● HERBICIDE FACTSHEET

ATRAZINE: TOXICOLOGY

Atrazine, a triazine herbicide, is one of the two most commonly used agricultural pesticides in the U.S.

According to the National Toxicology Program, atrazine is "immunotoxic," disrupting the function of the immune system. For example, it decreased the production of interferon, a molecule that fights viral infection.

Exposure to atrazine also disrupts hormone systems. Detailed research, much of it done by the U.S. Environmental Protection Agency (EPA), showed that testosterone, prolactin, progesterone, luteinizing hormone, estrogen, and a thyroid hormone are all affected by atrazine.

A study conducted by researchers at the University of Iowa found that more babies were born with low birth weight (for their gestational age) and birth defects in Iowa communities whose water supply was contaminated with atrazine than in other Iowa towns. The atrazine contamination did not exceed EPA drinking water standards.

In laboratory tests, atrazine delays puberty. In addition, inflamed prostates occur more often in the offspring of mother animals that were fed atrazine while they were nursing than in the offspring of unexposed mothers.

Atrazine has caused genetic damage in a variety of laboratory studies. For example, researchers from the University of Illinois found that atrazine at concentrations found in drinking water increases chromosome damage in hamster cells. In addition, a study of workers at an atrazine production facility found that "occupational exposure to atrazine causes a significant increase in the percentage of chromosomal damage" in the workers' blood cells.

Whether or not atrazine causes cancer has been a controversial subject. Although both laboratory studies and studies of exposed people have found an association between atrazine exposure and the incidence of certain cancers, EPA and an international agency disagree about how to classify its ability to cause cancer.

BY CAROLINE COX

Atrazine (see Figure 1) is a widely used herbicide in the triazine family. Certain crops (primarily corn and related crops) are tolerant of atrazine, and it is used to kill weeds without crop death in those situations.[1] Atrazine was first registered in the U.S. in 1959.[2] Currently, the major manufacturer is Syngenta (formerly Novartis Crop Protection, Inc.),[3] but it is marketed by many companies.[4] Use of atrazine has been the subject of significant concerns because it is one of the most commonly detected pesticide contaminants of rivers, streams, and wells.[5]

Use

Atrazine is "one of the two most widely used agricultural pesticides in the U.S."[6] according to the U.S. Environmental Protection Agency (EPA). Estimated annual use is between 64 and 75 million pounds. The primary crops on which atrazine is used are corn, sorghum, and sugar cane.[6]

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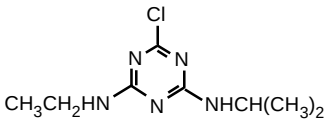
Figure 1
Atrazine



2-chloro-4-ethylamino-6-isopropylamino-s-triazine

Mode of Action

Atrazine kills plants by blocking photosynthesis, the process by which green plants use sunlight, carbon dioxide (from the atmosphere), and water to make sugars and related molecules. Without this "food," the plant is unable to grow and dies.[7]

Inert Ingredients

Like most pesticide products, commercial atrazine products contain ingredients other than atrazine. Misleadingly called "inerts," the identity of most of these compounds is not publicly available. For toxicological information about some inert ingredients that have been identified, see "Inert Hazards," p. 13.

Most of the toxicological tests used in the registration of a pesticide are done with the active ingredient only; when possible, the following summary of atrazine's toxicology will identify whether a particular study used atrazine alone or was done with commercial products (atrazine plus inerts).

Eye Injury

Some atrazine-containing herbicides cause eye injury. Atrazine 90DF causes "substantial but temporary eye irritation"; Atrazine 80 WP, Atrazine 90

WDG, Atrazine Plus, and several "weed and feed" atrazine products "cause eye irritation"; and Atrazine 90DF, Atrazine 90, Atrazine 4L, Atra-5, Atrazine 80, Atrazine 80W, and Atrazine 5F cause "moderate eye irritation."[4]

Effects on the Nervous System

Although herbicides, including atrazine, are not generally expected to be toxic to the nervous system, researchers at the University of Sassari in Italy demonstrated that "atrazine exerts a toxic action on [the] central nervous system."[8] Atrazine treatment of rats decreased the electrical activity of certain cells in the cerebellum (the part of the brain concerned with motor function, the control of muscle tone, and the maintenance of balance[9]), and decreased the electrical response of the same cells when they were stimulated by a nerve. These effects occurred following a dose of 100 milligrams per kilogram (mg/kg), the only dose tested.[8]

Atrazine also has effects on the nervous system that are related to the major effects the herbicide has on hormone systems. (See "Effects on Hormones," p.14.) Atrazine alters central nervous system production of two chemicals, dopamine and norepinephrine.[10] Both transmit nerve impulses between nervous system cells, and act as hormones.[9] Altered production of these chemicals, in turn, alters levels of two hormones, prolactin and luteinizing hormone.[10]

The major breakdown products of atrazine (hydroxyatrazine, deethylatrazine, deisopropylatrazine, and diaminochlorotriazine) also alter the synthesis of dopamine and norepinephrine in the central nervous system.[11]

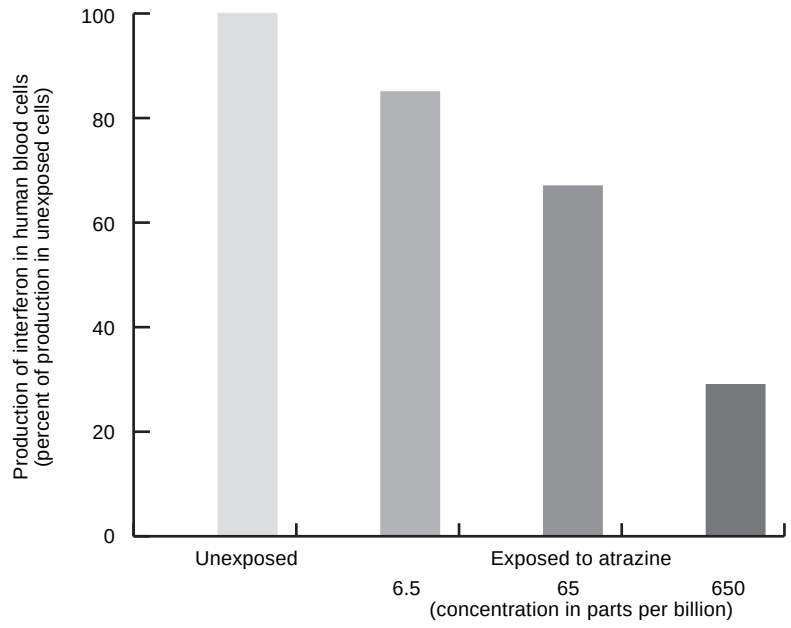
Effects on the Immune System

Four studies have shown that atrazine can disrupt normal immune system function, enhancing the risk of infectious disease or cancer.

In rats fed atrazine for three weeks, lymphopenia (a reduction in the number of white blood cells, cells that fight infection and disease[9]) was "pronounced"[12] at a dose of 100 mg/kg per day, the lowest dose tested.[12] This study compared immune system effects of 17 pesticides, and atrazine was one of five pesticides to which the immune system was most sensitive.[12]

In human blood cells, treatment with atrazine decreased the production of interleukin,[13] a regulatory protein in the immune system[9]; interferon,[13] an immune system protein that fights viral infections[9]; and tumor necrosis factor,[13] a protein that kills tumor cells.[9] (See Figure 2.)

Figure 2
Atrazine Reduces the Activity of the Immune System



Source: Hooghe, R.J., S. Devos, and E.L. Hooghe-Peters. 2000. Effects of selected herbicides on cytokine production in vitro. *Life Sci.* 66: 2519-2525.

Atrazine reduces the production of interferon by blood cells. Interferon is a protein used by the immune system to fight viral infections.

INERT HAZARDS

Publicly identified inerts in atrazine products include ethoxylated nonyl phenol, ethylene glycol, and sodium sulfite.[1,2] These chemicals pose the following hazards:

Ethoxylated nonyl phenols reduce fertility in laboratory tests[3] and act as co-carcinogens, increasing the potencies of other carcinogenic compounds.[3]

Ethylene glycol can reduce fertility, damage nerves, and damage the kidney. Symptoms of exposure include nausea and headaches.[4]

Sodium sulfite may cause vomiting, diarrhea, abdominal pain, and intestinal bleeding. Exposure to small amounts can cause severe allergic reactions.[5]

1. U.S. EPA. 2001. Letter from Calvin Furlow to Caroline Cox, May 1.
2. Novartis Crop Protection, Inc. 2000. Material safety data sheet: Aatrex None-0 Herbicide. www.cdms.net.
3. Talmage, S.S. 1994. *Environmental and human safety of major surfactants: alcohol ethoxylates and alkylphenol ethoxylates.* Boca Raton: Lewis Publishers. Pp. 311-315, 320-321
4. Sigma Chemical Co. 1998. Material safety data sheet: Ethylene glycol. St. Louis MO. www.sigma-aldrich.com.
5. Hazardous Substance Database. 2001. Emergency medical treatment: Sodium sulfite. http://toxnet.nim.nih.gov.

Cultures of spleen cells treated with atrazine produced fewer β-lymphocytes,[14] immune system cells that produce antibodies,[15] than untreated cells.[14]

A National Toxicology Program study of immune system function in mice concluded that "atrazine was found to adversely affect the immune system and, thus, is considered to be an immunotoxic compound."[16]

Effects on the Liver and Kidneys

Atrazine can damage both the liver and kidneys.

In a study of female pigs fed atrazine at a dose of 2 mg/kg per day for 19 days, researchers noted degeneration of the liver.[17] Liver degeneration also occurred in experiments with rats, but at higher doses.[18]

A study of kidney function found evidence of dysfunction, an increase in the protein content of the urine, in rats treated for 14 days with 10 mg/kg of atrazine per day.[19]

Effects on the Heart

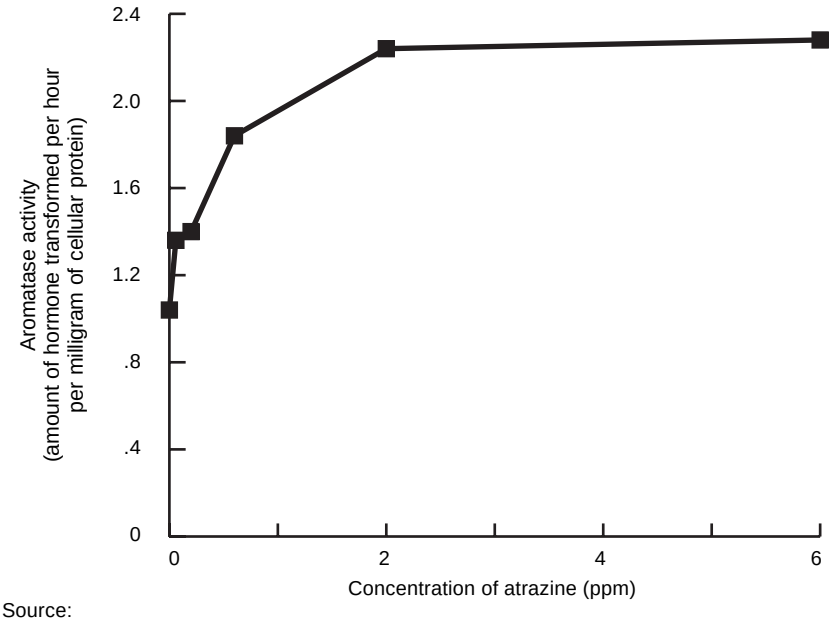
The "major treatment-related findings" in a dog feeding study were related to the heart. Electrocardiograms were altered, and degeneration of the heart muscles occurred.[20]

The atrazine breakdown product diaminochlorotriazine also damages the heart. In a dog feeding study, adverse effects included enlargement and softening of the heart, thickened valves, and lesions.[21]

Effects on Hormones

The impact that environmental pollutants can have on the normal function of human and animal hormone systems has been a significant concern in the past decade.[22] Hormones are biologically active molecules that control growth, development, behavior, and reproduction and thus are crucial to many important life functions.[23] Atrazine disrupts a stunning variety of hormone systems including the following:

Figure 3
Effect of Atrazine on a Hormone-transforming Enzyme



Source:
Sanderson, J.T. et al. 2000. 2-chloro-s-triazine herbicides induce aromatase (CYP19) activity in H295R human adrenocortical carcinoma cells: A novel mechanism for estrogenicity? *Toxicol. Sci.* 54: 121-127.

Atrazine, in cultures of human cells, increases the activity of aromatase, an enzyme that transforms androgens (male sex hormones) into estrogens (female sex hormones).

- **Testosterone.** Often called the "male" sex hormone, testosterone promotes the development of male sex characteristics.[24] It is converted into biologically active forms in various organs. A series of studies showed that atrazine inhibits this conversion in male laboratory animals, reducing the amount of the active forms in the pitutitary[25,26] and the hypothalamus.[26] A single dose of 1 mg/kg was sufficient to cause this inhibition,[25] and the atrazine breakdown product deethylatrazine had similar effects.[26] In addition, the number of testosterone receptors in the prostate gland was reduced by atrazine exposure[27] in both young adult rats and older rats.[28] Atrazine also reduces the ability of an active form of testosterone to bind to receptor molecules in the prostate.[29] Atrazine exposure of mothers during pregnancy and nursing affects testosterone levels in their offspring: exposure during pregnancy increases the amount of the active form of testosterone in the pituitary of the female offspring, but exposure during both pregnancy and nursing reduces these levels in male offspring. In addition, exposure to either atrazine or deethylatrazine during nursing decreased the number of testosterone receptors in the prostate of male offspring.[30]
- **Prolactin.** Prolactin stimulates the production of breast milk in nursing females.[9] Atrazine inhibits "surges" of prolactin that occur during nursing and in response to release of estrogen ("female" sex hormones).[31,32]
- **Progesterone.** Involved in the regulation of menstruation, progesterone also is important during pregnancy.[24] In female rats, exposure to atrazine induced "pseudopregnancies" in which, although the rats were not pregnant, their progesterone levels were high and the animals did not cycle through sexually active phases as they usually do.[33]
- **Luteinizing hormone.** Luteinizing hormone is produced in the pituitary gland and regulates the secretion of other sex hormones.[24] Atrazine blocks the "surge" of luteinizing hor-

mone that occurs before ovulation.[33,34]

- **Estrogens.** Often called "female" sex hormones, estrogens regulate the development of sex characteristics and the menstrual cycle, help maintain pregnancy, and prepare the breasts for nursing.[24] Atrazine is not estrogenic; that is, it does not cause certain physiological activities that estrogens cause. Atrazine does not cause increases in uterus weight, as estrogens do, nor does it cause cell division that normally occurs in response to estrogens.[35] However, atrazine does have estrogen-related activities. It increases the activity of an enzyme called aromatase that converts testosterone and related hormones to estrogens, and thus could increase estrogen levels.[36] (See Figure 3.) In a yeast that was genetically modified to produce the human estrogen receptor, atrazine displaced estrogens from the estrogen receptor at low estrogen concentrations, but not at high ones.[37] In addition, the atrazine breakdown product, deethylatrazine, has some estrogenic activity.[38]
- **Thyroid hormones.** In rats, atrazine caused a decrease in the blood levels of the thyroid hormone triiodothyronine,[39] a hormone that regulates metabolism and growth.

Effects on Reproduction

Studies of exposed people and laboratory tests show that atrazine and atrazine-containing herbicides reduce the ability to reproduce successfully.

Studies of exposed people have looked both at farmers and residents of agricultural areas.

In the Ontario [Canada] Farm Family Health Study, the incidence of premature birth in families in which the father applied atrazine on the farm was nearly double that of families in which the father was not exposed to pesticides.[40] The incidence of premature birth was even higher in families where atrazine was used in the yard.[40]

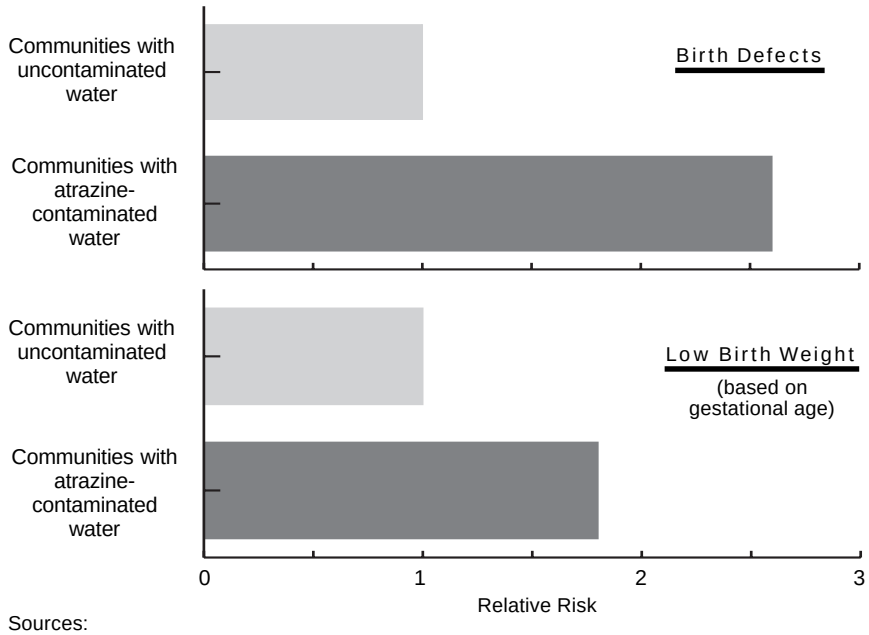
Another study, conducted by the University of Iowa, studied communities whose drinking water came from an Iowa reservoir that was more contaminated with herbicides than other Iowa water supplies. The average atrazine contamination level in this reservoir was 2.2 parts per billion (ppb), just below the federal drinking water standard of 3 ppb. Elsewhere in the state levels averaged 0.6 ppb. Researchers found that the incidence of what is called intrauterine growth retardation (IUGR), babies with low birth weight for their gestational age, was about double the incidence of IUGR in towns with less contaminated water.[41] In a companion study, researchers found that the incidence of birth defects was more than double that in towns with less contaminated water. (See Figure 4.) The incidence of limb reduction defects increased the most.[42]

A study that documented atrazine contamination of various tissues related to reproduction increases the concerns raised by the research summarized in the previous paragraphs. Researchers at the University of Bonn in Germany found atrazine in breast milk and cervical mucus in 20 percent (2/10) of the subjects tested.[43]

Effects on reproduction have also been demonstrated in female laboratory animals. Female rabbits which were fed atrazine had smaller litters and more miscarriages than unexposed rabbits. The lowest dose causing these effects was 75 mg/kg per day. In multigenerational studies with rats, animals fed atrazine had offspring which weighed less than the offspring of unexposed animals. The lowest dose causing these effects was 40 mg/kg per day.[44] At slightly higher doses (50 mg/kg per day), atrazine caused complete pregnancy loss (loss of the full litter) in rats of one laboratory strain (F344); similar results in other strains occurred at higher doses.[45]

Atrazine also disrupts the normal function of the male reproductive system in laboratory animals. In rats,

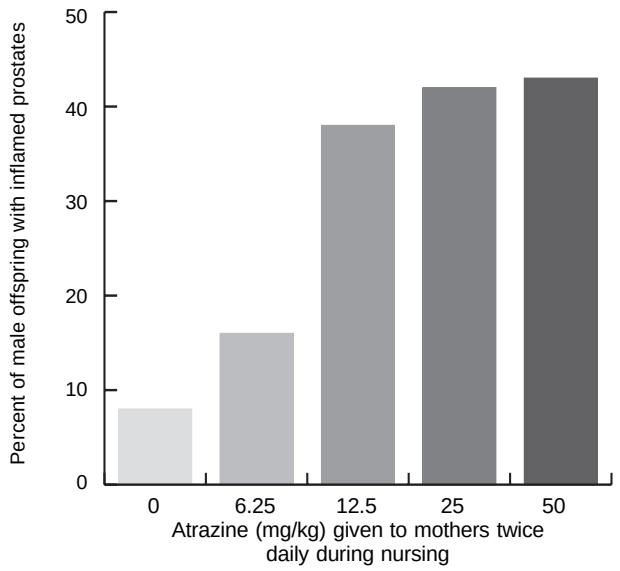
Figure 4
Associations between Atrazine-contaminated Drinking Water, Birth Defects, and Low Birth Weight



Sources:
Munger, R. et al. 1992. Birth defects and pesticide-contaminated water supplies in Iowa. *Amer. J. Epidemiol.* 136:959. (Abstract.)
Munger, R. et al. 1997. Intrauterine growth retardation in Iowa communities with herbicide-contaminated drinking water supplies. *Environ. Health Persp.* 105:308-314.

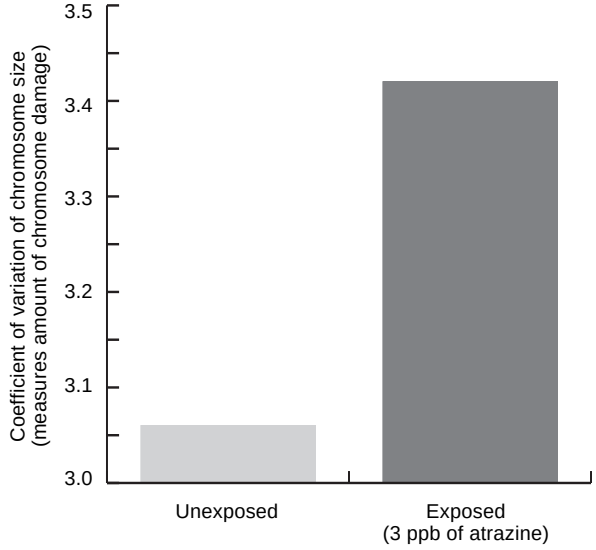
Birth defects and low birth weight babies (based on their gestational age) were more common in Iowa communities with atrazine-contaminated drinking water than in other Iowa communities. The average atrazine contamination was less than EPA's drinking water standard.

Figure 5
Atrazine and Prostate Inflammation



Source: Stoker, T.E., C.L. Robinette, and R.L. Cooper. Maternal exposure to atrazine during lactation suppresses suckling-induced prolactin release and results in prostatitis. *Toxicol. Sci.* 52:68-79.

Figure 6
Atrazine and Chromosome Damage



Source: Taets, C., S. Aref, and A. L. Rayburn. 1998. The clastogenic potential of triazine herbicide combinations found in potable water supplies. *Environ. Health Persp.* 106:197-201.

Exposure to atrazine during nursing causes inflamed prostates in the offspring. In addition, exposure of cells to concentrations of atrazine allowed in drinking water causes chromosome damage.

atrazine caused a reduction in the ability of sperm to move and a reduction in the number of sperm in the epididymis, the part of the testes in which sperm mature. These effects were caused by a dose of 60 mg/kg given twice a week.[46]

The atrazine breakdown product diaminochlorotriazine also reduces successful reproduction. Rats fed diaminochlorotriazine during pregnancy had offspring that weighed less than offspring of unexposed mothers and their bone development was also altered.[47]

Effects on Development

Recent studies have shown that atrazine can affect juveniles as they develop into adults. In studies conducted by EPA scientists, sexual maturity is delayed in rats fed atrazine from the time they are weaned until puberty. In males a dose of 12.5 mg/kg delayed puberty while a higher dose (50 mg/kg per day) was required to cause a delay in females.[48,49] In males, the primary breakdown products of atrazine have caused the same delay in puberty that atrazine does[50] as has exposure to atrazine before birth.[48]

Because feeding atrazine at relatively high doses reduces the weight of laboratory animals, it is possible that these effects on development could be related to reduced body weight rather than a direct effect of atrazine. To test this possibility, the EPA researchers in the studies of delayed puberty included in their experiments rats whose food was reduced so that their weight would match the weight of the atrazine-fed animals. In males, puberty was not delayed in the food-deprived animals as much as it was in the atrazine-fed animals.[48] Puberty of food-deprived females was not delayed.[49] Thus, atrazine directly affects the timing of puberty.

In addition, atrazine can affect the development of the prostate. When mother rats were treated with atrazine for the first four days after they gave birth (this is during the time that they are nursing their offspring), their male offspring were more likely to develop prostate inflammation. The dose required to cause inflammation was 25 mg/kg per day.[31] (See Figure 5.) When pregnant rats were exposed to atrazine between the fifteenth and nineteenth day of their pregnancies, their male offspring also developed inflamed prostates.[51]

Mutagenicity

EPA recently evaluated tests of atrazine's mutagenicity, its ability to cause genetic damage. This review included tests submitted to the agency as part of the registration process and tests published in the scientific literature.[52] EPA concluded that "the available evidence did not indicate a mutagenic effect of atrazine exposure."[53]

However, the EPA review omitted studies that raise serious concerns about atrazine's mutagenicity. A 1998 study of chromosome damage in blood cells of workers in an atrazine production facility found that "occupational exposure to atrazine causes a significant increase in the percentage of chromosomal damage."[54]

Also omitted from the EPA analysis were studies that looked at the ability of atrazine to cause genetic damage at the concentrations at which atrazine

has been measured in drinking water. The studies used cultures of cells from hamster ovaries, a standard cell culture for mutagenicity tests. The first study found that the incidence of chromosome breakage increased at concentrations less than 3 parts per billion,[55] the legally enforceable public drinking water standard.[56] A second study, using a similar protocol, found increased breakage of the largest chromosome at an atrazine concentration of 3 ppb (with borderline statistical significance) and a statistically significant increase at a concentration of 18 ppb. The highest atrazine concentration detected in Illinois water samples is 18 ppb.[57] The third study in this series found similar results: atrazine increased the frequency of chromosome damage at concentrations of both 3 and 18 ppb.[58] (See Figure 6.) These studies measured a kind of genetic damage not studied in any research included in the EPA analysis.

The EPA analysis omitted consideration of the role that "inert" ingredients play in the mutagenicity of atrazine-containing herbicides. The tests submitted to EPA as part of the atrazine registration process are all tests using atrazine alone,[59] as are most of the published studies. NCAP has identified one study that compares a commercial atrazine product with atrazine alone. In this study, the commercial product caused about twice as many mutations as did atrazine.[60]

In addition, EPA failed to consider the implications of the atrazine derivative called N-nitrosoatrazine. N-nitrosoatrazine is formed in the human digestive system when both atrazine and nitrate are present.[61] Because both compounds are common water contaminants[62], "there is much concern that this will increase the exposure to nitrosamines [N-nitrosoatrazine]."[63] Both atrazine and N-nitrosoatrazine can damage chromosomes in human blood cells. However, while concentrations of 1 part per million (ppm) of atrazine caused damage, much lower levels (0.1 ppb) of N-nitroso atrazine caused damage.[63] N-nitrosoatrazine was also "strongly mutagenic" in hamster cells.[64]

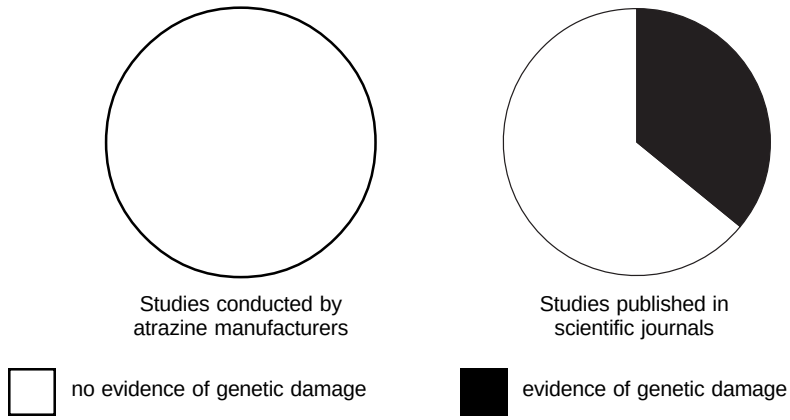
EPA also omitted consideration of synergistic effects with other herbicides. In a study in which human blood cells were exposed to low concentrations of linuron and atrazine (individually and together), both atrazine (at 1 ppb) and linuron (at 1 ppm) increased the frequency of broken chromosomes, but not significantly. The combination, at lower concentrations (0.5 ppm of linuron and 0.5 ppb of atrazine), caused a significant increase in broken chromosomes.[65] A study of chromosome breaks in the bone marrow cells of mice drinking water containing atrazine and/or the herbicide alachlor had similar results. Neither atrazine and alachlor alone (at concentrations of 20 ppm) caused chromosome damage, but the combination (10 ppm of each) did.[66] Like atrazine, alachlor is a common water contaminant.[5]

> "One study compares a commercial atrazine product with atrazine alone. In this study, the commercial product caused about twice as many mutations as did atrazine."

Although tests on cells from humans or other mammals should be most relevant to human hazards, EPA has given little consideration to the type of organism used in the mutagenicity studies they evaluated. In the tests using bacteria and yeast, only a few (5/23) were positive (showed genetic damage). However, in the tests using cells from humans or rodents a much larger proportion (10/23) were positive.[52] An older (1980) review for the European Community of a smaller number of studies also noted that the type of organism was important: most positive results in this review were in mammals and in whole-animal rather than cell culture tests.[67]

Finally, the differences between data provided EPA by atrazine manufacturers and data available in the published scientific literature are striking. A review published by EPA in 1993 found that all of the 8 studies submitted for registration purposes were negative, but 14 out of 39 published studies were positive.[68] (See Figure 7.)

Figure 7
Comparing the Results of Mutagenicity Studies Conducted by Atrazine Manufacturers and Published Studies



Source:
Dearfield, K.L., et al. 1993. A survey of EPA/OPP and open literature data on selected pesticide chemicals tested for mutagenicity. *Mut. Res.* 297:197-233.

An 1993 EPA review of atrazine mutagenicity studies found that while studies conducted by atrazine manufacturers showed no evidence of genetic damage, many (14/39) studies published in scientific journals found that atrazine did cause genetic damage,

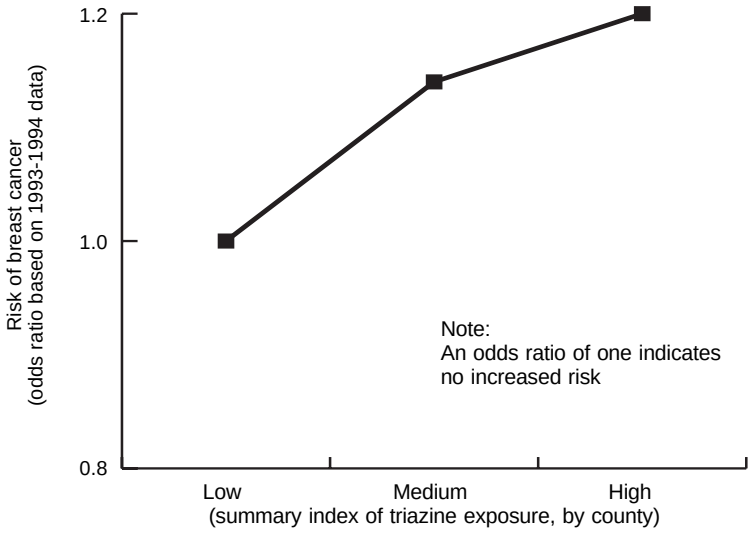
Supporting evidence for the mutagenicity of atrazine comes from a study of a protein called p53 in rats fed relatively low doses of atrazine (2.7 mg/kg per day). This protein plays a central role in "DNA repair and survival after DNA damage." (DNA is the molecule from which genetic material is made.) The percentage of blood cells containing the p53 protein increased dramatically (about 20-fold) in the animals that were fed atrazine.[69]

Carcinogenicity

Whether or not atrazine is carcinogenic (causes cancer) is a controversial subject that has been studied in both people and laboratory animals. Studies of exposed farmers and farmworkers that have demonstrated an association between atrazine exposure and cancer include the following:

- Researchers from the Italian National Cancer Institute studied the association between triazine use and ovarian cancer in women corn farmers. They found that women who applied triazines, or cultivated fields where triazines had been used, were more than twice as likely to have ovarian cancer as unexposed women.[70]
- Researchers from the University of Kentucky studied the association between the incidence of breast cancer in Kentucky and a composite measure of triazine exposure. (The index was based on well and drinking water contamination data, acreage of corn production, and estimates of triazine use.) The study found that breast cancer risk was higher (1.1-1.2-fold) in counties with medium and high levels of triazine exposure than it was in counties with low exposure.[71] (See Figure 8.)
- The Cancer Registry of Central California looked at correlations between atrazine use in California (by county) and the incidence of six types of cancer. The study found that for Hispanic males, the incidence of leukemia was associated with the use of atrazine. For black men, the incidence of brain and testicular cancer was associated with the use of atrazine.[72]
- Researchers from the University of Prince Edward Island and the University of Guelph studied associations between atrazine contamination of wells and drinking water and the incidence of six types of cancer in Ontario, Canada. They found the incidence of stomach cancer in both males and females increased with increasing atrazine water contamination.[73]

Figure 8
Triazine Water Contamination and Breast Cancer in Kentucky



Source:
Kettles, M.A. et al. 1997. Triazine herbicide exposure and breast cancer incidence: an ecologic study of Kentucky counties. *Environ. Health Persp.* 105: 1222-1227.

Breast cancer risk is increased in Kentucky counties where triazine-contaminated water is common.

Atrazine has caused cancer in the following laboratory studies:

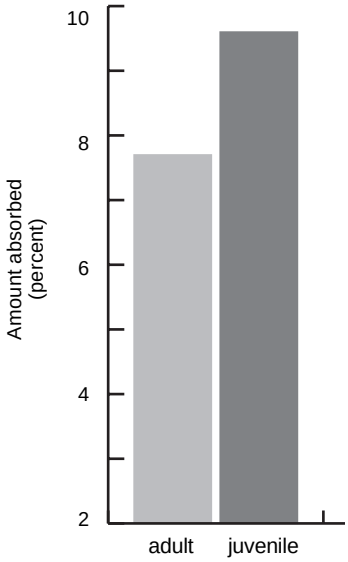
- In the Sprague-Dawley strain of laboratory rats, atrazine caused breast tumors in females.[74]
- In the F344 strain of rats, atrazine caused breast tumors in males. In females, atrazine caused cancers of the uterus, leukemia, and lymphoma.[75] (Another study of F344 rats, submitted as part of atrazine's registration found no increases in tumors or cancer.[74])

One final laboratory study is not a standard carcinogenicity study but rather a study of cancer-causing mechanisms. In this study, using cell cultures from rat intestines and human colons, atrazine caused cells to proliferate, to increase in number. Human cells were more sensitive to atrazine than rat cells. Proliferation of colon or intestinal cells is part of the development of colon or intestinal cancer.[76]

EPA's evaluation of these studies concluded that atrazine is "not likely to be carcinogenic in humans." With respect to the studies of exposed people, the agency stated that "there is no supporting evidence or a sound argument of biological plausibility that these cancers may result from exposure to atrazine. Also, the lack of confirming studies indicates that the human investigations by themselves do not make a strong case for an association between atrazine exposure and human cancer."[77]

With respect to the laboratory studies, EPA concluded, based on detailed studies, that "it is unlikely that atrazine's mode of cancer action in SD [Sprague-Dawley] rats is operative in humans." The agency believes that atrazine causes cancer in Sprague-Dawley rats by weakening surges of luteinizing hormone (See "Effects on Hormones," p. 14). This initiates the equivalent of menopause earlier than it occurs in unexposed rats. During "menopause" in the Sprague-Dawley

Figure 9
Absorption of Atrazine through Juvenile and Adult Skin



Source:
Shah, P.V. et al. 1987. Comparison of the penetration of 14 pesticides through the skin of young and adult rats. *J. Toxicol. Environ. Health* 21: 353-366.

Skin of juvenile laboratory animals absorbs more atrazine than adult skin. This suggests that children may be particularly at risk from activities that bring their skin into contact with atrazine, such as taking a shower in contaminated water.

rat, levels of the hormone estrogen are high, which causes breast tumors. In humans, menopause causes low levels of estrogen, so that the Sprague-Dawley rat results are not relevant.[77]

EPA's analysis leaves a critical question unanswered: if the hormonal effects of atrazine that cause breast cancer in Sprague-Dawley rats do not occur in humans, what is the effect on humans of this compound which appears to cause such significant disruption of hormone systems? What experiments can answer this question? Before giving atrazine a "not likely" cancer classification, shouldn't EPA find out what the effects in humans are likely to be? The International Agency for Research on Cancer (IARC) evaluated essentially the same set of studies and concluded that "atrazine is not classifiable as to its carcinogenicity to humans,"[78] leaving the door open for further studies. NCAP believes that IARC's conclusion is more appropriate and more protective of human health than EPA's conclusion.

Special Susceptibility of Children

Atrazine may pose particular hazards to children, not only because of the effects on reproduction and development identified above, but because they are more exposed to this herbicide. A laboratory study conducted by EPA researchers found that absorption of atrazine through the skin was greater for juveniles than for adults.[79] (See Figure 9.) This is the kind of exposure that might occur if, for example, a child bathed in atrazine-contaminated water.

The same study also showed that a higher proportion of the atrazine was absorbed when low concentrations of atrazine touched the skin, as opposed to medium or high concentrations.[79]

Children are also exposed to more atrazine than adults because, for their size, they drink more water than adults. According to EPA's standard estimates for water consumption children's consumption is 126 percent of an adult male, and infants' consumption is 540 percent of an adult male.[80]

Synergy

Synergy occurs when the combination of two chemicals is more toxic than either chemical alone. In terms of acute toxicity, atrazine is synergistic with a common class of insecticides, the organophosphates. A study using fruit flies as a test animal found that atrazine was synergistic with the organophosphate insecticides parathion, diazinon, dyfonate, and phorate.[81] A second study, using aquatic midges as a test animal, found that atrazine was synergistic with the organophosphates trichlorfon, malathion, chlorpyrifos, and methyl-parathion.[82]

An insecticide in another chemical family, carbofuran, was also synergistically toxic with atrazine to fruit flies.[81]

Atrazine can also act synergistically with respect to effects other than acute toxicity. As mentioned above (see "Mutagenicity," p. 17), atrazine causes more genetic damage in combination with other herbicides than it does alone. Another example concerns dinitrotoluene, a chemical that is transformed in the intestine of laboratory animals into carcinogenic and mutagenic compounds. Exposure to atrazine increased the formation of these mutagenic molecules.[83]

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● HERBICIDE FACTSHEET

ATRAZINE: ENVIRONMENTAL CONTAMINATION AND ECOLOGICAL EFFECTS

Atrazine, one of the two most commonly used agricultural pesticides in the U.S., is a pervasive water contaminant. It is typically the most common pesticide found in rivers, streams, and groundwater. The U.S. Geological Survey's (USGS's) recent national monitoring study found atrazine in rivers and streams, as well as groundwater, in all 36 of the river basins that the agency studied. It is also often found in air and rain; USGS found that atrazine was detected in rain at nearly every location tested. Atrazine in air or rain can travel long distances from application sites.

In lakes and groundwater, atrazine and its breakdown products are persistent, and can persist for decades. In soils, it is also persistent. Half lives (the amount of time required for 50 percent the atrazine applied to disappear) can be over 100 days in surface layers of soils. Below the surface, atrazine can persist for years.

Low concentrations of atrazine cause a variety of adverse effects in fish, including reduced sperm production, disruptions of normal behavior, kidney damage, and decreased ability to withstand warm temperatures.

The hormone systems of both amphibians and alligators are disrupted by atrazine.

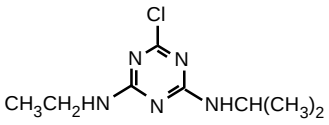
Atrazine causes genetic damage in a variety of plant species, including corn and sorghum (on which it is commonly used). Atrazine also stimulates fungi that cause plant diseases, including the common root rot *Fusarium*.

Atrazine can damage natural communities. For example, in a pond community, atrazine (at a concentration of 20 parts per billion) caused reductions in populations of aquatic plants, aquatic insects, and the fish that feed on them. Simulated drift of atrazine (at 8 percent of typical application rates) modified the abundance and dominance of winter annuals in a Pacific Northwest plant community and also reduced its productivity.

BY CAROLINE COX

The herbicide atrazine (Figure 1) is "one of the two most widely used agricultural pesticides in the U.S."[1] according to the U.S. Environmental Protection Agency (EPA). It is primarily used on corn, sorghum, and sugar cane.[1] This article summarizes research about its contamination of the environment and its ecological hazards; an earlier article discussed its toxicology (JPR 21(2):12-20). The first ten sections of this article discuss aquatic ecosystems, where atrazine is a pervasive contaminant. The last six sections, beginning on p.17, discuss terrestrial ecosystems.

Figure 1
Atrazine



2-chloro-4-ethylamino-6-isopropylamino-s-triazine

Contamination of Rivers and Streams

Atrazine frequently contaminates rivers and streams, according to the U.S. Geological Survey's (USGS's) National Water-Quality Assessment Program (NAWQA) begun in 1991. USGS has compiled data from the first 20 river basins studied by NAWQA and the summary paints a startling picture of atrazine contamination.[2] Atrazine was the most commonly detected pesticide in river basins from all three land uses studied (agricultural, urban, and mixed), and the atrazine breakdown product deethylatrazine was also commonly found. In agricultural basins, USGS found atrazine in about two-thirds of the samples tested. In urban basins, USGS found atrazine in 70 percent of the samples. In major rivers with mixed land uses, USGS found atrazine in 80 percent of the samples. Concentrations were as high as 120 parts per billion (ppb) in agricultural basins, 14 ppb in urban basins, and 22 ppb in river basins with mixed land uses.[2] At both agricultural and mixed land use sites, concentrations were close to or exceeded the U.S. drinking water standard of 3 ppb in about 5 percent of the samples.[3]

For information about contamination of a particular river basin, the NAWQA web site is an excellent resource: http://water.usgs.gov/pubs/nawqasum.

NAWQA and other studies document important patterns in atrazine's contamination of rivers and streams:

- Atrazine contamination is not geographically restricted. It is common in the midwestern "Corn Belt" where use is widespread, but rivers and streams from all 36 basins that have

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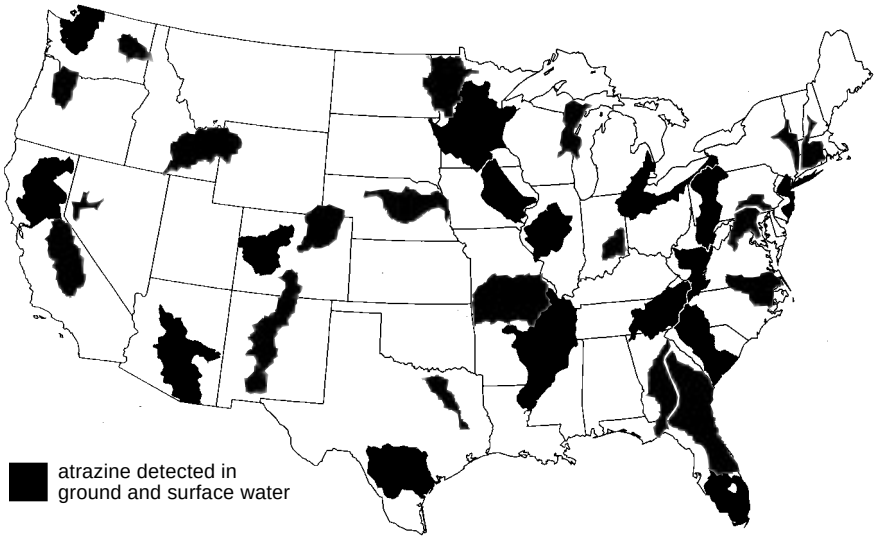
been studied by NAWQA are contaminated.[4] (See Figure 2.) Contamination is common in locations as diverse as Oregon's Willamette Valley,[5] south-central Texas,[6] Denver, Colorado,[7] and New York's Hudson River.[8]

- Highest atrazine concentrations are found in rivers and streams when there is rain following spring atrazine applications to agricultural land. These pulses of atrazine can exceed the drinking water standard set by EPA and are not removed by conventional water treatment.[9] For example, the cities of Lincoln and Omaha, Nebraska, draw their water from wells that are "hydraulically connected" (located near and using the same water) to the Platte River at Louisville, Nebraska. USGS found atrazine above EPA's drinking water standard in one third of the samples of river water from Louisville.[10]
- However, atrazine is often found year round, although concentrations are lower than they are during the spring.[7,11] Atrazine found during other seasons probably enters the river from contaminated groundwater. This contamination can originate at "some distance from the river."[11]
- Heavy rainfall and full streams lead to the highest pulse concentrations of atrazine, indicating that it is "a readily available constituent in the watershed that is being washed off in proportion to the amount of excess rainfall (runoff)."[12] Smaller rivers have larger and more abrupt pulses, while in large rivers, elevated concentrations can be spread out over several months.[13]
- There is not a simple relationship between atrazine use and levels found in rivers and streams. USGS scientists recently summarized atrazine loads in the Mississippi River between 1975 and 1997. While atrazine use in this basin declined during this period (from 38,000 to 25,000 tons), atrazine loads in the river did not decrease.[14] In smaller rivers and streams, however, and over a shorter time period (1989-1994), USGS found significant decreases in concentration even though use had declined only slightly. One possible explanation is that restrictions in atrazine use were implemented at this time.[15]
- Atrazine contamination of water is not restricted to areas downstream from where it is used. For example, British researchers who intensively studied a small watershed concluded that "atrazine was found at relatively high concentrations when it had not been applied to any of the fields draining to the sampling point."[16]

Figure 2
Contamination of Water (Rivers, Streams, and Groundwater) in the U.S.



Source: U.S. Geological Survey. National Water-Quality Assessment (NAWQA) Program. 1998-2000. Circulars 1144,1150, 1151, 1155-1171, 1201-1216. http://water.usgs.gov/pubs/nawqasum/.

The U.S. Geological Survey found atrazine in both surface water (rivers and streams) and in groundwater in all 36 river basins that the agency has studied.

Contamination of Groundwater

Atrazine commonly contaminates groundwater. It has been found in the groundwater of all 36 river basins studied by USGS.[4] Atrazine was often the most common pesticide detected. Deethylatrazine, formed when atrazine breaks down, was also common. About one-third of the agricultural well samples were contaminated with atrazine in the first 20 basins studied, as were about 15 percent of the urban samples and 10 percent of the samples from mixed use basins.[2]

For results of USGS monitoring for a particular river basin, the NAWQA web site is an excellent resource: http://water.usgs.gov/pubs/nawqasum.

Important reasons for atrazine's presence in ground water are its widespread use and long persistence.[17]

Reducing atrazine use can reduce groundwater contamination. For example, atrazine use in Iowa declined by 12 percent between the mid-1980s and the early 1990s. Over the same interval, the frequency of atrazine-contaminated wells declined 14 percent.[18]

As with rivers and streams, atrazine has contaminated groundwater in areas where it has not used nearby. Researchers from Environment Canada studying prairie springs found atrazine when "it was not used anywhere in the vicinity of the aquifers."[19] They suggest that transport in the atmosphere is the most likely source.[19]

Contamination of Rain

Atrazine is commonly found in rain. A USGS compilation of national, multistate, state, and local monitoring

studies showed that atrazine was found at nearly every site where rainfall was collected.[20] (See Figure 3.) In some cases, concentrations in rain are above drinking water standards.[21] The amount of atrazine deposited in rain can be large. For example, USGS calculates that the rain deposits 110,000 kilograms of atrazine in the Mississippi River basin every year, over one-third as much as is carried annually by the river.[22] Rain also can be a significant source of atrazine in the ocean: University of South Carolina researchers calculated that a two or three day rainstorm deposited atrazine along the South Carolina coast equal to 10 percent of the amount deposited annually by rivers.[23] Rain can carry atrazine long distances; for example, atrazine is deposited in rain in the remote Isle Royale National Park in Lake Superior.[24] Atrazine has also been found in fog in California.[25]

Persistence in Lakes and Ponds

According to EPA, atrazine "should be somewhat persistent"[26] in lakes or other water bodies with still water. In fact "somewhat persistent" may be an understatement. For example, USGS scientists estimate that persistence in deep lakes "may exceed 10 years"[24] and calculated that breakdown of atrazine in Lake Superior is "very slow (about 1 percent per year)."[27] Swiss scientists came to similar conclusions after studying a group of lakes: a small amount of atrazine degraded during the summer, otherwise the only losses of atrazine were by flushing. In 1989, Switzerland instituted "drastic application restrictions" for atrazine, but the amount of atrazine in the lakes did not decrease through 1994.[28]

Persistence in ponds is less, but still significant. German researchers found, for example, that the atrazine concentration in experimental ponds in April was over half what it had been the previous September, immediately after addition of atrazine.[29]

Persistence in Groundwater

Atrazine is persistent in groundwater. For example, in a laboratory study, the half life for atrazine in groundwater sediments was almost 6 years[30] and a two month study "did not show a significant decrease"[31] in atrazine concentrations. In Delaware, USGS researchers estimated that the atrazine breakdown product deethylatrazine persisted for 25 years.[32]

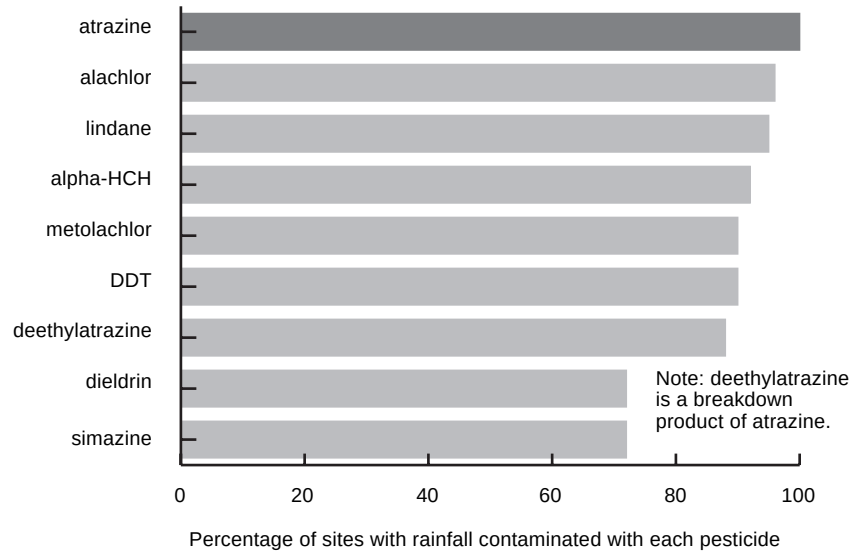
Effects on Fish

In laboratory studies, atrazine has a wide variety of effects on hormone systems. (See JPR 21(2):14-15.) Such effects can also occur in fish. For example, the startlingly low concentration of 0.04 ppb reduced the release of a sex hormone from testes cells in Atlantic salmon and reduced their milt (sperm) production by about 50 percent, according to a study by British fisheries biologists.[33] (See Figure 4.)

A USGS study of fish from 11 river basins nationwide had similar results.[34] The researchers found a striking relationship between pesticide contamination of river water and the ratio of the "female" sex hormone to the "male" sex hormone in fish. (Quotes indicate that both hormones are found in animals of both genders.) In female fish, levels of a "female" hormone are normally 4 times higher than levels of a "male" hormone, but this ratio declined at higher pesticide concentrations. At the highest pesticide concentrations (2.9 ppb), amounts of the two hormones were equal, as is typical for male fish from uncontaminated water. The steepest decline in the hormone ratio occurred at concentrations less than 1 ppb. USGS says that data are "not sufficient to determine which specific pesticides or groups of pesticides could be responsible."[34] However, atrazine appears to be important. For example, in the Platte River at Louisville, Nebraska, the site with the highest dissolved pesticide concentrations, atrazine was found in every sample, with peaks above 20 ppb.[35]

Effects on fish behavior have been observed when they are exposed to extremely low concentrations of atrazine. At a concentration of 0.5 ppb, the behavior of goldfish was affected: researchers observed more "burst swimming," a sudden spurt of non-directed movement, followed by

Figure 3
Atrazine in Rain



Source: Majewski, M.S. and P.D. Capel. 1995. *Pesticides in the atmosphere: Distribution, trends, and governing factors.* Chelsea, MI: Ann Arbor Press, Inc. Pp.78-80.

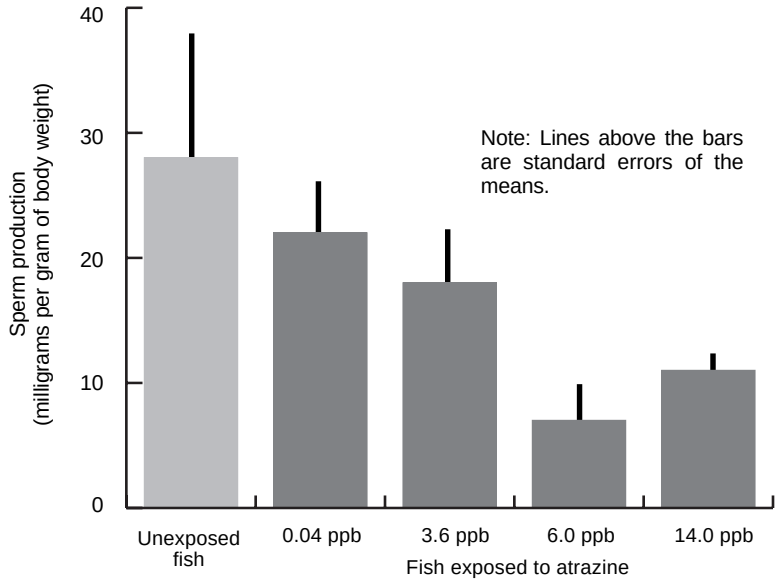
The USGS compiled national, multistate, state, and local studies of pesticide contamination of rain. Atrazine was the most common pesticide the agency detected and was found at almost every site.

immobilization of the fish. Burst swimming is a part of the normal alarm reaction of goldfish, but when this behavior occurs frequently, it "can increase the vulnerability of fish to predation."[36] At a concentration of 1 ppb, reproductive behaviors are disrupted. Male salmon normally respond to the smell of urine from female salmon that have recently laid eggs. However, atrazine (1 ppb) reduces this response.[37]

At slightly higher concentrations, other effects occur. Stress (measured by an increase in blood protein) occurred in rainbow trout at a concentration of 3 ppb.[38] At 5 ppb, Goldfishes' grouping behavior decreased,[36] swimming behavior of zebrafish was altered,[39] and kidney damage occurred in rainbow trout.[40] At 10 ppb, the ability of shiners to withstand warm temperatures decreased[41] and trout kidneys were damaged.[42]

Significant effects on reproduction of fish can occur at slightly higher atrazine concentrations. The number of offspring produced by bluegill sunfish was over 90 percent less in ponds treated with 20 ppb of an atrazine herbicide than in untreated ponds. The small number of offspring produced was related to the lack of prey for the bluegills. Atrazine killed the aquatic plants in the ponds, and greatly reduced the number of insects available as food. Bluegill in the treated ponds had less than 20 percent as much prey in their stomachs as did fish in untreated ponds. The numbers of mayflies, dragonflies, and beetles were particularly reduced. (20 ppb was the lowest concentration tested in this study.)[43] A similar experiment, lasting three years instead of four months, had similar results.[44]

Figure 4
Atrazine Decreases Sperm Production in Salmon



Source: Moore, A. and C.P. Waring. 1998. Mechanistic effects of a triazine pesticide on reproductive endocrine function in mature male Atlantic salmon (*Salmo salar* L.) parr. *Pest. Biochem. Physiol.* 62:41-50.

Atlantic salmon exposed to low concentrations of atrazine (as low as 40 parts per trillion) produced less sperm than unexposed fish. Researchers initiated sperm production by exposing the fish to urine from female fish who had been laying eggs.

Effects on Snails

Researchers from the University of Barcelona showed that freshwater snails searched for algae at a higher speed in streams treated with 15 ppb atrazine than they did in untreated streams. The snails in treated streams also had different searching patterns.[45]

Effects on Amphibians

Two studies have documented effects of atrazine on amphibians at relatively low concentrations. A study conducted by scientists at the University of Mississippi found that concentrations of 20 ppb increased mortality of tadpoles of the frog *Hyla chrysoscelis*.[46] A USGS study of larval tiger salamanders found that 75 ppb of atrazine caused blood levels of one growth hormone (thyroxine) to rise and another (corticosterone) to decrease. The result was to slow down the salamanders' metamorphosis.[47]

Effects on Alligators

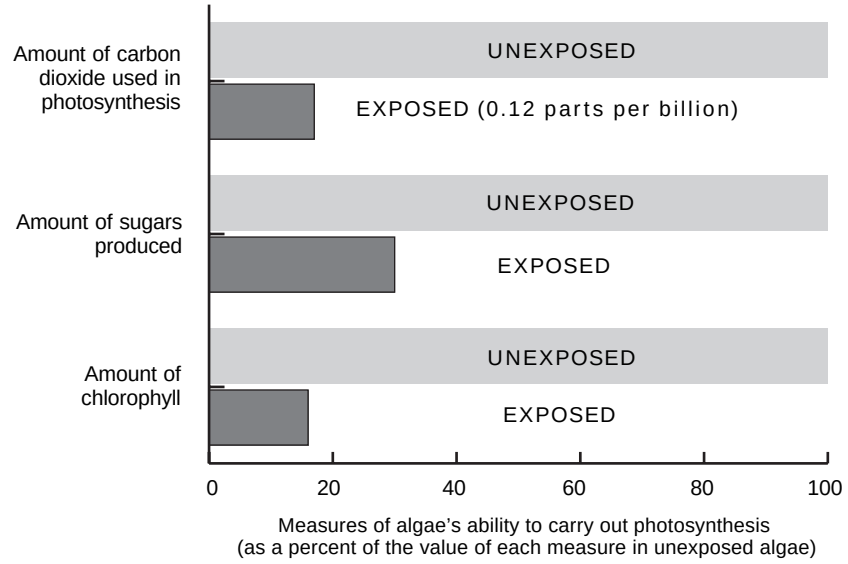
Intensive studies over the last decade have evaluated the effects of hormone-disrupting pollutants on Florida alligators. Atrazine, because it is a frequent water contaminant was included in some of these studies. Led by a zoologist from the University of Florida, these studies showed that atrazine inhibited activity of two hormones, one related to estrogen and one related to progesterone, in female alligator oviduct.[48] In addition, atrazine increased the activity of an enzyme that converts "male" sex hormones into "female" ones. The activity of this enzyme in male hatchlings from eggs treated with atrazine was intermediate between that typically found in males and that typically found in females.[49]

Effects on Aquatic Arthropods

Concentrations of 20 ppb caused dramatic declines in the abundance and diversity of plant-eating insects in experimental ponds in a study conducted at the University of Kansas. The number of adult insects emerging from the treated ponds was almost 90 percent less than emergence in untreated ponds, and diversity was almost 60 percent less.[50]

Much lower concentrations (0.1 and 1.0 ppb) caused declines in the population of water fleas in experiments conducted at a lake in northern Germany. In enclosures treated with atrazine, the populations of water fleas were less than 1/10 of the populations in untreated enclosures.[51] In an-

Figure 5
Low Concentrations of Atrazine Reduce Photosynthesis by Marine Algae



Source: Bester, K. et al. 1995. Biological effects of triazine herbicide contamination on marine phytoplankton. *Arch. Environ. Contam. Toxicol.* 29:277-283.

Exposure of North Sea algae to extremely low concentrations (0.12 ppb) of atrazine caused a decrease in the ability of the algae to photosynthesize. Triazine herbicides are typically found in the German Bight, part of the North Sea, at this concentration.

other experiment with water fleas, concentrations of 5 ppb during development skewed the sex ratio so that more males than expected were born.[52]

Effects on Algae

An expert panel convened by Ciba Crop Protection, atrazine's major U.S. manufacturer, to look at ecological risks of atrazine concluded that algae were "the most sensitive organisms"[53] but recovered quickly or reestablished so that "ecologically important"[53] effects required concentrations above 50 ppb.[53] However, a variety of studies have documented effects well below 50 ppb. Examples include the following:

- German scientists measured reductions in photosynthesis and productivity of marine algae at 120 parts per *trillion* (0.12 ppb), a concentration at which triazines are often found in the North Sea.[54] (See Figure 5.)
- French scientists found that 2 ppb of atrazine changed the abundance of the dominant algae species in experimental ponds.[55] This team of researchers also showed that 10 ppb inhibited the growth of the blue-green algae in the spring but stimulated growth during the summer.[56]
- British and Belgian biologists found that concentrations of atrazine above 3 ppb reduced chlorophyll levels in algae in experimental streams and concentrations above 11 ppb reduced the amount of algae.[57]
- German scientists measured almost a 25 percent reduction in photosynthesis in a freshwater green algae exposed to 12 ppb of atrazine.[58]
- Biologists from the University of Nebraska found that 12 ppb of atrazine reduced the amount of algae in experimental streams.[59]
- A study conducted by EPA researchers in experimental Minnesota wetlands found that algae exposed to 15 ppb were less productive than algae is untreated wetlands. This decrease in productivity led to a decrease in the amount of nutrients taken up by the algae.[60]
- Another team of German scientists showed that 20 ppb of atrazine reduced the abundance of algae in experimental ponds.[61]

All of these studies take on increased significance because of other studies which document the conditions under which atrazine is most toxic to algae. One such study was conducted by scientists from the University of Nebraska and the U.S. Fish and Wildlife Service. The study showed that a species of algae from the Platte River (Nebraska) exposed to chronic atrazine contamination at low levels (1 ppb) was more susceptible than unexposed algae to pulses of higher concentrations such as commonly occur in the spring and early summer. The researchers commented on the "important environmental implications" of these findings because their exposure scenarios mimicked those found in the Platte River.[62] A second study (by the French researchers mentioned above) showed that algae communities are most sensitive to atrazine in the early summer.[63] A third study (by researchers at Western Illinois University) found that low concentrations of the insecticide malathion increased the toxicity of atrazine to algae.[64] Malathion is one of the most frequently detected insecticides in rivers and streams.[2]

Effects on Aquatic Plants

The Ciba expert panel mentioned above also considered the effect of atrazine on aquatic plants and concluded "atrazine concentrations of 20 µg/L [ppb] result in little or no adverse effects on the function of aquatic plant communities."[53] However, a variety of studies have documented effects at or below 20 ppb. Examples include the following:

- Researchers from the University of Ulm (Germany) showed that 2 ppb of atrazine decreased photosynthesis of a water moss to about 10 percent of that in unexposed plants.[65]
- A biologist from the University of Sydney (Australia) found that 10 ppb of atrazine caused a decrease in photosynthesis of a seagrass.[66]
- Smithsonian Institution scientists measured 50 percent mortality and reduced reproduction of wild celery exposed to 12 ppb of atrazine.[67]

- Researchers from the University of Kansas showed that concentrations of 20 ppb reduced the growth and abundance of aquatic plants in experimental ponds.[44]

Effects on Aquatic Ecosystems

The effects on individual species summarized above can have special impacts on entire aquatic communities. For example, in the study of water fleas (see pp. 15-16), researchers found that populations declined after treatment with very low concentrations of atrazine (0.1 and 1.0 ppb), only when the entire community was studied. The population decline was caused because the water fleas did not have enough food to produce eggs. However, tests with the water flea alone, or with the water flea together with an algae that is an important food source, showed effects only at much higher concentrations. Including competitors and predators is a likely reason for the increased sensitivity of the experiment with natural communities.[51]

Similar complex interactions were found in a University of Kansas experiment that used experimental ponds to mimic natural communities. Decreases in aquatic plants led to decreases in the insects and tadpoles that use the plants for food and shelter, and then to decreases in the number of fish which feed on the insects. The authors of the study concluded that "a whole ecosystem can produce or experience effects of the chemical, or lack of effects, that are difficult to identify when only a portion of the ecosystem is used for the assessment."[44]

Contamination of Air

Atrazine is often found in air. Monitoring studies have found atrazine in air both near areas where the herbicide has been used in corn or sorghum production[68-71] as well as in areas distant from atrazine use. Examples of remote locations where atrazine has contaminated air samples include the Bering Sea[72] and the southern shore of Lake Superior.[71] (See Figure 6.)

Persistence in Soil

The results of field studies measuring atrazine's half-life vary widely as is the case with many pesticides. (The half-life is the time taken for 50 percent of the atrazine applied to disappear, including leaching, runoff, break down, and vaporization.) The shortest half-life in one compilation by the U.S. Department of Agriculture (USDA) is 13 days, and the longest is 173 days.[73] Another USDA compilation for just the north central U.S. reviews studies with half-lives between 14 and 109 days.[74]

These relatively long half-lives mean that significant amounts of atrazine persist for more than a year. For example, French scientists intensively studied the fate of atrazine in the upper meter of soil in a corn field on an experimental farm, with applications rates approximately 1 kilogram per hectare (0.9 pounds/acre). They found that about 40 percent persisted from one year until the next.[75] USDA researchers found that residues of atrazine persisted for two years after treatment in an Iowa corn-soybean farm.[76]

In certain types of soils, atrazine can be particularly persistent. Danish researchers found that soil from a freshwater wetland was unable to completely break down atrazine.[77] Because of atrazine's long persistence in wetlands, USDA and Clemson University scientists calculated that a wetland buffer would have to be at least 100 meters (325 feet) wide in order to mitigate atrazine-contaminated runoff.[78]

Subsurface soils break down atrazine only slowly: For example, atrazine persisted almost 3 years in soil 150 cm (5 ft.) below the surface of a University of Arkansas experimental farm.[79] Subsoil beneath an industrial area where atrazine had been applied for 20 years leached atrazine 8 years after the last application was made.[80]

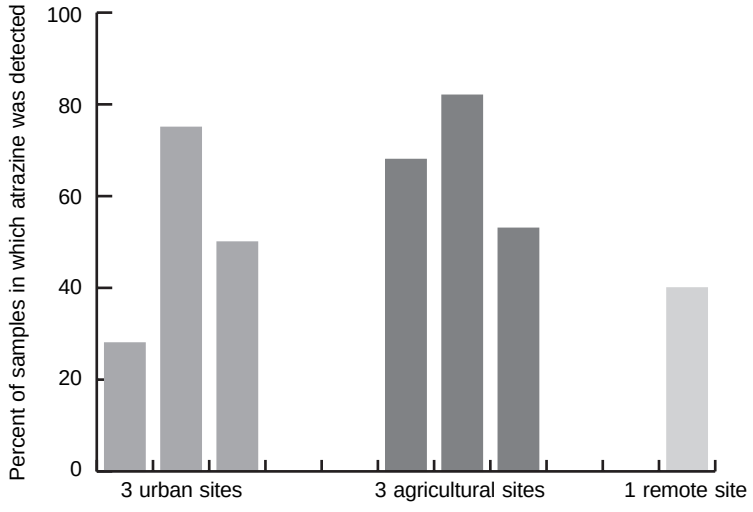
Effects on Earthworms

A study conducted by researchers from a Hungarian university showed that earthworms living in soil treated with an atrazine herbicide grew more slowly and reproduced less than earthworms living in untreated soil.[81]

Effects on Insects

As an herbicide, it is perhaps surprising that atrazine has adverse effects on insects. However, atrazine can cause genetic damage in insects, kill beneficial insects, and increase the

Figure 6
Atrazine in Air



Source: Foreman, W.T. et al. 2000. Pesticides in the atmosphere of the Mississippi River Valley, part II—air. *Sci. Tot. Environ.* 248:213-226.

A study of air along the Mississippi River found atrazine contamination was widespread; it occurred in both urban and rural air as well as in air from a remote site near Lake Superior.

potency of insecticides.

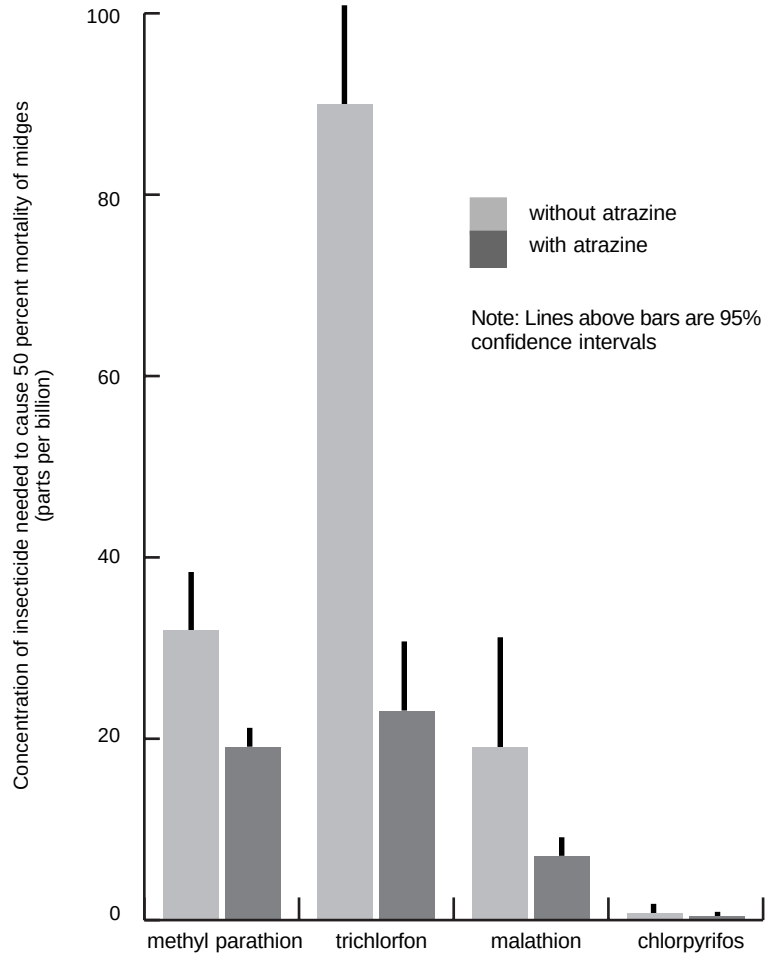
- **Genetic damage:** According to studies conducted at Berhampur University (India) and Western Illinois University, atrazine, both alone[82] and in a commercial product,[83] caused sex-linked lethal mutations in fruitflies.
- **Beneficial insects:** Insects that kill agricultural pests are often called beneficial insects. Atrazine herbicides can kill some species of these insects. For example, the International Organization for Biological Control found that the atrazine herbicide Gesaprim 50 caused over 99 percent mortality of a predatory beetle and over 50 percent mortality of both a parasitoid wasp and a predatory fly. In the field portion of this study, only mites, a relative of insects and spiders, were tested, but the atrazine herbicide caused over 50 percent mortality of one of the two predatory species tested.[84] Another study found effects on soil insects in an experimental corn field after atrazine treatment. Populations of springtails, immature beetles, and immature flies were reduced over 50 percent four months after treatment.[85]
- **Synergy:** Synergy occurs when the potency of two compounds mixed together is greater than the sum of their individual potencies. Atrazine synergistically increases the toxicity of insecticides in the organophosphate chemical family, including malathion, methyl parathion, and chlorpyrifos, as well as DDT, a notorious chlorinated hydrocarbon.[86,87] (See Figure 7.) Atrazine and insecticides are frequently found together in urban streams.[88]

Effects on Terrestrial Plants

As an herbicide, by definition atrazine is acutely toxic to most plants. However, atrazine also has other kinds of important effects on plants including the ability to cause genetic damage and the ability to stimulate disease-causing fungi.

- **Genetic damage:** Some of the early research done concerning atrazine's ability to cause genetic damage was done with sorghum, a crop on which atrazine is often used. Two studies done at Kansas State University showed that atrazine, applied at typical agricultural rates, caused chromosome abnormalities.[89,90] Researchers from the University of Illinois and Hope College (Illinois) found similar results in experiments with corn: applications of a commercial atrazine product at a typical agricultural rate doubled the frequency of a mutation in pollen grains.[91] Laboratory studies have shown that atrazine also can cause genetic damage in onions, vetch,[92] barley,[93,94] and *Tradescantia* (spiderwort).[95]
- **Diseases:** Research showing that atrazine can stimulate disease-causing fungi dates from the 1960s and 1970s. Researchers from Auburn University showed that concentrations of atrazine about two times what would be expected under typical rates of use stimulated the growth of *Sclerotium rolfsii*, a "destructive" fungi that parasitizes plant roots.[96] Researchers from Michigan State University showed that atrazine increased the abundance of root rot

Figure 7
Synergistic Toxicity of Atrazine and Insecticides



Source: Pape-Lindstrom, P.A. and M.J. Lydy. 1997. Synergistic toxicity of atrazine and organophosphate insecticides contravenes the response addition mixture model. *Environ. Toxicol. Chem.* 16: 2415-2410.

Atrazine increases the toxicity (lowers the lethal concentration) of common insecticides to a midge, *Chironomus tetans*, that is an important part of aquatic food webs.

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(*Fusarium*) in soil. Concentrations of 5 parts per million (ppm), about what would be expected under typical application rates, caused approximately a 2.5-fold increase in the number of root rot spores. A field study had similar results.[97] Researchers at Pennsylvania State University showed that atrazine treatment (1 and 5 ppm) of a corn variety that is resistant to maize dwarf mosaic virus increased the susceptibility of the corn to the virus.[98]

Development of Atrazine Resistance

Several weeds have developed resistance to atrazine; that is, they are not killed by amounts of atrazine that would normally cause mortality. For example, atrazine-resistant strains of the weeds *Chenopodium* and *Amaranthus* were collected from corn fields that had been treated with atrazine for 12 years.[99] Rigid ryegrass developed resistance to atrazine after 5 seasons of use.[100]

Effects on Natural Plant Communities (Terrestrial)

Like all pesticides, if atrazine drifts from the application site, it can impact surrounding areas. An EPA study looked at the effects of airborne atrazine at fractions (8 and 16 percent) of the amounts applied in agriculture in order to document some of these impacts. The study found that atrazine modified the abundance of certain species in a community of Pacific Northwest plants that were winter annuals. The most dominant species was replaced and the community overall was simplified. Community productivity, the amount of plant material produced, decreased.[101] ❧

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