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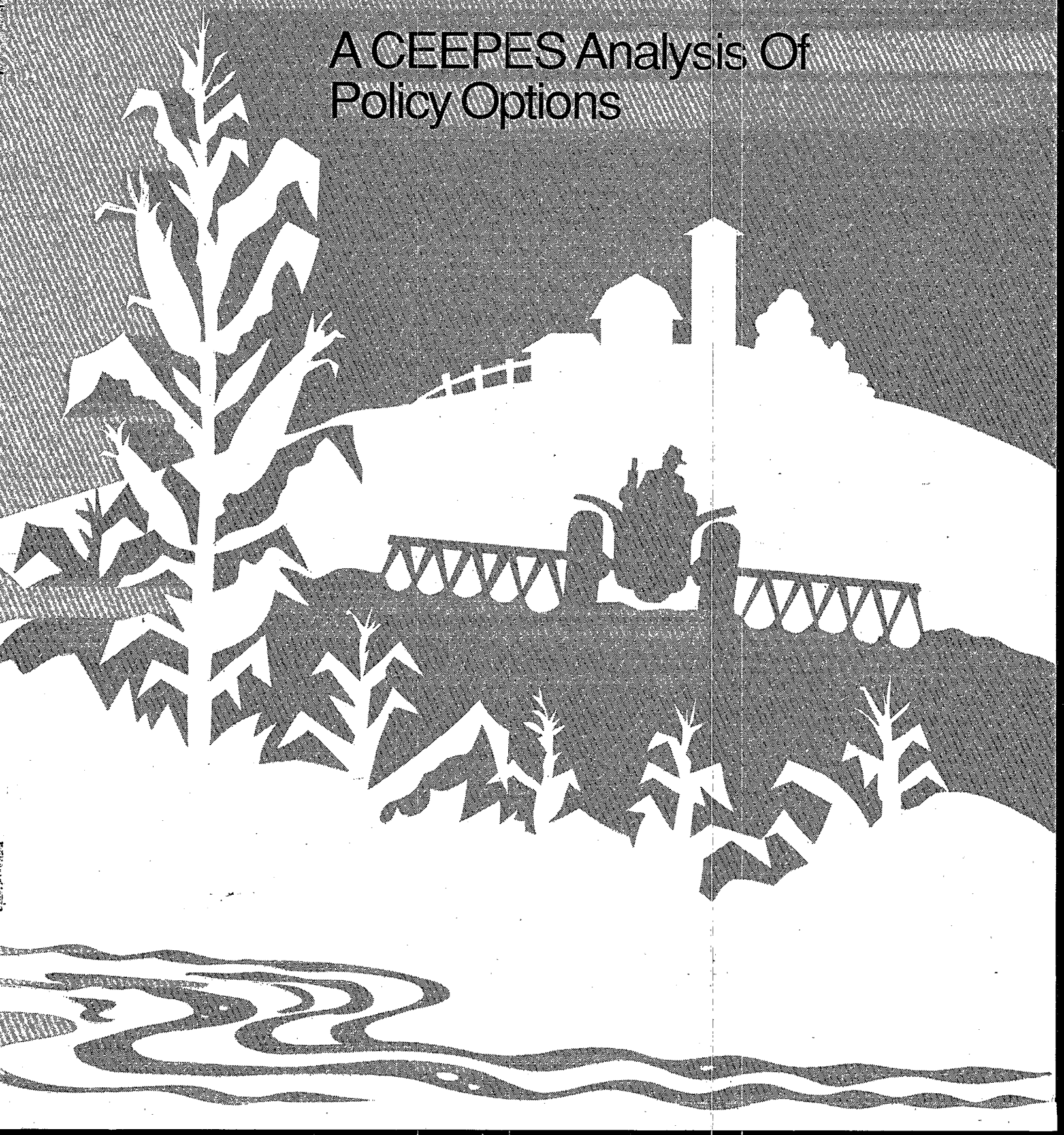
Agricultural Atrazine Use And Water Quality

A CEEPES Analysis Of Policy Options



Agricultural Atrazine Use and Water Quality: A CEEPES Analysis of Policy Options

US Environmental Protection Agency
Office of Program and Policy Evaluation
Water and Agricultural Policy Division
Agricultural Policy Branch

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Executive Summary

An ecological-economic modelling system was used to compare the risks and benefits of national bans on the use of the corn and sorghum herbicide atrazine, as well as the entire group of triazine herbicides. A major advance of the system is its linking of decisions on the choice of technology to environmental and economic impacts. It accomplishes this by linking biogeophysical process models with economic models. In response to alternative policies, the system simulates farmer substitution among inputs, crops, and agricultural practices. Because impacts may occur at different temporal and spatial scales according to the medium through which the damage occurs, the system aggregate results temporally and spatially. These results are linked, in turn, to the economic benefits derived from agricultural production in the corresponding spatial unit. It provides assessments of policy options at a local, regional, and national scale.

Atrazine and the other triazine herbicides were chosen for this analysis because they are the most widely detected group of pesticides in surface and groundwater. Current atrazine use in the Midwestern states also represents nearly 12% of total agricultural usage of pesticides in the United States. Hence policies designed to reduce corn and sorghum herbicide use can lead to significant reductions in overall pesticide use.

A ban on atrazine results in a decrease of $937 million in producer income and consumer effects. This loss would be counterbalanced in part by a sharp reductions in government expenditures for corn price support leading to an overall short-term economic loss of $365 million for the entire nation. Overall herbicide use would not decrease with an atrazine ban. Indeed, total triazine use would increase by 27% on corn, though it would decrease by 84% on sorghum. Nontriazine herbicide use would also increase as more acreage is treated with nontriazine herbicides at higher application rates. Use of the new low-dosage sulfonylurea herbicides would greatly increase, at least in the short run.

A ban on atrazine alone, without a significant shift away from chemically-intensive agricultural practices, could exacerbate the current public health concern regarding surface water quality. Though, exposures, in general, to herbicides in groundwater would generally decline and be of lower general health concern than under current use patterns in any region regardless of tillage practice, there could be an actual increase in site-specific short-term exposures to other triazine herbicides that pose greater ground water contamination risks. The increased use of alternative triazine and nontriazine herbicides from substitute weed control practices would lead to increases in their concentrations in surface water, with differential impacts by soil and tillage type, sometimes exceeding the risk associated with atrazine before a ban.

With a triazine ban, the overall economic loss would be $526 million. But under a triazine ban, human health risks from herbicide residues in groundwater would decline significantly. Health risk from herbicide exposures would decline overall, with exceptions for specific areas on a smaller proportion of soils from dicamba, bentazon, alachlor, and metolachlor and only under conventional and conservation tillage. There would be a major shift to the more widespread use of the sulfonylurea herbicides, resulting in concentrations well below their human health benchmarks. However, there are major uncertainties associated with these chemicals regarding pest resistance and their hazard to aquatic and nontarget terrestrial vegetation even at the extremely low concentrations expected in surface water from runoff or drift.

The conventional paradigm in addressing pesticide-related problems, i.e., bans or licensing restrictions, may not be the appropriate response for the corn and sorghum herbicides, in particular, or water-related problems of pesticides in general without a significant effort to change agricultural practices that rely less on synthetic pesticides. More geographically targeted mitigation measures short of bans may lead to superior environmental protection and minimal impact on producers and society on a whole.

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Introduction

The United States Environmental Protection Agency (EPA) regulates pesticides through its Office of Pesticide Programs under the authority of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (7 USCA, section 136) and the Federal Food, Drug, and Cosmetic Act (FFDCA) (21 USCA, section 348). FIFRA is a licensing statute that requires that all pesticides used in the United States be registered with EPA. EPA may deny registration if the requirements for registration have not been met.

Meeting registration requirements entails presenting evidence to verify that, among others, "the pesticide performs its intended functions without unreasonable adverse effect on the environment" when used in accordance with widespread and commonly recognized practice. FFDCA authorizes EPA to establish tolerances for pesticide residues that remain on food or feed at the time of marketing of the commodity.

Because most pesticides had been registered before the introduction of stringent data requirements, an amendment to FIFRA in 1972 required that all registered pesticides be reregistered in accordance with new standards for registration—the so-called "pesticide reregistration program." An additional amendment in 1988 called for the expedited reregistration of pesticides to meet current data requirements and testing protocols.

EPA has traditionally responded to evidence of unreasonable health or environmental risks associated with pesticides by refusing to register a new pesticide or new uses of an already registered pesticide; or by either withdrawing the registration of one or more uses of an existing pesticide (in essence, banning the pesticide) or restricting its use to a certified pesticide applicator. In assessing adverse effects on health and the environment as a consequence of its use, the Agency examines a variety of exposures associated with uses of the chemical and the crops to which it may be applied. Given its assessments of the intrinsic hazards to humans and to animal and plant species, it estimates the risk associated with each type of exposure: dietary, worker, drinking water, ecological. A determination of significant risk within at least one exposure dimension puts the burden of proof upon the registrant of the pesticide to show that, in all its uses, it can meet EPA's risk standards or that the risk, though greater than *de minimis*, is offset by the economic benefits that accrue to farmers and society.

In conducting the risk assessment, EPA relies upon best available information on how a pesticide is being used, as well as on the pesticides and practices that can serve as substitutes in the event of loss of the pesticide. The responsibility has been upon the registrant to identify how it could be used, as affected by labelling changes, and the crops for which it should be registered. A finding of unreasonable risk usually leads registrants to request that all registrations for crop uses that are marginally profitable be dropped in order to reduce the total exposure and hence risk associated with all registrations of the pesticide.

Generally the most profitable uses are also those associated with use on major field crops. Therefore, the array of pesticides available for minor use crops (crops other than the major commodity crops like corn, wheat, and soybeans) has diminished over time, while those uses associated with the most significant risks have been retained—those for major field crops. This loss of pesticides available for minor-use crops has allegedly inadvertently led to greater reliance and use of a small number of remaining pesticides registered for a particular use, resulting in problems of pest resistance and greater loadings of these pesticides into the environment. [Leonard Gianessi, 1992].

The focus in EPA's Office of Pesticide Programs has been primarily on dietary and worker sources of risks from pesticides—

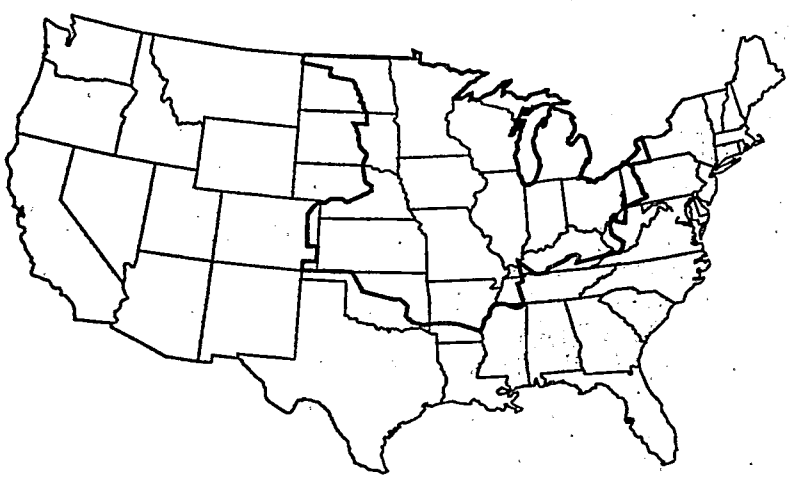
risks that are clearly national in nature. EPA's Science Advisory Board in its Relative Risk Reduction Project[1], however, recommended that greater attention be paid to ecological problems associated with pesticides. Also, the recent promulgation of new drinking water standards for pesticides[2] has resulted in greater attention paid to health problems associated with water exposures.

The current licensing paradigm for the prevention of health risks associated with pesticide use may no longer be defensible for management of water-related risks from agricultural uses of pesticides. The variety of factors, including weather, soil, and agricultural practices, that affect the loadings of pesticides to surface and ground waters requires a very large amount of information for national or state level licensing decisions. The need to generate and to evaluate the wide range of information, in turn, partly explains the delays in the making of decisions by EPA and hence the loss of public confidence in the government regulatory program. Furthermore, the geographic variability in risk is likely to make national restrictions on use socially and economically inefficient. This report is an attempt to evaluate the appropriateness of national ban/no ban decisions for protecting water quality from agricultural uses of pesticides, focusing on triazine herbicide use on corn and sorghum. It also illustrates the usefulness of a new analytical tool for multiobjective and multidimensional decision-making.

Given the need to take into account the complexity of water quality issues in assessing the risks and benefits associated with agricultural pesticide use, EPA funded the development by Iowa State's Center for Agricultural and Rural Development (CARD) of the Comprehensive Environmental Economic Policy Evaluation System (CEEPES). CEEPES is an integrated modeling system developed to estimate the economic and environmental consequences of alternative policies affecting the use of pesticides. CEEPES integrates diverse simulation models comprising four major components—policy, agricultural and economic decisions, fate and transport, and health and ecological risk.

A major contribution of the CEEPES system is the characterization of weed control technologies, resulting in the construction of over 300 alternative weed control strategies for corn production and over 90 strategies for sorghum. These strategies aim at controlling both grasses and broadleaf weeds. Each strategy includes a primary and a backup treatment (to deal with weeds that survive the primary treatment); a set of herbicides applied individually or in tank mixes; a tillage practice (no till, reduced, and conventional); chemical application rates; an application mode (broadcast, incorporated, banded); a timing of application (early pre-plant, pre-plant incorporated, pre-emergent, post-emergent); and temporal windows of application and effectiveness for both the primary and the secondary strategies. Thus, a ban on a particular herbicide does not simply imply a chemical-for-chemical substitution, but rather selection from among an entire array of weed control strategies that are potential substitutes. In addition, production risk is incorporated into the modeling system by simulating the impact of uncertainty regarding the weather on dates of

Figure 1.
CEEPES study region for the atrazine analysis



chemical application and the resulting effectiveness. This approach is embodied in WISH (Weather Impact Simulation on Herbicides). A more detailed description of WISH and its use in decision making under uncertainty is provided in Bouzaher et al. (1992a,b).

The CEEPES study region includes the Corn Belt and Lake States regions, plus portions of the Northern Plains region and five other United States Department of Agriculture farm production regions (Figure 1), which are henceforth refered to, collectively, as the Midwestern Cornbelt. The region includes more than 80% of US corn acreage and 30% of sorghum acreage. Details on the CEEPES system are provided in the section on methodology and are available in more detail in the Center for Agricultural and Rural Development's (CARD) Research Memos 3 and 4.

The system was used to evaluate two policies regarding the use of the herbicide, atrazine: an atrazine ban on corn and sorghum and a ban on the entire group of triazine herbicides of which atrazine is a member. This latter ban is henceforth referred to as a triazine ban and includes bans on atrazine, cyanazine, and simazine for corn and sorghum use.

Though the policies and the simulations apply only to the Midwestern Cornbelt in this analysis, the implications, given that the bulk of production for corn and sorghum is covered by the study area, apply nationwide. Bans that apply regionally, without scientific justification, would raise questions of equity for producers in the region and would not likely stand. A regional rather than a national analysis was conducted because it is very difficult to calibrate the models for corn-producing areas outside the Midwest and because the information on the risks and benefits of the impact of policies on marginal producing areas would not likely significantly affect the conclusions of the analysis.

Atrazine was chosen because it is the most widely detected pesticide in surface and groundwater. Belluck et al. (1991) note that the detection rate is 10 to 20 times more frequent than the next most frequently detected pesticide. The levels detected, often exceeding the Federal drinking water standard of 3 parts per billion (ppb), have led the US EPA and state agencies to review policies to control or ban atrazine use. Current use of atrazine in the midwestern states of the United States is estimated at 52 million pounds of active ingredient (USDA, 1991), accounting for nearly 12 percent of the total agricultural usage of pesticides in the U.S. (US EPA, 1992a).

The results in this report are aggregated over the entire study region, though most data generated by the analysis are available on a US Department of Agriculture production region, state, watershed, or county basis. A subsequent report, in which policies involving targeted watershed or county restrictions on use are analyzed, will present the results by watershed and county.

Methodology

Environmental policies relating to agriculture inherently reflect a trade-off between the need for production practices that minimize the costs of production and control of agricultural chemicals that are introduced into the environment by those practices. Besides producing bountiful crops, agricultural activities can sometimes lead to soil erosion, pesticide and nutrient contamination in surface and ground waters, worker exposures to pesticides, pesticide drift, and atmospheric transport. Adverse impacts include losses of ecosystems and their functions, public uncertainty about the safety of the food and drinking water supply, declines in plant and animal number and diversity, and reductions in soil fertility.

On the other hand, regulations or controls can have undesired economic effects: incremental loss of pesticides leading to increased costs to producers, higher prices of agricultural products for consumer goods, and reduced export earnings from agricultural products. Unintended adverse environmental effects can even occur if policies to protect ground and surface water quality from pesticides result in increases in soil erosion through greater reliance on soil tillage and hence sediment loadings to surface waters. Therefore, it is essential that analytical tools allow policy-makers to evaluate policies and practices in terms of both the needs of commodity production and protection of the environment.

CEEPES simulates risk-benefit trade-offs associated with non-point source pollution from agricultural productions. It links biophysical with economic modelling systems that have been integrated over the dimensions of time and space. Four components comprising the conceptual structure, illustrated in Figure 2, provide the necessary flexibility for model and policy integration: policy specification, fate and transport, agricultural decisions, and evaluative criteria relating to environmental and human health benchmarks and economic outcomes (impacts). To ensure congruence of temporal and geographic scale, "experiments" with calibrated geophysical process models produced response surfaces that have statistical integrity and known experimental and sampling error.

The information flow and configuration of the system is shown in Figure 3. Policy and regulatory space affects the range of strategies available to the producer. The system is configured to allow simulation of policy interventions restricting or enhancing producer behavior with regard to production decisions. The Resource Adjustment Modelling System (RAMS) is a linear programming model that simulates the profit maximizing decisions of producers. Producers choose an optimal mix of crop and crop rotations, chemical inputs, labor, tillage, and other factors to maximize net return. The Weather Impact Simulation for Herbicides model (WISH) identifies the most efficient weed control strategies for corn and sorghum based on timing and method of application, efficacy of chemical combination, and tillage. Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) is a process model that simulates crop growth, weed competition, and the interactions of management alternatives. The fate and transport models estimate loadings and concentrations of contaminants in the various environmental media, such as water and air. These concentrations are then either summarized directly as a ratio to health or environmental benchmarks or as a frequency that a benchmark is likely to be exceeded under a scenario.

The models that comprise the various components are shown in Table 1. They are described in detail below in conjunction with the component in which they function.

As schematically shown in Figure 4, various factors influence the domain of natural phenomena, as represented by the object at the top of the figure, to produce measurable outcomes of policy interest. A computer physical process model simulates the phenomena for a specific

rizes economic benefits and environmental risk indicators to allow comparisons of policy scenarios. Aggregation of concentrations and risk

come in applying CEEPES to a large region include the wide range of variation in temporal and spatial scales of different models requiring

between USDA and EPA with regard to data specification and development could improve accuracy for policy-making at a smaller geo-

Figure 2.
The four components of CEEPES

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Table 1.
Models that comprise CEEPES

Acronym	Name	Citation	Comment
Economic Decision/Production Models			
RAMS	Resource Adjustment Modeling System	Bouzaher et al. (1992)	Linear programming model that simulates profit-maximizing behavior
WISH	Weather Impact Simulation for Herbicide	Bouzaher et al. (1992)	Systems approach model for weed control strategies
ALMANAC	Agricultural Land Management Alternatives with Numerical Assessment Criteria	Jones and O'Toole (1986)	Process that simulates crop growth and weed competition
AGSIM	Agricultural Sector Integration Model	R. C. Taylor (1987)	Econometric model of national & international markets for 10 agricultural sectors
Environmental Fate & Transport Components			
RUSTIC	Risk of Unsaturated/ Saturated Transport and Transformation of Chemical Concentrations	Dean, et al. (1989)	Model that partitions mass of pesticides into various media; Groundwater model for pesticides (root zone; vadose zone)
STREAM	Stream Transport and Agricultural Runoff of Pesticides for Exposure: a Methodology	Donigian, et al (1986)	Surface water model for pesticides
BLAYER	Boundary Layer Model	McCorcle, M.D. (1988)	Atmospheric transport model
PAL	Point, Area, and Line Source	Peterson et al (1987)	Short-range air transport model

graphic scale, and facilitate the use of CEEPES for other crops and regions.

Environmental Fate Component

Chemical Leaching:

Herbicide leaching in the soil root and vadose zones was simulated with the PRZM and VADOFT components of the US EPA RUSTIC model. The PRZM (Plant Root Zone Model) component of RUSTIC partitions the mass of the pesticide into amounts available for volatilization, runoff, and leaching. The amount available for leaching becomes the input into the VADOFT component that moves the mass from the root zone through the vadose zone. We did not estimate lateral flow with RUSTIC. Statistical sampling of soil, climatic, pest management, and chemical parameters representative of the study region were used as inputs to RUSTIC to estimate groundwater concentrations. Thus using statistical procedures, we select a sufficient number of data for each key variable, within the range of values for the variable within the study region, that affect the concentrations in groundwater (or other medium) to achieve the desired level of statistical accuracy and reliability. We estimated peak and average pesticide concentrations at depths of 1.2 and 15 meters, which are assumed representative of vulnerable, shallow groundwater and are typical depths for the water table and rural domestic drinking water wells, respectively, in the study area.

Surface Water Concentrations:

Pesticide loadings to surface runoff from RUSTIC serve as input into the STREAM methodology to estimate chemical concentrations in surface water. STREAM is a screening-level tool for estimating in-stream solution and streambed pesticide concentrations. It is based upon 10-year simulation runs of the HSPF (Hydrological Simulation Program—FORTRAN [Johanason, R.C., et al] river basin model for representative watersheds of four main crop producing areas. STREAM estimates are generally within a factor of ten of actual monitoring values.

Air Transport:

Monitoring by the United States Geological Survey[3] and others have found pesticides in rainwater in areas where they have not been applied. To evaluate how the use of pesticides in agricultural activities may affect ecosystems at various distances from the source of application, we have included both a short-and long-range air transport component to CEEPES.

Preliminary work, which is not discussed in this report, has been performed with the Boundary Layer Model (BLAYER), a long-range numerical model and PAL, a short-range Gaussian plume model, to simulate short and long-range air transport of pesticides.[4] Volatilization data are obtained from RUSTIC, which is run for 10 years of weather data, 4 soil types, and 12 chemical properties. Output data consist of the amount of the chemical volatilized and the amount available for volatilization, in the top 0.5 cm of soil, on each day following May 9, or the day on which the chemical is applied, until June 30.

Agricultural Decision Component

Weed Competition:

The USDA ALMANAC model is used to simulate weed-crop competition. Statistical response functions of yield impacts were developed with ALMANAC based on a sampling design of crop, weed, soil, climatic, and pest management parameters representative of the study region. These response functions are used in WISH. A flowchart of processes in WISH is shown in Figure 5.

In Figure 5, the major land resource area (MLRA) defines spatial areas by grouping of soil types. MLRAs are aggregated up to a producing area (PA) corresponding roughly to the boundaries of a hydrologic area or watershed through a process of weighting. PAs are discussed in greater detail below. Post-emergent refers to whether or not the herbicide is applied before or after the corn plant has emerged. The effectiveness window corresponds to the period of time in which the farmer can apply the herbicide and have it be effective in reducing weed pressure. The variable weather is the most important factor in determining the size of the effectiveness window.

Input Substitution Model:

The WISH model simulates the efficacy and cost of over 300 alternative weed control strategies for corn and over 90 for sorghum. It simulates likely weed control management based on herbicide efficacy, weather conditions, timing of application and its effectiveness, mode of application, soil texture, targeted weeds, and observed farming practices. An example of output for one PA is shown in Figure 6.

An optimal strategy is one which has high mean net revenue per acre and low variance, i.e., less uncertainty regarding desired outcome given the uncertainties of weather. As shown in Figure 6, the plot of the status quo (SQ), or baseline, use of atra-

Figure 5.

Flowchart of the major processes simulated by WISH

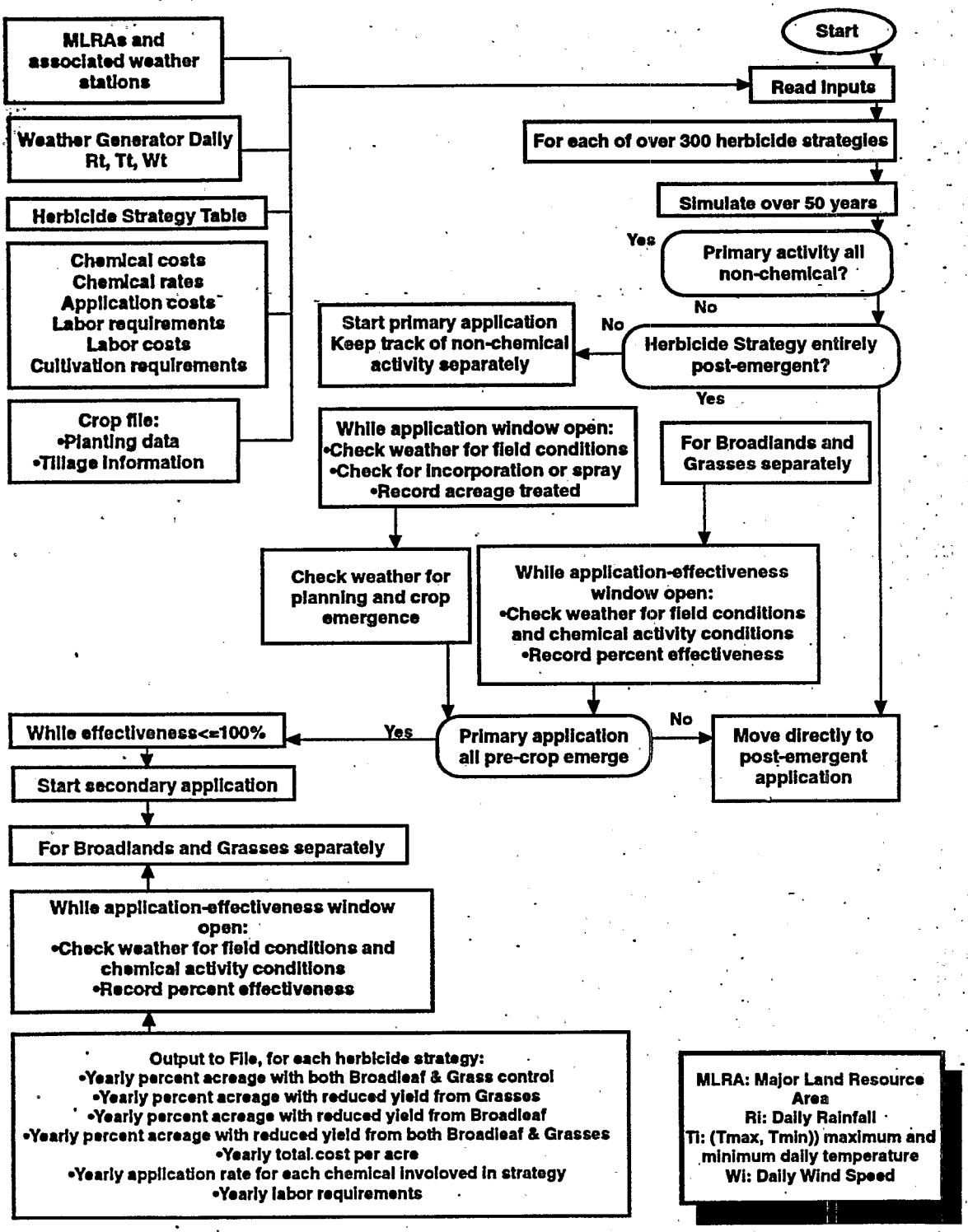
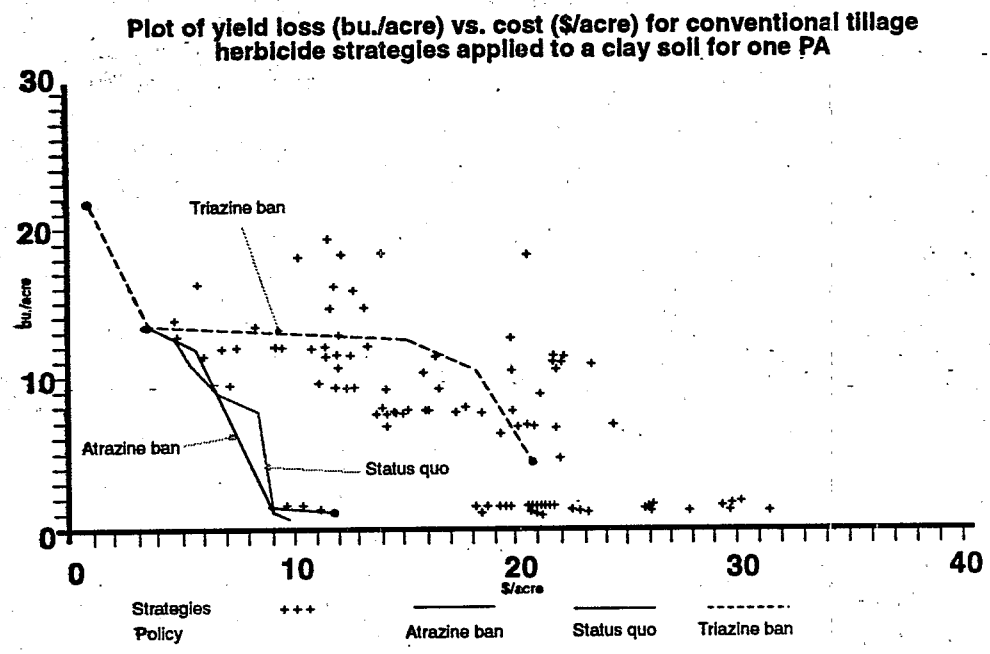


Figure 6.

Example of WISH Output



Note: The lines represent frontiers of strategies for each scenario that provide the lowest expected yield loss for a given expected cost

zine under conventional tillage, which plots closest to the origin (that is, the lowest yield loss at the lowest cost), is superior to that of alternatives that either substitute for atrazine or the triazines (AB & TB) or involve a change in agricultural practice. This is the consequence of the relatively low current price of atrazine and its reliability in controlling weeds relative to substitute pesticides and practices that may involve a greater cost due to increased labor requirements in lieu of herbicide use.

Economic Behavior Model:

RAMS simulates the manner in which policies affect the economic behavior by translating information on pesticide policy into constraints on farmer pest control strategies. It is a regional, short-term, profit-maximizing, linear programming model of agricultural production, defined at the PA level. PAs are hydrologic regions representing aggregated subareas defined by the Water Resources Council[5]. There are 105 PAs in the continental United States, excluding Alaska. RAMS estimates the economic impact of alternative agricultural and environmental policies in terms of acreage planted, rotation, tillage practice, chemical input, net return, yield, and cost of production for all PAs in the study region. For this analysis of corn and sorghum herbicides, 27 PAs were included. These results serve as inputs into a national econometric model, AGSIM, developed by Robert Taylor of Auburn University [Taylor (1987), (1991) and Penson and Taylor (1992)], to estimate changes in measures of economic welfare (producer income, domestic consumer effect, and government outlays).

The AGSIM model ties together econometrically estimated demand and supply equations for major crops and livestock through market clearing identities. Thus, the model solves for the set of crop and livestock prices that simultaneously ensure that supply meets demand (i.e., clear all markets) in a given year for given exogenous factors, that is, factors extraneous to the market, such as government policy. Due to the dynamics of supply and demand, market clearing prices are recursively obtained for each year simulated. Producer income is calculated as the sum of net crop income and net livestock income. The domestic consumer effect is defined as the sum of changes in outlay of livestock consumers, domestic crop food consumers, and the oil and meal markets. Government outlays encompass the sum of farm program payments (i.e., commodity deficiency

payments) and expenditures for Government milk purchases.

Risk Characterization and Weighting

The analysis used the ratio of predicted concentration to human health or ecological benchmarks (or, alternatively, the likelihood that a benchmark level would be exceeded) as the measure of risk of adverse impact resulting from environmental exposures. The greater this ratio is, the greater the risk that we would predict for exposure to a particular pesticide. Any value approaching or exceeding unity is of concern. The decision-maker must decide, using whatever information is available that is specific to a chemical, whether or not the risk depicted in the baseline scenario is of sufficient magnitude to warrant action. CEEPES can only assist in determining whether or not any action or policy to address the risk in the baseline scenario is likely to improve or worsen the overall environmental impact.

Since pest control strategies often call upon more than one pesticide being used in a tank mix and since different farmers use different strategies and hence pesticides, surface waters may contain a mixture of pesticides at any given point in time. Ground waters may also contain a mixture of pesticides where a variety of pest control strategies has been used over a number of years. For the purpose of comparing policy alternatives, we characterize the risk associated with exposures to these mixtures of pesticides in a particular medium, by adding the ratios of predicted concentrations to benchmarks for each pesticide in the mixture, in accordance with EPA guidelines on assessing risk from mixtures of chemicals. A final risk value for a category of environmental impact for a particular policy, such as, human health to ecological impact is arrived at through a process of assigning wieghts on the basis of relative importance. The method by which we arrive at weights is described below.

Minimizing total environmental risk requires the comprehensive evaluation of the fate of chemicals as they move through a medium, from one medium to another, the manner and types of exposures to receptor populations through contact with each medium, and the adverse health and ecological effects that are likely to result. A pesticide may leave little or no residue in food and hence pose minimal dietary risk to sensitive populations, but nevertheless partition itself in agricultural runoff where it can contaminate streams and rivers and pose aquatic risks. Conversely, it can pose little or no likelihood of contaminating water at all, yet, through volatilization and drift pose risks to agricultural workers or nearby residents of towns and even be transported great distances to the surface of lakes and rivers hundreds of miles away.

Balancing environmental risks with the benefits that accrue from the use of pesticides therefore involves weighing the risks associated with one medium or to one receptor with those associated with other media or receptors and trading off benefits for reductions in one or more impacts. These trade-offs often concern objects of dissimilar nature or risks of different duration or severity. One pesticide that is particularly effective in a specific use and manner of application, for example, may pose a threat to workers. Yet its less effective substitutes—were it to be banned—threaten wildlife because the application of the pesticides in the form of granules, for instance, increases the likelihood that birds mistake them for pebbles and eat them. Alternatively, a choice may be between an acutely toxic pesticide that can kill or injure a worker immediately or a substitute that poses uncertain long-term adverse health consequences from minute exposures.

Where options or choices present different types of risk and hence are not directly comparable, value judgments must be made in deciding their relative importance. Should economic gain be weighed against environmental risk? How should threats to birds be weighed against risks to humans or ecological habitats? Consensus can more easily be reached on how these decisions should be made if the following holds true: 1) technical and professional estimates are clearly separated from value judgments and 2) value judgments are appropriately made by policy-makers to whom the responsibility of political judgment has been given.

Weighting is not intrinsically a scientific exercise, but rather a political process that reflects personal values or group preferences. Nevertheless, science can be brought to bear to facilitate the process. In this analysis, we demonstrate one method that the field of operations research has recently provided by which such weighting may occur. The weighting procedure uses the

Analytical Hierarchy Process (AHP) as operationalized in the computer program Expert Choice[6]. A model is specified that relates key risk variables or categories of impacts to the goal of an analytical exercise. In this case, the goal would be least total environmental impact or risk. The relationship between variables is decided by weights. The weights, or estimates of relative importance or user preference, are elicited from the user through pairwise comparisons of options. Information, such as monitoring and field data on environmental levels of contaminants and knowledge of surface and groundwater impairments, is drawn upon in making the qualitative comparisons. Summing weighted risk variables produces an aggregate environmental hazard index value that is then compared against economic benefits.

[1] US EPA, Science Advisory Board, *Reducing Risk: Setting Priorities and Strategies for Environmental Protection*, SAB-EC-90-021, September 1991.

[2] US EPA, Office of Drinking Water, *Phase II Fact Sheet: National Primary Drinking Water Regulations for 38 Inorganic and Synthetic Organic Chemicals*, January 1991.

[3] Memorandum from Donald Goolsby, U.S. Geological Survey, to Andrew Manale, US EPA, see also USGS Selected Papers on Agricultural Chemicals in Water Resources of the Midcontinental U.S., Open file report 93-418.

[4] Work conducted under contract by Michael McCordle, SAIC, Springfield, Virginia.

[5] U. S. Water Resources Council, *Water Resources: Regions and Subregions for the National Assessment of Water and Related Land Resources*, U.S. Govt. Printing Office, Washington, D.C. (1970).

[6] Expert Choice™, based on the Analytic Hierarchy Process, by Decision Support Software, Inc., 4922 Ellsworth Ave., Pittsburgh, PA.

Results of Analysis of Atrazine and Triazine Bans

Baseline Use of Triazine Herbicides

The pesticide usage data used to calibrate, that is, to define the boundaries of, baseline herbicide use in CEEPES were obtained from Resources for the Future (RFF) (Gianessi and Puffer, 1991). Baseline atrazine use estimated by CEEPES is approximately 39 million pounds active ingredient (a.i.) on corn and about 3.3 million pounds a.i. on sorghum (Table 2). The use of all triazines combined is about 60 million pounds a.i. for corn and 3.3 million pounds a.i. for sorghum. The RFF and CEEPES estimates differ because, whereas the RFF data represent a single snapshot of herbicide use, CEEPES provides estimates for any given year based upon meteorological and other factors affecting use.

Economic Impacts

For both an atrazine and a triazine ban, corn acreage and corn yields are predicted to decline, with soybean acreage and soybean yields increasing (Table 3 & 4). For the atrazine ban, corn acreage would decrease by 3 percent from the baseline of 72.6 million acres, while soybean acreage would increase by 4.1 percent from the baseline of 44.2 million acres. Sorghum acreage increases slightly (0.7 percent for an atrazine ban and 1.9 percent for a triazine ban) offsetting some of the production loss due to yield decreases. Corn yield decreases by 2.8 percent for an atrazine ban and 4.1 percent for a triazine ban (Table 4). Yield decreases for sorghum are much larger at 5.7 percent and 6.8 percent for the two scenarios.

The cost of weed control per acre would increase between $6.00 and $8.00 for corn and less than $1.00 for sorghum (Table 5). In corn, banning atrazine requires the use of more costly weed control strategies to achieve a comparable level of control. In sorghum, banning atrazine leads to heavier reliance on comparably costly, but less effective strategies. Table 6 summarizes the changes in acres treated with triazines for both corn and sorghum. We separated the atrazine-treated acres according to whether or not atrazine would be applied at a rate of no more than 1.5 lb/acre rate (50.3 million acres of corn in baseline). [The distinction between rates of 1.5 lb/acre and rates greater than that is the consequence of heavy clay soils generally receiving greater application rates than lighter sandier soils. Thus, we predict a bimodal distribution of atrazine application rates that has been confirmed by surveys.] We note a significant increase in the use of cyanazine for sorghum and simazine for corn under an atrazine ban. This can be partly attributed to our current assumption of no significant crop injury from these two triazine herbicides. Convincing evidence from weed scientists may cause us to change this assumption.

The national economic welfare measures (changes in producer income, domestic consumer effect, and government outlays) associated with yield and cost impacts of an atrazine or triazine ban in the study area were estimated using the AGSIM Model. Because of the importance of the study area to corn and sorghum production (more than 80% of corn acreage and 30% of sorghum lies in the study area), changes in yield and cost affect prices nationally. Thus, though corn or sorghum production practices outside the study area would not be affected by the policies, growers in these areas would be affected by changes in prices paid for the commodities. Because most of the corn acreage is captured by the analysis, we would not expect a significant difference in results if the policies were applied nationally. We present both short-term (1993-96) and long-term (2005-2008) annual economic welfare effects for the nation in Table 7.

In the short term, the average annual decreases in total economic welfare for the nation would be about $365 million under an atrazine ban and $526 million under a triazine ban. With an atrazine ban, crop producers in the Corn Belt bear a large share of

Table 2.

Current (Baseline) use of atrazine and all triazines in the study region (in million lbs a.i.)

Crop	Chemical	RFF, 1991[1]	CEEPES[2] Baseline	NAPIAP Study*[3]
Corn	Atrazine	39.9	38.9	50.6
	All Triazines	58.7	60.7	72.3
Sorghum	Atrazine	6.3	3.3	4.1
	All Triazines	6.3	3.3	4.1

*NAPIAP (1992).
[1]Value reported is for the CEEPES study region.
[2]Value reported is for the CEEPES study region.
[3]Value reported is for 12 midwestern states.

Table 3.

Percentage changes in crop acreages from baseline for chemical restrictions

	Atrazine Ban	Triazine Ban
Corn	-3.0%	-2.7%
Sorghum	0.7%	1.9%
Barley	0.0%	0.0%
Cotton	0.0%	0.0%
Hay	-1.6%	-0.0%
Oats	1.3%	2.3%
Soybeans	4.1%	3.9%
Wheat	2.6%	1.1%

Table 4.

Percentage changes in per acre crop yields from baseline for chemical bans

	Atrazine Ban	Triazine Ban
Corn	-2.8%	-4.1%
Sorghum	-5.7%	-6.8%
Barley	-0.006	-0.007
Cotton	0.00%	0.00%
Hay	2.3%	.95%
Oats	0.29%	-0.69%
Soybeans	0.20%	0.24%
Wheat	-1.72%	-0.15%

Table 5.

Cost change per treated acre

	Atrazine Ban	Triazine Ban
Corn	$6.70	$8.25
Sorghum	$0.64	$0.12

Table 6.

Acres treated in study region

		Current Use in CEEPES (mil. acres)	Percent Change Atrazine Ban	Percent Change Triazine Ban
Atrazine (>1.5 lbs/acre):	Corn	22.9	-100%	-100%
	Sorghum	1.1	-100	-100
Atrazine (<1.5 lbs/acre):	Corn	50.3	-100	-100
	Sorghum	2.1	-100	-100
Cyanazine	Corn	39.4	-46	-100
	Sorghum	<0.1	>200	-100
Simazine	Corn	5.8	>200	-100
	Sorghum	..	..	..

Table 7.

Aggregate economic (welfare) effects of atrazine and triazine bans (million $)

	Atrazine Ban		Triazine Ban	
Economic Effects	**Short Term**	**Long Term**	**Short Term**	**Long Term**
Producer Income	-531	-312	-673	-423
Domestic Consumer Effect	-406	-421	-548	-553
Government Outlays	(-572)	(-18)	(-695)	(-21)
Total Economic Effect	-365	-715	-526	-955

Source: AGSIM

Note: Producer income is the change in the portion of net revenues for the nation that accrues to producers of corn and sorghum, domestic consumer effect is the change in consumer surplus for consumers in the US as a consequence of changes in the price of corn and sorghum, and government outlays is defined as the value of government transfer payments that accrue to producers through price support programs for corn and sorghum.

the burden. Producer income from crops is reduced by $234 million in the region. For a triazine ban, some of the losses in the Corn Belt are offset by higher corn prices and the loss in producer income of $168 million is less than with the atrazine ban. Some regions within the study area would see an increase in producer income, particularly those where little corn and sorghum are grown. Corn and sorghum producers outside the study area would benefit from the increase in prices for the two commodities. Under the two restrictions, significant short-term decreases occur in government expenditures, while losses occur in net livestock income due mainly to the combined effect of a decrease in corn production and an increase in corn and sorghum prices.

Long-term impacts may not be as meaningful for the current analysis because no information was included on new, potentially more effective, weed control technologies like biological controls or new chemical substitutes. Under the current assumptions, however, total economic impacts would be of the same magnitude as in the short run.

Table 8 shows the corresponding commodity price effects both for the short and the long run. In the short run, prices increase for corn (between 6.4 and 8.4 percent), sorghum (between 10.4 and 12.2 percent), all hay (1 percent), and hogs (0.8 to 1.1 percent); prices decrease for soybeans (about 1 percent), oats, wheat, and barley. In the long term, price impacts would be lessened, particularly for corn, sorghum, and soybeans.

Input Substitution Effects

The use of herbicides under the various scenarios is indicated by the distribution of corn and sorghum acres treated by different herbicide strategies (Appendix B). In the baseline, more than 65 percent of corn acres and more than 60 percent of sorghum acres are treated with a mix of strategies containing atrazine. Under an atrazine ban, more than 57 percent of corn acres and more than 15 percent of sorghum acres would be treated with a mix of strategies containing at least one triazine herbicide. Under a triazine ban, 27 percent of corn acres and 9 percent of sorghum acres would be treated with

Table 8.
Price effects of atrazine and triazine restrictions-selected commodities (% change)

	Atrazine Ban		Triazine Ban	
Price Effects	Short Term	Long Term	Short Term	Long Term
Corn	+6.4	+2.6	+8.4	+3.5
Sorghum	+10.4	+6.0	+12.2	+6.7
Soybeans	-1.2	-0.5	-1.3	-0.1
Oats	-0.8	-0.5	-0.9	-0.6
All Hay	+0.8	-0.0	+1.1	-0.0
Wheat	-0.8	-0.3	+0.4	-0.3
Barley	-0.4	+0.4	-0.7	+0.1
Hogs	+0.5	+0.5	+1.0	+1.3
Cows	-0.1	-0.1	-0.2	-0.1
Broilers	+0.2	+0.4	+0.3	+0.6
Turkeys	+0.3	+0.6	+0.4	+0.8
Eggs	+0.2	+0.4	+0.2	+0.4
Milk	0.0	+0.1	0.0	+0.1
Calf	-0.1	-0.2	-0.2	-0.3

Table 9.
Herbicide use in study region

		Current Use in CEEPES (mil. lbs. a.i.)	Percent Change Atrazine Ban	Percent Change Triazine Ban
Atrazine:	Corn	38.9	-100	-100
	Sorghum	3.3	-100	-100
All Triazines:	Corn	60.7	27	-100
	Sorghum	3.3	-84	-100
Non-triazines:	Corn	53.7	97	>200
	Sorghum	9.2	31	31
All Herbicides:	Corn	112.7	60	49
	Sorghum	12.5	1	-4

Table 10.
Average application rate for triazines

		Change (lbs. a.i.) Atrazine Ban	Change Atrazine Ban
Cyanazine:	Corn	0.94	249%
	Sorghum	-0.03	-4%
Simazine:	Corn	1.34	133%

rotary hoe and row cultivation as the main strategy. In addition, more than 50 percent of corn acres would be treated with strategies involving alachlor, metolachlor, butylate, EPTC, dicamba, and 2,4-D, and more than 90 percent of sorghum acres would be treated with strategies involving alachlor, metolachlor, dicamba, 2,4-D, and propachlor.

The newly registered, low dosage sulfonylurea herbicides, nicosulfuron (Beacon) and primisulfuron (Accent), which are used in ounces per acre and are believed to be of much less human health consequence than other corn and sorghum herbicides, could possibly play a very significant role in weed control strategies in lieu of atrazine or the other triazines. Nevertheless, there is concern regarding rapid development of weed resistance, crop injury under certain conditions, and offsite adverse impacts on nontarget crops and plants. Thus, in light of the uncertainty regarding the extent to which farmers will accept the risks associated with their use, we examined weed control strategies with and without them. The use of nicosulfuron and primisulfuron in backup strategies increases considerably when atrazine and all triazines are banned. If nicosulfuron and primisulfuron were not allowed, as illustrated in Figure 7, atrazine or triazine bans would result in a much greater reliance upon nontriazine herbicides that are generally applied post-emergent. Post-emergent backup strategies that include bentazon, bromoxynil, pendimethalin, dicamba, and 2,4-D in various combinations would be substituted.

We summarize herbicide use in the study region in Table 9. With an atrazine ban, total triazine use increases by 27 percent in corn and decreases by 84 percent in sorghum. The average application rate for cyanazine and simazine on corn increases by 249 percent and 133 percent, respectively, given an atrazine ban (Table 10), which translates into an increase in active ingredients by 0.94 lbs and 1.34 lbs per acre for cyanazine and simazine. In addition, we observe large increases in nontriazine and total herbicide use under both policy scenarios because the acres treated by nontriazines increase, and the substituted weed control strategies, with the exception of

Figure 7.

Percentage of corn acres treated by chemicals, with and without primisulfuron and nicosulfuron

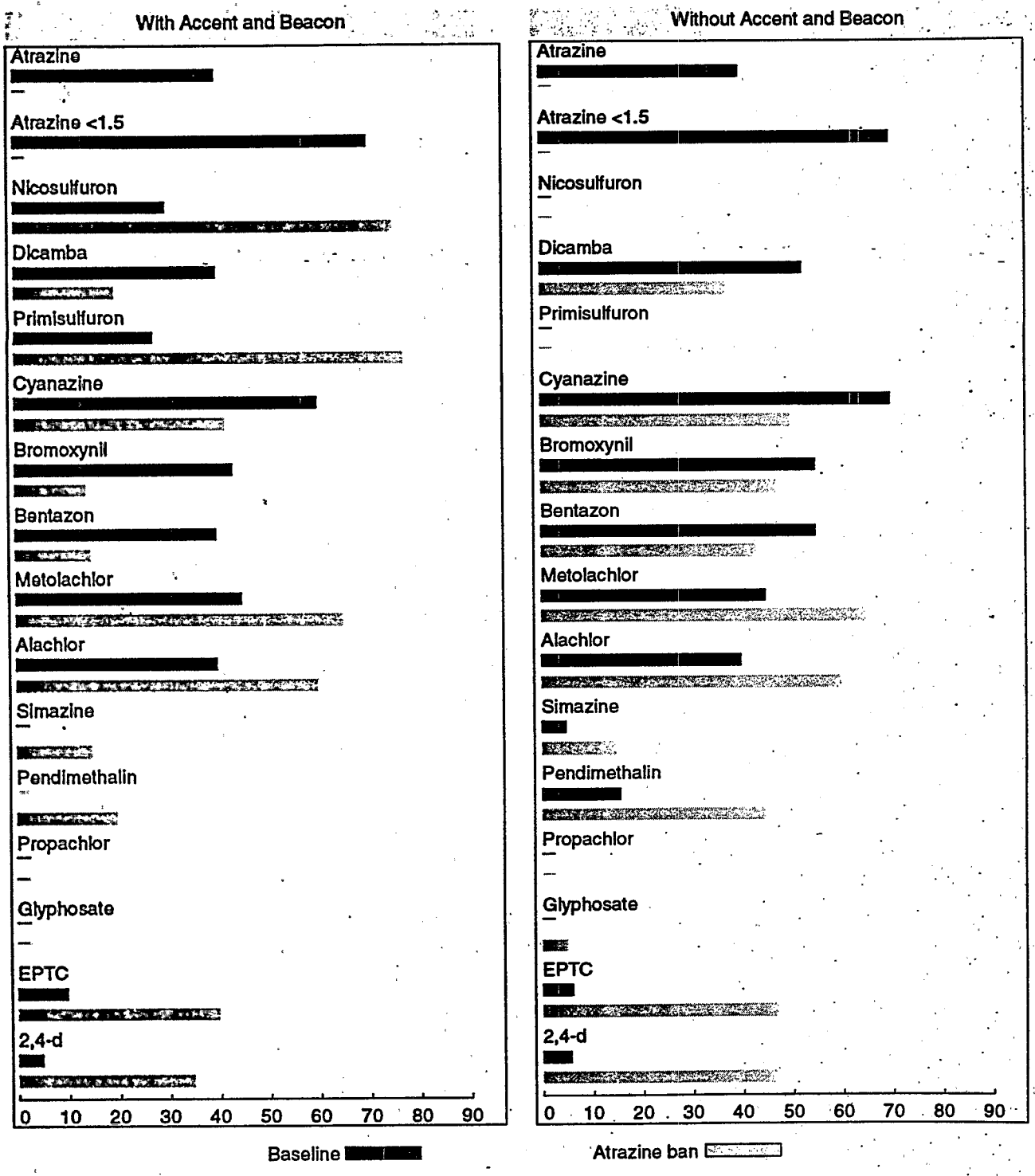


Table 11.

Changes in herbicide application rates with bans, with and without the sulfonylureas

	atr	atr <1½ lb.	nic	dic	pri	cya	bro	ben	met	ala	sim	pen	pro	gly	EPTC	2,4D
with the sulfonylureas																
SQ	0.98	0.30	0.004	0.07	0.001	0.39	0.01	0.03	0.78	0.87	1.25	0.11	1.34	0.00	2.86	0.07
AB	0.00	0.00	0.008	0.15	0.002	1.35	0.01	0.04	0.59	0.60	2.22	0.74	0.00	0.00	2.81	0.23
TB	0.00	0.00	0.01	0.16	0.003	0.00	0.02	0.04	0.48	0.54	0.00	0.00	0.00	0.71	2.82	0.23
without the sulfonylureas																
SQ	0.93	0.32	0.00	0.05	0.00	0.33	0.01	0.03	0.77	0.87	1.30	0.03	10.17	0.81	2.87	0.13
AB	0.00	0.00	0.00	0.11	0.00	1.10	0.02	0.05	0.59	0.61	2.16	0.33	0.00	0.76	2.82	0.22
TB	0.00	0.00	0.00	0.13	0.00	0.00	0.02	0.05	0.47	0.54	0.00	0.00	0.00	0.75	2.83	0.20

Note: Atr = atrazine, nic = nicosulfuron, dic = dicamba, pri = primisulfuron, cya = cyanazine, bro = bromoxynil, ben = bentazon, met = metolachlor, sim = simazine, pen = pendimethalin, pro = propachlor, gly = glyphosate, ala = alachlor. Rates reflect the average use over 50 years of weather. Because the weather does not permit application in every year, the values are lower than the average rate that is applied when weather permits.

those employing the sulfonylureas, entail relatively high application rates.

Table 11 provides more detail on the changes in application rates for 15 different herbicides for the Corn Belt (Appendix A lists these 15 herbicides by their chemical and trade names).

An atrazine ban causes a rate increase for both cyanazine, simazine, and other chemicals such as dicamba, bromoxynil, bentazon, pendimethalin, and 2,4-D. And though cyanazine application rates increase significantly, the total acreage upon which it is used decreases. Thus, total pounds of pesticide use would be a misleading measure of water quality in this case. Total pounds used would increase only slightly yet loadings to surface water in some areas, as will be discussed later, increase very significantly.

In sorghum, banning atrazine leads to heavier reliance on comparably costly, but less effective strategies. Average application rates for other triazines also increase.

We provide a summary of shifts in rotations in the CEEPES study region in Appendix C. The major rotation shifts occur between continuous corn, which decrease 16 and 16.5 percent under an atrazine and triazine ban, and corn-soybean rotation, which increase by 11 and 10.4 percent under the two restrictions. These changes are important because they occur for the two most frequent rotations. By shifting to a corn-soybean rotation, savings in nitrogen fertilizer and insecticide applications are possible, which is a benefit to water quality.

Environmental Impacts

Environmental indicators complete the picture of the societal impacts of an atrazine and a triazine ban in the study region. Since a single average indicator of water quality across the study region would be almost meaningless, we present results indicating both "relative risk" to humans and aquatic life, and the spatial distribution of these indicators identifying the most vulnerable soils. In addition, results are separated by tillage, surface water and groundwater, and chemical.

The peak and average chemical concentration levels found in surface and groundwater are transformed into a unitless measure of risk that we call exposure value. Pesticide-specific benchmarks for human health and aquatic habitat are used to weight the relative importance of pesticide concentrations.

The term "exposure value" is used to prevent confusing such values with estimates of absolute risk. Uncertainties in the data and in the methodology do not allow the generation of precise point estimates or probabilities. Instead, the purpose of the estimates is solely for screening-level comparison of policies and practices and serving as rough indicators of water quality.

Using a benchmark for environmental hazards, such as drinking water Maximum Contaminant Levels (MCLs) for long-term exposures and 10-day Health Advisories for short-term exposures, we calculate the exposure value for each chemi-

cal in the following way for both peak and average long-term levels:

$$\text{Exposure Value (hazard weighted exposure)} = \frac{\text{predicted concentration}}{\text{environmental benchmark}}$$

The exposure value normalizes concentration levels, thereby allowing us to compare risks across herbicides. If the exposure value exceeds unity, the concentration exceeds the benchmark and warrants further investigation; it does not necessarily indicate that there is a significant environmental impact. A chemical detected in ground or surface water represents a greater risk the larger the exceedance of the benchmark. Since the values represent averages of peak and long-term values over large areas, a value below the benchmark, conversely, does not indicate that there is no problem at specific sites. Note that more reliance should be placed on relative differences between exposure values than on absolute values [US EPA, (1992b)].

Table 12 presents the human health exposure values for surface water from peak loadings, by chemical and tillage, under baseline use and under an atrazine ban and a triazine ban in corn production. Each line in this table represents the percent of soil types present in the study area that are associated with high levels of pesticides in surface water runoff that could result in concentrations of possible health concern. For example, the first row in Table

Table 12.

Exposure distribution in surface water for the three scenarios
(% soils with concentrations exceeding EPA Benchmarks)

	Conventional tillage	Reduced tillage	No-tillage
BASELINE			
Atrazine	43.10	42.87	8.08
Atrazine <1.5 lb.	14.75	15.80	2.38
Dicamba	18.14	0.00	0.00
Cyanazine	24.91	0.92	0.00
Bentazon	2.39	45.90	0.00
Metolachlor	3.01	8.91	0.00
Alachlor	20.83	32.65	0.00
Simazine	86.95	67.66	40.12
Propachlor	6.65	38.44	..
Atrz_Slow_Decay	28.31	26.06	4.26
Atrz_Fast_Decay	11.73	0.01	1.13
ATRAZINE BAN			
Dicamba	35.08	1.21	0.00
Cyanazine	37.57	90.15	0.00
Bentazon	67.74	0.00	..
Metolachlor	0.06	26.93	12.63
Alachlor	4.70	31.61	18.28
Simazine	96.68	42.57	40.05
TRIAZINE BAN			
Dicamba	26.66	5.60	0.00
Bentazon	51.41	84.96	..
Metolachlor	0.00	13.59	0.00
Alachlor	0.67	0.00	0.00

Note: Bromoxynil, Butylate, Glyphosate, Nicosulfuron, Pendimethalin, Primisulfuron, and 2,4-D had zero probability of exceedance in all three scenarios.

12 shows that atrazine concentration levels exceed the short-term benchmark of 100 ppb (the drinking water Health Advisory level for short-term exposure) in 43, 43, and 8 percent of the soils in the study region, if the soils were cultivated under conventional tillage, reduced till, or no till systems, respectively. Under an atrazine ban a higher proportion of soils would lead to loadings to surface resulting in chemical concentrations exceeding the benchmark under all three tillage systems (e.g., dicamba, cyanazine, simazine, and bentazon with conventional tillage; dicamba, cyanazine, and metolachlor with reduced tillage; and metolachlor and alachlor with no till). Note that for groundwater, all average concentrations are well below the long-term exposure benchmarks for all soils and all tillage systems, under both an atrazine and a triazine ban. Thus, this information could be used in targeting areas, given the prevalence of certain soil types, where ground or surface waters may be vulnerable to herbicide leaching or runoff. Appendix D provides the details of predicted concentration and exposure levels for each chemical in the study region for the three scenarios, in corn production.

An alternative way to use CEEPES information to identify practices associated with surface water problems with herbicides is to examine the percent of total herbicide-treated corn acreage in a tillage system resulting in the exceedance of a benchmark. As Table 13 indicates, exceedance of the atrazine benchmark is currently more likely to occur as a consequence of weed control on land under reduced tillage than under conventional tillage. The opposite is predicted for cyanazine and simazine. Banning atrazine would lead to the prediction that more land under reduced tillage would be associated with cyanazine exceedances than under conventional tillage, whereas simazine use under conventional tillage would lead to the greatest percentage of land associated with high levels of herbicide runoff. Banning the triazines would greatly reduce the amount of land associated with exceedances of surface water benchmarks corn herbicides.

As shown in Figure 8, the exposure values for aquatic vegetation—which are used as indicators of ecological impacts—from corn production for the two policies tend to be high. The majority of aquatic exposure values exceed the aquatic benchmarks, which have either been only proposed as standards by EPA or have been derived according to EPA guidelines, often by more than a factor of more than 20. As mentioned before, these numbers are to be used for comparison purposes, not as estimates of absolute risk.

Aggregate Hazard Index

Developing an estimate of impact per medium:

The modelling results, as well as monitoring data[1], indicate that humans and aquatic flora and fauna are potentially exposed to a complex mixture of pesticides in water supplies. Adverse impacts associated with policies and agricultural practices are therefore, for the sake of comparisons, characterized in terms of the aggregate exposure. To evaluate the effect of exposure to mixtures of pesticides in each medium, we treat the exposure values in each medium in two ways: 1) the ratio of predicted pesticide concentrations to benchmark values are summed across all pesticides by acreage under different tillage practices for each policy option and presented for both acute and chronic exposures and 2) the highest exposure value is selected from among those of all pesticides predicted in a medium by tillage practice for both types of exposures (Table 14). This is done in order to derive a range of possible impacts since little is known about the additivity or synergism of multiple exposures. The weighted sum, or hazard index for a particular medium and health or ecological endpoint, was arrived at by multiplying the percentage of total acreage devoted to a type of tillage practice (Table 15) by either the sum of the exposure values or the highest exposure value in the medium. Acute impacts derive from peak concentrations of herbicides averaged over the study area and compared to benchmarks for health or ecological risks from short-term exposures and chronic from average concentrations compared to benchmarks for long-term exposures.

Even though conventional tillage is practiced on far more land than reduced or no till, more herbicides are typically substituted for less tillage to control weeds. Thus, a shift out of conservation tillage from an atrazine or triazine ban would result in less intensive herbicide use overall but aggregate use would increase as more corn is grown under conventional tillage. The surface and ground water impacts from pesticide use associated with conventional tillage would also tend to increase.

An atrazine ban would reduce the impact of long-term (chronic) exposures from pesticide use in corn production on ground water. Acute risks could slightly increase with the use of other triazine herbicides that, though less persistent, are greater leachers. A triazine ban would significantly reduce both acute and chronic risks as pesticides that tend

Table 13.

Herbicide-treated corn acres resulting in 24-hour surface water exceedances: Acres and percentage of exceedance relative to total corn acres by tillage

	Conventional tillage		Reduced Tillage		No Tillage	
	Acres	Pct (%)	Acres	Pct (%)	Acres	Pct (%)
BASELINE						
Atrazine	1,495,000	16.8	555,600	33.8	51,000	6.8
Atra<1.5	576,500	5.0	3,431,900	28.3	34,600	2.8
Dicamba	537,300	6.3	0	0.0	0	0.0
Cyanazine	2,323,800	25.7	222,000	2.4	0	0.0
Bentazon	66,900	1.0	1,162,600	17.5	0	0.0
Metolachlor	51,000	0.5	84,700	4.2	0	0.0
Alachlor	960,000	9.7	9,000	1.6	0	0.0
Simazine	452,500	34.6	354,000	29.3	36,400	10.6
Propachlor	700	0.2	1,800	2.4	0	0.0
Atrz_Slow_Decay	NA	28.8	NA	56.9	NA	8.6
Atrz_Fast_Decay	NA	11.2	NA	0.0	NA	2.3
ATRAZINE BAN						
Dicamba	688,000	10.0	645	0.05	0	0.0
Cyanazine	369,400	25.6	3,966,400	44.1	0	0.0
Bentazon	520,000	10.7	0	0.0	0	0.0
Metolachlor	4,600	0.04	600,000	12.2	23,200	7.3
Alachlor	715,000	6.6	471,000	12.7	21,800	6.8
Simazine	7,106,000	79.4	3,500	2.2	92,000	13.6
TRIAZINE BAN						
Dicamba	379,000	8.5	36,000	1.1	0	0.0
Bentazon	336,500	11.1	11,200	4.2	0	0.0
Metolachlor	0	0	137,300	4.3	0	0.0
Alachlor	102,000	0.5	0	0.0	0	0.0

Note: Bromoxynil, Buctril, Glyphosate, Nicosulfuron, Pendimethalin, Primisulfuron, and 2,4-D had zero exceedances.

to leach less or are less persistent are substituted for atrazine and the other triazines. There would be more tillage of the soil to control weeds and less corn would be grown that would require atrazine use under both bans.

For surface waters, the acute impact on health may actually increase with an atrazine ban with little change for chronic exposures to herbicides. With a triazine ban, the impact on health would diminish dramatically for both short- and long-term exposures. The combination of herbicides in surface waters suggest a more pronounced impact on health of the ecosystem with a hazard index for baseline use substantially above unity. Banning atrazine may, in fact, worsen the impact, and banning the triazine herbicides altogether suggests that the health of the ecosystem could actually decline further.

The impact of the policy options on soil erosion was examined under two scenarios—with and without the low-dose sulfonylurea herbicides—in light of the relatively little agricultural experience with this new class of herbicides. Atrazine, in part because of its persistence, is very effective in the control of weeds, especially where the soil is not tilled as in no-till corn production. Without atrazine, the amount of no-till

Figure 8.

Acute surface water exposure for aquatic habitat in the study area: conventional-, reduced-, and no-till practices

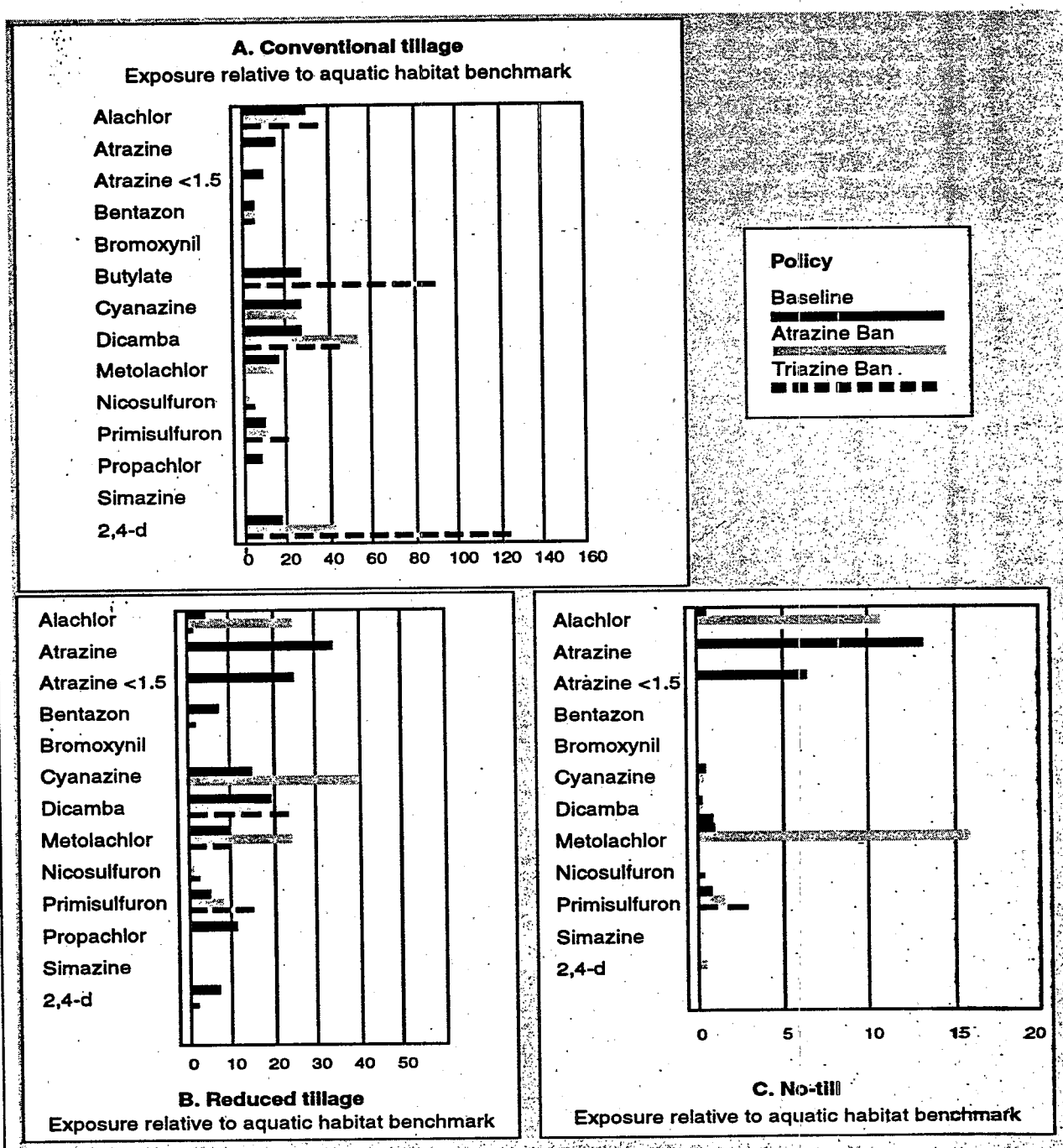


Table 14.
Relative impacts of policies on ground and surface waters

POLICIES		GROUND WATER Acute	GROUND WATER Chronic	SURFACE WATER Acute	SURFACE WATER Chronic	ECO	EROSION W/SU	EROSION W/O
BASELINE	CONVENTIONAL	1.5/0.9	0.09/0.08	2.48/ 0.7	14.2/4.4	189/30	..	..
	REDUCED TILL	2.8/2.3	0.2/0.2	1.86/ 0.7	13.4/9.8	131/58	..	..
	NO TILL	1.2/0.9	0.09/0.08	0.75/ 0.41	4.7/3.5	33/21	..	..
	Weighted sum	1.8/1.3	0.12/0.11	2.27/ 0.69	13.7/5.8	169/37	1.000	1.000
ATRAZINE BAN	CONVENTIONAL	2.8/2.7	0.04/ 0.04	3.98/ 2.7	15.8/8.4	203/53	..	..
	REDUCED TILL	0.05/0.03	0.0006/ 0.0005	1.34/ 0.8	7.3/4	114/40	..	..
	NO TILL	0.14/0.14	0.002/ 0.002	0.95/ 0.54	3.1/1.7	33/17		
	Weighted sum	2.0/1.9	0.028/ 0.028	3.19/ 2.13	13.2/7.0	175/49	1.038	1.009
TRIAZINE BAN	CONVENTIONAL	0.24/0.2	0.001/ 0.0006	1.02/ 0.37	6.5/4.7	344/123	..	..
	REDUCED TILL	0.02/0.02	0.0001/ 0.00009	0.24/ 0.1	0.88/0.6	57/23	..	..
	NO TILL	0.001/0.001	0.00002/ 0.00001	0.009/ 0.0036	0.07/ 0.04	5.9/3.3	..	..
	Weighted sum	0.18/0.15	0.0007/ 0.0004	0.17/ 0.07	0.6/0.4	258/93	1.014	1.018

Note: The first number in a box represents the sum of the pesticide exposure values in a medium. The second is the highest exposure value for any pesticide predicted in a medium.

Table 15.
Estimated percentages of acreage under different tillage practices under the 3 policy scenarios

	Baseline	Atrazine Ban	Triazine Ban
Conventional Tillage	0.6992	0.7031	0.7054
Reduced Tillage	0.2746	0.2708	0.2684
No Till	0.0262	0.0261	0.0262

corn acreage would be expected to decrease, leading to more conventional tillage and thus more soil erosion. The Conservation Compliance provisions of the Farm Bill, however, restrict how much land, particular those lands that are highly erodible, that can be taken out of conservation tillage. The loss of the triazine herbicides, which have been heavily relied on in shifting production from conventional to conservation tillage, would partly force the adoption of new technology—in the form of the sulfonylurea herbicides—to meet the demands of Conservation Compliance. The sulfonylureas, which are very effective in post-emergent use, allow the farmer to reduce the amount of tillage that would otherwise be necessary to control weeds.

Weighting and aggregating impacts:

In deciding whether or not the risks of the use of atrazine on corn outweigh its social benefits, EPA must not only determine the magnitude of these risks and benefits, but also whether or not curtailment of its use leads to a net environmental gain or loss under different economic and policy assumptions. If the use of atrazine on corn is banned in all areas of the country where ground water is susceptible to contamination, for example, will the switching of farmers to alachlor or the other alternatives lead to unacceptable worker health risks or levels of contamination of surface water? Are fish populations potentially placed at greater risk and do the benefits of use still outweigh this risk? How should ground and surface water problems associated with atrazine be traded off against dietary risks possibly associated with the greater reliance on the use of a herbicide that is more likely to leave residues on corn? What

do we have to believe about how toxic dicamba is, in light of the identified data gaps, such that we would decide to discourage switching to it in the event that atrazine is banned? How can we compare risks from this functional group of pesticides when used in different agricultural practices? The atrazine problem can be structured to answer any or all of these questions. This will be demonstrated in the following specification exercise.

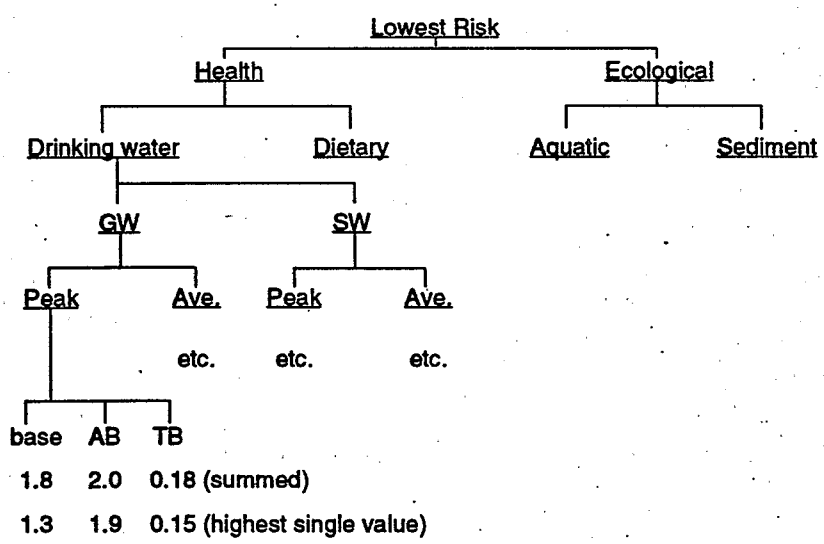
Identification of the goal is the first step in the process of specifying the model. The goal of the analysis is here defined as the best balance between lowest *total environmental risk* and *loss in economic benefit*, both to producers and society as a whole, in combatting an economic pest problem. We structure the analysis to identify the pesticides (and/or practices) that contribute the most (or conversely) the least to environmental risk and economic benefit.

Specification of the risk component is the next step. The decision-making structure in OPP lends itself best to separate analyses of human health risk and adverse ecological impact. The first branching point or node in the hierarchical tree occurs with the division of the total universe of risk into the categories of (1) human health risk and (2) ecological risk (Figure 9). This separation allows initial comparison of pesticides on the basis of only one category of environmental impact. Thus, at an early stage of the analysis, we do not have to make comparisons between pesticides that may pose human toxicological risks and those that kill fish, for example. Only after all the information has been entered and the problem completely structured do we confront the larger question of the trade-off between the identified human and identified ecological risks. A pesticide that poses both human health and ecological risks will be ranked according to how it compares with its alternatives against both criteria. Furthermore, the weighting of ecological versus human risks does not have to be explicitly made, but rather made through a series of what-if questions that identify the weighting that would result in a reordering of policies or practices.

The next branches on the hierarchical tree in Figure 9 are the environmental impacts. The impacts for human health risk for this analysis are dietary and drinking water risks. For ecological risk, the impacts were chosen to be risk to aquatic ecosystems and sediment loadings to surface water—the latter being a proxy for the ecological problems associated with sediment loadings. Clearly, worker risk, impacts of long-range transport, impacts on terrestial species, and bioaccumulation in fish could also have been included. They were not done so for the purpose of simplifying this analysis. Each human health impact is further differentiated by type of exposure: peak level, resulting in short-term or acute exposures, and average levels leading to long-term or chronic exposures.

The weighted values obtained from Table 14 for the policy alternatives that are to be compared serve as inputs to the leaves of the tree. Thus, 1.8, summed exposure values, and 1.3, highest value for any pesticide in the medium, are the input for baseline acute exposures to groundwater sources of drinking water in the category of human health, 2.0/1.9 for an atrazine ban, and 0.18/0.15 for a triazine ban. We create an initial weighting by setting each node of the tree to 0.5. The one exception is the setting of 0.1 to peak exposures for ground water and 0.9 to the corresponding average exposures because of the apparently low Agency concern regarding short-term expo-

Figure 9.
Hierarchal tree for atrazine policy impacts



sures to pesticides in ground water versus long-term exposures (Figure 10).

With these summed exposure values and the weights for impacts, we obtain an initial index score for the policy alternatives as shown in Figure 11. Baseline receives the score 0.387, an atrazine ban 0.414, and a triazine ban 0.199. Where we do not sum exposure values and use highest value obtained for any pesticide in the medium, the scores are baseline 0.41, atrazine ban 0.37, and triazine ban 0.2.

The key weight affecting the ordering of the alternatives is that for health impacts (Figure 12). Changing this weight to less than 0.2, where exposure values are summed (0.24, where they are not summed), results in a reordering of priorities. Thus, the decision-maker must decide whether or not ecological impacts associated with corn herbicide use greatly outweigh (by a factor of 3 to 5) those associated with human health in deciding whether or not to ban the atrazine or the triazine herbicides together. In fact, the more important ecological impacts are deemed to be, the less preferable becomes a triazine ban.

A similar sensitivity analysis could entail reweighting the relative importance of drinking water and dietary risks, as shown in Figures 13a and 13b. One must believe that the magnitude of risks associated with dietary risks must greatly exceed those of drinking water (0.62 to 0.38) to get a reordering of alternatives with respect to the health criterion. A similar sensitivity analysis could be conducted for the weights for each of the nodes of the tree.

In the next step, the aggregate hazard index is compared to the estimates of economic benefit. Economic benefit is drawn from the information in Table 7, whereby we use only the short-term measures. An atrazine ban results in the economic loss of $365 million and a triazine ban $526 million.

A plot of economic benefit against our estimate of risk (the relative hazard index), as shown in Figures 14a and b below, suggests that, if the status quo, as shown by baseline, is not desired, then an triazine ban is superior to a simple ban on atrazine. An atrazine ban buys little reduction in the hazard index, yet a roughly 50% increase in cost for a triazine ban leads to a halving of the risk. However, as indicated above, the greater the decision-maker decides to weight ecological impacts relative to impacts affecting human health, the less preferable a triazine ban is since its ecological impact is greater. Thus, the rationale for banning either atrazine alone or the triazines as a group diminishes the more important the ecological impact of herbicide use is relative to human health.

Figure 10.
Weighting of hierarchical tree nodes

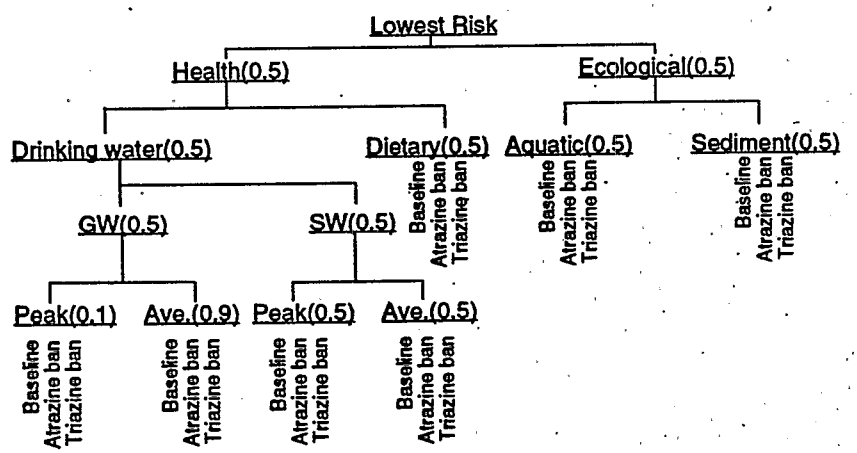


Figure 11.

Aggregate Hazard Index Score for health and ecological impacts weighted equally where exposure values are summed

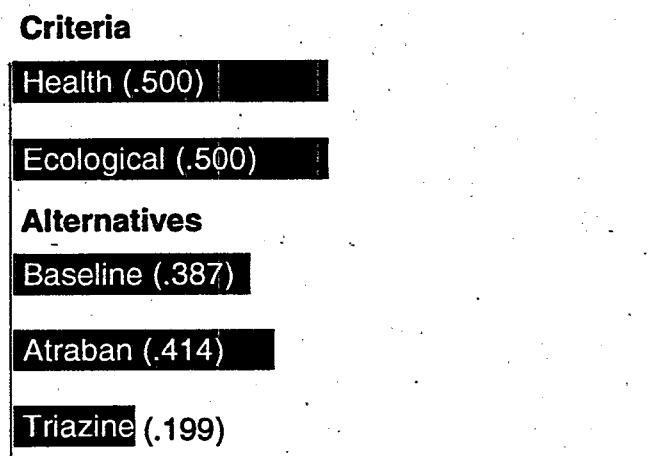


Figure 12.

Relative importance of health and ecological weights in rank order of alternatives

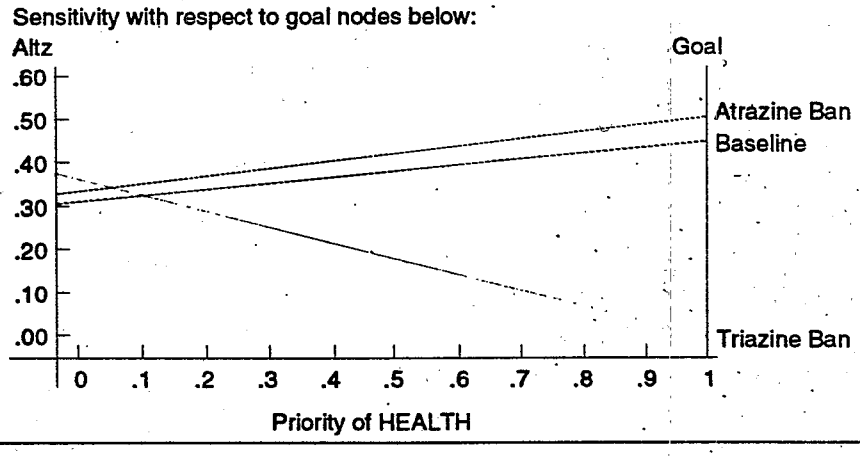


Figure 13a.

Ordering of alternatives with drinking water and dietary risks weighted equally (exposure values summed)

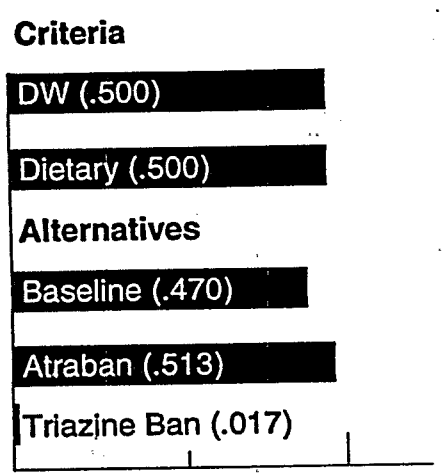


Figure 13b.

Relative importance of drinking water and dietary risks at point of indifference between accepting of status quo (baseline) and atrazine ban (exposure values summed)

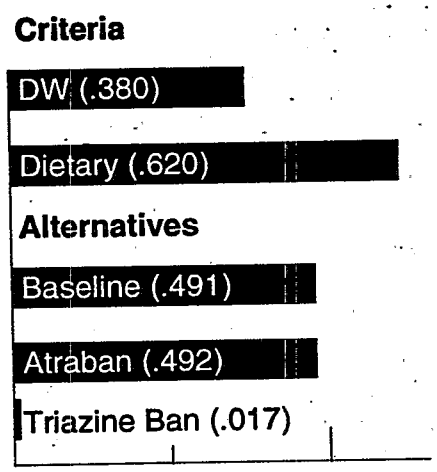


Figure 14a.

Plot of relative hazard index (using summed exposure values) against loss in economic benefit

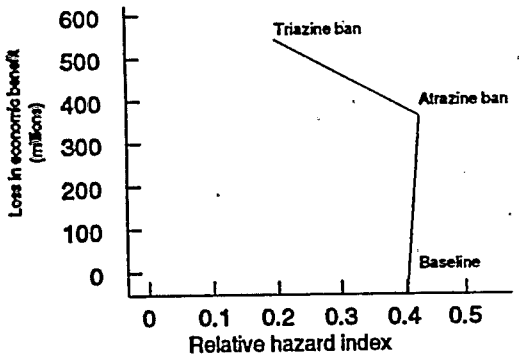
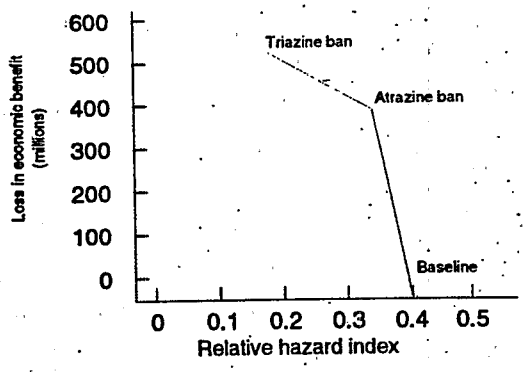


Figure 14b.

Plot of relative hazard index (using a maximum exposure value per impact) versus economic benefit



Conclusion

Our CEEPES analysis leads to a number of key conclusions. The overall goal of reducing environmental risk from agricultural non-point source pollution would not be met from an atrazine ban without a concomitant effort to move producers towards other, more environmentally protective practices. A ban on the triazine herbicides would be preferable to a ban on atrazine should the importance of reducing human health risks be considered more important than protecting the ecological integrity of hydrologic systems.

With an atrazine ban we estimate a decrease in both producer income and consumer effects of $937 million. Government expenditures for commodity price supports, however, would decrease significantly. Thus, the producer and consumer losses offset in part by the reduction in government transfer payments leads to an overall short-term economic loss of $365 million for the entire nation.

Overall herbicide use would not decrease with an atrazine ban. Indeed, total triazine use would increase by 27% on corn, though it would decrease by 84% on sorghum. Nontriazine herbicide use would also increase as more acreage is treated with nontriazine herbicides at higher application rates. Use of the new low-dosage sulfonylurea herbicides would greatly increase, at least in the short run. Given uncertainty regarding pest resistance to these new herbicides and phytotoxic effects on non-target plants, an alternate scenario wherein these herbicides are not available suggests a major shift to post-emergent use of other, non-triazine herbicides that could pose potential problems to surface waters.

We also observe minor shifts in tillage for all crops due to the constraint posed by the Conservation Compliance. We did, however, predict a significant shift away from continuous corn to corn-soybean rotation.

The environment would not necessarily be better off with an atrazine ban. Though exposures, in general, to herbicides in groundwater would generally decline and be of lower general health concern than under current use patterns in any region regardless of tillage practice, there could be an actual increase in site-specific short-term exposures to other triazine herbicides that pose greater ground water contamination risks. The increased use of alternative triazine and nontriazine herbicides from substitute weed control practices would lead to increases in their concentrations in surface water, with differential impacts by soil and tillage type, sometimes exceeding the risk associated with atrazine before a ban. Because the atrazine ban would result in decreased producer and consumer surplus and declines in surface water quality, there could be an overall decrease in welfare. Thus, a ban on atrazine alone, without a significant shift away from chemically intensive agricultural practices, could exacerbate the current public health concern regarding surface water quality.

With a triazine ban, the overall economic loss would be $526 million, resulting from further reductions in producer income and consumer effects, offset by reductions in government expenditures. But under a triazine ban, human health risks from herbicide residues in groundwater would decline significantly. Health risk from herbicide exposures through surface waters would decline overall, with exceptions for specific areas on a smaller proportion of soils from dicamba, bentazon, alachlor, and metolachlor and only under conventional and conservation tillage.

There would be a major shift to the more widespread use of the sulfonylurea herbicides, resulting in concentrations well below their human health benchmarks. However, there are major uncertainties associated with these chemicals regarding pest resistance and their hazard to aquatic and nontarget terrestrial vegetation even at the extremely low concentrations expected in surface water from runoff or drift. The more important one deems the ecological impacts associated with herbicide

use on corn and sorghum, the less preferable is a ban on triazine herbicides, or atrazine in particular, in light of the possibly greater ecological risks associated with chemical alternatives to atrazine use.

An important assumption underlying this analysis which should be reconsidered is that farmers will not opt out of Federal commodity programs. The consequence for producers of leaving the commodity programs is that they are no longer bound to adhere to requirements regarding conservation tillage practices on highly erodible land. The loss of atrazine and/or the other triazine herbicides could lead to greater reversion to conventional tillage practices. More widespread use of conventional tillage for the control of weeds would, in turn, lead to greater soil erosion and hence water quality problems resulting from sedimentation. This scenario could be examined by CEEPES by relaxing the constraint that the percentage of producers subject to Conservation Compliance remains constant. Nevertheless, the questionableness of the assumption does not detract from the overall conclusion drawn from the analysis that bans on atrazine alone or the triazines as a group would not likely result in significant water quality benefits.

We are addressing several issues associated with the comprehensiveness of the analysis. First, work is under way with the weed scientists of the study region to determine and incorporate yield impacts of crop injury. In addition, an effort is under way to review the weed control strategies developed for corn and sorghum and evaluate their efficacy based on local conditions in the various states. Second, we are revisiting the potential adoption of nicosulfuron and primisulfuron. Given that both chemicals are relatively new, more analysis is warranted with regard to the likelihood of their adoption. Third, there are several other policy options such as restrictions on use, technology, and timing of application that will be explored in the near future.

One can infer from the results that the conventional paradigm in addressing pesticide-related problems, i.e., bans or licensing restrictions, may not be the appropriate response for the corn and sorghum herbicides, in particular, or water-related problems of pesticides in general. More geographically targeted mitigation measures short of bans may lead to superior environmental protection and minimal impact on producers and society on a whole. The nature of these mitigation measures will be explored in future analyses with CEEPES.

Some measures that we are exploring include a mix of incentives and controls to encourage the more efficient use of chemicals and the adoption of agricultural practices that are more protective of water quality—that is, to manage resources better. The controls that are being considered are the following: atrazine label restriction to 1 lb a.i. per acre or less; no preemergent use (atrazine or herbicides in general); requirement of vegetative filter strips along surface water bodies; impact of crop rotations on yield and environmental risk. These and other policies and practices will be examined in future studies using CEEPES, with results presented by watershed.

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Appendix A

Herbicides Included in CEEPES Configuration for Atrazine and Water Quality

Herbicides included in CEEPES configuration for atrazine and water quality

Code	Chemical	Trade Name
LAS	Alachlor	Lasso
ATR	Atrazine	AAtrex
BAS	Bentazon	Basagran
BUC	Bromoxynil	Buctril
SUT	Butylate	Sutan
BLA	Cyanazine	Bladex
BAN	Dicamba	Banvel
ERA	EPTC	Eradicane
ROU	Glyphosate	Round-up
DUA	Metolachlor	Dual
ACC	Nicosulfuron	Accent
GRA	Paraquat	Gramaxone
BEA	Primisulfuron	Beacon
PRO	Pendimenthalin	Prowl
RAM	Propachlor	Ramrod
PRI	Simazine	Princep
TFD	2,4-D	2,4-D

Appendix B

Shifts in Weed Control Strategies

Table B.1.
Percentage of corn acres treated, baseline

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
66	Atrazine[b]-Bladex preemergence	Atrazine[b]-Basagran postemergence Atrazine[b]-Banvel preemergence Atrazine[b]-Buctril preemergence	16.0
156	Atrazine[a]-Lasso preplant inc. Atrazine[a]-Dual preplant inc.	Accent preemergence Beacon preemergence	11.7
157	Atrazine[b]-Bladex preplant inc.	Atrazine[a] preemergence	9.5
158	Atrazine[2]-Bladex preplant inc.	Atrazine[b]-Basagran preemergence Atrazine[b]-Banvel preemergence Atrazine[a]-Buctril preemergence	7.6
170	Atrazine[a]-Lasso preplant inc.	Atrazine[b]-Basagran preemergence Atrazine[b]-Banvel preemergence Atrazine[a]-Buctril preemergence	5.3
69	Atrazine[b]-Bladex preemergence	2,4-D preemergence	3.9
70	Atrazine[b]-Bladex preemergence	Banvel-2,4-D preemergence	4.4
219	Sutan preplant inc. & Banvel post	Accent preemergence	3.8
107	Dual-Banvel preemergence	Atrazine[b]-Basagran preemergence Atrazine[b]-Banvel preemergence Atrazine[b]-Buctril preemergence	3.6
67	Atrazine[b]-Bladex preemergence	Bladex preemergence Prowl-Bladex preemergence	3.4

[a]Atrazine applied at a rate > 1.5 lb/acre.

[b]Atrazine applied at a rate < 1.5 lb/acre.

Figure B.1.
Percentage of corn acres treated, baseline

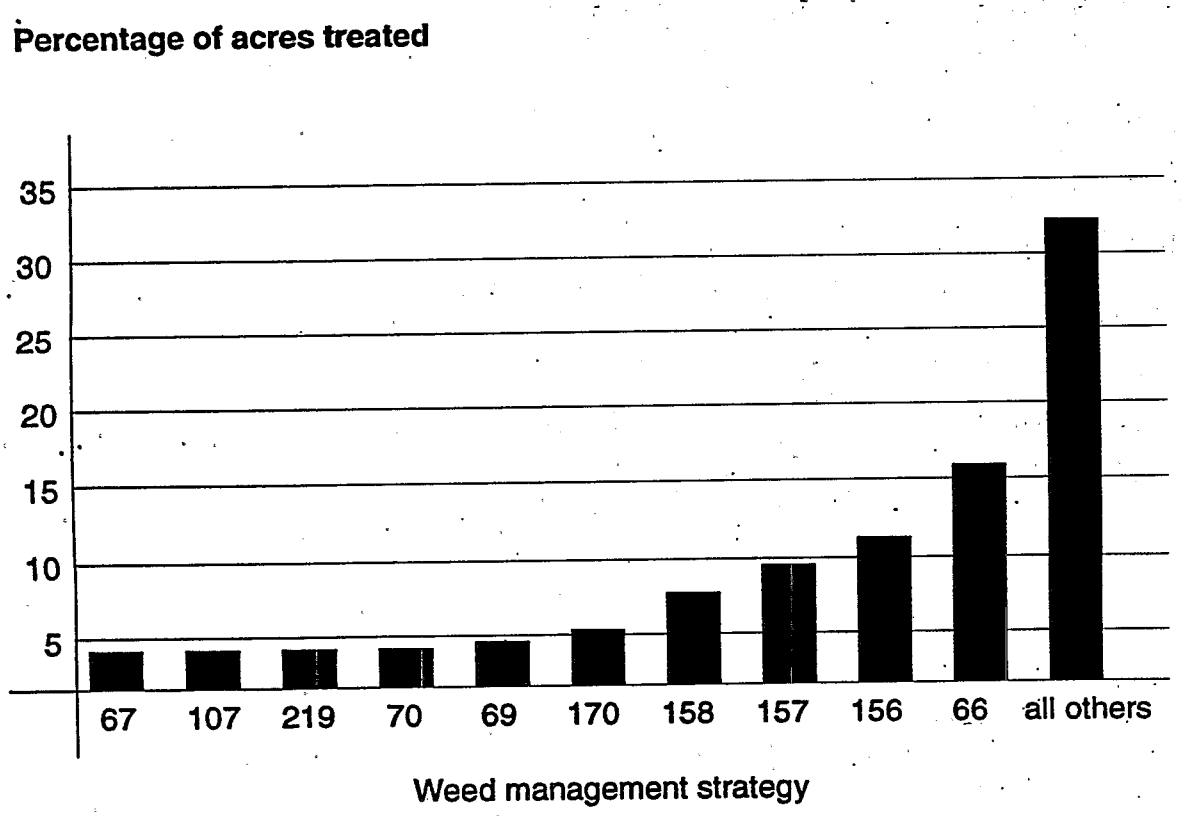


Table B.2.
Percentage of corn acres treated, atrazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
185	Princep preplant incorporated	Accent postemergence Beacon postemergence	22.8
127	Bladex-Prowl preemergence	Accent postemergence Beacon postemergence	15.6
225	Sutan preplant inc. & 2,4-D post Lasso preplant inc. & 2,4-D post Dual preplant inc. & 2,4-D post	Accent postemergence Beacon postemergence	11.9
99	Bladex-Lasso preemergence Bladex-Dual preemergence	Accent postemergence Beacon postemergence	11.3
223	Sutan preplant inc. & 2,4-D post Lasso preplant inc. & 2,4-D post Dual preplant inc. & Banvel post	Accent postemergence Beacon postemergence	11.1
219	Princep preplant incorporated	Banvel postemergence Buctril postemergence Basagran postemergence	3.8
183	Princep preplant incorporated	Banvel postemergence Buctril postemergence Basagran postemergence	3.8
191	Bladex-Lasso preemergence Bladex-Dual preemergence	Accent postemergence Beacon postemergence	3.4

Figure B.2.
Percentage of corn acres treated, atrazine ban

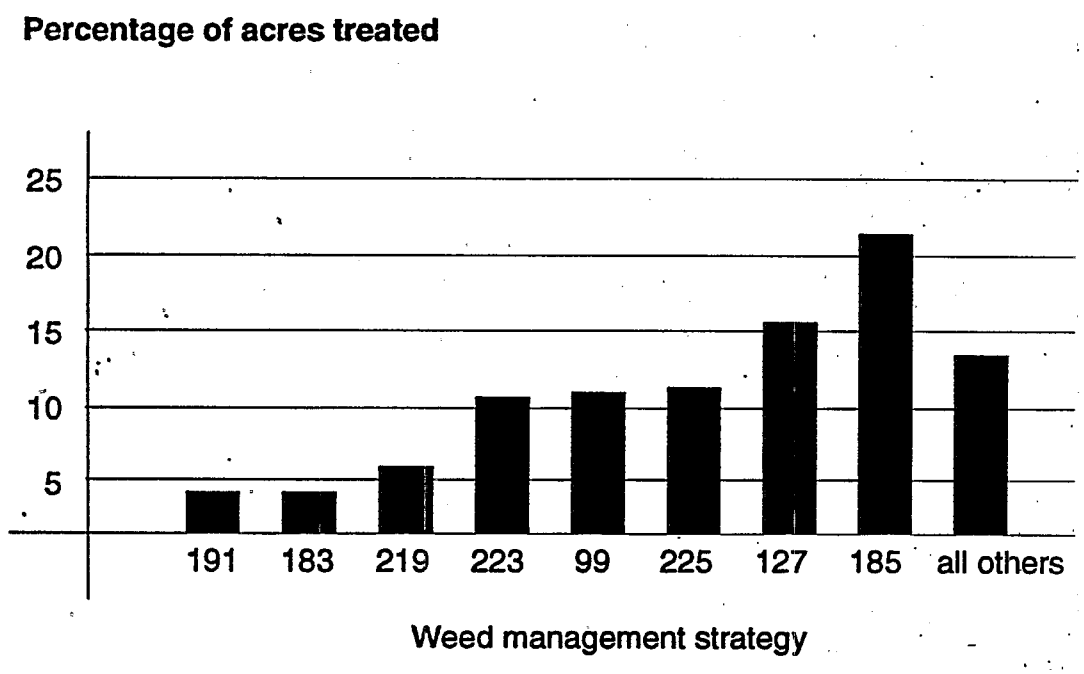


Table B.3.
Percentage of corn acres treated, triazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
225	Sutan preplant & 2,4-D post Lasso preplant inc. & 2,4-D post Dual preplant inc. & 2,4-D	Accent postemergence Beacon postemergence	43.9
144	Rotary hoe and row cultivation	Accent postemergence Beacon postemergence	27.0
223	Sutan preplant inc. & Banvel post Lasso preplant inc. & Banvel post Dual preplant inc. & Banvel post	Banvel postemergence Buctril postemergence Basagran postemergence	9.2
111	Dual-Banvel preemergence	Accent postemergence Beacon postemergence	4.3
219	Sutan preplant inc. & Banvel post Lasso preplant inc. & Banvel post Dual preplant inc. & Banvel post	Accent postemergence Beacon postemergence	4.3
133	Lasso preemergence & Banvel post Dual preemergence & Banvel post	Accent postemergence Beacon postemergence	3.9
52	Accent postemergence Beacon postemergence	None	3.1

Figure B.3.
Percentage of corn acres treated, triazine ban

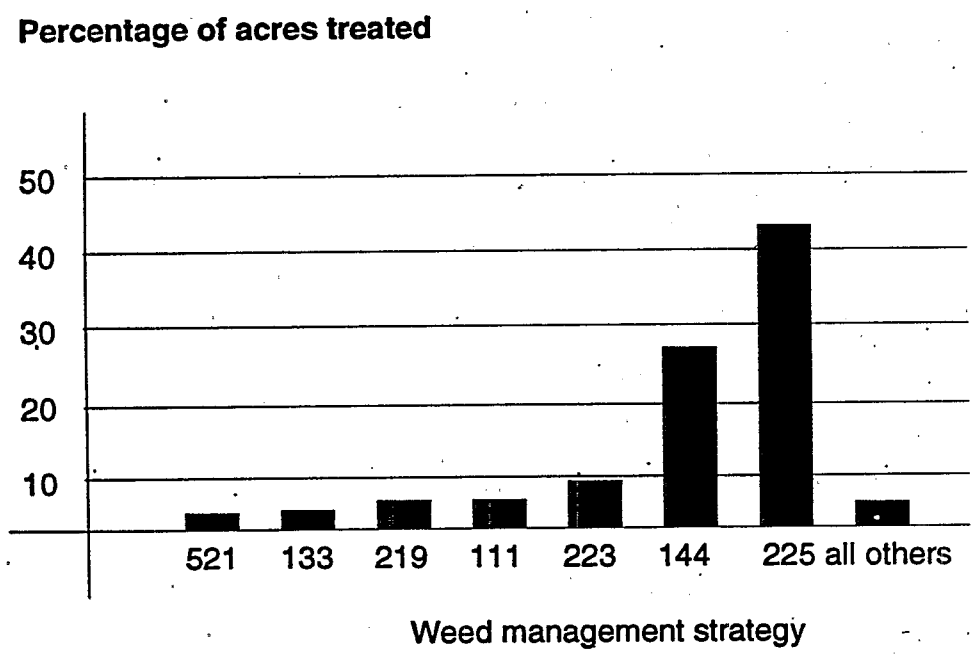


Table B.4.

Percentage of sorghum acres treated, baseline

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
1061	Lasso preplant inc. & Banvel post. Dual preplant inc. & Banvel post.	2,4-D postemergence Banvel 2,4-D postemergence	35.3
1059	Lasso preplant inc. & Banvel post. Dual preplant inc. & Banvel post.	Prowl-Atrazine[a] postemergence	22.0
1050	Atrazine[a] preplant incorporated	2,4-D postemergence	12.2
1042	Prowl-Atrazine[b] postemergence	None	10.3
1054	Atrazine[b]-Dual preplant inc.	Prowl-Atrazine[b] postemergence	10.2
1090	Atrazine[a] postemergence	None	5.9

[a]Atrazine applied at a rate > 1.5 lb/acre.
[b]Atrazine applied at a rate < 1.5 lb/acre.

Figure B.4.

Percentage of sorghum acres treated, baseline

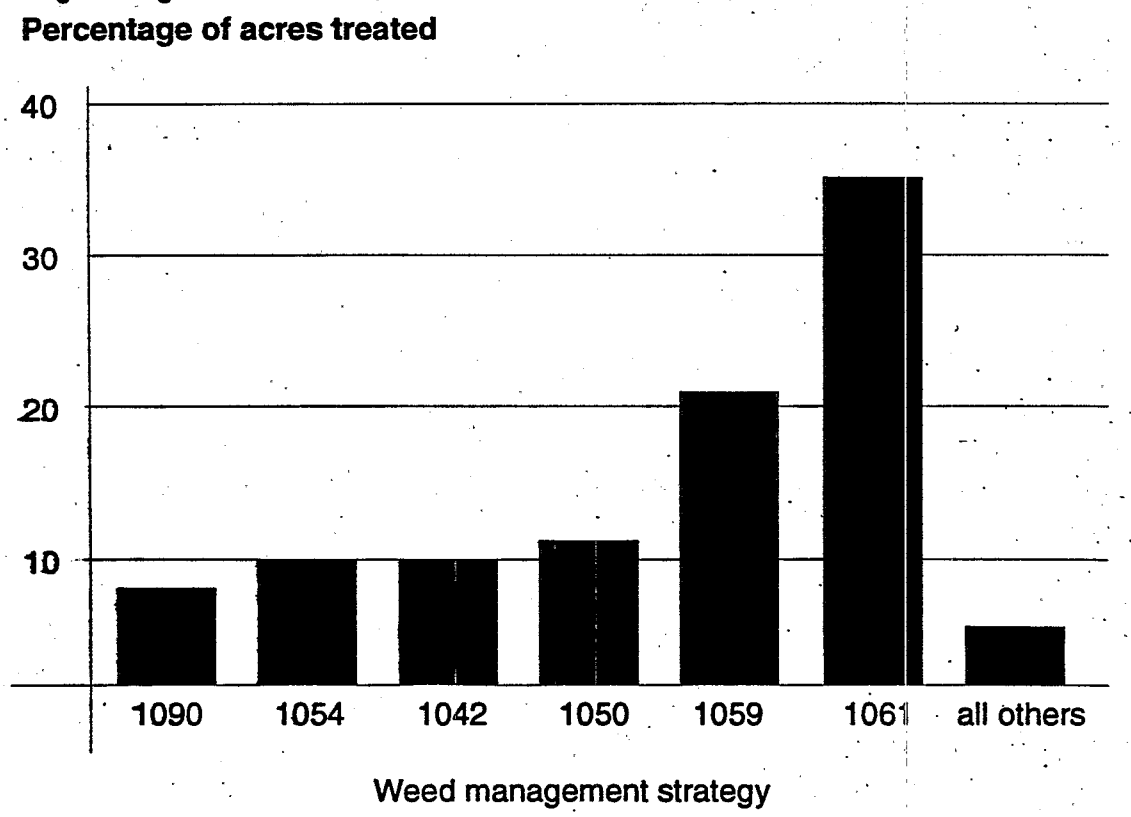


Table B.5.
Percentage of sorghum acres treated, atrazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
1061	Lasso preplant inc. & Banvel post. Dual preplant inc. & Banvel post.	2,4-D postemergence Banvel, 2,4-D postemergence	60.7
1066	Lasso preplant inc. & 2,4-D post. Dual preplant inc. & 2,4-D post.	2,4-D post-emergence Banvel 2,44-D	15.9
1025	Bladex-Ramrod preemergence	2,4-D post emergence Banvel, 2,4-D postemergence	15.5
1039	Lasso preemergence & Banvel post. Dual preemergence & Banvel post. Ramrod preemergence & Banvel post.	2,4-D post emergence Banvel 2,4-D postemergence	7.8

Figure B.5.
Percentage of sorghum acres treated, atrazine ban

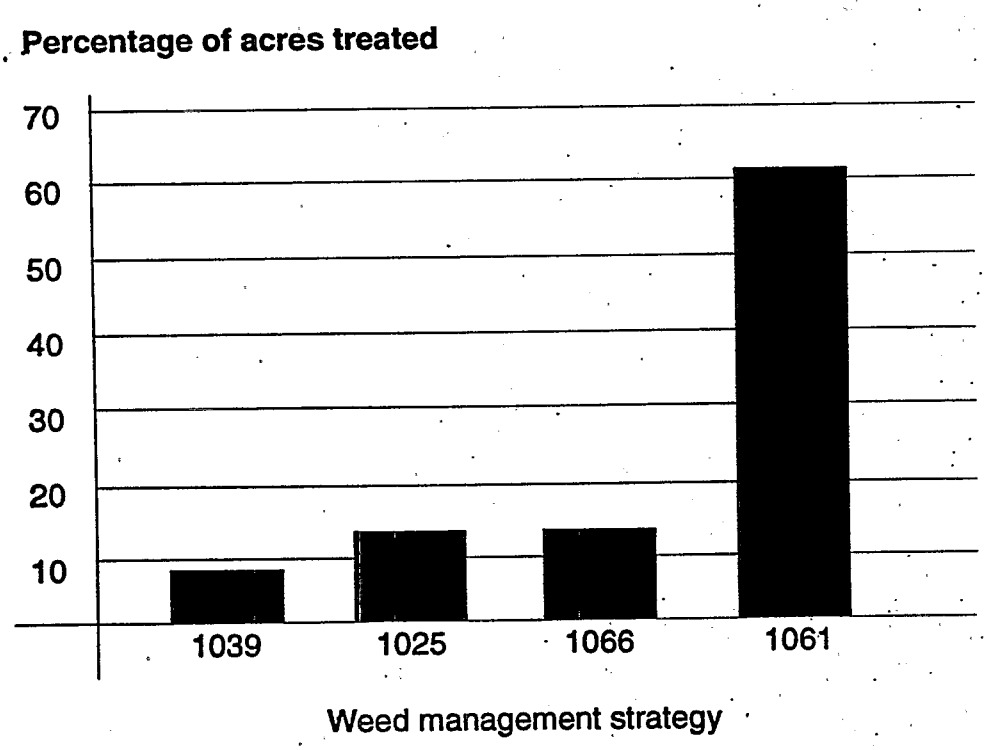
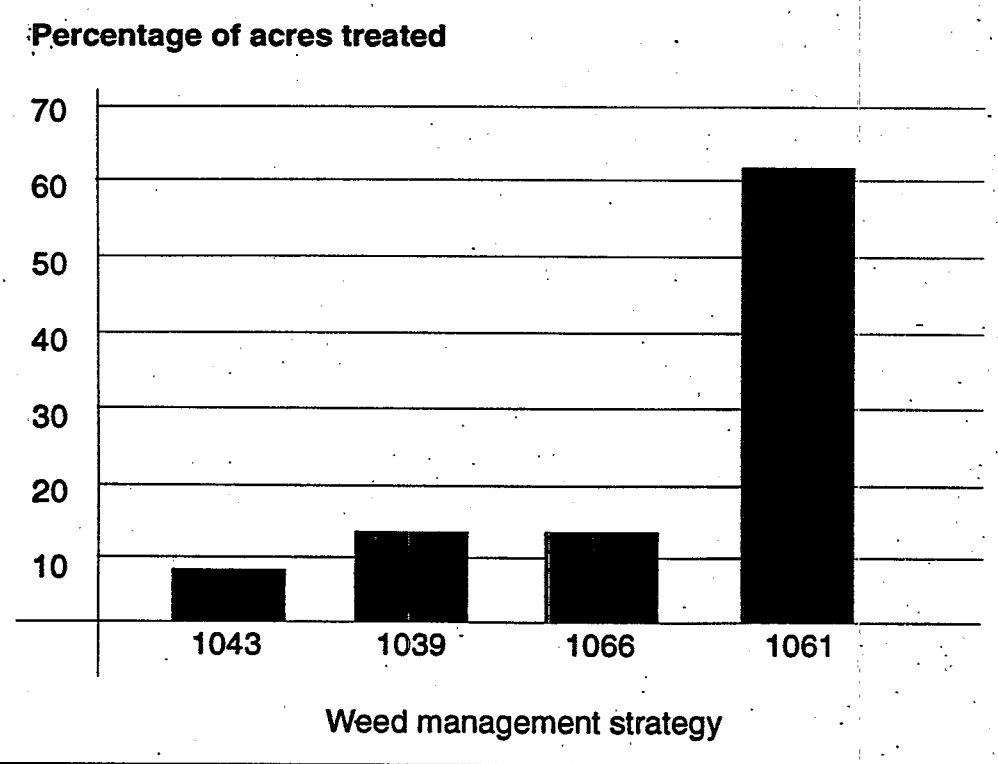


Table B.6.
Percentage of sorghum acres treated, triazine ban

Strategy Number	Primary Strategy	Secondary Strategy	Percent Treated
1061	Lasso preplant inc. & Banvel post.	2,4-D postemergence	60.2
	Dual preplant inc. & Banvel post.	Banvel 2,4-D postemergence	
1066	Lasso preplant inc. & 2,4-D post.	2,4-D postemergence	15.7
	Dual preplant inc. & 2,4-D post.	Banvel 2,4-D postemergence	
	Lasso preemergence & Banvel post.		
1039	Dual preemergence & Banvel post.	2,4-D postemergence	15.2
	Ramrod preemergence & Banvel post.	Banvel-2,4-D postemergence	
1043	Rotary hoe and row cultivation	None	8.8

Figure B.6.
Percentage of sorghum acres treated, triazine ban



Appendix C

Shifts in Rotations

Change in the distribution of crop rotation
(Percentage of change from the baseline)

Rotation	Code	Baseline	ATRZ_BAN	TRIZ_BAN
		mil. ac	% chng	% chng
BAR BAR SOY	2	4.1903	0.000	0.000
BAR BAR SMF	4	0.2606	0.000	0.000
BAR CRN CRN CRN	8	0.3952	0.000	0.024
BAR CSL	11	0.0639	0.000	0.000
BAR HLH HLH CRN CRN	21	4.4649	0.000	0.000
BAR SOY	70	0.0585	1.144	1.144
BAR SUN SMF SWT	78	1.1884	0.000	0.000
BAR SWT	80	0.1244	0.000	0.000
BAR SWT SUN SWT	81	2.6112	0.000	0.000
CRN	100	18.0974	-16.010	-16.552
CRN CRN CRN OTS NLH NLH	107	0.2161	-59.545	0.000
CRN CRN CRN SWT	109	0.0027	-6.520	-
CRN CRN CRN WWT HLH	111	0.1552	111.915	199.823
CRN CRN CRN HLH HLH HLH	115	0.7133	-	-
CRN CRN OTS HLH HLH	122	0.2444	0.006	0.025
CRN CRN OTS HLH HLH HLH	123	2.3169	-79.920	-25.077
CRN CRN OTS NLH NLH	125	1.1646	-1.025	0.212
CRN CRN OTS NLH NLH NLH	126	0.2579	108.965	-
CRN CRN SOY	131	15.3956	-14.495	-12.901
CRN CRN SOY OTS HLH	132	2.6669	0.227	0.201
CRN CRN SOY SRG	136	0.5747	-24.878	-24.878
CRN CRN SOY WWT	137	0.5524	0.000	0.000
CRN CRN SOY WWT HLH	138	2.0080	-8.512	-15.344
CRN CRN WWT HLH HLH	144	1.7473	0.351	0.976
CRN CRN WWT HLH HLH HLH	145	0.6041	0.000	0.000
CRN OTS HLH HLH HLH	162	0.8612	149.892	116.890
CRN OTS NLH NLH NLH	168	0.1723	0.000	0.049
CRN OTS WWT	170	0.1019	169.026	0.000
CRN SRG	178	0.1165	7.955	7.955
CRN SOY	186	51.6816	11.116	10.409
CRN SOY CRN WWT HLH HLH	189	1.3258	0.000	0.000
CRN SOY OTS NLH NLH	196	0.5885	-3.163	42.863
CRN SOY WWT	201	12.9918	-2.874	-2.800
CRN SOY WWT HLH HLH HLH	203	3.4480	21.207	20.580
CRN SWT	210	0.2238	39.355	38.925
CRN SWT SWT	215	2.1908	27.264	33.223
CRN WWT	218	0.7467	-15.374	0.000
CRN NLH NLH	231	0.2277	0.000	0.000
CRN NLH NLH NLH	232	0.4235	0.000	0.000

CSL	235	0.5276	2.427	4.812
CSL CSL CSL SWT	239	0.4141	0.042	-98.685
CSL CSL OTS HLH	242	0.9167	-0.324	-0.324
CSL CSL OTS HLH HLH	243	1.6314	-0.154	-0.108
CSL CSL OTS HLH HLH HLH	244	1.3533	12.500	15.486
CSL CSL OTS NLH NLH	246	0.2556	6.656	5.940
CSL CSL SOY	250	0.4473	-41.129	-60.806
CSL CSL WWT NLH NLH	252	0.0053	3.367	3.367
CSL OTS	259	0.5418	-0.418	-0.373
CSL OTS HLH HLH	261	0.2843	-12.559	-11.765
CSL OTS HLH HLH HLH	262	1.6779	-3.060	5.601
CSL OTS HLH HLH SWT	265	0.4283	-	-
CSL SOY CSL OTS NLH NLH	276	0.0874	-23.647	-21.877
CSL SOY HLH HLH HLH HLH	277	0.4449	0.000	0.000
CSL SWT	280	0.4112	-0.111	0.123
COT SOY	325	2.4551	0.000	0.000
HLH HLH HLH HLH SRG SOY	339	0.9416	15.14	0.000
OTS HLH HLH HLH	350	0.8094	48.51	-22.48
OTS HLH HLH HLH SRG SRG	354	0.4518	9.82	9.14
OTS NLH NLH NLH	366	2.2941	-10.40	-16.43
OTS NLH NLH NLH SOY	372	0.1380	0.000	0.000
OTS NLH NLH SSL SOY SSL	379	0.0204	5.11	6.55
OTS OTS SMF	384	0.7267	6.83	5.69
SRG	409	1.2112	0.03	-0.01
SRG SOY	415	1.4834	-15.79	-12.36
SRG SOY SOY	416	1.9871	-9.06	-9.06
SRG SOY WWT	417	0.2250	1.03	1.03
SRG SOY HLH HLH HLH HLH	419	0.2029	-0.09	-0.52
SRG WWT	424	3.3043	7.50	11.08
SRG NLH NLH	432	0.0240	1017.94	1017.94
SSL SSL WWT NLH NLH	434	0.0031	2.47	2.47
SSL WWT	439	0.0997	0.000	0.000
SOY SWT SWT	452	1.0513	0.000	0.000
SOY WWT	454	0.2606	-5.44	-5.40
SOY WWT SOY	458	0.8846	10.63	10.26
SOY WWT WWT WWT	459	1.6778	0.000	0.000
SOY NLH NLH NLH NLH	462	0.0431	-61.45	-61.45
SMF SWT	463	5.8720	-3.05	-4.20
SMF WWT	471	0.6293	-	-
SWT HLH HLH HLH	478	0.0519	0.000	781.34
WWT	490	2.8487	-12.63	-5.54
HLH HLH HLH HLH	503	18.2503	0.26	-0.09
NLH NLH NLH NLH	508	18.0575	-6.29	-3.95

Appendix D

Ground and Surface Water Concentrations and Exposure Values for 15 Herbicides in the Study Region for Baseline, Atrazine Ban, and Triazine Ban Scenarios in Corn Production

Ground and Surface Water Herbicide Concentrations (in parts per billion)

POLICY=Baseline CROP=Corn

Conventional Tillage

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.24904	2.3674	0.001296	0.009379	34.9458
Atrazine<1.5	0.23983	2.7014	0.001804	0.017331	17.8924
Nicosulfuron	0.00000	0.0000	0.000000	0.000000	0.0175
Dicamba	0.00064	0.1246	0.000000	0.000002	29.4817
Primisulfuron	0.00138	0.0130	0.000006	0.000026	0.1757
Cyanazine	0.00017	0.0325	0.000000	0.000008	63.7835
Bromoxynil	0.00000	0.0000	0.000000	0.000000	0.0309
Bentazon	0.00681	0.1796	0.000010	0.000147	2.9032
Metolachlor	0.00019	0.0133	0.000000	0.000009	17.1911
Alachlor	0.00009	0.0147	0.000000	0.000001	27.7008
Simazine	0.23551	1.8963	0.002580	0.019724	34.7559
Pendimethalin	0.00000	0.0000	0.000000	0.000000	0.0000
Propachlor	0.00001	0.0011	0.000000	0.000000	6.3120
Butylate	0.00983	2.7832	0.000000	0.000004	28.1301
2,4-D	0.00003	0.0145	0.000000	0.000000	15.7291
Atrz-Med-Decay	0.47923	4.3875	0.002944	0.022901	59.0422
Atrz-Slow-Decay	2.83069	10.8769	0.056920	0.099106	52.0976
Atrz-Fast-Decay	0.00009	0.0085	0.000000	0.000000	25.4502

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.60158	7.0364	0.004093	0.02418	65.918
Atrazine<1.5	0.52893	5.3189	0.003573	0.02304	51.643
Nicosulfuron	0.00000	0.0000	0.000000	0.00000	0.006
Dicamba	0.00064	0.1688	0.000000	0.00001	19.254
Primisulfuron	0.00090	0.0094	0.000003	0.00002	0.062
Cyanazine	0.00005	0.0093	0.000000	0.00000	19.215
Bromoxynil	0.00000	0.0000	0.000000	0.00000	0.072
Bentazon	0.02229	0.5347	0.000028	0.00030	7.704
Metolachlor	0.00004	0.0031	0.000000	0.00000	10.160
Alachlor	0.00001	0.0022	0.000000	0.00000	3.891
Simazine	0.22449	1.7034	0.002092	0.01350	22.949
Pendimethalin	0.00000	0.0000	0.000000	0.00000	0.000
Propachlor	0.00001	0.0037	0.000000	0.00000	11.067
2,4-D	0.00004	0.0226	0.000000	0.00000	6.071
Atrz-Med-Decay	1.10987	10.8803	0.007317	0.04236	133.502
Atrz-Slow-Decay	6.32963	26.2752	0.099055	0.14595	117.672
Atrz-Fast-Decay	0.00054	0.0515	0.000000	0.00000	23.729

No-tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.25210	2.73901	0.002933	0.023260	26.8218
Atrazine<1.5	0.10878	0.98029	0.000925	0.005138	13.7617
Nicosulfuron	0.00000	0.00000	0.000000	0.000000	0.0029
Dicamba	0.00001	0.00359	0.000000	0.000000	0.2557
Primisulfuron	0.00088	0.00857	0.000006	0.000024	0.0300
Cyanazine	0.00000	0.00055	0.000000	0.000000	1.7765
Bromoxynil	0.00000	0.00000	0.000000	0.000000	0.0006
Bentazon	0.00047	0.00986	0.000001	0.000008	0.0634
Metolachlor	0.00002	0.00125	0.000000	0.000001	0.8591
Alachlor	0.00000	0.00057	0.000000	0.000000	0.9827
Simazine	0.18579	1.11248	0.003074	0.012677	15.2363
Pendimethalin	0.00000	0.00000	0.000000	0.000000	0.0000
Glyphosate	0.00000	0.00000	0.000000	0.000000	0.0000
2,4-D	0.00000	0.00087	0.000000	0.000000	0.2505
Atrz-Med-Decay	0.35380	3.23373	0.003656	0.024598	45.8989
Atrz-Slow-Decay	2.05537	7.92776	0.062238	0.093926	40.4743
Atrz-Fast-Decay	0.00013	0.01297	0.000000	0.000000	8.0125

*see legend, page 58

Ground and Surface Water Herbicide Concentrations (in parts per billion)

POLICY=Atrazine Ban CROP=Corn

Cnventional Tillage

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.00000	0.000	0.000000	0.000000	0.027
Dicamba	0.00114	0.2313	0.000000	0.000003	53.845
Primisulfuron	0.00265	0.0281	0.000014	0.000061	0.256
Cyanazine	0.00017	0.0343	0.000000	0.000009	58.733
Bromoxynil	0.00000	0.0000	0.000000	0.000000	0.044
Bentazon	0.00592	0.1301	0.000008	0.000090	3.228
Metolachlor	0.00029	0.0220	0.000000	0.000033	13.308
Alachlor	0.00015	0.0244	0.000000	0.000010	21.492
Simazine	1.37028	10.9284	0.013849	0.090643	134.997
Butylate	0.01052	3.0583	0.000000	0.000004	28.729
2,4-D	0.00009	0.0365	0.000000	0.000000	42.603

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000	0.00000	0.00000000	0.0000000	0.0235
Dicamba	0.000418	0.10324	0.00000000	0.0000012	14.2105
Primisulfuron	0.002906	0.03080	0.00001459	0.0000550	0.2298
Cyanazine	0.000078	0.01260	0.00000000	0.0000006	79.8721
Bromoxynil	0.000000	0.00000	0.00000000	0.0000000	0.0026
Bentazon	0.000016	0.00097	0.00000000	0.0000000	0.1847
Metolachlor	0.000128	0.00887	0.00000003	0.0000044	23.2487
Alachlor	0.000040	0.00631	0.00000000	0.0000004	21.6838
Simazine	0.018520	0.13033	0.00029247	0.0018712	2.3393
Pendimethalin	0.000000	0.00000	0.00000000	0.0000000	0.0000
2,4-D	0.000003	0.00145	0.00000000	0.0000000	1.0366

No-till

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000	0.00000	0.0000000	0.0000000	0.0062
Dicamba	0.000001	0.00022	0.0000000	0.0000000	0.0260
Primisulfuron	0.001561	0.01534	0.0000131	0.0000478	0.0610
Cyanazine	0.000001	0.00012	0.0000000	0.0000000	0.5952
Metolachlor	0.000305	0.02146	0.0000006	0.0000456	16.6854
Alachlor	0.000058	0.00875	0.0000000	0.0000041	10.7396
Simazine	0.084350	0.53965	0.0010061	0.0062077	26.8990
Pendimethalin	0.000000	0.00000	0.0000000	0.0000000	0.0000
Glyphosate	0.000000	0.00000	0.0000000	0.0000000	0.0000

*see legend, page 58

Ground and Surface Water Herbicide Concentrations (in parts per billion)

POLICY=Triazine Ban CROP=Corn

Conventional Till

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000	0.00000	0.000000000	0.00000000	0.072
Dicamba	0.000849	0.17073	0.000000007	0.00000203	45.053
Primisulfuron	0.006444	0.07271	0.000034789	0.00014400	0.655
Bromoxynil	0.000000	0.00000	0.000000000	0.00000000	0.059
Bentazon	0.007219	0.19859	0.000034937	0.00011283	4.362
Metolachlor	0.000368	0.02846	0.000000535	0.00003907	22.064
Alachlor	0.000187	0.03158	0.000000074	0.00001069	37.631
Butylate	0.028833	9.79993	0.000000637	0.00015354	90.059
2,4-D	0.000347	0.17729	0.000000002	0.00000092	126.123

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.0000000	0.00000	0.000000000	0.00000000	0.0451
Dicamba	0.0007748	0.16183	0.000000004	0.00000238	22.7040
Primisulfuron	0.0060336	0.06930	0.000030323	0.00010681	0.4287
Bromoxynil	0.0000000	0.00000	0.000000000	0.00000000	0.0162
Bentazon	0.0000983	0.00590	0.000000003	0.00000014	1.1282
Metolachlor	0.0000694	0.00407	0.000000021	0.00000247	9.7194
Alachlor	0.0000085	0.00099	0.000000000	0.00000009	1.6802
2,4-D	0.0000035	0.00171	0.000000000	0.00000000	1.1657

No-tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.0000000	0.00000	0.000000000	0.000000001	0.01009
Dicamba	0.0000362	0.09751	0.000000000	0.000000117	1.08519
Primisulfuron	0.0028049	0.28281	0.000022393	0.000083589	0.09718
Metolachlor	0.0000049	0.00403	0.000000001	0.000000288	0.18317
Alachlor	0.0000026	0.00483	0.000000000	0.000000044	0.33859
Glyphosate	0.0000000	0.00000	0.000000000	0.000000000	0.00000

*see legend, page 58

Ground and Surface Water Exposures (relative to benchmarks)

POLICY=Baseline CROP=Corn

Conventional Tillage

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.08301	0.02367	0.00432	0.009379	0.34946
Atrazine<1.5	0.07994	0.02701	0.00601	0.017331	0.17892
Nicosulfuron	0.00000	0.00000	0.00000	0.000000	0.00040
Dicamba	0.00007	0.00042	0.00000	0.000001	0.09827
Primisulfuron	0.00001	0.00006	0.00000	0.000013	0.00084
Cyanazine	0.00002	0.00033	0.00000	0.000008	0.63784
Bromoxynil	0.00000	0.00000	0.00000	0.000000	0.00004
Bentazon	0.00034	0.00719	0.00000	0.000589	0.11613
Metolachlor	0.00000	0.00013	0.00000	0.000009	0.17191
Alachlor	0.00005	0.00015	0.00000	0.000001	0.27701
Simazine	0.00673	0.03793	0.00074	0.039448	0.69512
Pendimethalin	0.00000	0.00000	0.00000	0.000000	0.00000
Propachlor	0.00000	0.00000	0.00000	0.000000	0.01803
Butylate	0.00020	0.00116	0.00000	0.000000	0.01172
2,4-D	0.00000	0.00001	0.00000	0.000000	0.01430
Atrz-Med-Decay	0.15974	0.04388	0.00981	0.022901	0.59042
Atrz-Slow-Decay	0.94356	0.10877	0.18973	0.099106	0.52098
Atrz-Fast-Decay	0.00003	0.00008	0.00000	0.000000	0.25450

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.20053	0.07036	0.01364	0.02418	0.65918
Atrazine<1.5	0.17631	0.05319	0.01191	0.02304	0.51643
Nicosulfuron	0.00000	0.00000	0.00000	0.00000	0.00015
Dicamba	0.00007	0.00056	0.00000	0.00000	0.06418
Primisulfuron	0.00000	0.00004	0.00000	0.00001	0.00030
Cyanazine	0.00001	0.00009	0.00000	0.00000	0.19215
Bromoxynil	0.00000	0.00000	0.00000	0.00000	0.00010
Bentazon	0.00111	0.02139	0.00001	0.00121	0.30815
Metolachlor	0.00000	0.00003	0.00000	0.00000	0.10160
Alachlor	0.00001	0.00002	0.00000	0.00000	0.03891
Simazine	0.00641	0.03407	0.00060	0.02699	0.45898
Pendimethalin	0.00000	0.00000	0.00000	0.00000	0.00000
Propachlor	0.00000	0.00001	0.00000	0.00000	0.03162
2,4-D	0.00000	0.00002	0.00000	0.00000	0.00552
Atrz-Med-Decay	0.36996	0.10880	0.02439	0.04236	1.33502
Atrz-Slow-Decay	2.10988	0.26275	0.33018	0.14595	1.17672
Atrz-Fast-Decay	0.00018	0.00052	0.00000	0.00000	0.23729

No-tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Atrazine	0.08403	0.027390	0.000978	0.023260	0.26822
Atrazine<1.5	0.03626	0.009803	0.000308	0.005138	0.13762
Nicosulfuron	0.00000	0.000000	0.000000	0.000000	0.00007
Dicamba	0.00000	0.000012	0.000000	0.000000	0.00085
Primisulfuron	0.00000	0.000041	0.000000	0.000011	0.00014
Cyanazine	0.00000	0.000006	0.000000	0.000000	0.01777
Bromoxynil	0.00000	0.000000	0.000000	0.000000	0.00000
Bentazon	0.00002	0.000394	0.000000	0.000031	0.00254
Metolachlor	0.0000	0.000013	0.000000	0.000001	0.00859
Alachlor	0.00000	0.000006	0.000000	0.000000	0.00983
Simazine	0.00531	0.022250	0.000088	0.025355	0.30473
Pendimethalin	0.00000	0.000000	0.000000	0.000000	0.00000
Glyphosate	0.00000	0.000000	0.000000	0.000000	0.00000
2,4-D	0.00000	0.000001	0.000000	0.000000	0.00023
Atrz-Med-Decay	0.11793	0.032337	0.001219	0.024598	0.45899
Atrz-Slow-Decay	0.68512	0.079278	0.020746	0.093926	0.40474
Atrz-Fast-Decay	0.00004	0.000130	0.000000	0.000000	0.08013

*see legend, page 58

Ground and Surface Water Exposures (relative to benchmarks)

POLICY=Atrazine Ban CROP=Corn

Conventional Tillage

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000	0.00000	0.00000000	0.0000000	0.00061
Dicamba	0.000127	0.00077	0.00000000	0.0000000	0.17948
Primisulfuron	0.000013	0.00013	0.00000006	0.0000003	0.00122
Cyanazine	0.000019	0.00034	0.00000001	0.0000001	0.58733
Bromoxynil	0.000000	0.00000	0.00000000	0.0000000	0.00006
Bentazon	0.000296	0.00520	0.00000038	0.0000036	0.12914
Metolachlor	0.000003	0.00022	0.00000000	0.0000003	0.13308
Alachlor	0.000073	0.00024	0.00000003	0.0000001	0.21492
Simazine	0.039151	0.21857	0.00039569	0.0018129	2.69993
Butylate	0.000210	0.00127	0.00000000	0.0000000	0.01197
2,4-D	0.000001	0.00003	0.00000000	0.0000000	0.03873

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.00000000	0.0000000	0.00000000	0.000000000	0.00053
Dicamba	0.00004650	0.0003441	0.00000005	0.000000004	0.04737
Primisulfuron	0.00001384	0.0001466	0.00000695	0.000000262	0.00109
Cyanazine	0.00000868	0.0001260	0.00000002	0.000000006	0.79872
Bromoxynil	0.00000000	0.0000000	0.00000000	0.000000000	0.00000
Bentazon	0.00000080	0.0000386	0.00000000	0.000000001	0.00739
Metolachlor	0.00000128	0.0000887	0.00000003	0.000000044	0.23249
Alachlor	0.00002006	0.0000631	0.00000006	0.000000004	0.21684
Simazine	0.00052914	0.0026066	0.00083563	0.000037424	0.04679
Pendimethalin	0.00000000	0.0000000	0.00000000	0.000000000	0.00000
2,4-D	0.00000004	0.0000013	0.00000000	0.000000000	0.00094

No-tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.0000000	0.000000	0.000000000	0.00000000	0.00014
Dicamba	0.0000001	0.000001	0.000000000	0.00000000	0.00009
Primisulfuron	0.0000074	0.000073	0.000000062	0.00000023	0.00029
Cyanazine	0.0000001	0.000001	0.000000000	0.00000000	0.00595
Metolachlor	0.0000031	0.000215	0.000000006	0.00000046	0.16685
Alachlor	0.0000289	0.000088	0.000000014	0.00000004	0.10740
Simazine	0.0024100	0.010793	0.000028745	0.00012415	0.53798
Pendimethalin	0.0000000	0.000000	0.000000000	0.00000000	0.00000
Glyphosate	0.0000000	0.000000	0.000000000	0.00000000	0.00000

*see legend, page 58

Ground and Surface Water Exposures (relative to benchmarks)

POLICY=Triazine Ban CROP=Corn

Conventional Tillage

CHEMICAL*	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.00000000	0.0000000	0.00000000001	0.0000000000	0.00164
Dicamba	0.00009436	0.0005691	0.00000000072	0.0000000068	0.15018
Primisulfuron	0.00003069	0.0003462	0.00000016566	0.0000006857	0.00312
Bromoxynil	0.00000000	0.0000000	0.00000000000	0.0000000000	0.00008
Bentazon	0.00036095	0.0079435	0.00000024685	0.0000045131	0.17447
Metolachlor	0.00000368	0.0002846	0.00000000535	0.0000003907	0.22064
Alachlor	0.00009343	0.0003158	0.00000003709	0.0000001069	0.37631
Butylate	0.00057665	0.0040833	0.00000001273	0.0000000640	0.03752
2,4-D	0.00000496	0.0001612	0.00000000003	0.0000000008	0.11466

Reduced Tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000000	0.00000001	0.00000000001	0.00000000003	0.001025
Dicamba	0.000086086	0.00053943	0.00000000039	0.00000000794	0.075680
Primisulfuron	0.000028732	0.00033002	0.00000014440	0.00000050861	0.002041
Bromoxynil	0.000000000	0.00000000	0.00000000000	0.00000000000	0.000023
Bentazon	0.000004914	0.00023589	0.00000000015	0.00000000545	0.045130
Metolachlor	0.000000694	0.00004068	0.00000000021	0.00000002475	0.097194
Alachlor	0.000004230	0.00000994	0.00000000015	0.00000000095	0.016802
2,4-D	0.000000050	0.00000156	0.00000000000	0.00000000000	0.001060

No-tillage

CHEMICAL	AVG12	PK12	AVG15	PK15	PKSTRM
Nicosulfuron	0.000000000	0.00000001	0.00000000000	0.00000000003	0.0002293
Dicamba	0.000004024	0.00003250	0.00000000002	0.00000000039	0.0036173
Primisulfuron	0.000013357	0.00013467	0.00000010663	0.00000039804	0.0004628
Metolachlor	0.000000049	0.00000403	0.00000000001	0.00000000288	0.0018317
Alachlor	0.000001300	0.00000483	0.00000000003	0.00000000044	0.0033859
Glyphosate	0.000000000	0.00000000	0.00000000000	0.00000000000	0.0000000

*see legend, page 58

Legend	
AV12(15):	Average concentration of chemical (ppb) at 1.2 (15) meters below the surface
PK12(15):	Peak 1.2(15) meters below the surface
PKSTRM:	Peak surface water concentrations (edge of field loadings)
Benchmarks:	Drinking water maximum contaminant levels (MCLs) on drinking water health advisories