United States Department of Agriculture

Economic Research Service

Agricultural Economic Report Number 699

Atrazine: Environmental Characteristics and Economics of Management

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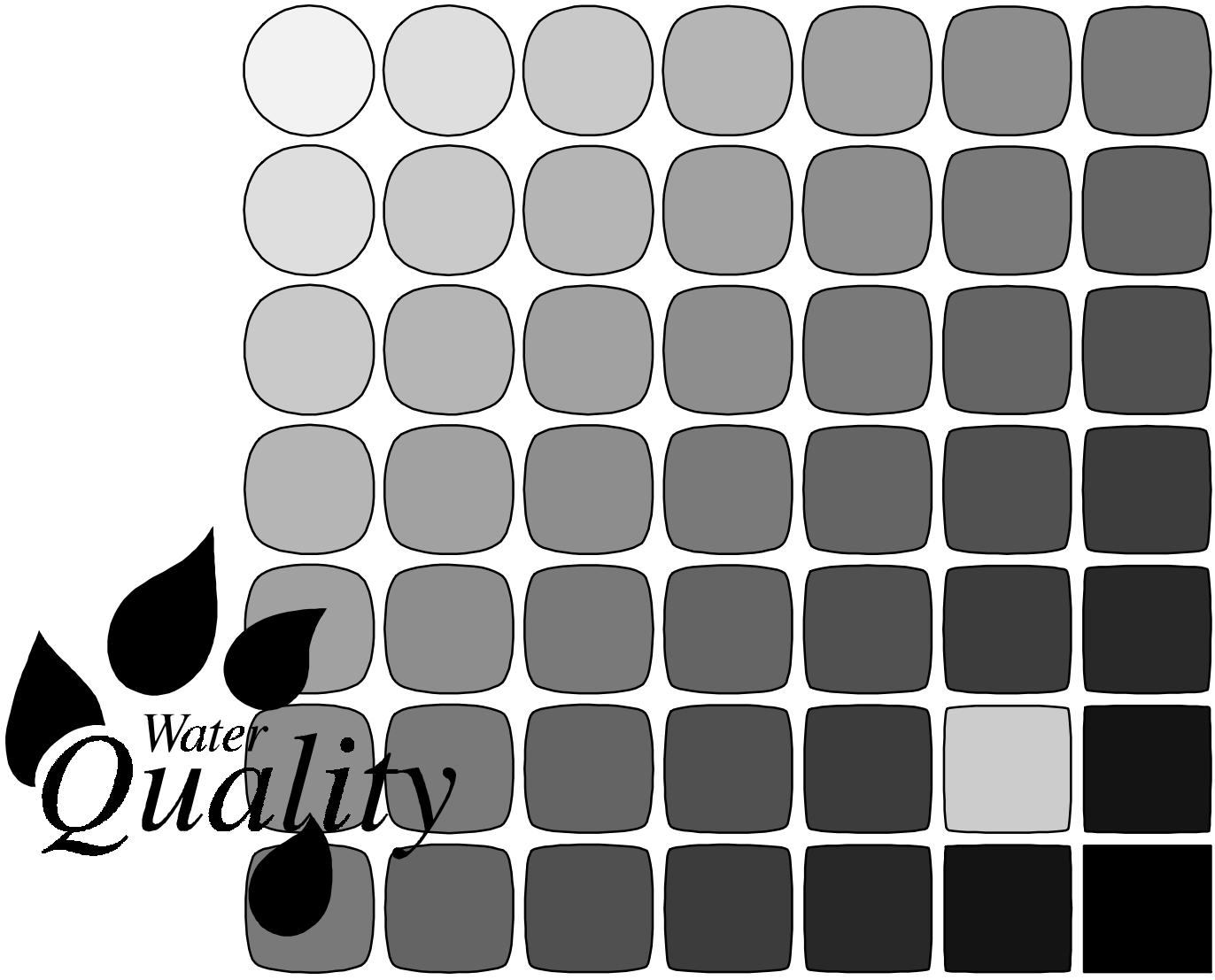

Atrazine: Environmental Characteristics and Economics of Management. By Marc O. Ribaudo and Aziz Bouzaher. Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report No. 699.

Abstract

Restricting or eliminating the use of atrazine in the Midwest would have important economic consequences for farmers and consumers. Atrazine is an important herbicide in the production of corn and other crops in the United States. Since atrazine is such an important herbicide, mandatory changes in application strategies are likely to generate sizable costs for producers and consumers. However, recent findings indicate that elevated amounts of atrazine are running off fields and entering surface water resources. This report presents the costs and benefits of an atrazine ban, a ban on pre-plant and pre-emergent applications, and a targeted ban to achieve a surface water standard. A complete atrazine ban is hypothesized to be the costliest strategy, while the targeted strategy is the least costly.

Acknowledgments

The authors acknowledge the contribution of Iowa State University researchers who were involved in the development of the Comprehensive Environmental Economic Policy Evaluation System over the years. P.G. Lakshminarayan worked on the simulation runs for the targeted control scenario. The authors also thank Steve Crutchfield of ERS, Don Epp of Pennsylvania State University, and Craig Osteen of the National Agricultural Pesticide Impact Assessment Program for their helpful comments.

1301 New York Ave., NW.
Washington, DC 20005-4788 September 1994

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Summary

Targeting atrazine use may be a more efficient method of protecting water supplies than banning it. Atrazine is a very important herbicide used in the production of corn and sorghum. It has been found in surface water used for public water supplies in the Midwest at levels greater than the standards established by the Environmental Protection Agency. The Safe Drinking Water Act requires that public utilities treat water for atrazine if the standard is violated. Installing advanced treatment systems for removing atrazine could result in substantial costs to the utilities and their consumers. Alternative strategies focus on controlling atrazine at its source and preventing or limiting its discharge into surface water.

Longrun costs to farmers and consumers would range between $295 million and $665 million per year, depending on the atrazine management strategy being used. This report examines three atrazine control strategies: (1) completely banning the use of atrazine, (2) restricting applications to after the emergence of the crop, and (3) targeting restricted use to meet a particular water quality goal (such as not using atrazine in those areas where it harms surface water quality). The atrazine ban is the costliest strategy, while targeting atrazine management measures to meet water quality goals achieves the greatest environmental protection at the lowest cost.

While restricting atrazine use would protect public water supplies, the restrictions would impose costs on farmers and consumers. Farmers would use alternative herbicides to control weeds. Other herbicides are not as effective as atrazine, and heavier applications would be required to achieve the same level of control. As a result, costs of production and food prices could rise and some of the environmental gains made by reducing atrazine could be offset by increased discharges of other chemicals.

The benefit from reducing atrazine discharges is the elimination of the need for water utilities to install additional treatment systems in order to meet Safe Drinking Water Act goals. The cost of treating all surface water consumed in the Midwest would be about $400 million each year. In reality, only a small portion of the surface water supplies would require treatment, but this figure provides a useful upper bound of potential treatment costs.

Banning atrazine entirely would eliminate the need to incur the additional water treatment costs, but the costs to producers and consumers would range between $517 million and $665 million. A general ban would therefore generate costs greater than the highest potential water treatment costs.

Restricting atrazine applications to only after the crop emerges would cost producers and consumers between $224 million and $295 million per year. However, this option does not eliminate the risk of significant amounts of atrazine entering surface water. This finding, plus the fact that only a small portion of surface water systems may actually need to install treatment in the absence of any atrazine control policies, strongly suggests that the costs outweigh the benefits.

Targeting atrazine management restrictions to meet water quality standards eliminates the need to install advanced water treatment systems at a cost between $328 million and $389 million. Once again, it is unlikely that benefits outweigh the costs, but this was the most cost-efficient approach. This approach also generates the greatest level of water quality when all herbicides are taken into account.

The results imply that targeted atrazine control methods, which might include local bans, 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 aggregate production impacts. Commodity price effects are minimized, and consumer costs are reduced. In addition, the overall costs to producers would be reduced because fewer producers would have to bear the full impact of atrazine restrictions. The issue becomes one of identifying those watersheds requiring atrazine runoff control, and the most appropriate alternative control strategies.

The results also demonstrate a problem with chemical-specific control strategies. When the use of atrazine was eliminated or reduced, the use of some other herbicides increased, along with their loadings to the environment and associated risks to the environment and to human health. Unlike atrazine, most of these substitutes do not yet have an enforceable drinking water standard. 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.

Atrazine

Environmental Characteristics and Economics of Management

Marc O. Ribaudo
Aziz Bouzaher

Introduction

Atrazine is an important herbicide in the production of corn and other crops in the United States. Recent findings indicate that elevated amounts of atrazine are running off fields and entering surface water resources (Goolsby, Coupe, and Markovchick).1 Water quality monitoring studies find atrazine 10 to 20 times more frequently than the next most detected pesticide (Belluck, Benjamin, and Dawson). These data raise the question of whether atrazine, which is considered a possible carcinogen, is affecting human health. If so, how can atrazine be kept out of water supplies?

Recent changes in the Safe Drinking Water Act make public water utilities legally responsible for providing drinking water with atrazine concentrations below a "safe" level of 3 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. Some groups favor placing a ban on atrazine and reducing atrazine discharge to zero. Two strategies that could be used instead of a ban are: (1) a mandatory change in application strategy wherever atrazine is used, and (2) a mandatory change in management strategy only in those areas where atrazine harms surface water quality. Since atrazine is such an important herbicide, mandatory changes in application strategies are likely to generate sizable costs for producers and possibly consumers. This report presents the costs and benefits of a complete ban on atrazine, a ban on pre-plant and pre-emergent applications, and a targeted management strategy to achieve a surface water standard. The complete ban is hypothesized to be the costliest strategy, while the targeted strategy is most likely the least costly.

Atrazine History and Use

Atrazine has been a major agricultural herbicide for more than 30 years. It was registered initially in 1958 by CIBA-GEIGY, the manufacturer, for weed control in corn and has been used extensively in the United States since the early 1960's. Atrazine is used primarily on corn, and is the primary pesticide used on corn. Over 65 percent of all corn acreage is treated with atrazine (U.S. Department of Agriculture (USDA), 1993). Atrazine is also used on sorghum, sugarcane, and a variety of specialty crops. Table 1 summarizes the trend in atrazine use on corn, and some additional information on total use. Table 2 summarizes atrazine use by major corn and sorghum producing State. Until recently, atrazine was also registered for industrial use, primarily right-of-way maintenance. Use has declined in recent years because of label changes and increased environmental concerns, but annual sales still range between 80 and 90 million pounds (U.S. Environmental Protection Agency (USEPA), 1992). Recent label changes are described in Appendix 1.

Atrazine selectively controls broadleaf (dicot) weeds, such as pigweed, cocklebur, and velvetleaf, and certain grass weeds. Selective control means that the

[1]Names in parentheses refer to sources listed in the references at the end of this report.

Table 1--Atrazine use trends

Year	Quantity		Acres treated			
	Corn	Total	Corn			All crops
	1,000 lbs a.i.		1,000 acres	Percent	Rate	1,000 acres
1964[1]	10,225	10,837	7,592	12	1.35	7912
1966[1]	21,066	23,495	13,740	21	1.53	14978
1971[1]	52,000	57,216	35,993	49	1.44	39842
1976[1]	83,790	903,40	56,863	67	1.47	61750
1980[2]	62,600	NA	42,200	56	1.48	NA
1982[1]	69,700	84,600	47,900	60	1.46	NA
1985[2]	NA	NA	35,200	59	NA	NA
1986[2]	NA	NA	38,205	68	NA	NA
1987[2]	NA	NA	35,694	70	NA	NA
1988[2]	NA	872,30[4]	31,807	60	NA	NA
1989[2]	NA	NA	33,023	57	NA	NA
1990[3]	58,125	NA	47,692	64	1.22	NA
1991[3]	52,060	NA	45,262	66	1.15	NA
1992[3]	54,939	NA	49,249	69	1.12	NA
1993[3]	49,553	NA	45,333	69	1.09	NA

a.i. = active ingredient.
NA = not available.
[1]National Pesticide Use Survey
[2]Cropping Practices Survey of Major Producing States
[3]Chemical Use Survey.
[4]CIBA-GEIGY, 1989.

Table 2--Atrazine use on corn and Sorghum, by major producing State, 1991

State	Corn		Sorghum	
	Area applied	Total applied	Area applied	Total Applied
	Percent	Mil. Lbs	Percent	Mil.lbs
Illinois	81	10,615		
Indiana	89	6,332		
Iowa	62	7,354		
Kansas	74	1,596	71	2,675
Kentucky	88	2,013		
Michigan	74	2,549		
Minnesota	32	1,684		
Missouri	85	2,911		
Nebraska	70	6,290	81	1,197
North Carolina	76	1,012		
Ohio	81	4,108		
Pennsylvania	78	1,329		
South Carolina	72	274		
South Dakota	18	490		
Texas	72	963	58	1,377
Wisconsin	52	2,048		

Source: USDA, 1992.

target weeds are controlled, with little or no injury to the crop. Atrazine is well tolerated by actively growing corn or sorghum, which absorb and metabolize the herbicide, thus deactivating it (Regehr, Peterson, and Hickman). These factors and atrazine's relatively low cost make it an extremely valuable herbicide.

Atrazine can be applied to corn pre-plant, pre-emergence, or post-emergence, making it a very flexible herbicide. Pre-plant and pre-emergent uses are the most popular. Atrazine can also be applied with irrigation water (chemigation) from center-pivot irrigation systems, although current regulations forbid this method.

Application rates of atrazine on corn depend upon climate and soil texture, with reduced rates being required on sand, loamy sands, and sandy loam soils. The average atrazine application rate on corn in the major corn producing States was 1.15 pounds per acre in 1991 and 1.12 pounds per acre in 1992. Rates have decreased from the average of 1.5 pounds active ingredient (a.i.) per acre during the 1966-82 period.

Atrazine is applied to sorghum in a similar manner as corn, although there are restrictions for sandy soils. The average application rate on sorghum was 0.97 pound per acre in 1991.

Atrazine Characteristics

Atrazine is one of the chloro-triazines, which also include simazine and cyanazine. Its chemical properties make it susceptible to leaching and runoff, especially during heavy rains. The screening procedure developed by Goss and Wauchope (1990) gives atrazine a "large" potential to leach or to move in surface solution, and a "medium" potential to adsorb to sediment particles.

The half-life of atrazine in loamy soils ranges from 60 to 150 days. However, when conditions in soils are changed from aerobic to anaerobic, the rate of degradation slows considerably (half-life of about 660 days in anaerobically incubated sandy clay sediments). In addition, atrazine degrades very slowly once it enters the water column. Half-life in reservoirs may be 1 to 2 years (Goolsby and others, 1993). This slowdown in rate of degradation has important consequences. When water containing residues of atrazine moves down through the soil profile and away from the root zone to where oxygen becomes less available, the persistence of atrazine is expected to increase. Likewise, the persistence of atrazine in groundwater and in poorly aerated surface waters is also expected to be higher than in well aerated waters. Thus, laboratory and field data show that atrazine and its degradates can persist in some soils and in reservoirs.

Little information is presently available on the occurrence of atrazine degradates in surface and groundwater. Based on groundwater monitoring data, it is estimated that if the concentrations of the degradation products are taken into account, total atrazine residues in groundwater are approximately double the concentration of atrazine alone (USEPA, 1991b). Surface water monitoring data indicate that concentrations of atrazine degradates are typically 1/10 to 1/2 the atrazine concentrations. While the toxicology of the degradates is not yet known, it is expected that these materials are at least as toxic as the parent material (CIBA-GEIGY, 1992).

Atrazine Toxicology

Long-term (chronic), high-dose animal oral exposure studies have shown a variety of adverse effects to heart, lungs, liver, kidney, spleen, adrenal glands, and brain. Observed effects included congestion of the heart, lungs, and kidney, hypertension, muscle spasms, anorexia, and degeneration of the adrenal gland (USEPA, 1991b; CIBA-GEIGY, 1991a).

The Environmental Protection Agency (EPA) has officially classified atrazine as a possible human carcinogen (class C). Some information indicates that atrazine causes cancer in rats receiving high doses over the course of their lifetimes.

Based on current data, atrazine can be characterized as practically nontoxic to birds on a dietary basis (USEPA, 1991b). There are sufficient data to characterize atrazine on an acute basis as moderately toxic to coldwater fish and moderately to slightly toxic to warmwater fish. Data report toxicity values of 4.5 ppm for Rainbow trout, 24 ppm and 57 ppm for Bluegill sunfish, and 0.065 and 0.12 ppm for Brook trout. Such values have rarely been approached in monitoring studies.

Data indicate that atrazine ranges from slightly to highly toxic, on an acute basis, to freshwater invertebrates (USEPA, 1991b). In aquatic invertebrate life-cycle studies, the maximum acceptable toxic concentrations were reported between 0.06 and 0.25 ppm, depending on the organism (USEPA, 1991b). There are sufficient data to characterize the effects of atrazine to estuarine and marine organisms as no more than moderately toxic.

Drinking Water Standards

Under the 1986 amendments to the Safe Drinking Water Act, EPA was required to establish safe drinking water standards for a number of chemicals, including atrazine. Two types of standards have been set. The first is the maximum contaminant level (MCL). This is an enforceable limit for public drinking water supplies. According to EPA, an individual could consume water containing a pollutant at or below the MCL on a daily basis throughout one's lifetime and suffer no adverse health impacts (Baker and Roberson). The second type of standard is the Health Advisory (HA). HA's are set for lifetime exposure levels as well as for shorter term exposures. The HA's are not enforceable, but are offered as guidance for interpreting risks.

The EPA Office of Drinking Water has established a lifetime HA and more recently an MCL of 3 ppb for atrazine. The MCL was promulgated in 1991 and became effective on July 30, 1992. The 10-day HA was established at 100 ppb, and the longer term, 7-year HA is 48 ppb for children and 168 ppb for adults (CIBA-GEIBY, 1991a). Because atrazine in drinking water may possibly increase the risk of cancer in humans, the MCL and lifetime HA include an additional margin of safety.

Human exposure to atrazine through food consumption is extremely low. The U.S. Food and Drug Administration has screened for atrazine in its Market Basket Surveys for years. In all of the samples analyzed, atrazine has been detected twice at levels of 0.1 ppm (CIBA-GEIBY, 1991a).

Detections in the Environment

A number of water quality monitoring studies that included atrazine have been conducted over the past decade on river systems, water supply facilities, and groundwater. Based on the results of these studies, atrazine does not appear to pose a problem for groundwater. The EPA National Survey of Pesticides in Drinking Water Wells found detectable levels of atrazine in 1.7 percent of community water system wells and 0.7 percent of rural private wells. Measured concentrations were well below the MCL of 3 ppb. In a 1991-92 groundwater reconnaissance study by the U.S. Geological Survey (USGS), atrazine was detected in 20.8 percent of wells tapping near-surface aquifers, with concentrations averaging less than 2.09 ppb (Goolsby and others, 1993).

General reconnaissance surveys of river systems in the Midwest have found that significant quantities of atrazine are transported to streams during late spring and early summer (Thurman and others). Highest concentrations in rivers are found on small rivers and streams having agricultural watersheds. During spring planting, concentrations can exceed the MCL, especially for smaller rivers. High levels can persist for over a month (Goolsby, Coupe, and Markovchick). Atrazine has also been found to persist in river systems throughout the year, although concentrations are low prior to spring applications.

Annual mean concentrations of atrazine greater than the MCL have been found on parts of the Missouri (Keck; Ross and Balu), Mississippi (Ross and Balu), Des Moines (Ross and Balu), Wabash (Roux), Maumee (Baker), and Sandusky Rivers (Baker) and on smaller streams in Illinois (Illinois EPA; Taylor, A.G.; USEPA, 1992), Ohio (USEPA, 1992), and Indiana (USEPA, 1992). Some of the rivers and streams are used for public water supplies.

Surveys of lakes and reservoirs have found that atrazine concentrations persist longer in reservoirs than in streams. Also, except for a short period shortly after application, atrazine concentrations are generally higher in reservoirs than in streams (Goolsby and others). During the spring, when recharge generally occurs, heavy loads of herbicides may enter a reservoir. Since reservoirs store water, these chemicals remain trapped for an extended period of time, with only slow degradation. Water supply reservoirs in Kansas (U.S. Corps of Engineers; Langemeier), Missouri (Langemeier), Iowa (Langemeier; USEPA, 1992), Nebraska (Langemeier), Ohio (CIBA-GEIGY, 1991a), and Illinois (USEPA, 1992) have been found to have average annual concentrations of atrazine greater than the MCL. These findings have prompted the current concern over atrazine use.

Some general statements can be made based on the results of the studies listed above. Atrazine is sometimes found in groundwater, but rarely above the MCL. Drinking water drawn from surface supplies seems to be most at risk from atrazine. Public water supplies with mean concentrations above or near the MCL (based on four quarterly samples) tend to draw upon smaller rivers or reservoirs having agricultural watersheds. Low levels of exposure occur in community water supplies drawing from the Great Lakes, large rivers, and rivers draining large watersheds dominated by forests or grazing land, although seasonal spikes on larger rivers may approach or even exceed the MCL. Approximately 42 percent of the

population of the Midwest, about 21 million people, receive drinking water from surface rivers and reservoirs (Baker and Roberson).

The seasonality of atrazine concentrations in rivers raises questions as to whether the quarterly sampling strategy called for in the Safe Drinking Water Act provides an adequate measure of annual exposure. Four samples per year are inadequate to accurately characterize annual average concentrations given the pattern of atrazine loadings (Baker and Roberson). Actual mean concentrations could be overestimated or underestimated by large amounts. If a sample happens to be taken in May or June immediately after a "runoff event," the chances are that the concentration will be above 12 ppb. This one reading will put the utility out of compliance for that year, even if the "true" mean concentration, based on daily readings, is below the MCL. However, the high analytic costs are a deterrent to frequent sampling for many small utilities.

Treatment Technology

If a utility detects atrazine in the water source, the utility is usually faced with two alternatives: implement nonpoint source controls in the watershed, or treat the raw water. The treatment technology designated by EPA as Best Available Technology (BAT) for the control of herbicides (including atrazine) in drinking water is granulated activated carbon (GAC) (Montgomery). Alternative approaches, such as nonpoint source watershed controls, would have to be at least as effective. Powdered activated carbon (PAC) treatment has been considered appropriate for full-scale treatment without extensive plant studies. Some other techniques that show promise but require further study include ozone, advanced oxidation, reverse osmosis, photocatalytic reactions, and synthetic resins.

GAC has been shown to reduce atrazine levels to below analytical detection limits. This implies that any alternative strategies for reducing atrazine would have to produce the same result. Removal success depends on the carbon usage rate and the system design. GAC has an advantage in that it addresses other treatment requirements such as taste and odor, and provides continuous control. This system may be the treatment alternative of choice, especially for plants experiencing routine baseline levels of atrazine.

PAC is a cheaper and more flexible approach. Rather than a fixed bed of activated carbon, powdered carbon is added to the water during treatment. PAC does not require the capital equipment of GAC, can be added to the treatment stream at any of several points, and operation costs are a function of use. The size of the dose is dependent on influent concentration of target compound, desired concentration, contact time within the system, type of carbon used, and competitive interaction of organic matter and chemicals in the water. Tests show that higher doses of carbon are needed when atrazine concentration exceeds 15 ppb.

The low cost of the system and the ability to treat only when needed are features that may make this system more attractive to water suppliers experiencing seasonal herbicide occurrences. Atrazine follows such a trend, as demonstrated by Goolsby and others.

Projected Impacts of New Atrazine Drinking Water Standards

Given the current monitoring data, it appears that surface water supplies are the only ones at risk from atrazine. Social costs of contamination, or conversely, the benefits from preventing contamination, can therefore be properly measured by changes in treatment costs. This requires the reasonable assumption that the supply and quality of drinking water remain unchanged given the change in quality of untreated input water (Freeman).

Based on information from various sources of monitoring data, including those from the USGS and the American Water Works Association, 11 public water supplies in EPA Region VII (Missouri, Kansas, Nebraska, and Iowa) are predicted to need advanced treatment in order to meet the new atrazine MCL (Langemeier). These are: Jefferson Co. RWD #1 and Jefferson Co. RWD #10, both served by Perry Reservoir in Kansas; Labelle, Lewistown, Cameron and Perry in Missouri; and Osceola, Corydon, Ft. Madison, Humeston, and the University of Iowa in Iowa. The initial cost of establishing adequate treatment systems for these 11 suppliers is $8.3 million. Annual treatment costs were estimated to be approximately $180,000 (Langemeier).

The above systems supply about 36,000 people. Per-capita costs for GAC treatment are therefore $229 for capital costs and $5 for annual operation and maintenance costs. Public water systems using surface water supply 21 million in the atrazine-use area. If all these systems had to incur the same costs as the 11 systems listed above, annual treatment costs would be about $400 million, including $277 million in capitalized costs of GAC systems annualized over 30 years at 4 percent and $105 million in annual operation and maintenance costs. This is obviously an overestimate, since most systems appear to be in compliance with the atrazine drinking water standards, at least currently (Richards, Baker, Christensen, and Tierney).

Also, using PAC instead of GAC would lower treatment costs. However, this estimate provides a useful upper bound for benefits from preventing atrazine from reaching water systems.

Atrazine Management

Atrazine can enter water resources through point source or nonpoint source discharges. Point source discharges are generally due to accidents during storage, mixing, disposal, and application. Point source discharges can be important. In one study in Ontario, 22 percent of pesticide detections in 11 watersheds were linked to carelessness with operating equipment adjacent to streams (Frank and others). The best management practices for dealing with point source discharges center on simple care in handling the material.

Nonpoint discharges occur when the chemical leaches through the soil profile or is carried with surface runoff before it is degraded. Such occurrence is not necessarily a matter of carelessness, although careless handling and application could exacerbate a problem. Some of the alternative management practices available for reducing atrazine loadings where the chemical is applied include alternative chemicals, reduced application rates, changes in timing of application, runoff management, and alternative crops. Some of the alternative crop management practices are conservation tillage, banding or incorporation of atrazine, integrated weed management, crop rotations, filter strips, and drainage improvements.

Economic Analysis of Reducing Applications

Two previous studies evaluated the economic impacts of atrazine reduction policies. Osteen and Kuchler (1986) evaluated the economic implications for farmers and consumers of bans on corn pesticides, including atrazine. Banning atrazine resulted in an increase in net producer income of $1.1 billion, and a decrease in consumer surplus of $1.9 billion.

The National Agricultural Pesticide Impact Assessment Program (NAPIAP) coordinated an evaluation of the effects of restricting atrazine use on corn and sorghum in order to reduce surface water contamination in the upper Mississippi River Basin. The study region for corn included the Corn Belt, Lake States, Northern Plains, and Kentucky. For sorghum, the study region included the Northern Plains. Banning atrazine only in the study region (as opposed to nationally, as in the previous study) increased corn prices by 1 percent and sorghum prices by 3 percent. Producer income is decreased by $342 million and consumer surplus is reduced by $470 million. Reducing application rates did not affect prices measurably. As a result, producers bear the brunt of decreased yields and/or increased production costs. Producer income decreased by $80 million for reduced application rates for all pre- and post-emergent applications, and $320 million for allowing only post-emergent applications.

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. CEEPES (Comprehensive Environmental Economic Policy Evaluation System) is an integrated system designed to systematically evaluate alternative agri-ecological economic policy tradeoffs. CEEPES combines diverse simulation models into a unified policy evaluation system that provides both ecological and economic indicators of welfare. CEEPES has four main components: policy, agricultural decision, fate and transport, and environmental and health risk (Bouzaher and Manale, 1993; Bouzaher and others, 1992, 1993).

CARD used CEEPES to examine how a ban on atrazine would affect both economic and environmental measures of welfare in the major corn and sorghum producing areas. The study area encompassed 27 production areas, which includes all or part of Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Wisconsin, and Colorado.

The CEEPES model allows farmers to select from over 500 weed control strategies for corn and over 150 for sorghum. The CEEPES model contains a greater number of alternative weed management strategies than were considered in previous analyses. All strategies are aimed at full control of weeds given ideal weather. Weather is stochastic in the model, and risk is defined as the probability that a given herbicide strategy is ineffective due to unfavorable weather conditions. The model assumes that farmers trade expected pest damage for expected application costs when deciding on a weed control strategy.

Changes in surface water concentrations are estimated with a surface water fate and transport model (STREAM model). Changes in groundwater concen-

trations are estimated using a groundwater fate and transport model (RUSTIC model). Welfare measures associated with yield and cost impacts are estimated with an econometric model of the U.S. agriculture sector (AGSIM model) (Taylor, C.R., 1987, 1991; Penson and Taylor). Appendix 2 provides some additional information on CEEPES.

Total Atrazine Ban Scenario

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

Corn grain yields decreased 1.2 percent and sorghum yields decreased 3.4 percent under the total atrazine ban (table 3). Total corn acreage decreased 2.4 percent. Sorghum acreage decreased 3.7 percent. Largely in response to more widespread use of corn-soybean rotations, soybean acreage increased 3.5 percent.

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 do not make up for the decrease in atrazine, in terms of pounds of active ingredient. Atrazine makes up 54 percent of the total triazine use on corn, but total triazine use declined only 20.6 percent (table 4). 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 4). Total herbicide applications on corn decreased 1.1 percent, and applications on sorghum increased 13 percent.

Accompanying 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 practice

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:

Exposure Value = Predicted concentration/Environmental benchmark.

A chronic exposure value is calculated by using the predicted average herbicide concentration and the long-term MCL as an environmental benchmark. An acute exposure value is calculated by using the peak concentration and the short-term Health Advisory. 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 5 presents the percentage of corn acres, by chemical, where the acute exposure values for surface water have values greater than 1. For each herbicide, the peak concentrations in water are calculated by soil type with the STREAM model in CEEPES. These individual concentrations are compared with the EPA benchmark Health Advisory values 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 0. 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 6. 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 are weighted across tillage and crop (corn and sorghum).

Table 3--Summary of production effects

Production variable	Scenario		
	Ban	Post use	Standard
	Percent		
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
Corn price			
Short term	1.8	0.4	1.4
Long term	2.2	1.1	1.5
Sorghum price			
Short term	2.4	-0.2	1.7
Long term	3.2	0.1	2.2

Table 4--Summary of herbicide use changes

Herbicide	Scenario		
	Ban	Post use	Standard
	Percent		
Atrazine use on corn	-100	-90.7	-78.8
Atrazine use on sorghum	-100	-44.0	-25.6
Triazine use on corn	-20.6	-16.5	-20.6
Triazine use on sorghum	-65.6	-32.2	-13.9
Non-triazine use on corn	25.6	21.2	24.1
Non-triazine 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

Table 5--Proportion of herbicide-treated corn acres at risk for exceeding surface water benchmarks

Chemical	Scenario			
	Baseline	Ban	Post use	Standard
	Percent			
Atrazine>1.5 lbs a.i./acre	7.8	0.0	2.4	0.0
Atrazine<1.5 lbs a.i./acre	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

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

Table 6--Relative impacts of policies on groundwater, surface water, and ecosystems

	Reference	Scenario			
	Benchmark	Baseline	Ban	Post Use	Standard
Groundwater 1.2m	Acute	.112/.056	.067/.061	.072/.061	.007/.006
	Chronic	.363/.259	.012/.012	.049/.042	.001/.001
Groundwater 15m	Acute	.001/0	0/0	0/0	0/0
	Chronic	.016/.012	.001/0	.005/0	0/0
Surface water	Acute	2.222/.889	1.676/.895	1.772/.898	.036/.022
Eco-system 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 is the highest weighted exposure value for any pesticide predicted in a medium.

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 exposures are higher for acute groundwater and surface water, and for ecosystem risk, that is, 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 percent for corn and 2.4 percent for sorghum (table 3). Producer income in the study area decreased $268 million and the economic welfare of domestic consumers and foreign consumers decreased $249 million (table 7). In the long term, corn and sorghum prices are 2.2 percent and 3.2 percent higher, respectively, than the baseline. As a result, producers' impacts are mitigated somewhat, losses totaling $207 million. However, annual consumer losses increase to a total of $458 million.

The increases in crop prices result in some U.S. Department of Agriculture (USDA) program savings. In the short term, deficiency payments decreased $572 million. In the longer term, these savings are $248 million. The assumption is made throughout the analysis that programs are not changed. While these savings are not considered changes in welfare, they are important in assessing the impact on the Federal budget of the atrazine ban or any other atrazine control policy. Impacts on the budget will weigh heavily on any decision.

Banning Pre-Plant, Pre-Emergent Applications

An alternative to totally banning atrazine is to minimize runoff by restricting use. One approach is to ban all pre-plant and pre-emergent applications, thus allowing only post-emergent applications. Allowing only post-emergent uses resulted in a 2.6-percent decrease in corn acreage and a 0.5-percent decrease in sorghum acreage (table 3). A shift to corn-soybean rotations resulted in a 3.5-percent increase in soybean acreage. Corn yields decreased 1.1 percent and sorghum yields increased slightly. Herbicide costs per treated acre increased 5.7 percent for corn and 17.5 percent 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 percent and atrazine use on sorghum decreased 44 percent (table 4).

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 4). The use of nontriazines increased 21.2 percent on corn and 42.7 percent on sorghum. Because of the substitution of less effective strategies, total pounds of active ingredients used on corn decreased only 0.8 percent, and total pounds on sorghum increased 6.7 percent.

The changes in weed control strategies were accompanied by changes in tillage practices, although once

Table 7--Summary of welfare effects

	Scenario		
	Ban	Post use	Standard
		Million dollars	
Producer income			
Short term	-268	-204	-200
Long term	-207	-50	-53
Consumer surplus			
Short term	-249	-20	-189
Long term	-458	-245	-275
Government outlays			
Short term	-287	-65	-227
Long term	-248	-1	-75
Total[1]			
Short term	-517	-224	-389
Long term	-665	-295	-328

[1]Change in producer income plus change in consumer surplus.

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 0 (table 5). The proportion of acreage treated with atrazine at rates greater than 1.5 pounds per acre at risk decreased from 7.8 percent to 2.4 percent. On the other hand, the proportion of acreage treated with cyanazine, bentazon, and simazine that is at risk increased.

The relative impacts of the policy on water and environmental quality are presented in table 6. A pattern similar to that seen for the 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 percent. The largest price effects are a 0.4-percent increase in the price of corn and a 0.6-percent increase in the price of hay (table 3). 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 7). Government outlays for deficiency payments decreased by $65 million. In the long term, welfare decreased $295 million, producer net income decreased $50 million, and consumer surplus decreased $245 million.

As expected, the welfare effects of allowing post-emergence use only are less than those of the atrazine ban. While still restrictive, this scenario allows greater producer flexibility in dealing with weed problems.

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 allow 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-percent decrease in corn acreage and a 2.2-percent increase in sorghum acreage (table 3). Corn grain yields decreased 1.2 percent while corn silage yields increased slightly. Sorghum yields decreased 2.8 percent. Herbicide costs per treated acre increased 4.6 percent for corn and 27 percent for sorghum.

The percentage of corn acreage treated with atrazine decreased 67 percent, while the percentage of sorghum acreage treated with atrazine increased 5 percent. The amount of atrazine used in corn production decreased 79 percent, while atrazine used in sorghum production decreased almost 26 percent (table 4).

The surface water standard restriction forces some shifting to other herbicides. The total use of triazines decreased 20.6 percent on corn, indicating that the use of the other triazines increased (table 4). Nontriazine use increased 24 percent. For sorghum, triazine use decreased 13.9 percent, but nontriazine use increased 55.7 percent. Overall, herbicide use decreased 2 percent for corn and increased 22.3 percent 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 percent 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 5. The surface water scenario greatly reduced the area at risk from herbicides. Acreage treated with atrazine that is at risk declined to 0. Also, the acreage treated with metolachlor, alachlor, and simazine that are at risk decreased. However, the acreage treated with cyanazine and bentazon that are at risk increased.

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 6). This scenario resulted in lower exposure values than the atrazine ban or the atrazine post scenarios. The cropping practices and the herbicides selected were more geared toward reducing runoff and leaching than the ones selected under the other scenarios.

In the short term, corn and sorghum prices are estimated to increase 1.43 percent and 1.70 percent, respectively (table 3). Corn prices are expected to increase 1.47 percent in the long term, while sorghum prices are estimated to increase 2.22 percent. In the short term, producer income decreased $200 million, while consumer surplus losses are $189 million (table 7). In the longer term, producer losses are $53 million and consumer surplus losses are $275 million. Because of short-term price increases, government program outlays in the short run decreased $227 million. In the longer term, outlays decreased $75 million. The surface water standard policy is less costly than the ban, but more costly than the atrazine post restriction. However, the environmental benefits are greater than those from the atrazine post scenario, 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 pre-plant and pre-emergent use of atrazine greatly reduces the acreage at risk from atrazine, but does not eliminate the risk.

Monitoring studies show that atrazine concentrations in some surface waters exceed drinking water standards established for community water treatment systems. The costs of treating all surface water consumed by those living in the Midwest would be about $400 million annually. Banning atrazine would eliminate the need to incur these costs, but the costs to producers and consumers range between $517 million and $665 million. Based on these results, it appears that a general ban would generate costs greater than water treatment benefits. Health and environmental benefits are not included in these estimates, but these benefits are highly uncertain, and probably quite small given current concentrations of atrazine found in water resources. Treatment cost savings estimates are almost certainly overestimated because they assume that all water treatment systems in the Midwest

need to be upgraded. Only a portion are likely to be out of compliance, namely those on small rivers and small reservoirs in agricultural watersheds. An atrazine ban is even less attractive when put in this light.

Banning all pre-plant and pre-emergent applications would generate producer costs of between $224 and $295 million. The benefits of this option, measured as the elimination of the need to install additional treatment in municipal water treatment plants, appear to outweigh the welfare costs if a substantial number of treatment plants would need the additional treatment without any atrazine reductions. Water quality monitoring data do not currently indicate that this will be the case. In addition, this scenario may not eliminate the need to install advanced treatment in all systems, as some of the corn acreage is still at risk from atrazine.

The targeted surface water standard scenario generates smaller welfare costs than the atrazine ban for achieving the desired water quality standards. However, the costs are greater than for allowing only post-emergent applications. Whether benefits outweigh costs, which range between $328 and $389 million, depends on a substantial number of water treatment plants needing advanced treatment upgrades. However, the overall cost-effectiveness of reducing the sum of exposure value to surface water is the greatest of the three scenarios. This scenario did the best job of reducing total herbicide discharges to water resources.

The results imply that targeted atrazine control methods, which might include local bans, 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. 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 the 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 5, 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.

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Appendix 1—Label History

Atrazine was first registered in 1958. In the early 1980's, test data raised concerns about the dietary risk of exposure through water resources (USEPA, 1991a). In 1988, EPA required the registrant to submit surface and groundwater monitoring studies as well as additional usage, product performance, residue chemistry, and ecological effects data. In 1990, EPA approved risk reduction measures voluntarily submitted by CIBA-GEIGY for atrazine to reduce worker exposure and point-source contamination of groundwater. These measures included reclassifying atrazine as a restricted-use pesticide. In 1990, the label for atrazine required that the following guidelines be used:

- Adopts restricted-use classification (groundwater concerns) for all products containing atrazine except for lawn care products containing 2 percent or less active ingredient.

- Prohibits the mixing, loading, using, or storing of atrazine products within 50 feet of all wells, including abandoned and drainage wells, and sink holes.

- Establishes a maximum use rate of 3 pounds of active ingredient (a.i.) per acre for corn and sorghum for any one calendar year; limits the use of atrazine for quackgrass suppression on corn and sorghum acreage to spring applications only.

- Limits the maximum application rate for industrial weed control in noncrop areas to a maximum of 10 pounds a.i. per acre per calendar year.

- Prohibits the use of atrazine through any type of irrigation system.

In response to the finding of atrazine in surface water, CIBA-GEIGY voluntarily changed the label for atrazine in 1992. The following changes were made:

- The product may not be mixed/loaded or used within 50 feet of all wells, including abandoned wells, drainage wells, and sink holes. In addition, the product may not be applied aerially or by ground within a minimum of 33 feet of perennial or intermittent streams, lakes, ponds, or rivers, or within 200 feet around surface water used as drinking water supplies.

- Post-emergence application to corn and sorghum must be made before corn and sorghum reaches 12 inches in height.

- The maximum application rate for corn and sorghum is 2.5 lbs a.i. per acre per calendar year. Applications for quackgrass suppression in corn and sorghum are restricted to spring application only. No fall applications are permitted.

- For soil applications prior to crop emergence on highly erodible soils, if conservation tillage is utilized the maximum rate is 2 lbs a.i. per acre. If plant residue is less than 30 percent, the maximum rate is 1.6 lbs a.i. per acre. On soils not highly erodible, the maximum rate is 2 lbs a.i. per acre.

- The product may not be applied through any type of irrigation system.

- Industrial uses, such as clearing rights of way, are prohibited.

Appendix 2—CEEPES Model

The Comprehensive Environmental Economic Policy Evaluation System (CEEPES) is an integrated modeling system developed to estimate the consequences for economic and water quality indicators of policies affecting pesticides. CEEPES simulates a farmer's substitution among herbicides, other inputs, crops, and agricultural practices in response to a specified policy.

The four major components of CEEPES are policy, agricultural decision, fate and transport, and environmental exposure. These components are designed to support a modular research strategy and to facilitate configuring the system to explore different agricultural and environmental policy issues.

The agricultural decision component models the choice of agricultural practices under alternative policies. The outcomes include acreage planted, rotation, tillage practice, chemical regime, yield, and cost of production for each producing area 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.

Incorporated into the RAMS model is a detailed weed control subsector linked to crop production through herbicide management practices, productivity response, and chemical costs. The Weather Impact Simulation on Herbicide (WISH) model simulates over 500 alternative weed control strategies for corn and over 150 strategies for sorghum. All weed control strategies are 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 strategy.

Risk is defined in WISH as the probability that a given herbicide strategy is ineffective. An environmental policy, such as a herbicide ban, will change the set of efficient weed control strategies. Farmers are assumed to have a main strategy for weed control and a back-up strategy in case the main strategy fails. Failure can occur if weather conditions are less than ideal.

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 the herbicide strategy table and a weather file which contains daily average information on temperature, rainfall, and wind. For each herbicide strategy over a period of 50 years of weather history, starting with the primary application, the model considers the weather and records the percentage of acres treated during the window of application; it also records the application rate and cost for 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 too dry or too wet years where a farmer may have to apply herbicides more than once or does not have time to apply herbicides and sustain a major yield loss.

The Agricultural Land Management Alternative with Numerical Assessment Criteria Model (ALMANAC) simulates the impact of weed competition on crop yields. ALMANAC is a process model that simulates crop growth, weed competition, and the interactions of management factors, for a variety of soil properties and climatic conditions.

Fate and transport models use information on agricultural activity in each geographic unit to produce 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 is 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 streambed 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 through market clearing identities. Thus, the model solves for the set of crop and livestock prices that allow the market described by the RAMS results 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.