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ABSTRACT

A methodology is presented that permits simultaneous consideration of the economics of production and groundwater contamination hazard of pesticide use. An example is constructed for weed control in soybean (Glycine max) production at Clayton, North Carolina. A cost/groundwater hazard frontier is developed that can be used to identify and illustrate the cost tradeoffs of selecting alternative weed control strategies that reduce the risk of adverse health effects from drinking contaminated groundwater. The methodology relies on models to estimate costs, crop yields, pest competition, and leaching of pesticides; thus, its applicability depends on availability of local data and appropriately validated models for the site considered. The cost/groundwater hazard frontier provides an excellent decision aid to assist pesticide users in making cost-effective and environmentally favorable production decisions. It is also useful in evaluating policy or the value of new pest control technologies, as it indicates a farmer's ability to substitute alternatives for currently used practices.

Coupling Groundwater Contamination With Economic Returns When Applying Farm Pesticides

Concern about agricultural pollution is increasing throughout the world. In the United States, efforts to develop or strengthen policy have been on the rise since the 1985 Farm Bill, which created programs to conserve soil and wetlands. The 1990 Farm Bill extended conservation provisions and called for additional programs such as protecting groundwater and endangered species. While the 1990 Farm Bill did not bring about as many programs to prevent groundwater pollution as some expected (Zinn, 1989), it authorized a variety of programs that will directly or indirectly influence farm contributions to water pollution (U.S. House of Representatives, 1990). Many state governments are also implementing programs to protect the environment from agriculture (Batie et al., 1989; Zinn and Tiemann, 1989). These programs include regulations on pesticide and nutrient use and cost-share programs to reduce soil erosion or facilitate animal waste handling.

While the majority of policymakers, farmers and farm advisors favor more emphasis on environment, developing and implementing effective programs will prove difficult. It will require detailed information about the impact of policies on farms and the environment. Soil conservation was relatively easy to address in the 1985 Farm Bill, since the United States had a long history of experience with the problem and an infrastructure already in place to administer conservation programs. Solutions to problems related to groundwater and surface water pollution, pesticide residues on food, and farm worker safety may not come so easily, however, since information about these problems is relatively scarce.

Policy can bring about change in three ways. Educational programs can be created to teach techniques to manage the environment better. Research can be funded that will create new technologies, and financial incentives or disincentives can be imposed to alter farmer behavior. In this paper, a methodology called a cost/environmental hazard frontier is developed to evaluate tradeoffs between environmental hazards and farm profitability. This method can be used to compare the potential for education, new technology, or financial incentives (or disincentives) to reduce environmental pollution from farms. While this technique has a variety of applications, the focus here is groundwater contamination from application of soybean herbicides. An empirical example is developed for Clayton, North Carolina.

Groundwater Contamination in North Carolina

Before the late 1970s, soils were assumed to be efficient natural filters for pesticides. In recent years, however, groundwater monitoring studies have documented that pesticides contaminate groundwater and that human health can be threatened by such contamination (Lee and Nielsen, 1987; Williams et al., 1988;USEPA, 1988; Berteau and Spath, 1986; Stara et al., 1986; Sumner and Stevens, 1986). Yet, little is known about the extent of groundwater contamination and the risk it poses to society (Lee and Nielsen, 1987). Berteau and Spath (1986, p. 433) found that in California "although a relatively large number of pesticides have been reported only a few are occurring to such an extent that their effects warrant consideration from a toxicological point of view." Results from the national groundwater sampling survey conducted by the U.S. Environmental Protection Agency (USEPA) show that less than 10 percent of wells are expected to be contaminated by pesticides and less than 1 percent are expected to exceed safe levels (USEPA, 1990).

Although evidence is inconclusive, policymakers are searching for solutions to prevent groundwater pollution by pesticides (Batie et al., 1989; Zinn and Tiemann, 1989). Therefore, a method is needed to compare the risk of groundwater contamination to the costs of preventing it. The soybean herbicide example examined here supports the view that such a method must allow for sensitivity to climatic, soil, pest, and financial conditions at the farm level (Batie et al., 1989).

A Farm Cost/Environmental Hazard Frontier

Ideally, the administrative costs and reduction in farm income incurred in preventing environmental pollution should be weighed against the private and public value of any environmental gains. On the vertical axis of the hypothetical example in Figure 1, the cost of preventing pollution is measured in dollars per hectare to implement each production technology. Environmental damage is recorded along the horizontal axis. Often it is difficult to assign dollar values to environmental or human health risks that result from farm activities. Therefore, for illustrative purposes, damages are represented on a relative scale from 0 (no damage) to 100 (the worst system).

Using this framework, the cost and environmental damage of various farming strategies can be mapped, as shown by the strategies labeled with capital letters. For example, the strategy labeled "C" causes more damage than any other strategy and therefore is rated at 100 percent on the environmental hazard scale. At $33/ha, it costs less than 20 percent of the most expensive strategy,"A," which is the least hazardous.

One advantage of mapping the costs and environmental consequences of available production technologies is that the cost of reducing pollution can be compared between any two strategies. Some strategies are eliminated because others cost less and cause less damage to the environment. For example, a grid may be placed over any strategy, as has been done for strategy "Z" in Figure 1. If the reasonable assumption is made that a person prefers more profit to less and less environmental damage to more, strategies in quadrant I would be preferred by no one. Without knowing an individual's preferences for farm profits relative to environmental concerns, strategy "Z" cannot be compared to strategies in quadrants II and IV. However, strategies in quadrant III would be preferred to "Z," since they cost less (or no more) and reduce environmental hazards (or do not increase them). Therefore, strategy "Z" is preferred to strategy "S," and cannot be compared to strategies "U" and "V," and is less desirable than strategy "Y."

A frontier of the non-dominated strategies can be derived by applying the evaluation criteria described above. Frontiers are useful tools that have been applied to a variety of environmental problems (Walker et al., 1988; Heimlich and Ogg, 1982;). The frontier in Figure 1 is the line connecting strategies "A," "B," and "C."

The cost/environmental hazard (C/EH) frontier screens out inefficient strategies. Information and education programs could be used to reduce pollution if commonly used strategies lie off the frontier. However, strategies that lie along the frontier involve a tradeoff between farm income and environmental risk. An individual or policymaker who places a relatively low value on environmental risks compared to farm returns might select a strategy at the extreme right side of the frontier, whereas another person might be willing to trade income for reduced environmental hazard.

The shape of the frontier defines the costs, or sacrifices, that must by made to attain a given reduction in environmental hazard. Where the frontier is steep, the cost per unit of hazard reduced is high. A flatter curve signifies a smaller cost per unit of reduction. For example, to move from strategy "C" to "B" would reduce the hazard by about 75 percent and increase costs by only a few dollars per hectare. Replacing strategy "B" with strategy "A," however, would reduce the hazard only slightly, whereas costs would increase by over fourfold. With these frontiers, subsidies, taxes and other policies can be evaluated. In addition, the frontiers can be customized to a farmer's situation, thereby offering a farmer more information upon which to make management decisions.

Groundwater Risks of Treatment Strategies

Leachability of a pesticide depends on several factors attributable to site conditions, managerial practices and to the chemical properties of the pesticide's active ingredient (A.I.). Managerial practices include such factors as the rate, timing and method of pesticide application as well as the care exercised by farm workers when transporting and applying pesticides. Any method that lessons exposure of a pesticide to the environment would reduce the potential for that pesticide to leach into groundwater.

Total groundwater contamination hazard is a function of a chemical's toxicity and the quantity that leaches into the groundwater. The quantity that leaches depends on the persistence of pesticides used and their mobility through soil. In a draft working document, a group of mostly EPA scientists concerned about the Chesapeake Bay area proposed the following groundwater index (Koroncai et al., 1989):

$$I = \frac{\text{application rate x percent leached}}{\text{drinking water criterion x 100}}$$

Percent of pesticide leached was to be estimated by the LEACH model (Dean et al., 1984) and the water quality criterion was to be based on indicators of toxicity. The Soil Conservation Service devised a similar pesticide evaluation procedure relying on the partition coefficient (K_{oc}), soil half-life ($t_{1/2}$), and acute oral toxicity (LD_{50}) of a pesticide to predict its potential to leach and its toxicity (SCS, 1988).

Rao et al. (1985), Jury et al. (1987), Dean et al. (1984) and others have found that local environmental and soil conditions (rainfall, organic matter, depth to groundwater, etc.) also influence the migration of chemicals into groundwater. However, Gustafson (1989) showed that Jury's results fit closely with a model independent of soil properties but dependent on chemical properties of sorption and dissipation. Gustafson also showed that K_{oc} alone is a reasonable measure of the average mobility of chemicals that sorb mainly to the organic carbon fraction of soil. For most soils, the K_{oc} can be calculated from K_d (ratio of concentrations in soil to aqueous phase) by dividing through by the organic carbon content of the soil. Thus, K_{oc} can function as a soil-independent measure of mobility (SCS, 1988; Gustafson, 1989).

The use of K_{oc} and $t_{1/2}$ reduces data requirements and produces results sufficient to demonstrate the C/EH frontier. Using the curves representing percent leached in 2 percent intervals for log K_{oc} and log $t_{1/2}$ values (Figure 6 in Gustafson (1989)), the percent leached was interpolated for each pesticide's active ingredient form. The contour lines in Gustafson's Figure 6 are based on a steady-state, analytical solution of a convective-dispersive equation using the following parameter values: growth rate of the dispersion coefficient of 0.5; mean velocity of water of 1 cm/day; soil bulk density of 1.4 g/cm^3; and field capacity water content of 0.2 cm^3/cm^3. For use on specific farms, the estimates of the fraction leached could be improved by using a transient water flow environmental fate model (e.g., Nofziger and Hornsby, 1987) and site-specific data for soils and climatic variables.

To develop the groundwater hazard index (GHI), a measure of pesticide toxicity in groundwater must be compared to the amount leached through the soil profile. The most serious threat to human health from pesticides in groundwater is through drinking water. The USEPA has developed health advisory levels (HAL) for about 60 pesticides used in crop production (USEPA, 1989b). These advisories describe possible health effects of pesticides and define a concentration threshold in drinking water that represents no adverse health effect when consumed at that concentration for a lifetime (70 years). The thresholds include a "margin of safety" and are based on consideration of both chronic and acute health effects.

Unfortunately, health advisories have been developed for relatively few pesticides. Only five of the soybean herbicides examined here have been assigned HAL values: acifluorfen (5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid), bentazon (3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide), chlorimuron (2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino] carbonyl] amino] sulfonyl] benzoic acid), metribuzin (4-amino-6-(1,1-dimethylethyl)-3-(methylthio-)-1,2,4-triazin-5(4*H*)-one), and trifluralin (2,6-dinitro-*N*,*N*-dopropyl-4-(trifluoromethyl)benzeamine). The LD_{50} is sometimes used as a next best proxy for exposure risk (Heimlich and Ogg, 1982; SCS, 1988). The LD_{50} is the dose of the chemical necessary to kill half of the population exposed to it over a given time period. The LD_{50} has been determined for relatively harmless chemicals as well as for harmful ones and measures only acute risk.

Although EPA has released relatively few lifetime health advisory levels (HALs) for pesticides, reference-dose values are available for many additional pesticides; this permits calculation of HAL estimates using the same procedure as the USEPA (USEPA, 1989b). As shown in Figure 2, the USEPA uses dose-response functions to portray risks of harmful health effects from chemicals. For cancer, the potency is defined as the increased lifetime risk of getting cancer from a lifetime average daily dose of 1 mg per kg per day. For noncancerous health effects, a threshold dose is defined as the dose below which a person suffers no adverse health effects. The linear estimate of the cancer potency curve is estimated with statistical models that are likely to overestimate risk. The threshold levels for noncancerous chemicals are adjusted downward by dividing by 10 to 1000 to factor in added safety.

The toxicity and leachability of chemicals as defined above form the groundwater hazard index (GHI):

$$\text{GHI} = \frac{C_{gw}}{\text{HAL}}, \quad C_{gw} = \frac{\text{amount A.I. leached per unit area}}{\text{(unit area)(depth of mixing)(aquifer porosity)}}$$

where C_{gw} is the concentration (μg/l) in the groundwater assuming: 1) that pesticides leaching below the 1.0-m soil depth will not further degrade; 2) that they will mix only to a depth of 1.0 m in the aquifer; 3) that the aquifer porosity is 0.25; and 4) that the aquifer is horizontally confined (no dilution by off-site lateral groundwater flow). Appropriate unit conversion is necessary for this calculation.

Where EPA lifetime HALs are published, they are used. For pesticides for which the USEPA has not yet issued HALs and that are not suspected to be carcinogenic, HAL equivalents have been calculated by multiplying the reference dose, RfD, by 7,000. The estimates used here likely will not differ by more than a factor of 10 from the HAL values ultimately released by the USEPA.

For herbicide strategies that involve multiple active ingredients, the GHI is calculated as follows:

$$GHI = [(C_{gw,1}) / (HAL_1)] + [C_{gw,2}) / (HAL_2)] + \cdots\cdots\cdot [(C_{gw,n}) / (HAL_n)]$$

where subscripts 1, 2, ····· n designate multiple chemicals used in a given strategy. The above GHI assumes that the groundwater health hazard associated with each strategy is additive if multiple active ingredients constitute the chemical strategy. Although this assumption may be controversial, it is a logical approach until interactive effects are quantified, since the consumption risks of many chemicals are additive.

The actual concentration of pesticide residues in groundwater consumed by humans is highly difficult to estimate with the limited site data available. The assumptions made above are extremely conservative in that: 1) some further degradation of the pesticides likely will take place between the one meter soil depth and the groundwater table; 2) no drinking water well should be screened within 1 m of the water table (10 meters would be a more reasonable minimum depth considering fluctuating water tables and pathogen contamination of shallow wells); and 3) horizontal flow from areas not treated with pesticides is likely to reduce the concentration in other areas through dilution. Thus, the GHI as calculated above gives a conservative estimate of pesticide concentration in drinking water for each chemical control strategy. Essentially the root-zone, soil-solution concentrations are being compared to groundwater concentrations that the USEPA has determined causes no adverse effects to human health. Actual concentrations in groundwater would likely be lower and the period of exposure is not considered, since it is unlikely that the same chemicals will be used over a seventy-year period.

The GHI values fall on a continuum from very small numbers greater than zero to values exceeding 1.0, to an unknown magnitude. A GHI value of 1.0 is equivalent to the HAL in drinking water where the risk of adverse health effects are expected to be insignificant. GHI values less than 1.0 indicate with relative certainty insignificant risks to human health, since conservative assumptions have been made about exposure. Values greater than 1.0 indicate higher health risk associated with drinking water supplies but do not necessarily imply a significant risk because of the conservative exposure assumptions made here.

An Application

Clayton, North Carolina, the site of a North Carolina State University agricultural research station, is the location of the example developed in this paper. Based on judgments of Cooperative Extension crop and weed scientists, common cocklebur (Xanthium strumarium), redroot pigweed (Amaranthus retroflexus) and rhizome johnsongrass (Sorghum halepense) were selected as weed species likely to be found in the Clayton area.

Usually information needed to develop a detailed farm-level C/EH frontier is scarce. Fortunately, in this case, data generation was facilitated by a soybean weed management simulation model, WEEDING, developed at North Carolina State University (Wiles et al., 1989). Given a selected set of weeds, their corresponding population densities, and annual weather records, WEEDING was used to simulate soybean and weed growth. The model allowed for scouting at any time ten days after the crop was planted. Each simulation can include one pre-emergence treatment and up to two post-emergence treatments. Simulations were designed to imitate farm conditions by modeling crop and weed growth, weed competition with the crop, scouting, and to follow Extension recommendations to determine treatment alternatives.

Using herbicide recommendations provided by the North Carolina Agricultural Chemical Handbook (Lewis et al., 1989), seventeen plausible weed treatment strategies were determined for cocklebur, pigweed and johnsongrass. Each treatment strategy was recommended by the handbook as a good or excellent control for the type of weed modeled. Not all of the herbicide possibilities are contained in the present version of WEEDING, which limited the available treatment strategies. WEEDING was used to simulate the efficacy of herbicide treatments under high and low weed populations. Measured as plants per 10 meters of row, a low density of cocklebur, pigweed and johnsongrass was defined to be 2, 4.2 and 25, respectively. High density was defined to be 50, 60 and 90, respectively.

Costs for high and low weed pressure are shown in Table 1. The cost of each treatment strategy is equal to the cost of the chemical applied plus the "opportunity cost" or value of yield losses that the strategy fails to prevent. The opportunity cost is determined by multiplying the price of soybeans by the difference in the weed-free yield and yield realized with the treatment. For simplicity, yield estimates represent only one year, 1984, and one soil type in Clayton, North Carolina.

Yield without any weeds would be 2741.8 kg/ha. Without any herbicide, yields would fall to 2466.2 kg/ha with low weed pressure and 1337.3 kg/ha with high weed pressure. The cost of each strategy with high weed pressure is two and one-half times greater on the average than for strategies under low pressure. With high weed pressure, greater yield losses are incurred from weeds not controlled by the herbicide treatment. The standard deviations of costs under high pressure are also much greater than under low pressure for the same reason.

The cost ranking of the treatment strategies differs under high and low weed pressure. For example, the strategy using Scepter alone is less costly than the one using Scepter plus Fusilade under low weed pressure, because the Fusilade costs more than the extra weed protection it provides. However, the strategy using Scepter alone costs twice as much under high weed pressure because Fusilade's added weed control would justify its cost. Therefore, weed pressure is a critical determinant of control cost and of a grower's opportunity to alter practices to reduce groundwater contamination.

Results

Soil $t_{1/2}$, K_{oc}, HAL, and the resulting groundwater hazard index for each alternative herbicide treatment strategy are listed in Table 2. As shown in column (h), the GHI for no herbicides, strategy 1, is zero, since nothing was applied. Three strategies, 10, 13, and 16, had GHI values greater than 1.0. Each of these strategies used acifluorfen at a 0.567 kg/ha rate. Strategies 3, 4, 6, and 9 have GHI values of 0.61 to 0.69 primarily because of the properties of metribuzin. The remaining strategies had GHI values below 0.28.

Most of the strategies had very low GHI values. These strategies appear to pose very little threat to human health, especially considering the conservative groundwater concentration estimation procedure used. At the rates applied, imazaquin(2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid) and fluazifop ((*RS*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl] oxy] phenoxy] propionic acid) each were less than 1.2 percent of the concentration HAL that EPA considers safe. Chlorimuron was relatively low at 0.07 when used at a rate of 0.040 kg/ha (Classic) and at 0.66 when applied at 0.086 kg/ha (Canopy).

The GHI values presented for each strategy in Table 2 are plotted against the cost of each strategy from Table 1 to construct cost/groundwater hazard frontiers (C/GHI) for high and low weed pressures (Figures 3 and 4). The shapes of actual frontiers vary significantly with farm circumstances. The income effect of a strategy change is substantially larger for the farmer with high weed pressure (Figure 3). For example, yield losses from using a strategy of no pesticides would cost a farmer about $62/ha under low weed pressure compared to about $309/ha under high weed pressure.

These results demonstrate that local conditions can be important in defining a farmer's ability to reduce groundwater risk. Only one of many possible factors (weed pressure) that could alter the slope of the frontier has been considered. Other factors specific to each farm could also be evaluated and likely would further alter the frontier slopes and therefore the cost-groundwater hazard tradeoffs. For example, adding one new weed (sicklepod, for example) would completely change the costs of the alternative treatment strategies because of the abilities of the individual chemicals to control that particular weed.

Only four strategies, 7, 17, 2, and 1, are contained in the high weed pressure frontier (Figure 3), and strategies 2 and 1 make up the frontier under low weed pressure (Figure 4). Both frontiers contain strategies with GHI values ranging from near zero to about 30 percent (0.30) of the HAL concentration in groundwater. Three strategies, 10, 13, and 16, have GHI values greater than 2.0 for both low and high weed pressures. Moving away from these strategies to any of the other 14 strategies would reduce groundwater hazard. Ten strategies are more efficient, cost less, and have lower GHIs under low weed pressure, and nine under high weed pressure. Both frontiers show that from a technical standpoint risk may be reduced at no cost to the farmer, and sometimes to his benefit. A creative educational program may be necessary to convey the frontier concepts effectively. In addition, farmers may have legitimate concerns about a third dimension other than cost or GWH that results in a rational choice of a strategy off the frontier.

Strategies along the frontiers involve tradeoffs between profit and risk that can vary greatly for different individuals. It may be inexpensive to reduce risk for some individuals, but others may face sizable costs. For example, the cost difference between the lowest risk strategy and the least costly strategy is only \$6/ha on the low-weed frontier but is over \$251/ha on the high weed frontier. The high weed frontier yields a relatively small tradeoff (\$10.41/ha) when moving from a GHI of 0.27 for the least costly strategy (7) on the frontier to a GHI of 0.08 for the second least costly strategy (17). Moving further along the frontier to the next strategy (2) would cost an additional \$57.79/ha with a GHI of 0.02.

New policies could be introduced to provide financial assistance for producers to move from one point on the frontier to another. Financial penalties could achieve the same goal, and money for research and development could also be increased. New technology could alter the shape and therefore the cost-hazard tradeoffs. For example, without strategy 2, the low-weed pressure frontier in Figure 3 would contain strategies 7, 5, and 1 and would be less steep.

The GWH indexes fell into three groups: greater than 1.0, 0.61 to 0.69, and less than 0.28. Only three strategies had groundwater concentrations greater than 100 percent of the USEPA lifetime HALs in the root zone. These strategies are not necessarily hazardous (considering the conservative estimation procedure), but further investigation is warranted. Acifluorfen, for example, has not been found in groundwater at significant levels and therefore may be influenced by some mitigating factors. As for those strategies with GHI values less than 0.28, it could be reasoned that there is no statistical difference in hazard between the majority of those presented here, given measurement error.

Taking a less conservative approach, it is more likely that the mixing depths that represent rural domestic drinking water wells will be more on the order of 10 m rather than 1 m. This will have the effect of reducing the GHI and C_{gw} values in Table 2 by an order of magnitude. Under this scenario, the largest GHI value for any strategy would be slightly less than 0.23, indicating that human health hazard is minimal.

The results of this example indicate that public expectations for farmers to reduce groundwater contamination from applied pesticides may not always be justified, since all strategies considered here were below reasonable levels that may cause adverse health effects. Results will vary for different soils, pests, climates and general farm conditions. However, further analysis is in order, since it cannot be assumed either way that pesticides are or are not a health concern in other situations.

Summary and Conclusions

A cost/groundwater contamination hazard frontier was developed for herbicide applications to soybeans in North Carolina. Soybean growth was simulated with a model using an empirical example and crop production experts to define field conditions, weed type and density, weather, soil type and other agronomic factors. Extension recommendations for weed management were utilized much the same way a farmer would use them to develop a variety of practical weed treatment strategies. The cost and risk of groundwater contamination were then computed and compared for each strategy.

The tradeoff of cost for groundwater contamination risk was very different under high and low weed pressures. Nevertheless, under both scenarios, the pesticide concentration in groundwater could be reduced to less than 20 percent of the EPA health advisory levels simply by choosing a lower risk strategy with equal or greater profitability. With little or no information to guide them in choosing pesticides that avoid excessive leaching, farmers historically have paid little attention to groundwater pollution in their production choices. These decisions probably resulted in greater risks to groundwater than are technically necessary. Therefore, an education program to show farmers economic and groundwater risk tradeoffs for their soils may be valuable if administrative costs are not prohibitive.

For this example, the cost/hazard frontier provided only marginal information. Only three strategies imposed risks exceeding the EPA lifetime health advisory levels, even under the conservative assumptions made here (mixing in aquifer to 1.0 m depth), and none were on the frontiers. The strategies on the frontier likely were not statistically different from others nearby.

The results of the low and high weed pressure scenarios showed that the cost to reduce risk under efficient strategies (those on the frontier) could vary considerably under different production conditions. Altering the weed types or densities in the examples would have yielded other results. Initial weed conditions and other agronomic factors likely will affect a farmer's cost to reduce environmental risks. Therefore, some farmers may be in a better position than others to alter their production practices to reduce groundwater contamination.

This analysis also has highlighted the importance of considering measures of toxicity in evaluating the significance of human health hazards that might otherwise be inferred from considering only the leaching and persistence of pesticides in soils. Imazaquin leaches more readily than other products in Table 2; however, the low application rate and low toxicity result in the lowest GHI index of the herbicide strategies presented in this paper. While sorption and degradation certainly are important parameters to use in estimating exposure, toxicity as expressed in the GHI determines the hazard and must be incorporated in indices used to guide stewardship of pesticides in agricultural and urban settings. These results highlight the need for improved information about risk assessment for agricultural chemicals.

Finally, this paper has used a single example to demonstrate the concept of a cost/environmental hazard frontier. The methodology employed can be applied to a variety of practical problems. Fate and transport models, weather, soil types, pest types and densities, cost of pest treatments, and other variables can be redefined as needed to fit the questions asked and the conditions where they are asked.

Nomenclature: Acifluorfen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid; Bentazon, 3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide; Chlorimuron, 2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino] carbonyl] amino] sulfonyl] benzoic acid; Fluazifop, (*RS*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl] oxy] phenoxy] propionic acid; Imazaquin, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid; Metribuzin, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio-)-1,2,4-triazin-5(4*H*)-one; Trifluralin, 2,6-dinitro-*N*,*N*-dopropyl-4-(trifluoromethyl)benzeamine.

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Table 1: Yields and costs of soybean weed treatment alternatives in Clayton, North Carolina.[†]

ALTERNATIVE TREATMENT[‡] STRATEGIES			TREAT-MENT COSTS	YIELD[§] WEED PRESSURE		COST[¶] WEED PRESSURE	
#	TIME	CHEMICALS		LOW	HIGH	LOW	HIGH
			--$/ha--	----kg/ha----		----$/ha---	
1.	none	none	0.00	2466.2	1337.3	61.61	308.99
2.	pre	Scepter	29.78	2627.5	2305.0	54.91	125.87
3.	pre	Canopy	37.04	2627.5	2305 0	62.17	133.13
4.	pre	Salute	25.63	2553.6	1639.7	67.02	268.88
5.	pre	Treflan	8.02	2513.3	1451.5	58.29	291.88
6.	pre	Sencor	26.37	2546.9	1666.6	69.24	262.91
7.	pre post	Scepter Fusilade	57.65	2741.8	2741.8	57.65	57.65
8.	pre post	Treflan Scepter	40.99	2641.0	2392.3	63.16	117.86
9.	pre post	Sencor Fusilade	54.25	2654.4	1854.7	73.47	249.40
10.	pre post	Treflan Blazer	43.31	2607.4	1969.0	72.88	213.32
11.	pre post	Treflan Storm	59.60	2641.0	2385.6	81.78	137.96
12.	post	Storm	51.58	2620.8	2264.6	78.19	156.55
13.	post	Blazer	35.28	2587.2	1908.5	69.29	218.61
14.	post	Classic	40.22	2620.8	2305.0	66.83	136.32
15.	post post	Storm Fusilade	79.46	2728.3	2688.0	82.41	91.28
16.	post post	Blazer Fusilade	63.16	2688.0	2237.8	74.99	174.04
17.	post post	Classic Fusilade	68.10	2741.8	2741.8	68.10	68.10
Summary statistics per treatment:							
			-$/ha-	----kg/ha----		----$/ha----	
MEAN :			42.38	2624.0	2129.1	68.29	177.46
STD Deviation:			20.27	74.3	420.8	8.00	79.24

[†] Soybean variety Ransome (7) produced in 1984 under a typical weed population of cocklebur, redroot pigweed and rhizome johnsongrass (<20.3 cm) on Norfolk sandy loam soil (fine loamy, siliceous, thermic, typic, paleudult) with organic matter content of less than 5%.

[‡] Treatment alternatives selected on the basis of recommendations made by Lewis et al. (1989).

[§] YIELD determined from WEEDING simulation model by Wiles et al. (1989).

[¶] COST is equal to treatment cost plus $0.22/kg times difference in actual yield and the potential "weed-free" yield of 2741.8 kg/ha.

Table 2. Chemical properties, leaching, toxicity and pesticide hazard index for alternative herbicide treatments for soybeans.

Treatment Strategies¶¶ No.	Type	Trade ame	Common Name	(†) A.I. Appl. kg/ha	(‡) K_{oc} M^3/kg	(§) $T_{1/2}$ days	(¶) Percent Leached %	(#) Amount Leached kg/ha	(††) HAL or HALEQ* µg/l	(‡‡) Conc. in GW µg/l	(§§) GWH INDEX (g)/(f)
1	n/a##	none	n/a	0.0	n/a	n/a	0.0	0.0	n/a	0.0	0.0
2	pre	Scepter	imazaquin	0.140	0.020	60	58	0.0812	1750*	32.48	0.02
3	pre	Canopy	6:metribuzin	0.540	0.090	40	48	0.2592	200	103.68	0.66
			1:chlorimuron	0.086	0.110	40	6	0.0052	14	2.06	
4	pre	Salute	1:trifluralin	0.420	8.000	60	0.1	0.0004	2	0.17	0.69
			1:metribuzin	0.631	0.090	40	48	0.3029	200	121.16	
5	pre	Treflan	trifluralin	0.560	8.000	60	0.1	0.0006	2	0.22	0.09
6	pre	Sencor	metribuzin	0.631	0.090	40	48	0.3029	200	121.15	0.61
7	pre	Scepter	imazaquin	0.140	0.020	60	58	0.0812	1750*	32.48	0.27
	post	Fusilade	fluazifop	0.142	5.700	15	0.1	0.0001	7*	0.06	
8	pre	Treflan	trifluralin	0.560	8.000	60	0.1	0.0006	2	0.22	0.11
	post	Scepter	imazaquin	0.140	0.020	60	58	0.0812	1750*	32.48	
9	pre	Sencor	metribuzin	0.631	0.090	40	48	0.3029	200	121.15	0.61
	post	Fusilade	fluazifop	0.142	5.700	15	0.1	0.0001	7*	0.06	
10	pre	Treflan	trifluralin	0.560	8.000	60	0.1	0.0006	2	0.22	2.34
	post	Blazer	acifluorfen	0.567	0.113	14	1.0	0.0057	1	2.27	
11	pre	Treflan	trifluralin	0.560	8.000	60	0.1	0.0006	2	0.22	0.18
	post	Storm	1:bentazon	0.420	0.034	20	7	0.0294	20	11.76	
			1:acifluorfen	0.213	0.113	14	0.1	0.0002	1	0.09	
12	post	Storm	1:bentazon	0.420	0.034	20	7	0.0294	20	11.76	0.09
			1:acifluorfen	0.213	0.113	14	0.1	0.0002	1	0.09	
13	post	Blazer	acifluorfen	0.567	0.113	14	1.0	0.0057	1	2.27	2.28
14	post	Classic	chlorimuron	0.040	0.110	40	6	0.0024	14	0.96	0.07
15	post	Storm	1:bentazon	0.420	0.034	20	7	0.0294	20	11.76	0.10
			1:acifluorfen	0.213	0.113	14	0.1	0.0002	1	0.09	
	post	Fusilade	fluazifop	0.142	5.700	15	0.1	0.0001	7*	0.06	
16	post	Blazer	acifluorfen	0.567	0.113	14	1.0	0.0057	1	2.27	2.29
	post	Fusilade	fluazifop	0.142	5.700	15	0.1	0.0001	7*	0.06	
17	post	Classic	chlorimuron	0.040	0.110	40	6	0.0024	14	0.96	0.08
	post	Fusilade	fluazifop	0.142	5.700	15	0.1	0.0001	7*	0.06	

† A.I. Appl. = kilograms active ingredient applied per hectare (recommended rate).

‡ K_{oc} = sorption coefficient normalized with respect to soil organic carbon. Values taken from Wauchope et al. (1991).

§ $t_{1/2}$ = degradation half-life in soil, a measure of persistence. Values taken from Wauchope et al. (1991).

¶ Percent Leached = percent of active ingredient leached as predicted by steady state model (Gustafson, 1989).

\# Amount Leached = A.I. applied,(a), multiplied by percent leached (d).

†† HAL or HALEQ* = the U.S. EPA lifetime health advisory level or equivalent calculated from USEPA reference dose, RfD, multiplied by 7000.

‡‡ Conc. in G.W. = Concentration in groundwater, C_{gw}, (assume 1.0m mixing depth, 0.25 porosity, and no dilution from horizontal flow).

§§ GHI = Groundwater hazard index, C_{gw} divided by HAL or HALEQ*. For multiple active ingredients in a given treatment alternative, an additive index was used, as defined in the text.

¶¶ Pre = Pre-emergent or pre-plant application of pesticides; Post = post emergence application of pesticides.

\## n/a = not applicable.

Figure 1: Conceptual cost/envionmental hazard frontier. Points (asterisks) represent alternative control strategies for pest control.

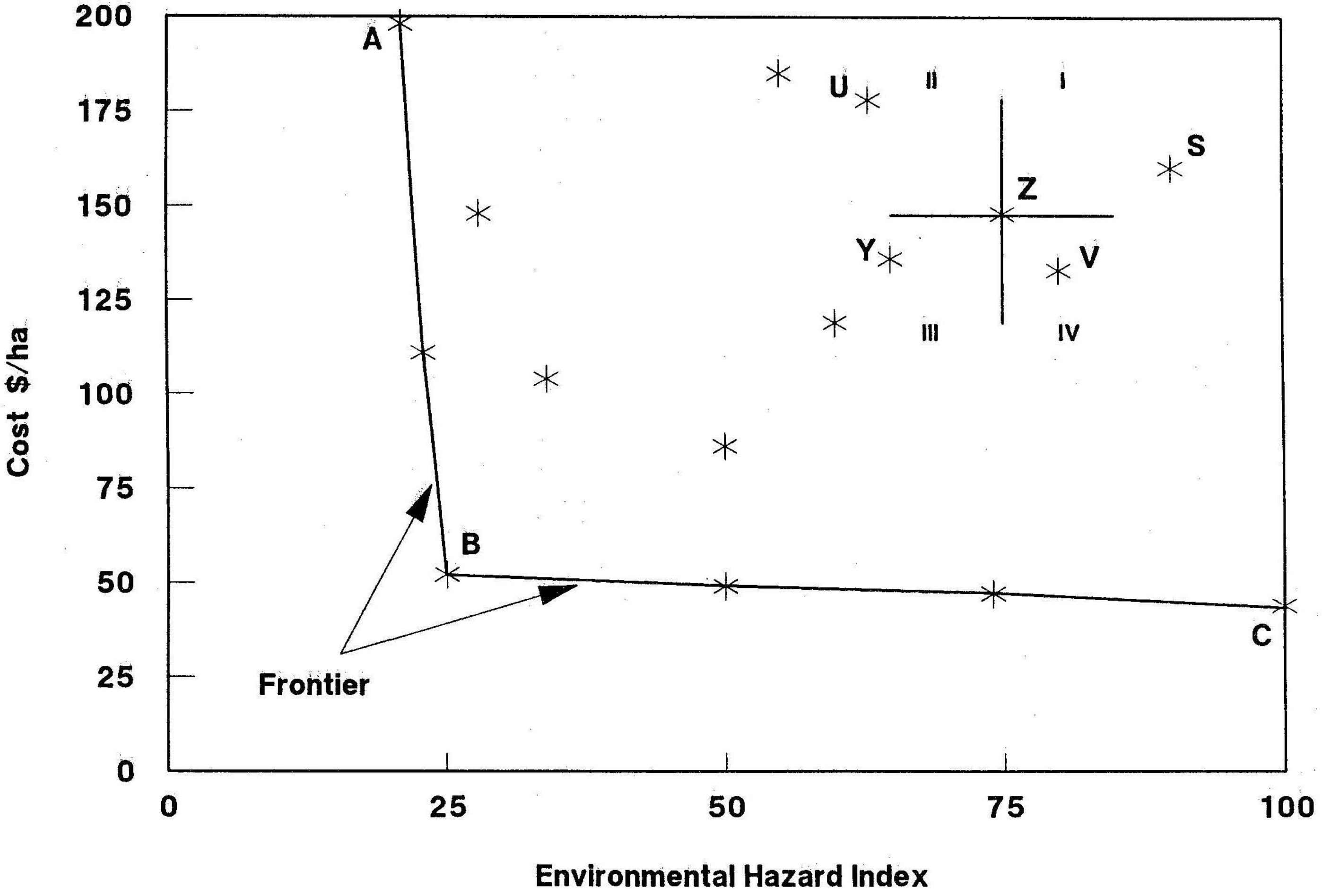

Figure 2: The USEPA approach to dose-response estimates.

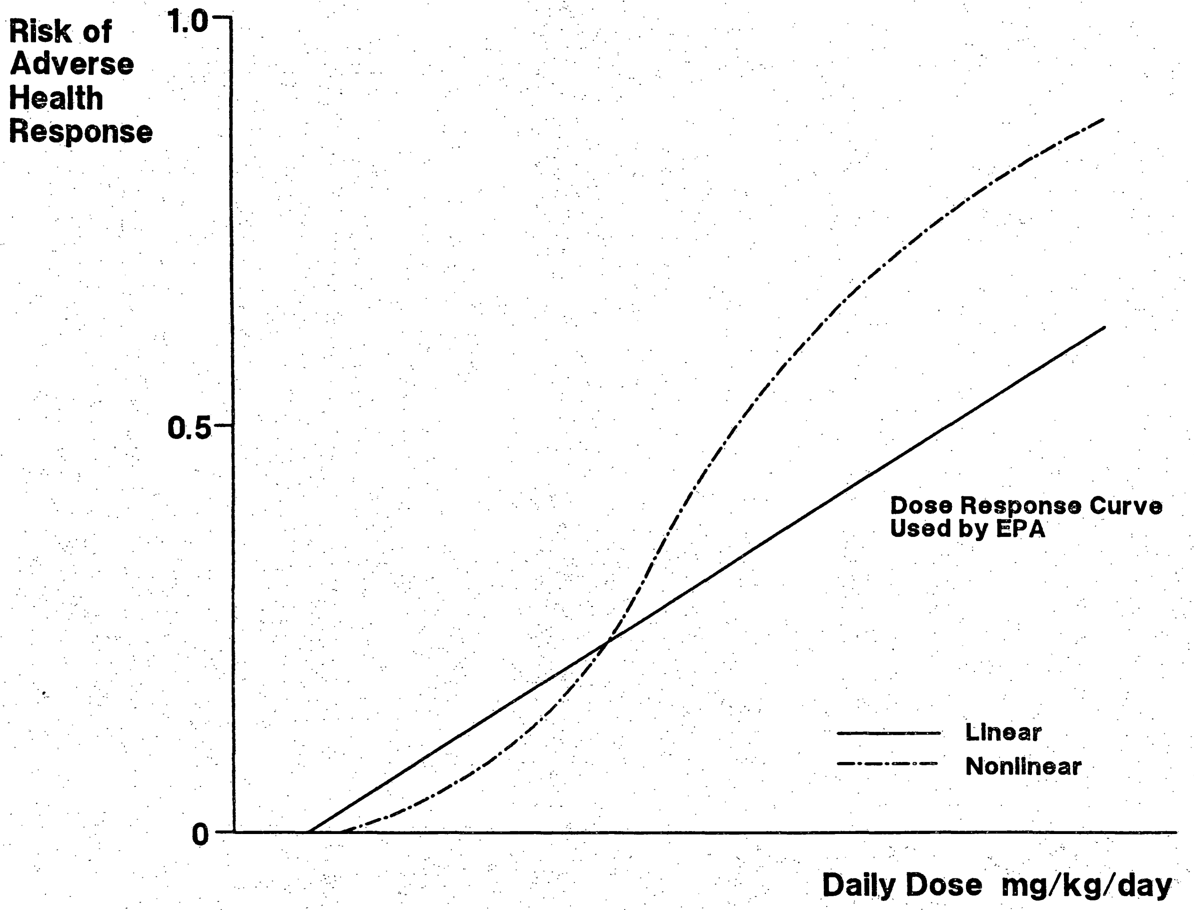

Figure 3: Cost/groundwater hazard frontier for soybean production under high weed pressure assuming 1.0-m mixing depth in the aquifer with a porosity of 0.25. Points (asterisks) represent alternative herbicide strategies for control of specific weeds.

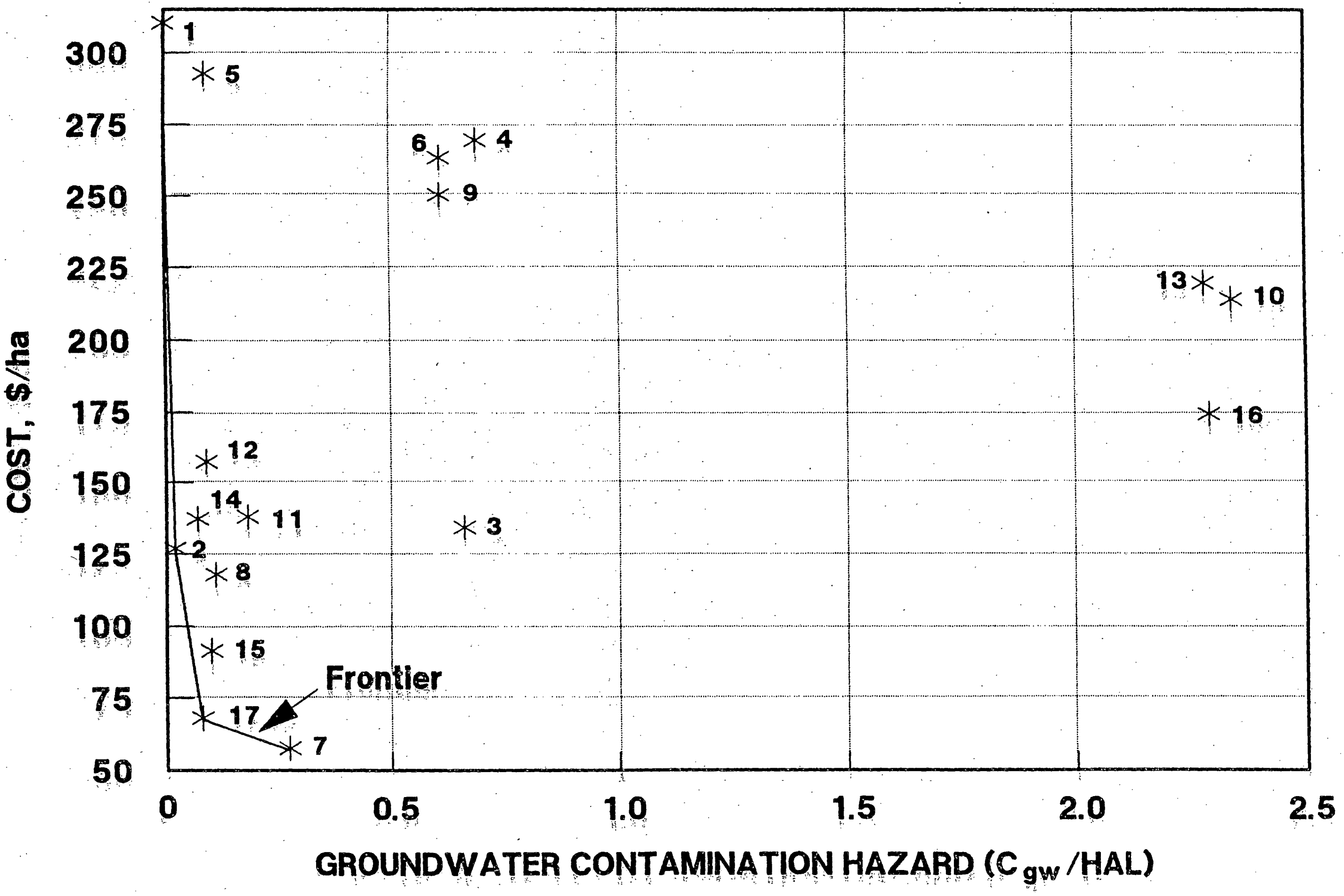

Figure 4: Cost/groundwater hazard frontier for soybean production under low weed pressure assuming 1.0-m mixing depth in the aquifer with a porosity of 0.25. Points (asterisks) represent alternative herbicide strategies for control of specific weeds.

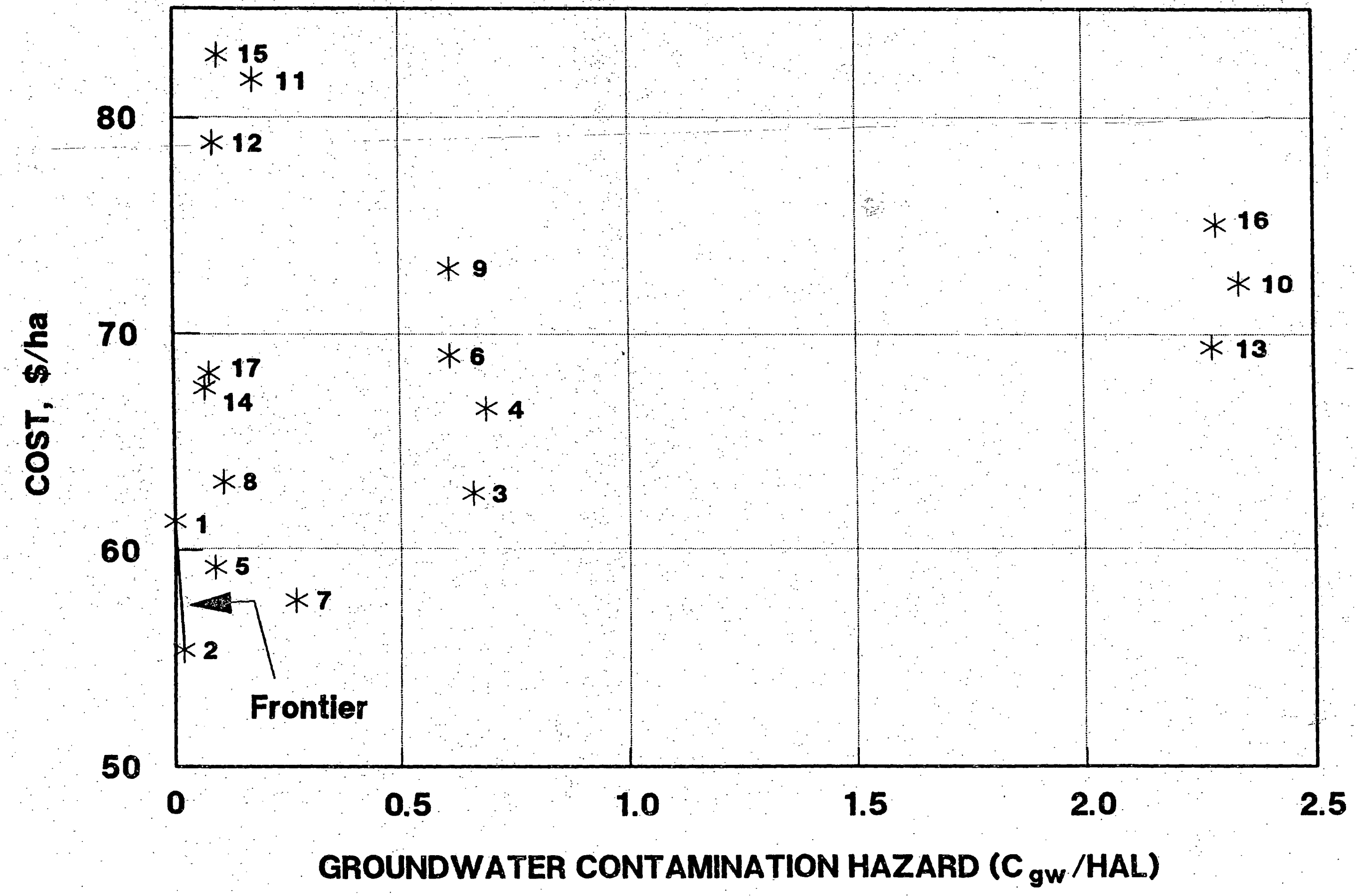

Figure 5 : Cost/groundwater hazard frontier for soybean production under high weed pressure assuming 10.0-m mixing depth in the aquifer with a porosity of 0.25. Points (asterisks) represent alternative herbicide strategies for control of specific weeds.