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The Economics of a Stock Pollutant:

Aldicarb on Long Island

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Abstract

A stock pollutant is a residual waste that can accumulate or degrade over time. Aldicarb was a pesticide used by farmers growing fruit and vegetables. Potato growers on eastern Long Island, New York, used aldicarb from 1975 to 1979 to control the Colorado potato beetle and the golden nematode. In August of 1979 aldicarb residues were detected in well water, and subsequent testing found more than 2,000 wells with concentrations in excess of the New York State health standard of 7 parts per billion (ppb). Aldicarb was banned from use on Long Island after 1979. In this paper we develop a dynamic model of a stock pollutant. The model is calibrated for aldicarb on eastern Long Island and steady-state solutions for static profit maximization and the maximization of discounted net benefits (welfare) are estimated. The New York State health standard of 7 ppb is associated with a pesticide application rate less than one-tenth the profit-maximizing rate and it implies that health officials assess the marginal cost of groundwater contamination at about $1.5 million. Simulations indicate that the average concentration of aldicarb is not expected to decline below 7 ppb until 1996.

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I. Introduction and Overview

The use of agricultural chemicals offers society substantial benefits in terms of pest control and higher crop yields. Pesticides and fertilizers, however, are now recognized as a significant source of groundwater contamination. A recent study sponsored by the Soil Conservation Service found that 42 of the lower 48 states reported some regional, local or suspected groundwater contamination due to pesticide use (Fairchild 1987). Thirty four states blame nonpoint agricultural pollution for their failure to achieve federal water quality goals, while 29 states have identified groundwater contamination by chemicals as a major concern (Anderson 1987). It is estimated that 46 percent of the counties in the contiguous United States have some groundwater contamination caused by the use of agricultural chemicals. In these areas it is further estimated that there are 19 million people who obtain drinking water from private wells, with an additional 34.5 million people served by public groundwater systems. The widespread extent of contamination from agricultural chemicals can be partially attributed to the 300 percent increase in fertilizer and pesticide use in the United States since 1964 (Nielsen and Lee 1987). This rapid growth in fertilizer and pesticide use, and the large extent of agricultural groundwater contamination has focused attention on what some regard as an inherent conflict between large-scale agricultural production and the need for clean groundwater.

The basic issues that characterize groundwater problems have been of long-standing interest to resource economists. The early and mid-1970s saw a series of papers that extended the theory of optimal economic growth to the optimal management of stock pollutants - residual wastes that accumulate and degrade over time. Papers by Plourde (1972), Smith (1972), Keeler, Spence and Zeckhauser (1972), and Forster (1977) are frequently cited examples of this earlier work. More recently, Kitabatake (1989) has formulated a more general model that contains these earlier models, and some models of renewable resources, as special cases.

The earlier literature was essentially theoretical, with only passing reference to examples of stock pollutants. Applied studies of actual instances of groundwater contamination, on the other hand, would generally abstract from dynamic considerations and only focus on static equilibrium. Shechter (1985) estimates economic damages from contamination at the Price Landfill in New Jersey. Edwards (1988) uses survey methods to estimate individual willingness-to-pay to prevent future nitrate contamination of groundwater drinking supplies. Lichtenberg et al. (1989) examine the regulation of cancer risk from DBCP contamination in Fresno County, California. Raucher (1986) proposes a conceptual model to measure the benefits of groundwater protection and the cost of remediation, and examines potential net benefits at three superfund sites.

Our paper is most closely related to the study by Anderson et al. (1985), who examine the use of aldicarb and groundwater contamination in Rhode Island. Using data from 85 individual wells they estimate a contamination function that depends on well depth and distance from the presumed application site. They then solve for the static application rate that satisfies the upper bound standard on contamination for drinking water.

The objective of this paper is to develop a dynamic model of pesticide use and groundwater contamination and to use the model as a framework for examining groundwater contamination by the pesticide aldicarb on Long Island, New York. Aldicarb was registered by the U.S. Environmental Protection Agency (EPA) in 1974. It was used to control a variety of pests affecting the production of fruits and vegetables. Potato growers on Long Island found it effective in controlling the Colorado potato beetle (*Leptinotarsa decemlineata*) and the golden nematode (*Globodera rostochiensis*).

Toxicological studies of aldicarb have provided no indication that the pesticide is carcinogenic, mutagenic or teratogenic. It is, however, highly toxic at large doses. A cross-section, epidemiologic study of 50 women has suggested a possible association between the consumption of aldicarb-contaminated groundwater and abnormalities in T-cell subsets, although no clinically apparent immunodeficiency was noted (Foire et al. 1986).

Aldicarb is mobile in the environment and has been found in the groundwater of at least 15 states (Nielsen and Lee 1987). In August of 1979 aldicarb residues were detected in water from private wells on Long Island. In subsequent testing, approximately 2,300 wells were found to have concentrations of aldicarb and its oxides, sulfone and sulfoxide, in excess of the New York State health guideline of 7 micrograms per liter (μg/L); equivalent to 7 parts per billion (ppb). Aldicarb was banned from use on Long Island after 1979.

In this paper the dynamics of aldicarb are modeled by a simple difference equation relating surface application to groundwater concentration. The equation gives a good fit to observations on the average concentration of aldicarb in the aquifer for eastern Long Island. Expressions for the optimal levels of pesticide application, potato yield and aldicarb concentration are derived for the case when the production function for potatoes and the damage function for aldicarb are quadratic. By reversing the normal flow of logic in such equations, we also solve for the implied damage coefficient as a function of the various "hydronomic" parameters *and* the New York safe drinking water standard. An approximately-optimal, feedback control is determined that might be used to set the pesticide application rate when the aldicarb concentration is not optimal. To our knowledge, our research is the first attempt to apply a dynamic model to an actual incident of contamination by a stock pollutant.

In the next section we develop a fairly general model of pesticide application and groundwater pollution. A likely time path for the stock pollutant is suggested as farmers proceed from levels of pesticide application that maximize static profit to levels regulated by an environmental agency. In the third section the model is calibrated for the case of aldicarb on Long Island. Parameter estimates permit us to calculate what the average concentration would have been had the ban on aldicarb not been imposed. We also calculate the damage coefficient and the level of pesticide application when the New York State safe drinking standard is regarded as optimal. The final section summarizes our results and calculates the implied marginal opportunity cost of the current standard.

II. A Model of Pesticide Application and Groundwater Contamination

The general model and case study make use of the following notation. Let

Y_t = total production of the agricultural commodity in year t,

S_t = the amount of pesticide, per hectare, applied in year t,

Z_t = the pesticide concentration in the groundwater in year t,

$Y_t/ha = F(S_t)$ = a per hectare concave production function,

N = the number of hectares under cultivation,

p = the per unit (farmgate) price for the commodity, Y_t,

c = the cost, per unit, for the pesticide, S_t,

$W(S_t,Z_t)$ = a concave welfare or net benefit function for society,

γ = the degradation rate of the pesticide in groundwater,

α = a scaling parameter, also reflecting degradation in the unsaturated zone (above the water table),

$\rho = 1/(1 + \delta)$ = a discount factor, where δ is the annual discount rate,

τ = the residence time, in years, for the pesticide in the unsaturated zone.

We will begin by considering the likely time path for the pollution stock when the pesticide is applied to N hectares by farmers who seek to maximize static profit. We assume initially that these farmers have no concern or legal responsibility for groundwater pollution and that the pesticide accumulates unnoticed by health officials until some future date.

Such a farmer would select a level of pesticide application which maximizes profit, $\pi = pF(S) - cS$. The first-order condition $d\pi/dS = 0$ implies $pF'(S) = c$, where $F'(S) > 0$ is the first derivative of the per hectare production (response) function. If the production function is quadratic with $Y/ha = a + bS - dS^2$, where $a > b > d > 0$, then the profit maximizing level of pesticide application is given by the expression $S_\pi = (pb - c)/(2dp)$, assuming $pb > c$.

With N hectares, each receiving S_π kilograms per year, the total annual application rate for the region would be NS_π. If this rate were applied for a long time, the concentration of the pesticide in the groundwater might approach an equilibrium where the biological and chemical processes affecting degradation and oxidation precisely offset the rate of accumulation from surface application. As an approximation, suppose that the pesticide moves through the unsaturated zone to the aquifer where it accumulates or degrades according to

$$Z_{t+1} = (1 - \gamma)Z_t + \alpha N S_{t-\tau} \tag{1}$$

If the pesticide is applied at rate S_π per hectare for all t, the steady-state concentration of the pollution stock is given by $Z_\pi = (\alpha/\gamma)NS_\pi$. Starting from an unpolluted condition ($Z_0 = 0$) the stock pollutant will accumulate, asymptotically approaching Z_π (see Figure 1). Next, suppose that the contamination is discovered just before t_2 and that health officials or environmental regulators impose restrictions on the application rate to reduce the concentration below Z_π. Perhaps there is a health target, Z^*, which is regarded as an acceptable concentration. Figure 1 shows this target being reached at $t = t_3$.

If Z_π exceeds the optimal concentration, Z^*, some form of regulation or economic incentives may be required to induce farmers to apply the pesticide at the optimal rate. How are we to determine Z^* and the optimal approach from Z_π?

Conceptually we might proceed by defining the social net benefit function $W_t = \Phi(Y_t, Z_t) = W(S_t, Z_t)$, where the production function has been directly substituted into $\Phi(\cdot)$ and where $W_S > 0$ and $W_Z < 0$ are the partial derivatives of $W(\cdot)$ with respect to S_t and Z_t, respectively. Maximization of the present value of net social benefits may be stated mathematically as

$$\text{Maximize} \sum_{t=0}^{\infty} \rho^t W(S_t, Z_t)$$

$$\text{Subject to } Z_{t+1} = (1 - \gamma)Z_t + \alpha N S_{t-\tau}$$

The Lagrangian for this problem may be written as

$$L = \sum_{t=0}^{\infty} \rho^t \{W(S_t, Z_t) + \rho\lambda_{t+1}[(1 - \gamma)Z_t + \alpha N S_{t-\tau} - Z_{t+1}]\} \tag{2}$$

In the Appendix we derive the first order conditions and evaluate them in steady state. They can be reduced to two equations

$$W_S = \frac{-\rho^{\tau}\alpha N W_Z}{(\delta + \gamma)} \tag{3}$$

$$Z = (\alpha/\gamma)NS \tag{4}$$

which characterize the optimal steady-state values of S^* and Z^*. Equation (3) requires the marginal net benefit of pesticide application, W_S, be equated to the present value (in perpetuity) of marginal social cost (or damage), where the increment in pesticide application is applied to all N hectares, transformed by α, lagged by τ periods and evaluated at the augmented discount rate of $(\delta + \gamma)$.

Consider the following form for the objective functional.

$$W_t = N[p(a + bS_t - dS_t^2) - cS_t] - mZ_t^2 \tag{5}$$

The expression in the square brackets is net revenue per hectare. The cost of contaminated groundwater is assumed to be proportional to the square of the concentration. Because of the uncertainty in dose-response relationships it is probably impossible to obtain a direct estimate of m. If the regulatory standard is treated as the optimal level of contamination, Z^*, it is possible to solve for the associated value of m and the marginal social cost of groundwater contamination. For the quadratic form in equation (5) we can use the steady-state equations to solve for two related expressions

$$S^* = \frac{\gamma[pb - c](\delta + \gamma)}{2[\alpha^2 N\rho^\tau m + \gamma dp(\delta + \gamma)]} \tag{6}$$

and

$$m = \frac{\{\alpha N[pb - c] - 2\gamma dpZ^*\}(\delta + \gamma)}{2\alpha^2 N\rho^\tau Z^*} \tag{7}$$

Equation (6) defines the optimal pesticide application rate as a function of all the parameters, including m. Note, that as $m \to 0$, $S^* \to S_\pi = [pb - c]/(2dp)$. Thus, if there were no cost to groundwater contamination the static profit-maximizing application rate is optimal in the long run. Equation (7) defines the implied value of m associated with the hydronomic parameters and the prevailing health standard, Z^*.

III. Aldicarb on Eastern Long Island

To calibrate the model for aldicarb pollution on Long Island we begin by attempting to reconstruct the pesticide application rate (or loading) from 1975 through 1979. Table 1 contains information on the number of hectares (ha) planted in potatoes, total production (Y_t, in hundred weight, cwt.), the yield per hectare (Y_t/ha) and an estimate of the kilograms (kg) of aldicarb applied from 1970 through 1979. The recommended application rate was three pounds per acre which converts to 3.362 kg per hectare (where 2.471 acres = 1 hectare and 1 kilogram = 2.205 pounds). The estimated aldicarb application in 1975 is problematic. We assume that one-half of the fields applied aldicarb at the recommended dosage. From 1976 through 1979 it is believed that aldicarb was used on *all* fields (Pacenka et al. 1987).

The soils on eastern Long Island are sandy, with rapid percolation from the unsaturated zone to the water table. It seems likely that all or most of the aldicarb applied in the spring or summer would pass through the unsaturated zone within a year. This would imply that $\tau = 0$. This assumption was subsequently borne out by preliminary numerical analysis where we employed a grid search for combinations of τ, γ, and α that minimized the mean sum of squares of simulated from observed concentrations. With $\tau = 0$ it is possible to estimate γ and then calculate α.

In 1980 the Suffolk County Department of Health Services began an extensive monitoring program of wells within the county. In the second column of Table 2, under the heading $\overline{Z}_t$, we report the average aldicarb concentration for wells that tested positive from 1980 through 1989. The observation in 1981 (11.6 ppb) is regarded as an outlier by public health officials. With τ equal to zero we ran two regressions to estimate the degradation rate, γ. In the first we replaced the outlier by the average of the 1980 and 1982 observations. In the second we discarded the 1980 and 1981 observations. In both we used OLS, regressing $\overline{Z}_{t+1}$ on $\overline{Z}_t$, while suppressing the intercept. The regression results are summarized in Table 3.

The estimates of $(1 - \gamma)$ were significant at the one percent level in both regressions. Adjusted R^2, though inappropriate when the intercept has been suppressed, are also reported. Positive serial correlation is present in both regressions but does not bias our estimate of γ. In the first regression the estimated value of γ is 0.0793, corresponding to a half-life of 8.378 years. In the second regression the estimated value of γ is 0.0684, corresponding to a half-life of 9.783 years.

With $\tau = 0$, equation (1) will imply that the observed concentration in 1980 depends on the aldicarb applications from 1975 through 1979. Alternatively, given the observed concentration in 1980 (from Table 2), the annual total loadings (from Table 1), and an estimate of γ we can calculate α according to

$$\alpha = \frac{\bar{Z}_{1980}}{\sum_{t=1975}^{1979} (1-\gamma)^{(1979-t)} N_t S_t} \tag{8}$$

For $\gamma = 0.0793$, we calculate $\alpha = 2.010\text{x}10^{-4}$. For $\gamma = 0.0684$, we calculate $\alpha = 1.971\text{x}10^{-4}$.

Given values for τ, γ, and α, annual pesticide loadings and assuming $Z_{1975} = 0$, we can simulate equation (1) and compare the simulated values to the observed values. This was done for the two estimates of γ (and their associated α-values) with the results listed in third and fourth columns of Table 2 and plotted in Figure 2. It is interesting to note in Simulation I, with the larger γ and thus shorter half-life, that the average aldicarb concentration is not projected to decline below 7 ppb until 1996. In Simulation II, with the lower γ and longer half-life, the average aldicarb concentration is not projected to decline below 7 ppb until 1998.

The production or response function for potatoes was calibrated in the following way. In the period prior to aldicarb use (1970-1974) the average yield was 577.8 cwt/ha. From 1976 through 1979, when all farmers were applying aldicarb, the average yield increased to 726.5 cwt/ha. We assume that the recommended application rate of 3.362 kg/ha was also the profit maximizing rate. This results in two equations: $726.5 = 577.8 + b(3.362) - d(3.362)^2$ and $3.362 = (pb - c)/(2pd)$. The first equation is the quadratic production function evaluated at the profit maximizing application rate and the second defines the static, profit-maximizing application rate.

The parameters p and c are the price per hundred weight for Long Island potatoes and the cost per kilogram for aldicarb. The average price for Long Island potatoes for the period 1976-1979 was p = \$3.78/cwt (*New York Agricultural Statistics, 1983*, p. 16) while the cost for aldicarb in 1976 was \$5.51/kg. Given these parameter values the two equations imply b = 87.00159 and d = 12.72218 and the per hectare production function becomes

$$Y_t/\text{ha} = 577.8 + 87.00159\ S_t - 12.72218\ S_t^2 \qquad (9)$$

where the average yield for the period 1970-1974 serves as the intercept. This curve is drawn in Figure 3.

In the numerical analysis that follows we will use the estimates of γ and α when the outlier was replaced by the average of the 1980 and 1982 observations. The discount rate is set at five percent (δ =

0.05) and we assume a constant production area of N = 9,350 hectares. We then have the following parameter set.

$\alpha = 2.01 \times 10^{-4}$ $\delta = 0.05$ $(\rho = 0.9524)$ $\gamma = 0.0793$

$\tau = 0$ $a = 577.8$ $b = 87.00159$ $c = 5.51$

$d = 12.72218$ $N = 9{,}350$ $p = 3.78$

As a benchmark, consider the case where the damage coefficient, m, is zero, implying there is no cost to aldicarb accumulation in the groundwater. In this case static profit-maximization solves the welfare-maximization problem and we obtain Y^*/ha = 726.5 and $Z^* = 79.69$ ppb. The latter concentration is an estimate of the average concentration that would have existed in the aquifer underlying eastern Long Island had pesticide application remained at the profit-maximizing rate on N = 9,350 hectares.

If the New York State health standard of 7 ppb is adopted as the optimal concentration, Z^*, then we can calculate the implied damage coefficient according to equation (7) as m = 13,550 ($/ppb^2). Given the values of α, γ, and N, the New York State standard of 7 ppb could only be maintained with a pesticide application rate of $S^* =$ 0.295 kg/ha. It is unlikely that such a low application rate would be effective in controlling the Colorado potato beetle.

The current ban on using aldicarb implies that health officials are seeking to reduce the groundwater concentration of aldicarb as rapidly as possible. This policy is sometimes referred to as the "most rapid approach path" (MRAP), and would be optimal in a discrete-time control problem where the objective function can be expressed as a quasi-concave function of the state variable (Spence and Starrett 1975). Our objective function does not satisfy the conditions for MRAP to be strictly optimal and a less rapid approach path, in the vicinity of (Z^*, S^*), should be adopted.

With $\tau = 0$, the first-order necessary conditions can be shown to imply a system of two first order difference equations given by

$$S_{t+1} = \left(\frac{\alpha m}{dp}\right) Z_t + \left[\frac{\alpha^2 mN + (1+\delta)dp}{(1-\gamma)dp}\right] S_t - \frac{(\delta+\gamma)[pb-c]}{2(1-\gamma)dp} \tag{10}$$

$$Z_{t+1} = (1-\gamma)Z_t + \alpha N S_t \tag{11}$$

In steady-state these two equations will imply two isoclines in Z-S space (see Figure 4). The optimal feedback control policy (also called the stable manifold) is shown as a line segement through (Z^*, S^*) which directionals indicate to be a saddle-point equilibrium. For the parameter estimates in our model the eigenvalues (or characteristic roots) are 0.7214 and 1.4555.

It is well known (Sargent 1979) that the optimal feedback control is linear in a problem with a quadratic objective function and linear dynamics. In Z_t-Z_{t+1} space (or policy space), the optimal policy rule will take the form $Z_{t+1} = \varepsilon + \eta Z_t$, where η, in the case of a saddle-point equilibrium, is the smaller root, lying within the unit circle. In our case $\eta = 0.7214$, and we can solve for ε by noting that at the steady-state optimum $\varepsilon = (1 - \eta)Z^*$. For $Z^* = 7$ ppb we calculate $\varepsilon = 1.9502$. This yields the optimal policy $Z_{t+1} = 1.9502 + 0.7214 Z_t$.

We can obtain the optimal feedback control by substituting equation (1), with $\alpha = 2.01\text{x}10^{-4}$, $\gamma = 0.0793$, $N = 9350$ and $\tau = 0$, for Z_{t+1} in the optimal policy, and then solve for S_t. When this is done we obtain $S_t = 1.0375 - 0.1060 Z_t$. This line corresponds to the stable manifold in Figure 4 and can be used to guide the system to (Z^*,S^*) in an optimal fashion. It is interesting to note that the intercept of the optimal feedback control on the Z_t axis occurs at approximately 9.79 ppb, implying that aldicarb should not be used until the concentration declines below 9.79 ppb. With the average concentration at 12.1 ppb in 1989, continuation of the ban, in our model, is optimal.

IV. Conclusions

A stock pollution model was developed and calibrated for the problem of groundwater contamination by aldicarb on eastern Long Island. A dynamic optimization problem was posed and equations identifying the steady-state optimum were obtained for the case where yield per hectare and pollution costs were quadratic. With no pollution costs the profit-maximizing application rate is dynamically optimal. If the profit-maximizing application rate was 3.362 kg/ha, our estimates of γ and α predict that the average concentration of aldicarb would have equilibrated at about $Z_{\pi} = 80$ ppb.

The average concentration never reached Z_{π}. The presence of aldicarb in excess of the New York State health standard of 7 ppb prompted a ban on its use in 1979 which is still in effect today. If the New York State standard is regarded as the steady-state optimum, then the implied damage coefficient in our quadratic objective function is m = 13,550 ($\$/\text{ppb}^2$). The associated optimal application rate is only 0.295 kg/ha, less than one-tenth of the recommended dosage. It is unlikely that such a low application rate would be effective in controlling the Colorado potato beetle and golden nematode, and other methods of pest management will remain necessary even when the concentration level declines below 7 ppb. For our estimates of τ, γ, and α, the concentration of aldicarb does not decline below 7 ppb until 1996 or 1998.

The steady-state Lagrange multiplier has an interesting interpretation. Mathematically it is given by the equation

$$\lambda = -(1 + \delta)[p(b - 2dS^*) - c]/\alpha \tag{12}$$

For our parameter estimates, and $S^* = 0.295$ kg/ha, the value of λ is approximately - $1,540,500. This may be interpreted as the annual marginal opportunity cost of the health standard of 7 ppb. In our model, if the annual health risks of an aldicarb concentration in excess of 7 ppb are thought to exceed $1.5 million, then New York State may be justified in the current standard.

References

Anderson, G. L., Opaluch, J. J., and W. M. Sullivan. 1985. "Nonpoint Agricultural Pollution: Pesticide Contamination of Groundwater Supplies" *American Journal of Agricultural Economics* 67(5):1238-1243.

Anderson, J. H. 1987. "Agriculture and Natural Resources: The Broadening Horizon" in *Rural Groundwater Contamination*, F. M. D'Itri and L. G. Wolfson, eds., Chelsea, Michigan, Lewis Publishers.

Bureau of Drinking Water. 1990. *Status of Pesticide Sampling Programs 1980-1989.* Suffolk County Department of Health Services, Suffolk County, New York.

Edwards, S. F. 1988. "Option Prices for Groundwater Protection" *Journal of Environmental Economics and Management* 15(4):475-487.

Fairchild, D. M. 1987. "A National Assessment of Groundwater Contamination from Pesticides and Fertilizers" in *Groundwater Quality and Agricultural Practices*, D. M. Fairchild, ed., Chelsea, Michigan, Lewis Publishers.

Foire, M. C., H. A. Anderson, R. Hong, R. Golubjatnikov, J. E. Seiser, D Nordstrom, L. Hanrahan and D. Belluck. 1986. "Chronic Exposure to Aldicarb-contaminated Groundwater and Human Immune Function" *Environmental Research* 41:633-645.

Forster, B. A. 1977. "On a One State Variable Optimal Control Problem," in *Applications of Control Theory to Economic Analysis* (J. D. Pitchford and S. J. Turnovsky, eds.), pp.35-56, North Holland Publishing Company, Amsterdam.

Keeler, E., A. M. Spence, and R. Zeckhauser. 1972. "The Optimal Control of Pollution" *Journal of Economic Theory* 4:19-34.

Kitabatake, Y. 1989. "Optimal Exploitation and Enhancement of Environmental Resources" *Journal of Environmental Economics and Management* 16(3):224-241.

Lichtenberg, E., Zilberman, D., and K. T. Bogen. 1989. "Regulating Environmental Health Risks Under Uncertainty: Groundwater Contamination in California" *Journal of Environmental Economics and Management* 17(1):22-34.

New York Agricultural Statistics Service. 1979 and 1983. *New York Agricultural Statistics*. Albany, New York.

Nielsen, E. G. and K. L. Lee. 1987. "The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals" *Agricultural Economics Report*, No. 576, Economic Research Service, USDA. Washington D. C., U.S. Govt. Printing Office.

Pacenka, S., Porter, K. S., Jones, R. L., Zecharias, Y. B., and H. B. F. Hughs. 1987. "Changing Aldicarb Residue Levels in Soil and Groundwater, eastern Long Island, New York. *Journal of Contaminant Hydrology* 2: 73-91.

Plourde, C. G. 1972. "A Model of Waste Accumulation and Disposal," *Canadian Journal of Economics* 5: 119-125.

Raucher, R, L. 1986. "The Benefits and Costs of Policies Related to Groundwater Contamination" *Land Economics* 62(1):33-45.

Sargent, T. J. 1979. *Macroeconomic Theory*, Academic Press, New York

Shechter, M. 1985. "An Anatomy of a Groundwater Contamination Episode" *Journal of Environmental Economics and Management* 12(1):72-88.

Smith, V. L. 1972. "Dynamics of Waste Accumulation: Disposal versus Recycling," *Quarterly Journal of Economics* 86: 600-616.

Spence, A. M. and D. Starrett. 1975. "Most Rapid Approach Paths in Accumulation Problems" *International Economic Review* 16:388-403.

Appendix

The first order necessary conditions associated with the Lagrangian given as equation (2) in the text are as follows.

$$\frac{\partial L}{\partial S_t} = \rho^t W_S + \rho^{t+\tau+1}\lambda_{t+\tau+1}\alpha N = 0$$

$$\frac{\partial L}{\partial Z_t} = \rho^t\{W_Z + (1-\gamma)\rho\lambda_{t+1}\} - \rho^t\lambda_t = 0$$

$$\frac{\partial L}{\partial[\rho\lambda_{t+1}]} = \rho^t\{[(1-\gamma)Z_t + \alpha N S_{t-\tau} - Z_{t+1}]\} = 0$$

Simplifying

$$W_S + \alpha N\rho^{\tau+1}\lambda_{t+\tau+1} = 0$$

$$(1-\gamma)\rho\lambda_{t+1} - \lambda_t = -W_Z$$

$$Z_{t+1} = (1-\gamma)Z_t + \alpha N S_{t-\tau}$$

At the steady-state optimum

$$\rho\lambda = -W_S/(\alpha N\rho^\tau)$$

$$\rho\lambda[(1-\gamma) - (1+\delta)] = -W_Z$$

$$Z = (\alpha/\gamma)NS$$

Substituting the expression for $\rho\lambda$ into the second equation yields

$$W_S = \frac{-\rho^\tau\alpha N W_Z}{(\delta+\gamma)}$$

which is numbered as equation (3) in the text.

Figure 1. A Possible Time Path for the Stock Pollutant Z_t.

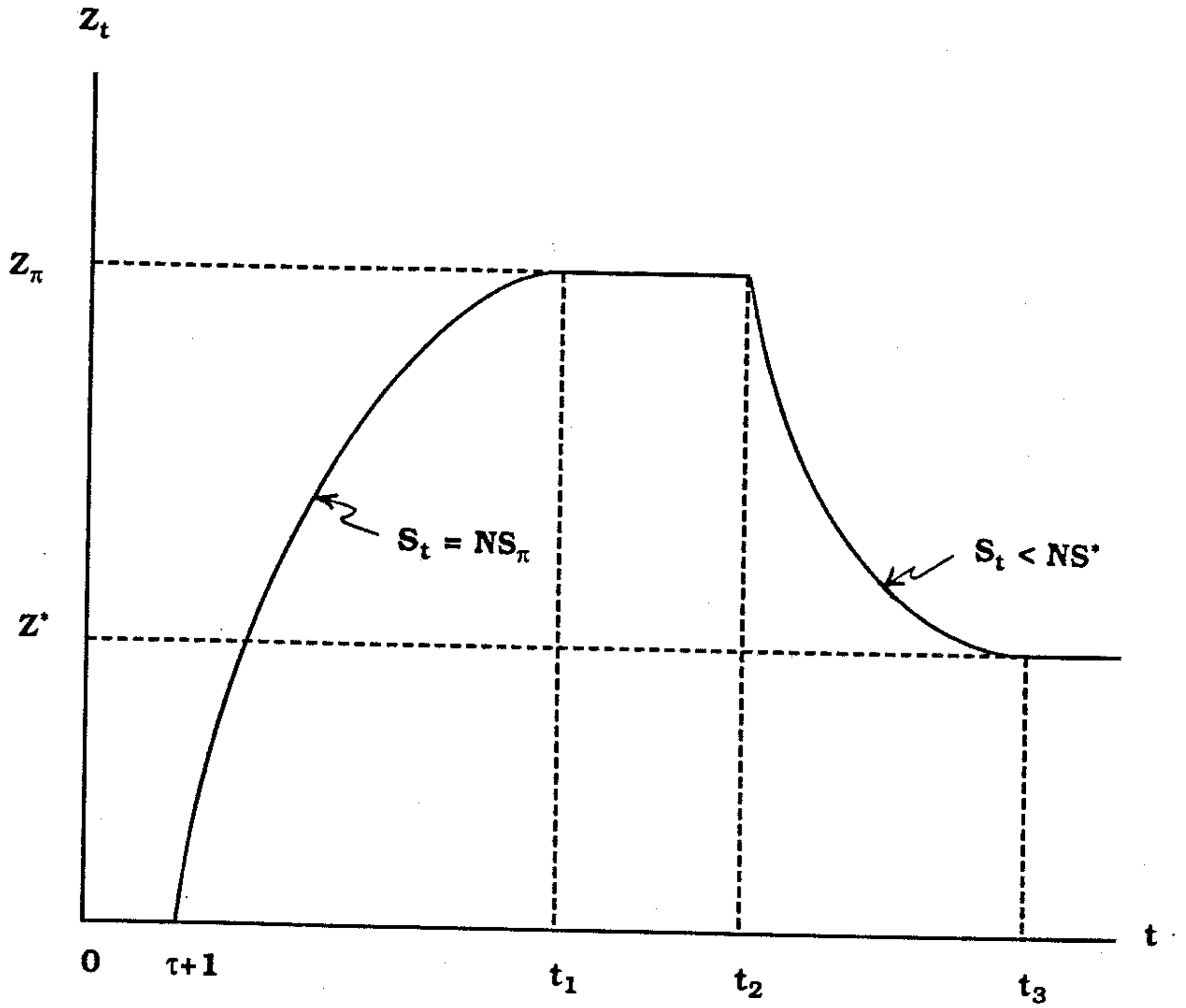

Figure 2. Observed and Simulated Aldicarb Concentrations

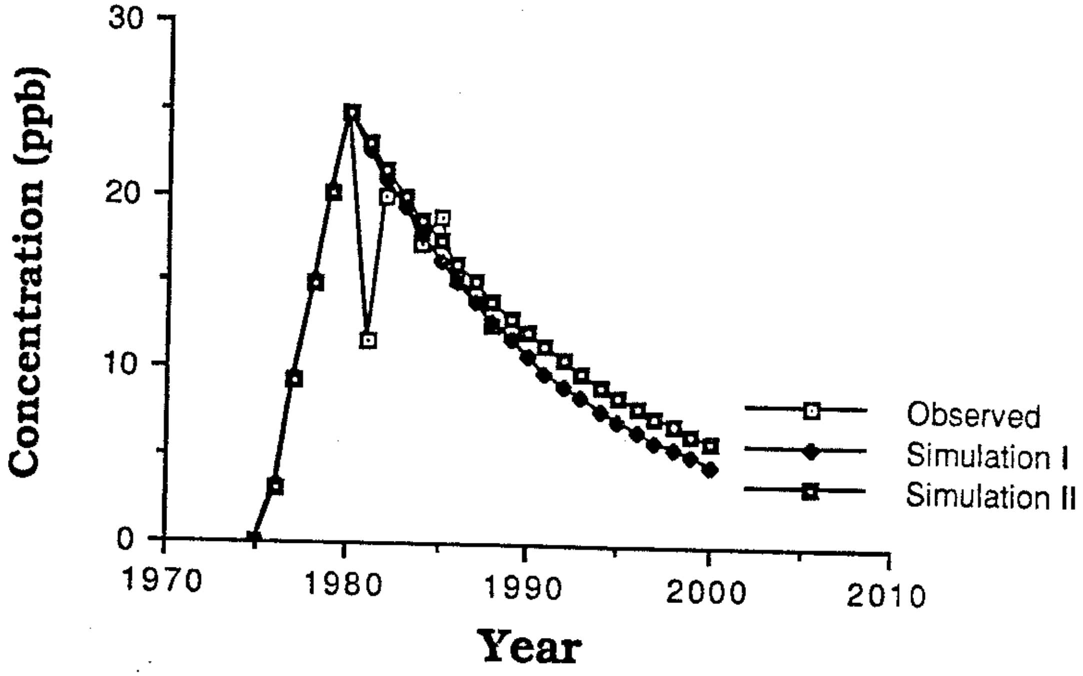

Figure 3. The Per Hectare Production Function for Long Island Potatoes

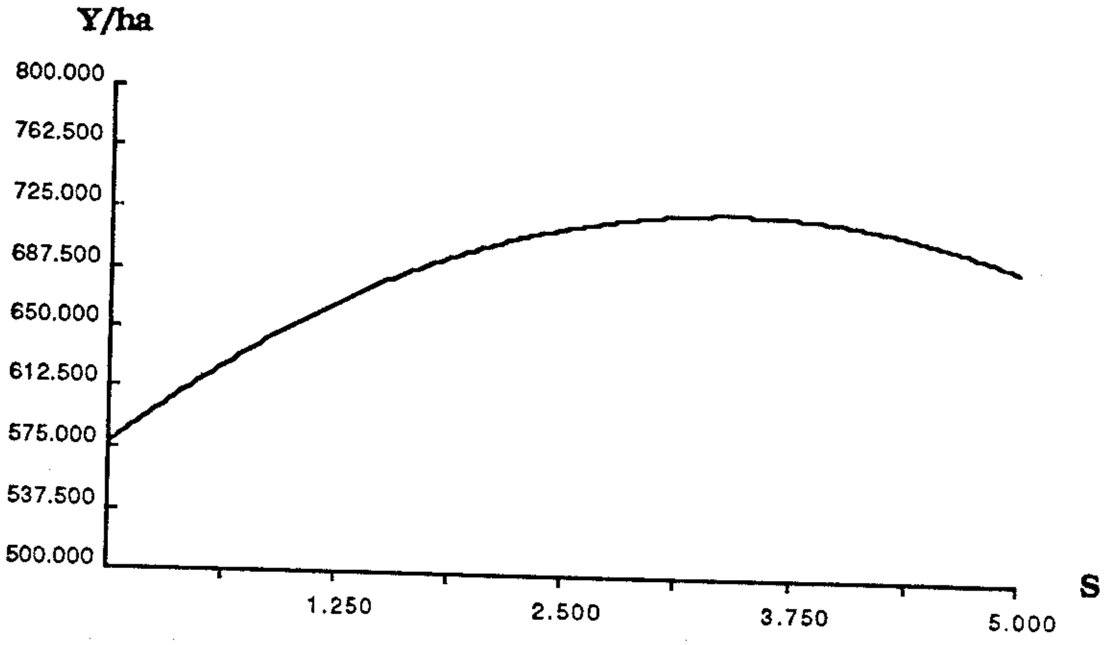

Figure 4. Isoclines, Directionals and the Stable Manifold for the Saddle-Point Equilibrium (Z^*,S^*)

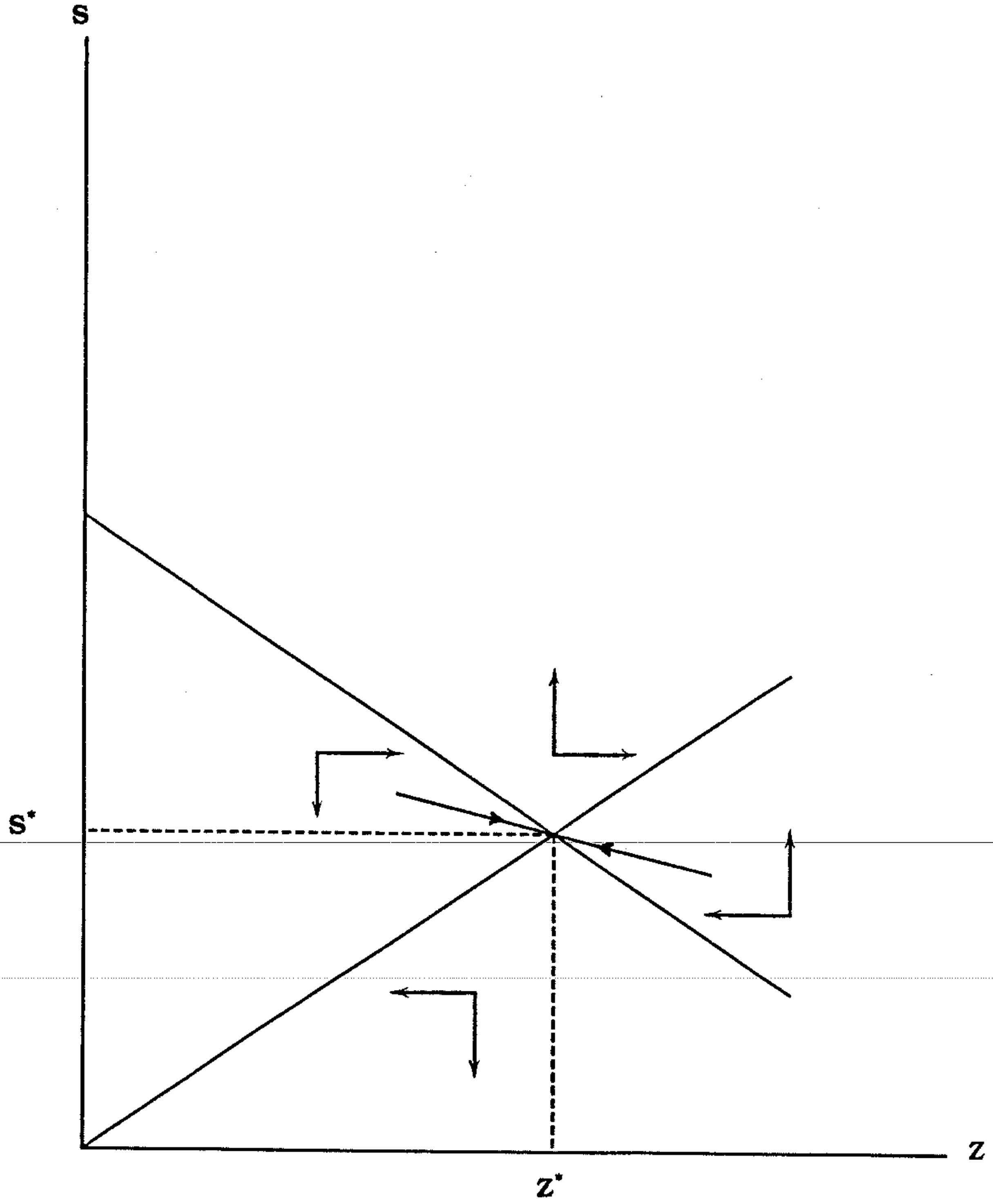

Table 1. Production, Hectares, Yield per Hectare and Aldicarb Application on Eastern Long Island, 1970-1979.

Year (t)	Production	Hectares	Yield/Hectare	Aldicarb
1970	8,293	12,545	661	0
1971	7,245	12,747	568	0
1972	5,585	10,926	511	0
1973	5,375	10,117	531	0
1974	6,750	10,926	618	0
1975	6,058	9,510	637	15,986
1976	7,409	9,712	763	32,651
1977	7,182	9,307	772	31,290
1978	6,175	9,510	649	31,972
1979	6,431	8,903	722	29,931

where

Production is measured in hundred weight (cwt.) x 10^3,

Hectares are converted from acreage figures in *New York Agricultural Statistics, 1979* ,p. 16, where 2.471 acres = 1 hectare (ha),

Total Aldicarb equals N_tS_t, where N_t are the number of hectares planted in year t and we assume that S_t = 3.362 kg/ha was applied to *half* the hectares planted in potatoes in 1975 and to *all* hectares planted in 1976 through 1979,

The mean yield per hectare from 1970 through 1974 was 577.8, while the mean yield from 1976 through 1979 was 726.5.

Table 2. Simulation of $Z_{t+1} = (1 - \gamma)Z_t + \alpha N_t S_t$ from $Z_{1975} = 0$, Aldicarb from Table 1, estimates of γ and calculated α.

Year	Obsereved Concentrations $\bar{Z}_t$	Simulation I $\gamma = 0.0793$ $\alpha=2.01\text{x}10^{-4}$	Simulation II $\gamma = 0.0684$ $\alpha=1.971\text{x}10^{-4}$
1975	-----	0.00	0.00
1976	-----	3.21	3.15
1977	-----	9.52	9.37
1978	-----	15.06	14.89
1979	-----	20.29	20.18
1980	24.7	24.70	24.70
1981	11.6	22.74	23.01
1982	20.0	20.94	21.44
1983	19.9	19.28	19.97
1984	17.2	17.75	18.60
1985	18.7	16.34	17.33
1986	15.3	15.05	16.15
1987	14.3	13.85	15.04
1988	12.6	12.75	14.01
1989	12.1	11.74	13.05
1990	-----	10.81	12.16
1991	-----	9.95	11.33
1992	-----	9.16	10.55
1993	-----	8.44	9.83
1994	-----	7.77	9.16
1995	-----	7.15	8.53
1996	-----	6.58	7.95
1997	-----	6.06	7.41
1998	-----	5.58	6.90
1999	-----	5.14	6.43
2000	-----	4.73	5.99

where

(1) $\bar{Z}_t$ are the average concentration (ppb) of aldicarb in wells that tested positive, taken from Bureau of Drinking Water (1990),
(2) In Simulation I the value for γ results from an OLS regression, intercept suppressed, of $\bar{Z}_{t+1}$ on $\bar{Z}_t$ when $\bar{Z}_{1981}$ was replaced by 22.35, the average of the observed values in 1980 and 1982, and
(3) In Simulation II the value for γ results from an OLS regression, intercept suppressed, of $\bar{Z}_{t+1}$ on $\bar{Z}_t$ omitting the observed values in 1980 and 1981.

Table 3. OLS Estimates of γ

1. Outlier Replaced by the Average of the 1980 and 1982 Concentrations

$$\overline{Z}_{t+1} = (1 - \gamma)\overline{Z}_t = \underset{(0.0255)}{0.9207}\ \overline{Z}_t$$

Number of Obsevations = n = 9
t-statistic = 36.0278
Adjusted R^2 = 0.8395
Durbin-Watson Statistic = 3.4120
Implied Value for γ = 0.0793
Implied Half-life = 8.378

2. 1980 and 1981 Observations Deleted

$$\overline{Z}_{t+1} = (1 - \gamma)\overline{Z}_t = \underset{(0.0358)}{0.9316}\ \overline{Z}_t$$

Number of Obsevations = n = 7
t-statistic = 25.9917
Adjusted R^2 = 0.7066
Durbin-Watson Statistic = 3.3339
Implied Value for γ = 0.0684
Implied Half-life = 9.783

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