constraint multiplied by the change in the constraint for a change in the choice variable is appended to (13) and (14).

8. Putting It All Together: Options for Managing Water Quality

The analysis has considered four options to manage water quality: restrict chemical applications, restrict soil erosion, directly regulate groundwater quality, and directly regulate surface water quality. Each policy will have different effects on ground water and surface water quality. The effectiveness of any policy choice for prevent agricultural pollution will depend on many factors, including the physical parameters of the fate and transport relationships (2) through (5) and the characteristics of the production function.

To determine the qualitative effects of these restrictions on surface and ground water quality, we first derive the comparative statics results (Samuelson (1947), Silberberg (1978)) for the choice variables, C_t and S_t for a change in the relevant parameter values $\bar{C}$, $\bar{S}$, $\bar{G}$, and $\bar{S}$ from the restrictions. The comparative statics results are then used to determine the qualitative impacts on ground and surface water quality. Conditions that characterize the qualitative shifts in water quality are presented in Table I. (Space limitations prevent a full discussion of the details of the comparative statics analysis).

As can be seen, when the effect of the constraints is to lower both chemical residues in the soil ($R^* < R^0$) and chemical applications ($C^* < C^0$) then both surface water quality and groundwater quality tend to increase. However, it may be the case that for some values of the underlying parameters soil erosion may increase at the same time chemical residuals fall, so the impact on surface water quality is ambiguous. Similarly, if both soil erosion and chemical residuals in the root zone decrease then the effect on groundwater quality is also ambiguous. There are some cases where efforts to enhance the quality of one resource may have an negative impact on the quality of the other. The only cases where input use, soil loss, or water quality constraints clearly contribute to improving the quality of both surface and ground water are situations where the optimal values of both chemical application, soil erosion, and chemical residuals in the root zone are less than their corresponding unconstrained values.

The results presented in Table I highlight two critical questions. The first is the issue of input substitutability: If one factor of production is regulated, with the use of the other factor increase or decrease? For instance, if we restrict chemical use will soil erosion in the constrained case (S^*) be greater than or less than soil erosion in the unconstrained case (S^0)? If soil erosion increases when chemical use is restricted (for example, through increased use of mechanical cultivation for weed control), then transport of chemicals and sediment to surface waters may increase. The second consideration is the effect of the constraints on the presence of chemicals in the soil. Chemical carry over and availability in the root zone (R_t) depends on both application rates and soil erosion. If both S and C are changing in response imposed constraints, the net effect on R may be ambiguous if S and C change in different directions.

Table I

Impacts of Alternative Management Policies
on Surface and Ground Water Quality

Policy Under Consideration	**Groundwater Quality Impact**	**Surface Water Quality Impact**
Chemical Input Use Constraint: $C < C$		
$S^* < S^0, R^* < R^0$	+	+
$S^* < S^0, R^* > R^0$	?	?
$S^* > S^0, R^* < R^0$	+	?
Soil Erosion Constraint: $S < S$		
$C^* < C^0, R^* < R^0$	+	+
$C^* < C^0, R^* > R^0$	?	?
$C^* > C^0, R^* > R^0$	-	?
Groundwater Quality Constraint: $G < G$		
$S^* < S^0$	+	+
$S^* > S^0$	+	?
Surface Water Quality Constraint: $Q < Q$		
$C^* < C^0, R^* < R^0$	+	+
$C^* > C^0, R^* < R^0$	?	+
$C^* < C^0, R^* > R^0$	?	+
$C^* > C^0, R^* > R^0$	-	+

A superscript "0" represents the value of the variable in the unconstrained situation. A superscript "*" indicates the value of the variable after imposing the constraint. A "+" represents an increase in groundwater quality arising from the imposition of the restriction in question, while a "-" represents a decrease in water quality. A "?" indicates that the effect of the restriction cannot be determined unambiguously; and will depend on the magnitude of the relevant parameters of the equations governing fate and transport of residuals in the root zone, surface water, and ground water.

9. Conclusions

A simplified model of crop production was used to explore the effects of soil loss and input use restrictions and water quality constraints on groundwater quality and surface water quality. The effects on water quality of any binding restriction on soil loss or chemical use depend on the shape of the water quality functions and on-farm response to imposition of the restriction (which will depend, in turn, on the elasticity of input substitution).

The effects of restricting either soil loss or input use alone need to be weighed carefully. A-priori, neither restricting soil loss nor agricultural chemical use alone ensures that both surface and groundwater quality will increase. If conservation tillage practices requiring more use of farm chemicals are adopted in response to a soil loss constraint it is possible (if not particularly likely) that farm income, groundwater quality and surface water quality will all decrease. Although the imposition of a restriction on agricultural chemicals will improve the quality of either ground or surface water, farm income will decrease and, possibly, the quality of the other water resource may decrease. Similarly, directly regulating either ground water quality or surface water quality alone (as opposed to regulating farming practices) may have undesirable effects on the unregulated resource.

To ensure that both ground water quality and surface water quality increase, it is necessary to regulate either both soil loss and farm chemicals, or both ground and surface water quality. Such regulatory schemes will reduce the optimal level of purchased input use. The optimal level of soil loss may increase or decrease depending on the relative values of ground water quality and surface water quality. If groundwater quality is relatively highly valued, it possible for the optimal level of soil loss to increase. The adoption of any restrictions requires further study to ensure that optimal levels of groundwater quality and surface water quality are targeted.

To fully evaluate the effects of soil conservation and input restrictions on farm income and environmental quality, further research is needed to better quantify the linkages between on-farm production decisions by farmers and the off-farm impacts on water quality. Considerable uncertainty surrounds the fate and transport of agricultural chemicals and sediment in the environment which our simplified transition equations have necessarily glossed over. In addition, much more work needs to be done on the key consideration of input substitutability. Our results show that an unambiguous appraisal of the effects of soil conservation and agricultural chemical restrictions on water quality cannot be determined without fully characterizing the ability of producers to substitute among various inputs and outputs. This question becomes even more important when other substitution possibilities (such as land for purchased inputs or crop switching) are considered in a more general multiple-input, multiple output framework. Our work here can be considered a first step in that direction.

Notes

1. Crowder and Young (1988) examined some of the tradeoffs between surface water and ground water quality in an ad-hoc manner; however, their analysis was not based on an economic model of farm production and farmer behavior.

2. Equation (12) is a functional equation in a standard dynamic programming problem (Bellman (1957), Hiller and Lieberman (1980), and Kamien and Schwartz (1981))

3. The second order conditions of this model are somewhat complex, and are not reproduced here due to space limitations. Essentially, sufficient conditions for an interior maximum implied by the second order conditions are: 1) concavity of $Y(C,Z)$, 2) concavity of the value function $V(R,Z)$, and 3) $V_r < 0$, and small in absolute value. Full details are available from the authors upon request.

4. The first order conditions and optimal values of the state variables are quite complex, and space considerations preclude their inclusion in this paper. Full results are, of course, available from the authors upon request.

5. Restricting soil erosion has historical precedent: USDA policy regarding soil erosion has generally focussed on reducing soil loss to some "tolerable" level T (usually between three and five tons per acre per year). Also, since surface water quality problems relating to agriculture and nonpoint in nature, it is more difficult to establish and cause-and-effect relationship between changes in ambient surface water quality and actions taken on individual farms.

References

Anderson, Glen, James Opaluch, and Michael Sullivan. 1985 "Nonpoint Agricultural Pollution: Pesticide Contamination of Groundwater Supplies." **American Journal of Agricultural Economics** Vol. 67, No. 4, pg. 1231-1235

Baker, Brian. 1988. "Groundwater Protection Policy and Agricultural Production: A Recursive Stochastic Analysis." **Northeastern Journal of Agricultural and Resource Economics.** Vol. 17, No. 2, pp. 121-138.

Bellman, R. E. 1957. **Dynamic Programming**, Princeton University Press, Princeton, New Jersey.

Braden, J., G. Johnson, A. Bouzaher, D. Miltz. 1987. "Optimal Spatial Management of Agricultural Pollution." **American Journal of Agricultural Economics** Vol. 89, No. 3, pp. 404-413.

Clark, Edwin H., J. A. Haverkamp and W. Chapman, 1985. **Eroding Soils The Off-farm Impacts**, The Conservation Foundation, Washington, D.C.

Conrad, Jon M. 1988. "Pollution Control with Risk of Irreversible Accumulation" Paper presented at the American Agricultural Economics Association annual meetings, Knoxville TN, July 31-August 1, 1988.

Crowder, Bradley and C. Edwin Young. 1988. **Managing Farm Nutrients: Tradeoffs from Surface- and Ground-Water Quality.** Agricultural Economic Report No. 583, US Department of Agriculture, Economic Research Service, Washington DC. January, 1988.

Griffin, Ronald and Daniel Bromeley. 1982. "Agricultural Runoff as a Nonpoint Externality: A Theoretical Development." **American Journal of Agricultural Economics** Vol. 64, No. 3, pg. 547-552.

Hillier, F. S. and G. J. Lieberman, 1980. **Introduction to Operations Research** (Third Edition), Holden-Day, Inc., San Francisco.

Kamien, M. I. and N. L.Schwartz, 1981. **Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management**, North Holland, New York, New York.

McConnell, Kenneth E. 1983. "An Economic Model of Soil Conservation, **American Journal of Agricultural Economics**, 59:83-89 (1983).

Nielsen, Elizabeth and Linda Lee, 1987. **The Magnitude and Costs of Groundwater Contamination From Agricultural Chemicals: A National Perspective**, Agricultural Economic Report No. 576, U.S. Department of Agriculture, Economic Research Service, October 1987.

Raucher, Robert L. 1986a. "Regulation Pollution Sources under a Differential Protection Strategy. " **American Journal of Agricultural Economics** Vol. 67, No. 4. 1225-1228

Raucher, Robert L. 1986b. "The Benefits and Costs of Policies Related to Groundwater Contamination." **Land Economics** Vol. 62, No. 1. pp. 33-45

Samuelson, Paul. 1947. **Foundations of Economic Analysis**, Harvard University Press, Cambridge, MA.

Shortle, James and James Dunn. 1986. "The Relative Efficiency of Agricultural Source Water Pollution Control Policies." **American Journal of Agricultural Economics** Vol. 68, No. 3. 668-677.

Shortle, James and John Miranowski, 1987. "Intertemporal Soil Resource Use: Is it Socially Excessive?," **Journal**

of Environmental Economics and Management, 14:99-111.

Silberberg, Eugene. 1978. **The Structure of Economics: A Mathematical Analysis**. McGraw-Hill, New York, NY.

Soil Conservation Policy Task Force, American Agricultural Economics Association, 1986 Soil Erosion and Soil Conservation in the United States, Occasional Paper No. 2, American Agricultural Economics Association.

U.S. Environmental Protection Agency, 1986. Pesticides in Groundwater: Background Document.