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Economic and Environmental Effects Associated with Reducing the Use of Atrazine: An Example of Cross-Disciplinary Research

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ABSTRACT

Restricting or eliminating the use of atrazine in the Midwest would have important economic consequences for farmers, consumers, and the environment. These consequences can only be evaluated with cooperation between economists and weed scientists. The weed control choice set available to farmers cannot be observed through deductive research. Economists and weed scientists worked together to identify all possible weed control strategies for corn and sorghum in the Midwest and to incorporate them into an economic model. An atrazine ban was found to be the costliest strategy, and a targeted, water-quality based strategy the most cost effective.

Key Words: atrazine, deductive research, environmental exposure, herbicides, inductive research, welfare.

Both economists and physical scientists spend years studying the methodologies and paradigms that dominate research activities in their respective disciplines. For economists, this means a predominant emphasis on deductive reasoning and the use of sophisticated statistical techniques to test hypotheses using uncontrolled data. Conversely, physical scientists rely more on inductive reasoning and controlled experimentation. Both methodologies are equally valid. However, the differences in the research approaches can stymie collaborative efforts.

Applied policy analysis requires an interdisciplinary approach if it is to be properly conducted. No evaluation of an agricultural policy or program is complete without an assessment of the impacts on the environment. The process of growing crops and the eventual fate of soil, water, and chemical inputs are characterized by physical and biological relationships. Physical scientists are adept at explaining these physical and biological processes. The demand for agricultural commodities and the decisions as to which crops to produce and how to produce them are derived from complex social institutions. Economists are adept at explaining the social processes that shape the demand for agricultural products. In order to address the challenges facing agriculture today, it is necessary for economists and physical scientists to combine their efforts in collaborative ventures.

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The CEEPES project—Comprehensive Environmental Economic Policy Evaluation System—is an attempt to bridge the methodological gap. CEEPES is a simulation model that combines both physical and economic models to explore the ramifications of changes in agricultural policy on agricultural production, agricultural markets, and the environment. To demonstrate how economists and physical scientists can work together in a collaborative effort such as CEEPES, we will focus on a project that examined alternative policies for reducing atrazine in water resources in the Midwest (Ribaudo and Bouzaher).

Policy Issue

Atrazine is an important herbicide in crop production in the United States, particularly for corn. Over 65% of all corn acreage is treated with atrazine. Recent findings indicate that elevated amounts of atrazine are running off fields and entering surface water resources (Goolsby, Coupe, and Markovchick). Water quality monitoring studies find atrazine 10 to 20 times more frequently than the next most detected pesticide (Belluck, Benjamin, and Dawson).

The Safe Drinking Water Act makes public water utilities legally responsible for providing drinking water with atrazine concentrations below a "safe" level of three parts per billion (ppb). Based on monitoring studies, some publicly owned drinking water systems in the Midwest may have to alter their treatment systems to meet the atrazine standard. Such changes would impose higher costs on water system users, while protecting the water supply. Evidence suggests that individual consumers are willing to pay substantial amounts of money for safe water supplies (Abdalla, Roach, and Epp; Sun, Bergstrom, and Dorfman).

Several options are available for protecting water systems from atrazine. One option is to treat the water supplied to consumers by installing the necessary treatment technology. An alternative to treating water is to reduce the amount of atrazine entering water resources. The three policies evaluated with the CEEPES model are: (*a*) a ban on atrazine use, (*b*) a mandatory change in the application strategy wherever atrazine is used, and (*c*) a mandatory change in the management strategy only in those areas where atrazine harms surface water quality. Bans, general application restrictions, and geographic use restrictions are all policies currently being used at the federal and state levels to address pesticide problems.

The implications of banning or restricting the use of atrazine cannot be fully understood by only observing current production decisions, or even production decisions over time. The introduction of a chemical control policy may force a farmer to use practices that are not currently being used, and therefore cannot be observed through deductive research. It is necessary that the economic and physical impacts of all possible atrazine alternatives be identified, even those that are not selected under current economic conditions. The characteristics of a weed control strategy that are important to a producer are both economic and agronomic. Chemical costs, timing, and efficacy for target species are all important factors in a farmer's selection of a weed management strategy. The economists and physical scientists who developed CEEPES fully integrated both physical and economic models in an attempt to capture the full impact of government policy on agricultural markets, farm programs, and the environment.

The CEEPES Model

Economic and environmental effects of alternative atrazine control strategies were evaluated by the Center for Agriculture and Rural Development (CARD) at Iowa State University with the CEEPES model, which is an integrated modeling system developed to estimate the consequences of policies affecting agricultural production on economic and water quality indicators. CEEPES simulates a farmer's substitution among chemicals, other inputs, crops, and agricultural practices in response to a specified policy. We used CEEPES to examine how different atrazine control policies would affect both economic and environmental measures of welfare in the major corn and sorghum producing areas. The study encompassed 27 production areas, including all or part of Colorado, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, and Wisconsin.

The four major components of CEEPES are policy, agricultural production decision, fate and transport, and environmental exposure (Bouzaher et al.). The policy component is defined by economists, and in this case consists of the alternative atrazine management strategies. The agricultural decision component models the choice of agricultural practices under alternative policies. The outputs include acreage planted, rotation, tillage practice, chemical regime, yield, and cost of production for each producing region in the study area.

There are two key modeling systems in this component. The Resource Adjustable Modeling System (RAMS) is a regional, short-term, static, profit-maximizing, linear programming model of agricultural production, defined at the producing area (PA) level. The goal of the RAMS model is to estimate the economic impact of alternative agricultural and environmental policies.

Feeding into RAMS are the weed control strategies defined by WISH—Weather Impact Simulation on Herbicides. The WISH component of CEEPES simulates the efficacy and cost of alternative weed control strategies. WISH determines the tradeoffs between minimum cost weed control strategies and yield losses. A weed control strategy describes the target weed, herbicides, application timing and rate, soil type, tillage practice, method of application, and number of treatments. Implementing WISH requires exact identification of the possible weed control strategies that farmers may select. WISH then selects the strategies that minimize the cost of achieving a given yield loss.

The structure of the weed control strategies is based on weed management methods commonly used in the U.S. Each weed control strategy is made up of one or two primary herbicide treatments, and a secondary herbicide treatment. Primary treatments are either preplant, preemergent or post-emergent. Secondary treatments are necessary whenever the primary treatment fails because of weather conditions, and are post-emergent. Both primary and secondary treatments can be either a single herbicide or a tank mix of herbicides.

For each strategy, there is an "application window" and an "effectiveness window." The application window defines the number of days that herbicides can be applied. It depends on the particular herbicides used, planting date, and days from planting to crop emergence. The effectiveness window defines the number of days that a herbicide can control weeds if weather conditions are favorable. It depends on the particular herbicides, application dates, and weed categories (grass or broadleaf). The application windows and effectiveness windows in each of the primary and secondary treatments are state and chemical specific due to different planting dates and different herbicide characteristics. Thus, the set of efficient weed control strategies can vary widely across the study region. WISH simulated over 500 alternative weed control strategies for corn and over 150 strategies for sorghum. All weed control strategies aimed at full control under ideal weather conditions. Farmers are assumed to trade expected pest damage for expected application cost when deciding to adopt a pest management strategy.

Based on herbicide timing of application and effectiveness, mode of application, targeted weeds, and observed farming practices, a herbicide decision tree is constructed to represent the average farmer's most likely management approach to pest control. WISH reads a herbicide strategy table and a weather file that contains daily average information on temperature, rainfall, and wind. For each herbicide strategy over a 50-year period of weather history, the model considers the weather and, starting with the primary application, records the percentage of acres treated during the window of application; it also records the application rate, cost of each chemical used, and any cultivation requirements. Time advances and weather conditions are checked during the window of effectiveness. An indicator variable cumulatively records the percentage effectiveness of the primary strategy for each weed group. If this variable is less than one, the secondary application is triggered and the same information is recorded. This process accounts for the effects of those years where a farmer may have to apply herbicides more than once, or does not have time to apply herbicides and sustains a major yield loss.

The impact of weed competition on crop yield was simulated with a separate process model that simulates crop growth, weed competition, and the interactions of management factors for a variety of soil properties and climatic conditions.

The chemical fate and transport component of CEEPES uses information on agricultural activity in each geographic unit to produce environmental damage-relevant concentration measures for each damage category, the geographic unit where the chemical was applied, and other geographic units which may be affected by pollutant transport. The main fate and transport model was the Risk of the Unsaturated/Saturated Transport and Transformation of Chemical Concentrations model (RUSTIC). RUSTIC estimates chemical flow through the root zone and over the surface. Climatic variation, soil and crop characteristics, and management practices are accounted for in the model.

Runoff estimates from RUSTIC are inputs into the Stream Transport and Agricultural Runoff of Pesticides for Exposure Assessment Methodology (STREAM). STREAM is a screening-level tool for estimating in-stream solution and stream bed pesticide concentrations for exposure assessment purposes. STREAM accounts for chemical parameters, soil parameters, management parameters, and weather.

The results from the RAMS model serve as inputs into the AGSIM model for estimating changes in measures of economic welfare. The AGSIM model contains econometrically estimated demand and supply equations for major crops and livestock that are solved through market clearing identities. Thus, the model solves for the set of crop and livestock prices that allow the market described by RAMS to clear. Producer income is calculated as the sum of net crop income and net livestock income. The domestic consumer effect is defined as the change in area beneath domestic and foreign consumers' demand curves for livestock, food crops, oil, and meal. Government outlays include the sum of farm program payments and expenditures for government milk purchases.

Table 1. Summary of Production Effects

Production Variable	Scenario		
	Ban	Post-Use	Standard
	(%)		
Acreage:			
Corn	−2.4	−2.6	−2.4
Sorghum	−3.7	−0.5	2.2
Soybean	3.5	3.5	3.0
Summer fallow	−2.0	−2.3	−2.0
Yield:			
Corn	−1.2	−1.2	−1.2
Corn silage	1.0	1.7	0.1
Sorghum	−3.4	0.4	−2.8
Herbicide Cost:			
Corn	10.0	5.6	4.6
Sorghum	36.2	17.4	27.0
Price:			
Corn	1.8	0.4	1.4
Sorghum	2.4	−0.2	1.7

Total Atrazine Ban Scenario

Banning atrazine in the Midwest resulted in increases in per acre weed treatment costs of 10% for corn and 36% for sorghum. For corn, more costly weed control strategies that achieve a comparable level of control were adopted. For sorghum, banning atrazine led to heavier reliance on cheaper, less effective secondary strategies.

Corn grain yields decreased 1.2%, and sorghum yields decreased 3.4% under the total atrazine ban (table 1), and under this scenario, total corn acreage decreased 2.4%, and sorghum acreage decreased 3.7%. Largely in response to more widespread use of corn/soybean rotations, soybean acreage reflected a 3.5% increase.

Table 2. Summary of Herbicide Use Changes

Herbicide	Scenario		
	Ban	Post-Use	Standard
	(%)		
Atrazine use on corn	−100.0	−90.7	−78.8
Atrazine use on sorghum	−100.0	−44.0	−25.6
Triazine use on corn	−20.6	−16.5	−20.6
Triazine use on sorghum	−65.6	−32.2	−13.9
Nontriazine use on corn	25.6	21.2	24.1
Nontriazine use on sorghum	85.6	42.7	55.7
Total herbicide use on corn	−1.1	−0.8	−2.0
Total herbicide use on sorghum	13.0	6.7	22.3

Banning atrazine induced shifts to other herbicides. The use of other triazine herbicides (cyanazine and simazine) increased, as both the acreage treated and application rates increased. However, the increased use of simazine and cyanazine does not make up for the decrease in atrazine, in terms of pounds of active ingredient. Atrazine makes up 54% of the total triazine use on corn, but total triazine use declined only 20.6% (table 2). In addition, large increases in nontriazines were observed, as the acreage treated by nontriazines increased and the substituted weed control strategies entailed relatively high application rates (table 2). Total herbicide applications on corn decreased 1.1%, and applications on sorghum increased 13%.

Accompanying the changes in weed control strategies are shifts in tillage practices, although the shifts were minor. Two percent of total corn acreage shifted from conventional till and no-till systems to reduced till. A similar shift was seen for sorghum. The shifts in tillage did not result in any appreciable change in soil erosion in the study region. The model runs assumed that the conservation compliance provision of the 1985 Farm Bill would be enforced, thus limiting erosion on highly erodible land.

Changes in weed treatment regimes and application rates affect the nature of herbicide threats to water quality. These changes vary across tillage practices. For the purposes of comparing policies, peak and average chemical concentrations found in surface and groundwater are transformed into a unitless measure of risk called an "exposure value," whereby pesticide-specific benchmarks for human health and aquatic habitat are used to weight the relative importance of pesticide concentrations. Using a benchmark for environmental hazards, we calculate the exposure for each herbicide as follows:

$$\text{Exposure Value} = \text{Predicted Concentration} \div \text{Environmental Benchmark.}$$

A chronic exposure value is calculated by using the predicted average herbicide concentration and the long-term maximum contaminant level (MCL) as an environmental benchmark. An acute exposure value is calculated by using the peak concentration and the short-term health advisory. An aquatic environment exposure value is calculated by using EPA toxicity benchmarks for aquatic vegetation. The exposure value normalizes concentration levels, thereby allowing us to compare risks across pesticides and across policies. If the exposure value exceeds unity, the concentration exceeds the benchmark. Table 3 lists human and aquatic exposure levels for major herbicides.

Table 4 presents the percentage of corn acres, by chemical, where the acute exposure values for surface water are greater than one. For each herbicide, the peak concentrations in water are calculated by soil type with the

Table 3. EPA Toxicity Benchmarks Used in Calculating Exposure Value

Chemical	Water Exposures (ppb) Acute	Chronic	Aquatic Vegetation
Atrazine	100	3	2
Alachlor	100	2	1
Bentazon	25	20	1
Bromoxynil	700	140	1
Butylate	2,400	50	1
Cyanazine	100	8	2
Dicamba	300	9	1
EPTC	875	175	1
Glyphosate	20,000	700	60
Metolachlor	100	100	1
Paraquat	100	30	500
Pendimethalin	1,400	300	1
Propachlor	350	70	1
Simazine	50	35	500
2,4-D	1,100	70	1
Nicosulfuron	44,000	44,000	0.03
Primisulfuron	210	210	0.03

Table 4. Proportion of Corn Acres at Risk for Exceeding Surface Water Benchmarks, by Herbicide Treatment

Chemical	Scenario Baseline	Ban	Post-Use	Standard
	(%)			
Atrazine > 1.5[a]	7.8	0.0	2.4	0.0
Atrazine < 1.5	23.7	0.0	0.0	0.0
Cyanazine	12.5	14.6	17.8	14.9
Bentazon	3.6	5.1	6.0	5.0
Metolachlor	1.9	0.9	1.4	0.8
Alachlor	8.4	3.8	2.9	3.8
Simazine	35.0	38.5	38.5	32.4

Note: Risk is measured as peak 24-hour surface water concentrations exceeding the acute EPA surface water benchmark values.

[a] Atrazine > 1.5 denotes those acres receiving more than 1.5 pounds active ingredient per year.

STREAM model in CEEPES. These individual concentrations are compared with the EPA benchmark health advisory levels for human health exposure. The herbicide treated acreage that exceeds the benchmark is aggregated for each chemical. This "at risk" area is reported as a percentage of total acreage treated with that herbicide.

The corn acreage treated with atrazine that is at risk for producing runoff with concentrations of atrazine greater than the health advisory benchmark is reduced to zero. However, the percentages of acreage treated with cyanazine, bentazon, and simazine that are at risk increased because of the substitution of these chemicals for atrazine.

Changes in total herbicide loadings in the study area may affect water quality irrespective of the health benchmarks. The relative impacts of the changes of herbicide strategies across tillage practices for corn and sorghum on water quality and the environment are presented in table 5. Water quality impacts are evaluated by cumulative exposure values (summing the individual herbicide exposure values for each herbicide) and the maximum exposure value of any herbicide. These values

Table 5. Relative Impacts of Policies on Groundwater, Surface Water, and Ecosystems

Medium	Reference Benchmark	Scenario Baseline	Ban	Post-Use	Standard
Groundwater:	Acute	0.112 / 0.056	0.067 / 0.061	0.072 / 0.061	0.007 / 0.006
1.2m depth	Chronic	0.363 / 0.259	0.012 / 0.012	0.049 / 0.042	0.001 / 0.001
Groundwater:	Acute	0.001 / 0	0 / 0	0 / 0	0 / 0
1.5m depth	Chronic	0.016 / 0.012	0.001 / 0	0.005 / 0	0 / 0
Surface water	Acute	2.222 / 0.889	1.676 / 0.895	1.772 / 0.898	0.036 / 0.022
Ecosystem risk	Aquatic	32.47 / 8.84	26.87 / 8.86	27.95 / 9.16	26.54 / 8.22

Note: The first number in a cell represents the weighted sum of the pesticide exposure values for a given medium, and the second number is the highest weighted exposure value for any pesticide predicted in a given medium.

Table 6. Summary of Welfare Effects and Government Outlays ($ mil.)

	Scenario		
	Ban	Post-Use	Standard
Producer income	−268	−204	−200
Consumer surplus	−249	−20	−189
Government outlays	−287	−65	−227
Total welfare[a]	−230	−159	−162

[a] Change in producer income plus change in consumer surplus minus the change in government outlays is the measure of change in social welfare.

are weighted across tillage and crop (corn and sorghum).

For each medium, the atrazine ban results in acute and chronic values of sum-exposure that are generally lower than those in the baseline. However, the maximum exposure values are higher for acute shallow groundwater and surface water, and for ecosystem risk, i.e., peak loadings have increased for at least one chemical.

The changes in acreage, yields, and production costs affect supply and prices. In the short term, reduced production resulted in price increases of 1.8% for corn and 2.4% for sorghum (table 1). Producer income in the study area decreased $268 million and the economic welfare of domestic consumers and foreign consumers decreased $249 million (table 6).

The increases in crop prices result in some U.S. Department of Agriculture (USDA) program savings, based on commodity programs prior to the Federal Agricultural Improvement and Reform (FAIR) Act.[1] In the short term, deficiency payments decreased $287 million. Net social welfare from changes in production therefore decreased $230 million (table 6).

Banning Preplant, Preemergent Applications

An alternative to totally banning atrazine is to minimize runoff by restricting use. One approach is to ban all preplant and preemergent applications, thus allowing only post-emergent applications. Allowing only post-emergent uses resulted in a 2.6% decrease in corn acreage and a 0.5% decrease in sorghum acreage (table 1). A shift to corn/soybean rotations resulted in a 3.5% increase in soybean acreage. Corn yields decreased 1.2% and sorghum yields increased slightly (0.4%). Herbicide costs per treated acre increased 5.6% for corn and 17.4% for sorghum. These cost impacts are not as great as for the atrazine ban.

Atrazine use decreased sharply, but was not eliminated. Atrazine was used largely as a backup strategy and no longer as a primary strategy. Overall atrazine use on corn decreased 90.7%, and the corresponding figure for sorghum was a decrease of 44% (table 2).

The use of other triazine herbicides increased with the atrazine restriction, so the overall reduction in triazine use is less than the reduction in atrazine (table 2). The use of nontriazines increased 21.2% on corn and 42.7% on sorghum. Because of the substitution of less effective strategies, total pounds of active ingredients used on corn decreased only 0.8%, and total pounds on sorghum increased 6.7%.

The changes in weed control strategies were accompanied by changes in tillage practices, although once again, the changes are small. Two percent of total corn acreage shifted from conventional till and no-till to reduced till. There was no change in tillage systems from sorghum. The impact on soil erosion was slight.

The changes in chemical regimes and application rates did not reduce the acreage at risk from atrazine to zero on corn acreage receiving more than 1.5 pounds per acre of atrazine per year (table 4). The proportion of acreage treated with atrazine at rates greater than 1.5 pounds per acre at risk decreased from 7.8% to 2.4%. On the other hand, there was an increase in the proportion of at-risk acreage treated with cyanazine, bentazon, and simazine.

The relative impacts of the policy on water and environmental quality are presented in table 5. A pattern similar to that seen for the

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[1] The FAIR Act of 1996 would alter these results. Producers would capture more of the gain from higher prices, and budget savings would be less.

atrazine ban is apparent. Exposure values decreased for all mediums. However, the acute maximum exposure values increased. The potential for higher peak short-term loadings increased because of the increased use of some herbicides.

In the short term, commodity prices changed less than 1%. In the long term, price impacts are slightly higher. The average annual decreases in economic welfare are about $224 million in the short run, with producer income declining $204 million and consumer surplus decreasing $20 million (table 6). Government outlays for deficiency payments decreased by $65 million. Net social welfare from changes in production decreased $159 million.

Meeting Surface Water Standards

Evidence from surface water monitoring studies indicates that the problem of atrazine in drinking water supplies is not widespread. A more efficient policy might be to target only those areas where atrazine controls are needed, and to give farmers as much flexibility as possible in finding a set of management practices that allows water quality standards to be achieved. The CEEPES model was used to assess the economic consequences of restricting the 24-hour acute concentration of atrazine in surface water to the 10-day health advisory level (HAL) of 100 ppb.

Since the economic decision model is defined at the production area level, which is a collection of several soil types, it is not possible to force the model to achieve the runoff standards exactly. Instead, the model eliminates those weed control practices that result in a violation of the surface water standard. In effect, farmers operate under a restricted set of available weed control strategies for particular soils and climates. However, the number of strategies available is generally greater than for the other two scenarios.

The surface water standard scenario resulted in a 2.4% decrease in corn acreage and a 2.2% increase in sorghum acreage (table 1). Corn grain yields decreased 1.2%, while corn silage yields increased slightly (0.1%). Sorghum yields decreased 2.8%. Herbicide costs per treated acre increased 4.6% for corn and 27% for sorghum.

The percentage of corn acreage treated with atrazine decreased 67%, while treated sorghum acreage increased 5%. The amount of atrazine used in corn production decreased 78.8%, compared to a 25.6% decrease for atrazine used in sorghum production (table 2).

The surface water standard restriction forces some shifting to other herbicides. The total use of triazines decreased 20.6% on corn, indicating that the use of the other triazines increased (table 2). Nontriazine use on corn increased 24.1%. For sorghum, triazine use decreased 13.9%, but nontriazine use increased 55.7%. Overall, herbicide use decreased 2% for corn and increased 22.3% for sorghum.

The surface water standard restriction resulted in little overall change in tillage practices. The amount of conventionally tilled corn was unchanged. About 1% of corn acreage shifted from no-till to reduced till. Three percent of sorghum acreage shifted from conventional till to reduced till. The impacts on overall soil erosion were slight.

Herbicide threats to human health, as defined by corn acreage generating peak concentrations that exceed the short-term health benchmark, are presented in table 4. The surface water scenario greatly reduced the area at risk from herbicides. Acreage treated with atrazine that is at risk declined to zero. Also, the at-risk acreage treated with metolachlor, alachlor, and simazine decreased. However, there was an increase in the at-risk acreage treated with cyanazine and bentazon. Cyanazine is a more potent carcinogen than atrazine.

The water quality standard restriction resulted in significant decreases in loadings to surface and groundwater. The sum of exposure values and the highest exposure value for any pesticide decreased for all mediums (table 5). This scenario resulted in lower exposure values than the atrazine ban or the atrazine post scenarios. The cropping practices and the herbicides selected were better at reducing runoff and leaching than the ones selected under the other scenarios.

In the short term, corn and sorghum prices are estimated to increase 1.4% and 1.7%, respectively (table 1). In the short term, producer income decreased $200 million, while consumer surplus losses were $189 million (table 6). Because of short-term price increases, government program outlays in the short run decreased $227 million. Net social welfare from changes in production showed a decrease of $162 million. The surface water standard policy is less costly than the ban, but more costly than the atrazine post-use restriction. However, the environmental benefits are greater than those from the atrazine post-use restriction, based on environmental loadings.

Conclusions

The atrazine ban and the targeted water quality standard policies both eliminate the threat of atrazine to surface water. Banning preplant and preemergent use of atrazine greatly reduces the acreage at risk from atrazine, but does not eliminate the risk. The costs of achieving the level of protection offered by the ban and the surface water standard policies are greater than for the post-plant policy. However, the overall cost effectiveness of reducing the sum of exposure value to surface water is the greatest for the water quality standard approach.

The results imply that targeted atrazine control methods are more efficient than an overall ban of atrazine, or even an overall ban on a class of weed control strategies. Targeted control would allow continued use of atrazine in those areas where it does not pose an environmental risk, thus lessening the production impacts. Price effects are minimized, and consumer costs reduced. In addition, the overall costs to producers would be reduced because fewer producers would feel the full impact of atrazine restrictions, although those producers who are affected would be hurt economically. The issue becomes one of identifying those watersheds requiring atrazine runoff control, and the most appropriate alternative control strategies. The administrative and budget burdens of such a targeted management strategy may, however, somewhat reduce the attractiveness of this option.

The results demonstrate a problem with chemical-specific control strategies. While the use of atrazine was eliminated or reduced, the use of some other herbicides increased. Unlike atrazine, most of these do not yet have an enforceable drinking water standard. For example, under the post-emergent use scenario, the concentrations of cyanazine and simazine in edge-of-field runoff increase. As seen in table 4, a greater percentage of acreage treated with these herbicides is at risk. There may be areas where the concentrations of these chemicals in drinking water supplies will generate concern. A strategy that considers both the target chemical and its substitutes will provide health and ecosystem protection more quickly than an iterative, chemical-by-chemical approach.

These results would not have been possible without the cooperation between economists and weed scientists. The evaluation of a policy such as this requires that all possible substitute strategies for weed control be considered in a framework that represents, as closely as possible, the farmer's economic decision-making process. Failure to account for alternative strategies in such a framework would lead to incorrect conclusions about farmers' choices in the face of atrazine restrictions, and the potential consequences to water quality. This paper demonstrates that the value of better designed policies may be very large—on the order of millions of dollars.

Facilitating Cooperation

CEEPES demonstrates that the fundamental differences between economists and physical scientists can be overcome. To promote the success of collaborative efforts, collaboration should begin as early as possible in a new research program. Collaborators should remain focused on the areas of the program where they have a comparative advantage, but should maintain a general understanding of the program as a whole so they can offer useful insights that facilitate the integration of the parts to the whole.

For example, over the past several years, economists at CARD have continued to collaborate with prominent weed scientists from around the country in an effort to improve the WISH component of the CEEPES model. This team has worked to identify and eliminate several important shortcomings of WISH. WISH assumed that the efficacy of a particular weed control strategy depended generally on weather conditions. If adverse weather conditions prevented herbicide application, failed to activate the herbicide, or caused the herbicide to run off, the weed control strategy was assumed to fail. Otherwise, full control was assumed. Contrary to the model's assumptions, experiments conducted by weed scientists have found that full control was generally not possible, and more importantly, that different weed species respond quite differently to alternative herbicides. For example, when applied preplant or preemergent, atrazine is more effective on pigweed than on foxtail, while Frontier is more effective on foxtail than on pigweed. Assuming that atrazine and Frontier are equally effective on foxtail and pigweed masks important substitution opportunities faced by farmers. WISH no longer assumes full control when weather conditions are favorable. It now uses herbicide efficacy ratings developed by weed scientists to determine the effectiveness of different herbicides on different weed species.

Originally, WISH only simulated a single weed species in a given crop, while weed scientists have found that it is more common for crops to be infested by three or four different species. When herbicide efficacy ratings are explicitly modeled, this assumption may cause WISH to inappropriately indicate that specialized herbicides are more effective. If one herbicide is only effective on foxtail and another is not as effective on foxtail but is also effective on pigweed and ragweed, then WISH would generally favor the first herbicide in a field that may be dominated by foxtail but also contains significant populations of pigweed and ragweed. If the second herbicide is only marginally less effective on foxtail and is nearly completely effective on pigweed and ragweed, the second herbicide may be more effective overall. To improve how WISH models weeds, weed scientists identified the 10 most common weed species in each of the 34 states modeled by WISH. Using their observations and expertise, they assigned probabilities to the likelihood that each weed appears in any given field. WISH now incorporates this information by randomly assigning weeds to the simulated fields based on the prescribed probabilities.

Since WISH now considers multiple weeds, the previous algorithm for determining yield loss will not work because it was based on a single weed species, crop competition model. Turning to the weed science literature, a useful model relating crop yields to weed densities for multiple weed species was found. However, in order to use this model, information on important parameters was needed: the competitiveness of different weed species, estimates of weed-free yields, average densities of different weed species, and estimates of the percentage of yield loss as weed density approaches a maximum. Weed scientists supplied the appropriate information based on their knowledge of the weed science literature and their expertise.

While additional changes have been made to the WISH model, the three modifications discussed here specifically illustrate how economists and weed scientists have continued to effectively collaborate in order to improve an economic model of farm-level decision making that incorporates important features of the physical production process and weed control. It is important to note that the role of weed scientists in this collaborative effort was twofold. First, the weed scientists provided important insights into how to model weeds and their distribution across fields. Second, the weed scientists synthesized volumes of information on various parameters in order to provide WISH with the most accurate and reliable information available.

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