Groundwater Protection Policy and Agricultural Production: a Recursive Stochastic Analysis

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Contamination of groundwater by agricultural practices presents a dilemma between protecting a vital resource and maintaining a valuable part of the economy. Policies to balance these objectives are presented. In addition to an historical baseline, policies that ban certain pesticides, taxes and subsidies, and control cultural practices are also considered. A model is developed to reflect the current state of agriculture in Eastern Suffolk County. This model consists of a recursive programming component, which has input for it generated by a stochastic model of Colorado potato beetle pest dynamics and management strategies to control those pests. While income is reduced by banning pesticides, the reduction is small when compared with the improvement in environmental quality. Further efforts to reduce pesticide use resulted in a reduction in potato acreage and incomes, as well as yields. Analysis concludes that improvements in both farm income and environmental quality could be achieved through the adoption of subsidies for low-input conservation crops.

Groundwater contamination by agricultural chemicals is a growing concern of rural communities (Nielsen and Lee; Fairchild). Management of agricultural chemicals presents a tradeoff between concerns over public health and environmental quality, and a viable farm economy. Policies that regulate pesticide use and promote cultural practices less likely to have an adverse effect on groundwater have been avoided because of their perceived economic costs. These policies can be analyzed for both their economic and environmental impacts.

Agencies responsible for the protection of water quality have been historically reluctant to regulate agriculture. Institutions that regulate agricultural impacts on groundwater faced uncertainties that have impaired program development (Milon). Adjustment to resource policies is usually adaptive, not instantaneous (Day). A recursive stochastic programming model is developed to predict changes in pesticide use, cropping patterns, and returns to farmers. A model developed to analyze the tradeoff between agricultural production and pollution incorporated stochastic elements influencing production and pollution. The incremental changes associated with responses to policy are modelled recursively. The model is then used to analyze the likelihood of further contamination and health risk. Aggregate production and pollution are analyzed to evaluate alternative policies.

A number of policies proposed to protect groundwater from agricultural pollution are presented for analysis. These included modelling production with and without a ban on pesticides; taxes and subsidies; and district management of crop rotations. The model uses Suffolk County, New York for an empirical case study.

Located on Long Island 100 miles from New York City, eastern Suffolk County has long been a major center of potato production. Recent urban growth has reduced agricultural land, with cultivated acreage falling from over 100,000 acres in 1954 to fewer than 30,000 in 1984, 14,000 of which were potatoes. Town and county governments have sought to preserve farmland in the region through a variety of programs, including property tax reductions and purchase of development rights.

Abundant potato foliage and a favorable climate created the conditions for a severe Colorado potato beetle (CPB) infestation. The CPB is a voracious feeder on solanaceous crops that reproduces rapidly on potatoes throughout the season. Resistance problems have complicated control efforts. Pesticides used to control the CPB have been found in Suffolk County's groundwater, the sole source of

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drinking water for the county's 1.5 million people (Baier and Robbins). Three of these pesticides, aldicarb, carbofuran, and oxamyl, have been prohibited from further use on Long Island.

A baseline scenario is constructed where the banned pesticides are assumed available. This is then compared to the current policy, with the bans on aldicarb, carbofuran and oxamyl. Other policies modelled include a tax rather than a ban on pesticides, a conservation subsidy for growing low input crops, and the formation of a pest control district. Policies other than the baseline and the pesticide tax assume that pesticides that have been banned or removed from the market are not available for use on Long Island. Re-registration of the banned pesticides is widely regarded as politically unacceptable. The baseline policy, however, provides a useful point of reference for the income losses associated with the subsequent ban on pesticides.

The Model

A recursive stochastic programming model of Long Island's agriculture is constructed for policy analysis. Simulations are conducted over a five year time horizon. Resource allocation in the model is based on recursive linear programming. The objective function of the model is

$$\text{(1)} \quad \text{MAX } E[\Pi_t] = \sum_{i\epsilon I}\sum_{k\epsilon K} p_i y_{ik} - \sum_{i\epsilon I}\sum_{k\epsilon K} c_{ik}x_{ik} - \sum_{\psi\epsilon\Psi} c_\psi Z_{\psi k} \quad \{t = 1, \ldots 5\}$$

Farmers are assumed to be risk neutral where $E[\Pi_t]$ is the expected profit in year t, p_i is the price of crop i, y_{ik} is the yield per acre of crop i on land k; c_{ik} is the variable cost per acre of producing crop i on land k (not counting pesticide variable costs); x_{ik} is the number of acres of crop i grown on land k; c_ψ is the cost of pesticide ψ; and $Z_{\psi k}$ is the amount of pesticide ψ used on land k. Land categories k are divided according to fertility, climate, irrigation, and cropping history: continuous potato, potato/grain rotation, potato/vegetable rotation, or continuous vegetable. Rotations are recursively linked. Activities included potatoes; field crops such as rye, wheat, oats, soybeans, field corn, dry beans and sunflowers; and vegetables, including cabbage, cauliflower, cucumbers, lettuce, onions, peppers, snap beans, spinach, sweet corn, tomatoes, summer and winter squash. The model has two sets of constraints. The first are a fixed set of constraints, B_{jt}, with technical coefficients, A, and resources, j, available in year t.

$$\text{(2)} \quad \text{s.t.} \sum_{i\epsilon I}\sum_{k\epsilon K} A_{ik}x_{ik} \leq B_{jt} \quad \{(j\epsilon J; t = 1, \ldots 5\}$$

Data from farm budgets by Lazarus and White (1983), Phelps and How, and Snyder were used for the objective function and technical coefficients. The fixed constraints included family and hired labor by season. Labor is a seasonally binding constraint that inhibits expanded cultivation of high-value, labor intensive crops, such as cauliflower and lettuce. Transfer rows are used to link production and market activities.

Land available for cultivation is determined by a set of flexibility constraints for the different crops. This models the adjustment process. Flexibility constraints for each crop are calculated by multiplying the upper and lower flexibility coefficients, $\bar{\beta}_i$ and $\underline{\beta}_i$, respectively, by the amount of crop i grown in period t − 1. The flexibility constraints are

$$\text{(3a)} \quad \sum_{k\epsilon K} x_{ikt} \leq (1 + \bar{\beta}_i)\, x_{ik(t-1)}, \text{ and}$$

$$\text{(3b)} \quad \sum_{k\epsilon K} x_{ikt} \geq (1 + \underline{\beta}_i) x_{ik(t-1)}.$$

Acreage data to estimate the flexibility coefficients were provided by New York Crop Reporting Services; and by Sanok. The constraints were set by maximum historic changes [Appendix A].

Yields of potatoes are a stochastic function of CPB population density. Farmers adapt to increased CPB resistance to pesticides by changing pest control strategies. Pest population dynamics of the CPB are an important component of the model. Adult pest densities have been shown by Logan to be a function of degree-days. The functional form used by Logan was estimated for Long Island data collected in 1981 and 1982 using a Maximum Likelihood technique. Non-linearities prevented use of ordinary least squares (OLS) estimation.

$$\text{(4)} \quad CPB = e^{b_0 + b_1(°D) + b_2(°D^2) + b_3(°D^3)},$$

where °D is the number of degree days at 10° centigrade, and b_0, b_1, b_2, and b_3 are coefficients. The coefficients were adjusted for climate, soil type, irrigation practices, and rotations [Appendix A].

These coefficients were used to simulate beetle populations for subsequent runs of the model. The variable °D was randomly generated using Monte Carlo methods. The resulting predicted CPB populations were used to simulate integrated pest management (IPM) activities, such as scouting and timing of applications. Foliar pesticides were assumed to be applied to potatoes only when CPB populations exceeded the threshold (CPB*) for a given field.

Farmers were assumed to use the thresholds provided by Wright et al. for CPB*.[1] Scouting took place in two week intervals from May to September. The model gave farmers a selection of methods to control the CPB. The decision to spray is represented by the following conditional expression

$$(5)\quad \begin{cases} Z_{\psi k \tau} = \alpha_\psi & \text{if } CPB_{k\tau} \geq CPB^* \\ Z_{\psi k \tau} = 0 & \text{if } CPB_{k\tau} < CPB^* \end{cases}$$

where $Z_{\psi k \tau}$ is the loading rate for pesticide ψ on land k in scouting period τ and α_ψ is the recommended application rate for pesticide ψ. This relation assumes both perfect information from scouting and perfect compliance with label instructions. When pesticides are applied, a certain percentage of the beetles will be killed. This percentage, known as the mortality rate, is a function of the size of the dosage, the toxicity of, and the resistance in the insects to the pesticide being used. The rate of survival can be thought of as

$$(6)\quad S_{\psi\tau} = CPB_\tau(1 - M_\psi), \{0 \leq M \leq 1\}$$

where $S_{\psi\tau}$ is the survival rate of CPBs treated with pesticide ψ in scouting period τ, and M_ψ is the mortality rate for CPBs to pesticide. The insects then recover from $S_{\psi\tau}$ and continue their growth. This model assumes that growth rates are unchanged by insecticide application within a season and remain affected only by time and temperature.

The mortality rate declines over the years as the insects become resistant to a given pesticide. This introduces a recursive aspect to the model, requiring a feedback loop that accounts for the declining efficacy of a pesticide. This states that for a given year, t, the mortality rate associated with a given pesticide will be a function of whether that pesticide was used the previous year. R_ψ is the resistance factor of pesticide ψ. This relationship is shown in (7).

$$(7)\quad M_{\psi t} = \begin{cases} \dfrac{M_{\psi(t-1)}}{R\psi} & \text{if } Z_{\psi(t-1)} > 0 \\ M_{\psi(t-1)} & \text{if } Z_{\psi(t-1)} = 0. \end{cases}$$

Predicted potato yields were calculated from cumulative CPB densities over the season. A linear function estimated by Logan was used to capture the plant/pest interaction.

$$(8)\quad \hat{Y}_k = \bar{Y}_k - \gamma\left[\sum_{\tau\epsilon t} \int_0^{{}^\circ D_\tau} CPB(^\circ D)\, d^\circ D\right],$$

where $\hat{Y}_k$ is the predicted yield of potatoes on field k, and $\bar{Y}_k$ is the maximum potential yield of field k, γ is the slope of the plant/pest interaction (estimated by Logan to be 0.000168); and $^\circ\bar{D}_\tau$ is the cumulative number of degree days in period τ. The expression in the brackets explains crop damage as a function of CPB population feeding over the season. Populations are larger and more active during warmer summers.

The pesticide loading rate for a field in a given year is derived by summing over scouting periods in the season (9).

$$(9)\quad Z_t = \sum_{\tau\epsilon t} Z_\tau.$$

The baseline model simulated farm production and pollution without a ban on pesticides. A constraint is introduced to reflect the elimination of the option to use banned pesticides. The baseline model is modified to analyze how different polices to protect groundwater change farm income and pesticide loading rates. The first is the ban on the pesticides aldicarb, carbofuran and oxamyl. Pest control decisions were based upon a choice between the pesticides kryocide, fenvalerate and rotenone.

Taxes and Subsidies

Taxes and subsidies offer farmers the opportunity to reallocate resources when correcting an externality. Several policy instruments are more likely to improve environmental quality and maintain production (Hochman, Zilberman, and Just). A tax on agricultural inputs has several advantages over other measures to remedy pollution. The cost to enforce practices would be high compared with the cost to set and collect a tax when many producers are involved (Carlson).

Equation 10 gives the objective function for a policy to tax, rather than ban, pesticides found in the groundwater.

$$(10)\quad \text{MAX } E[\Pi_t] = \sum_{i\epsilon I}\sum_{k\epsilon K} p_i y_i - \sum_{i\epsilon I}\sum_{k\epsilon K} c_{ik}x_{ik} - \sum_{\psi\epsilon\Psi}\sum_{k\epsilon K}(c_\psi + \Theta_\psi)Z_{\psi k}, \quad \{t = 1, \ldots 5\}$$

where Θ_ψ is the tax on pesticide ψ. Only the banned pesticides were taxed. Parametric programming was used to derive the tax that would drive the banned pesticides out of the optimal solution during an average infestation. This would give farmers the

[1] The objective of the analysis was more the prediction of farmer behavior given existing information, rather than optimization of thresholds. Therefore, exogenous, rather than endogenous thresholds were used. The optimal thresholds derived by Wright et al. should provide results close to endogenously determined thresholds.

option of applying materials that would otherwise be banned during severe outbreaks, but at a much higher price.

The next policy modelled was a subsidy for the cultivation of crops that required few, if any, agricultural chemicals. These are predominantly field crops with few pest, disease, or weed problems. Crops suitable for cultivation on Long Island that require few inputs and little labor include rye, oats, wheat, soybeans, sunflowers, and dry beans. Other than rye, these do not have a local market outlet, and are less profitable than potatoes (Lazarus and White, 1983). The subsidized objective function is:

$$(11) \quad \text{MAX } E[\Pi_t] = \sum_{i \epsilon I} \sum_{k \epsilon K} p_i y_i - \sum_{i \epsilon I} \sum_{k \epsilon K} (c_{ik} - ;\sigma_i) x_{ik} - c_\psi Z_{\psi k}, \quad \{t = 1, \ldots 5\}; \sigma_i > 0$$

where σ_i is the subsidy for rye, oats, wheat, soybeans, sunflowers, and dry beans, and zero for all other crops. A subsidy of $750 per acre was used. This level was sufficient to put 50% of all potato land into low-input crops. Annual payments ranged between $4 and $7 million. Subsidies lower than that would not offer farmers returns competitive with potatoes, and would therefore not be effective. Subsidies to achieve 100% participation would cost over $1,000 per acre. At that level, the subsidy would approach $20 million.

Integrated Pest Management (IPM) practices often involve externalities and public goods problems. If one farmer practices crop rotation as an IPM strategy, and his neighbors plant a host crop, that crop can serve as a reservoir for a mobile pest. If the host crop subsequently infests a rotated field, the beneficial effects of crop rotation are negated. Districts have been created for other crops to manage pest and disease controls. Examples are citrus, cotton, and sugar-beet districts in California and cotton pest control districts in North Carolina. A similar district could be formed for potatoes on Long Island.

Several tasks of the pest control district are simulated in the model. Specifically, these are that potatoes cannot be grown on the same field in two consecutive years. Pesticides are rotated to delay resistance and are selected to reduce environmental impacts to groundwater and wildlife. The district also bears the cost of scouting, and application of pest control materials. Participation is mandatory and region-wide. The crop rotation requirements of the pest control district are modelled by

$$(12) \quad \sum_{k \epsilon K_p} x_{kt} \leqslant 0.50\, x_{k(t-1)},$$

where $x_{k(t-1)}$ is the potato acreage in period $t - 1$ and x_{kt} is the acreage in potatoes in period t. Equation (12) places an upper limit on the acreage of potatoes following potatoes. Rotation from potatoes to grains are expected to disrupt the feeding of the CPB (Lazarus and White, 1984). Pesticide applications were limited to a synthetic pyrethroid with low mammalian toxicity and short half-life, fenvalerate, used with a synergist, PBO. A requirement was made that at least one-fifth of the applications use rotenone to forestall the build-up of resistance. The policies described above were analyzed for their effect on farm income, environmental risk, and fiscal impact.

Policy Analysis

The effect of the different policies on farm income, net of hired labor, variable costs, and purchased inputs, are presented in Table 1. Discounting did not change the ranking of policies. Income loss associated with the ban on pesticides can be calculated to be approximately $2.2 million undiscounted over five years. The policy that results in the highest farm income is the conservation subsidy. This is followed by the baseline policy and the policy that taxes the pesticides that have been banned. The policies that ban the use of the carbamates aldicarb, carbofuran and oxamyl do not yield as high an income as the previously mentioned policies. The policy with the lowest income is the pest control district.

The conservation subsidy provides higher in-

Table 1. Average Annual Gross Margin Under Different Policies

Rank	Policy	Million $
1.	Conservation Subsidy	37.214
	(Subsidy Payment)*	(5.931)
2.	Baseline Policy	35.145
3.	Tax on Pesticides	32.959
	(Tax Receipts)	(0.147)
4.	Current Policy	32.760
5.	Pest Control District	31.474

*The figures in parentheses represent government transfer payments.

come, both through the subsidy itself, and through releasing labor tied up in potato production to the production of high value, labor intensive vegetable crops, such as cauliflower, cabbage, sweet corn, spinach, and onions. The subsidy was set to attract one-third of the acreage in an average year. At this rate, the subsidy accounted for about 16% of farm income over a five year period. If the subsidy was too low, no farmer would adopt conservation practices. If the subsidy was set high enough, farmers would grow nothing but subsidized crops. Setting the optimal tax for pollution policy is empirically difficult (Baumol and Oates). If the tax is too low, then the result is identical to the baseline. If the tax is too high, the result is the same as a ban. Parametric programming was used to set the tax at a level that would eliminate the banned pesticides in an average year. If a CPB outbreak was significantly greater than average, the banned pesticides would enter the optimal solution.

Farm income under the pest control district was lower than other policies, despite the subsidized services provided. The opportunity cost of restrictions on potato acreage more than offset the benefits of pesticide rotation and free scouting. The pest control district policy yields a farm income 4% less than the baseline and 15% less than the conservation subsidy.

Too many factors are involved to confidently predict the fiscal impact of different policies. The cost of treating groundwater, or providing an alternative source of drinking water for wells that have already been contaminated is, in itself, a major undertaking. The most fiscally attractive policy is the taxation of pesticides, becuase it provides a source of revenue. Each alternative to the baseline policy has enforcement costs. While the baseline policy has no direct administrative costs, the great potential for leaching toxic chemicals makes its cost unpredictable and possibly great. The current policy of banning chemicals is attractive to regulatory agencies because of its predictability. Both the conservation subsidy and pest control district are potentially expensive.

Environmental Quality Indices

Economic effects alone would not adequately evaluate the different policies presented. Environmental risk is more difficult to quantify than farm income. Simulation of groundwater flows were notably unsuccessful at predicting groundwater contamination *ex ante*. Prediction of contamination levels over a large region would be inaccurate. Even if contamination levels could be accurately predicted, those levels would require heroic assumptions to translate them into dollar values.

Because of the multi-attribute nature of environmental hazard, a single number cannot give an absolute measure of risk. Pesticides have different characteristics and properties that make them have dissimilar environmental impacts. Solubility, adsorption, volatility, persistence, and toxicity all contribute to the probability that a pesticide will leach into the water table and, if it does, the degree of threat to public health. Some pesticides are more toxic than others, some more persistent. Models of solute transport are based on the interaction of these physical, chemical, and biological characteristics with soil, climate, management, and crop cover. These quantitative attributes can be combined to derive a relative measure of risk. The result is an index that can be used to rank alternative policies for their potential hazard to public health and the environment. Two indices are presented based on chemical and physical properties of different pesticides. Derivation and calculation of these indices are explained in appendix B. The leaching index gives an ordinal ranking of the likelihood that pesticides will reach the groundwater under different policies. The hazard index takes into account the acute toxicity of pesticides that are likely to contaminate groundwater. The results of the environmental indices are given in table 2.

The baseline policy has the highest leaching potential. This ranking reflects the high leaching potential of aldicarb used under this policy. The conservation subsidy has the lowest leaching potential, because it encourages the cultivation of crops that do not require the use of groundwater threatening pesticides.

There are several differences between the ranking of policies between the two indices. Rather than

Table 2. Environmental Indices

Policy	Leach Index	Hazard Index
Conservation Subsidy	0.38	0.76
Current Policy	1.00	1.00
Tax on Pesticides	1.03	0.94
Pest Control District	1.44	0.60
Baseline Policy	59.53	11,539

being the second most environmentally damaging policy as the leaching index indicates, pest control districts are the least damaging. This is brought about by the substitution of pesticides with low mammalian toxicity for more toxic ones used in the other policies.

The baseline policy is unquestionably the most harmful to human health and the environment. The evidence of this is indicated by the contamination levels of aldicarb and carbofuran in the drinking water near potato fields. Aldicarb would remain present in wells near fields in continuous potatoes. The banning of these pesticides is a sound remedy, and a good basis for other policies.

Conclusion

Research indicates that the ban on pesticides, while burdensome to farmers, still results in a positive return. Different policies to reduce pesticide use beyond banning them had little impact on the potential for groundwater contamination. Subsidies for low-input crops offer farmers the highest return of any policy, but at a cost for local government. Environmental quality indices suggest that water soluble carbamate pesticides ought not be used on Long Island. Other policies yielded indices close to one another, so the relative ranking may not be robust. However, the policy with the lowest potential for leaching pesticides is subsidy for conservation crops, while the one that poses the least hazard to public health is the formation of a pest control district.

One limitation of the model is that it does not adequately reflect transition to non-agricultural uses. Flexibility constraints control the pace at which farmland is retired, and is a naive part of the model. It is also limited because of the singular nature of Long Island.

Land use is complicated by the large and growing non-farm population in the region. Agricultural land preservation has cost local government millions of dollars, both through the purchase of development rights, and through property tax incentives. Policymakers have been reluctant to impose any regulations that would further jeopardize Long Island agriculture. Polluting agricultural practices have undermined the public support that farmland preservation programs have received. The benefits afforded by open space are negated by groundwater contamination. Public policy on Long Island seeks the means to preserve farmland and preserve agriculture.

While Long Island is a unique situation, so is every contamination incident. No single optimal policy can correct market failure in every case (Lipsey and Lancaster). This is particularly true of groundwater contamination where specific conditions and practices make generalizations misleading at best and impossible at worst. Long Island offers useful lessons because of the severity of the contamination.

Further research is required on the economics of cultivating high value specialty crops with reduced inputs. The lack of budgets for such cultivation practices mean the conservation subsidy results may not accurately reflect farm income and the fiscal impact. Despite this, the conservation subsidy appears to be the most promising policy to protect groundwater quality while allowing farms to remain solvent.

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Appendix A

Table A.1 Flexibility Coefficients for Long Island Crops

	$\bar{\beta}$	$\underline{\beta}$
Beans	1.12	0.76
Cabbage	1.30	0.87
Cauliflower	1.27	0.86
Cucumbers	1.17	0.86
Field Corn	2.00	0.80
Grains	1.57	0.67
Lettuce	1.17	0.86
Onions	1.07	0.89
Peppers	1.09	0.79
Soybeans	3.00	0.00
Spinach	1.17	0.81
Squash	1.17	0.86
Sunflowers	3.00	0.00
Tomatoes	1.09	0.81

Source: Derived from New York State Dept. of Ag. and Markets, *New York Agricultural Statistics*, 1962–1982; William Sanok, Suffolk County Cooperative Extension, Personal Communication.

Table A.2. Potato Beetle Growth Rate Coefficients

Field	b_0	b_1	b_2	b_3
1	−0.20E+00	0.12E−01	−0.40E−04	−0.60E−07
2	−0.20E+00	0.11E−01	−0.40E−04	−0.65E−07
3	−0.20E+00	0.12E−01	−0.40E−04	−0.60E−07
4	−0.20E+00	0.11E−01	−0.40E−04	−0.65E−07
5	−0.25E+00	0.12E−01	−0.40E−04	−0.60E−07
6	−0.25E+00	0.11E−01	−0.40E−04	−0.65E−07
7	−0.25E+00	0.12E−01	−0.42E−04	−0.60E−07
8	−0.25E+00	0.11E−01	−0.42E−04	−0.65E−07

Source: Adapted from Patrick A. Logan, "Estimating and Projecting Colorado Potato Beetle Density and Potato Yield Loss" in *Advances in Potato Pest Management*.

Field	Description
1	North Fork Irrigated Potato Land
2	North Fork Unirrigated Potato Land
3	North Fork Irrigated Field Land
4	North Fork Unirrigated Field Land
5	South Fork Irrigated Potato Land
6	South Fork Unirrigated Potato Land
7	South Fork Irrigated Field Land
8	South Fork Unirrigated Field Land

Appendix B
Derivation and Calculation of Environmental Indices

Indices used in the study were based on the physical, chemical and biological characteristics that influence the propensity of chemicals to leach into the water table and cause acute toxicity to consumers. The fate of pesticides depends on aqueous solubility (SOL_ψ), measured in mg/L; vapor pressure (V_ψ), measured in Pascals; and adsorption, (Koc_ψ), measured in L/Kg; and half-life ($t^{1/2}{}_\psi$), measured in days. Hydrogeology, soil and climate are also important in determining fate of pesticides. However, for the purpose of this study, these are assumed homogeneous for the study area.

Leaching potential increases as half-life and solubility increase, and decreases as volatility (vapor pressure) and adsorption increases. As vapor pressure increases, more of the pesticide is volatilized and less is apt to reach the groundwater. Similarly, if a pesticide is likely to be adsorbed to soil particles, it is less likely to reach the groundwater. A leaching index based on these principles for each pesticide in the model ($LEACH_\psi$) is presented in B_1 (Laskowski, Goring, McCall, and Swann).

$$\text{(B1)} \qquad LEACH_\psi = \left[\frac{(SOL_\psi)(t^{1}/_{2\psi})}{(V_\psi)(Koc_\psi)} \right]$$

The index is calculated by weighting the pesticide loading rate of each pesticide in the model, Z_ψ, measured in pounds of active ingredients, by the characteristics for each pesticide, $LEACH_\psi$, and summed over all pesticides (B2).

$$\text{(B2)} \qquad LEACH = \sum_{\psi \in \Psi} (LEACH_\psi)(Z_\psi)$$

Another index is constructed to take into account the acute toxicity of pesticide use under each policy. One measure of acute toxicity is LD_{50}, which is the lethal dosage for half of a test animal population in a controlled experiment. As LD_{50} decreases, toxicity and therefore hazard increase. Leaching potential is divided by $LD_{50\psi}$, the LD_{50} for each pesticide. This index is used again to weight the pesticide loading rates from the model. This is represented by HAZARD in B3.

$$\text{(b3)} \qquad \text{HAZARD} = \sum_{\psi \in \Psi} \left[\frac{\text{LEACH}_\psi}{\text{LD}_{50_\psi}} \right] (Z_\psi)$$

While the hazard index offers some measure of threat to human health, several precautions should be taken when interpreting it. One cannot extrapolate the number of poisonings from the index, without making very strong assumptions about the functional form and relation between the characteristics in the index, as well as about the population at risk. One can only say that, in comparing two policies, one with a higher hazard index has a greater chance of causing acute toxicity incidents than another. The indices fail to account for chronic toxicity, such as cancer, and fail to discount for future risks to health. Synergistic effects are assumed to be nil, and the by-products of the decay of pesticides are assumed to be non-toxic. In spite of these limitations, the environmental indices here can be useful as guides for improving policy.