● HERBICIDE FACTSHEET

DIURON

Diuron, commonly sold under the brand names Karmex, Direx, and Diuron, is widely used for vegetation control along rights of way. Other significant uses include weed control in citrus orchards and alfalfa fields.

Exposure to diuron causes formation of methemoglobin, an abnormal form of the oxygen-carrying molecule in blood, hemoglobin. Many diuron herbicides are also irritating to eyes.

The U.S. Environmental Protection Agency classifies diuron as a "known/likely" carcinogen because it has caused bladder cancer, kidney cancer, and breast cancer in studies with laboratory animals.

Diuron has caused genetic damage in developing embryos and in bone marrow cells in mice. It also decreased the production of substances necessary for normal immune system function, and caused reduced birth weights when laboratory animals were exposed during pregnancy.

Diuron is a widespread water contaminant. The U.S. Geological Survey found diuron in about 20 percent of the rivers and streams the agency sampled in its national monitoring program.

An extremely low concentration of diuron, 0.1 parts per billion, reduces photosynthesis by aquatic plants.

Nitrogen-fixing bacteria are affected by the concentration of diuron found in soil after applications made at typical agricultural rates.

BY CAROLINE COX

Diuron (see Figure 1) is an herbicide in the urea chemical family. Related herbicides include linuron and tebuthiuron.[1] Diuron-containing herbicides were first registered for use in the United States in 1966 by E.I duPont de Nemours and Company[2] and are currently sold by a variety of companies including Griffin L.L.C., Dow Agrosciences, and Drexel Chemical Company. Common brand names include Karmex, Direx, and Diuron.[3]

Use

Diuron herbicides are used for complete vegetation control in noncrop areas and selective weed control in certain crops.[3] In California, where pesticide use data are more comprehensive than in other states, major uses of diuron include rights of way (roadsides, utility easements, etc.), citrus, and alfalfa.[4]

Use of diuron in the U.S. totals between 2 and 4 million pounds per year according to U.S. Environmental Protection Agency (EPA) estimates.[5]

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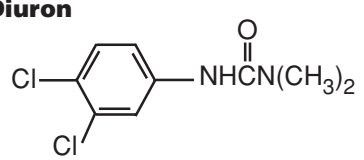
Caroline Cox is NCAP's staff scientist.

Figure 1
Diuron



3-(3,4-dichlorophenyl)-1,1-dimethylurea

Mode of Action

Diuron kills plants by inhibiting photosynthesis, the process by which plants use light, water, and carbon dioxide from the atmosphere to form plant sugars and cellulose. Diuron blocks electron transport at a critical point in this process.[1]

Symptoms of Acute Exposure

Formation of methemoglobin: Exposure to diuron can cause the formation in blood of a molecule called methemoglobin.[6] Methemoglobin is an abnormal form of hemoglobin, the protein in red blood cells that carries oxygen. Methemoglobin occurs when the iron in hemoglobin is "altered so that it does not carry oxygen well,"[7] and can result in bluish skin, weakness, and shortness of breath.[6]

Eye irritation: The label for almost all diuron herbicides states that the product "causes eye irritation" or "causes moderate eye irritation."[3]

Skin irritation: About two-thirds of the diuron products surveyed by NCAP may irritate skin.[3]

Nose and throat irritation: Over half of the diuron products surveyed by NCAP may also irritate the nose and throat.[3]

Symptoms reported by physicians treating exposed patients include burning eyes, headache, shortness of breath, itchy rashes, and nausea.[8]

Effects on the Liver

The liver is a target of diuron toxicity. Researchers from the Industrial Toxicology Research Centre (India) showed that relatively low doses of diuron (equivalent to less than 4 milligrams per kilogram (mg/kg) of body weight)[9,10] caused an increase in liver

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weight (indicating that the "functional load of the organ"[9] had increased) in a laboratory study of rats. They also found an increase in the blood concentration of liver enzymes that are a "sensitive indicator of organ damage."[9]

Effects on the Circulatory System

Diuron causes a startling variety of effects on blood. As mentioned above, it causes the formation of methemoglobin. Researchers at the Chung Sang Medical and Dental College showed that long-term (14 month) exposure of rats to diuron increased the formation of methemoglobin at least 80 percent at all dose levels tested. The same experiment also showed that diuron exposure caused a decrease in the number of red blood cells, an increase in abnormally shaped red blood cells (see Figure 2), a decrease in the hemoglobin concentration, and an increase in the number of white blood cells. All of these effects occurred at all dose levels tested.[11]

Mutagenicity (Ability to Cause Genetic Damage)

The National Institute for Occupational Safety and Health categorizes diuron as a mutagen based on old (1978) studies of mice (including a study of the synthesis of genetic material in the testes) and bacteria.[12,13] Two recent studies support this categorization, a study of dominant lethal mutations and a study of bone marrow abnormalities.[14,15]

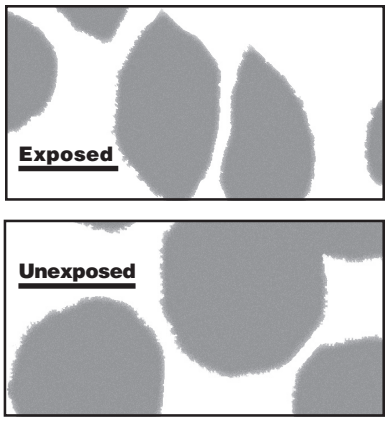
Dominant lethal mutations are genetic damage in sperm that is lethal to the fertilized egg or the developing embryo.[16] Researchers from the Industrial Toxicology Research Centre (India) measured the incidence of dominant lethal mutations in mouse embryos after single exposures or 8-week exposures of male mice to diuron. The study showed that dominant lethal mutations were more frequent in embryos from pregnant females who had mated with exposed males than in females mated with unexposed males.[14]

The same researchers looked at micronuclei formation in mouse bone marrow cells.[15] Micronucleui are small nuclei (the part of the cell in which genetic material is found) that are separate from a cell's normal nucleus. Micronuclei are produced during cell division by lagging chromosomes or chromosome fragments.[17] A single dose of diuron (170 mg/kg) caused a threefold increase in the number of micronuclei in red blood cells in the bone marrow.[15]

Effects on the Immune System

Diuron disrupts the normal functioning of the immune system. Toxicologists at the Free University of Brussels (Belgium) showed that exposure of human white blood cells reduced the production of three molecules that

Figure 2
Diuron Causes "Spindle-shaped" Red Blood Cells



Source: Wang, S.-W. et al. 1993. Haemotoxic effect of phenylurea herbicides in rats: role of haemoglobin-adduct formation in splenic toxicity. *Fd. Chem. Toxic.* 31:285-295.

Diuron exposure caused blood cells to develop into an abnormal shape.

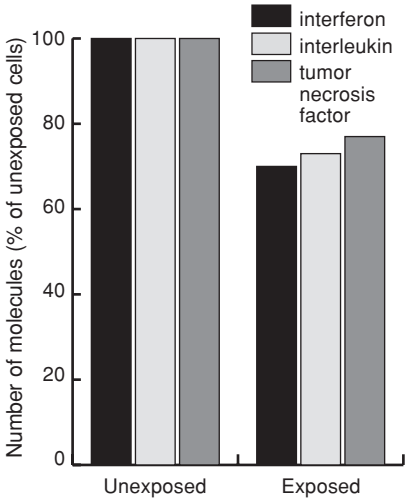
"INERT" INGREDIENTS

Like most pesticides, diuron herbicide products contain ingredients in addition to diuron. Many of these ingredients, according to U.S. pesticide law, are called "inert."[1] Some inert ingredients in diuron products have been identified by the U.S. Environmental Protection Agency (EPA) or on material safety data sheets. These include the following:

- **Sodium salt of lignosulfonic acid** is an ingredient of Karmex DF and Direx 80DF.[2] It is a by-product of the paper making process. Scientists at the University of California, Davis showed that it efficiently prevents sperm from fertilizing eggs. The researchers suggested that it "is a strong candidate for development as a vaginal contraceptive."[3]
- **Ethylene glycol** is an ingredient of Direx 4L, Diuron 4L and Diuron 4L IVM.[4] Commonly used as antifreeze, EPA's summary of its health hazards includes "throat and upper respiratory tract irritation," "kidney toxicity and liver effects," and "increased incidence of fetal malformations."[5]
- **Sodium polyphosphate** is an ingredient of Karmex DF and Direx 80DF.[2] It causes eye irritation, skin irritation, and respiratory irritation. It also can cause nausea, vomiting and diarrhea.[6]
- **Kaolin** (clay) is an ingredient of Karmex DF, Direx 80DF,[2] and Diuron 80DF (IVM).[7] Epidemiologists from the Nofer Institute of Occupational Medicine (Poland) found that occupational exposure to dust containing kaolin increased lung cancer risk.[8]

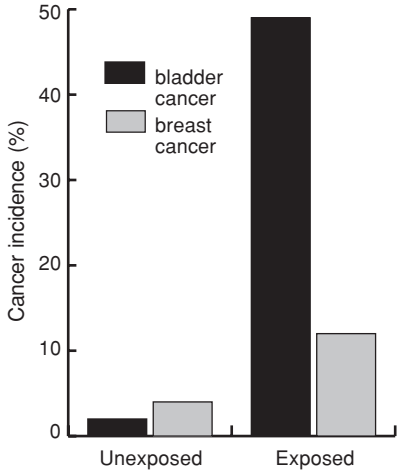
1. Federal Insecticide, Fungicide and Rodenticide Act § 2(a) and 2(m).
2. U.S. EPA .2002. Response to Freedom of Information Act requests 00032-03 and 0736-03.
3. Tollner, T.L. 2002. Lignosulfonic acid blocks in vitro fertilization of Macaque oocytes when sperm are treated either before or after capacitation. *J. Androl.* 23:8889-898.
4. Agriliance, L.L.C. 1998. Material safety data sheet (MSDS) for Diuron 4L; Dow AgroSciences. 2000. MSDS for Diuron 4L IVM; and Griffin L.L.C. 2002. MSDS for Direx 4L. Available at www.cdms.net.
5. U.S. EPA. Technology Transfer Network. 1999. Air toxics website: Ethylene glycol. www.epa.gov/ttn/atw/hlthef/ethy-gly.html#ref7.
6. Acros Organics. 2000. MSDS for sodium tripolyphosphate. www.fishersci.com.
7. Dow AgroSciences. 2000. MSDS for Diuron 80DF IVM. Available at www.cdms.net.
8. Szadkowska-Stanczyk I. and W. Szymczak. 2001. Nested case-control study of lung cancer among pulp and paper workers in exposures to dusts. *Am. J. Ind. Med.* 39:547-556.

Figure 3
Effect of Diuron on Production of Immune System Components



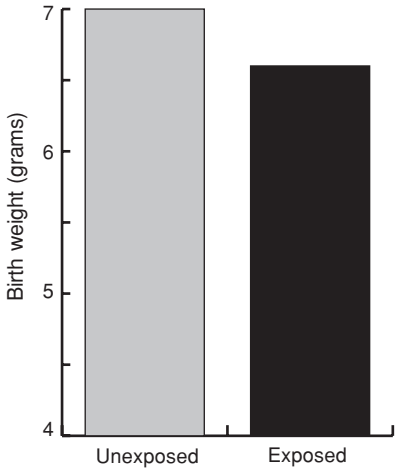
Source: Hooghe, R.J., S. Devos, and E.L. Hooghe-Peters. 2000. Effects of selected herbicides on cytokine production in vitro. *Life Sci.* 66: 2519-2525.

Figure 4
Effect of Diuron on Incidence of Cancer



Source: Calif. EPA. Office of Environmental Health Hazard Assessment. 2002. Chemical meeting the criteria for listing as causing cancer via the authoritative bodies mechanism, Mar. 29. www.oehha.org/prop65.html.

Figure 5
Effect of Diuron on Birth Weight



Source: Calif. EPA. Office of Environmental Health Hazard Assessment. 2002. Evidence on the developmental and reproductive toxicity of diuron. Draft. www.oehha.org/prop65.html.

In laboratory tests, diuron reduced production of essential immune system components, increased cancer incidence, and reduced birth weight.

are important components of the immune system: interferon, interleukin, and tumor necrosis factor. (See Figure 3.) At the lowest exposure level tested, production of all three declined over 20 percent. The low exposures tested had stronger effects on the immune system than higher exposures.[18]

Carcinogenicity (Ability to Cause Cancer)

EPA has classified diuron as a "known/likely" carcinogen since 1997. This classification is based on the results of two studies submitted to EPA by diuron manufacturers as part of the registration process. In a study of rats, both males and females fed diuron had a higher incidence of bladder cancer than unexposed animals. Male rats fed diuron also had more kidney cancer than unexposed rats. In a study of mice, animals with higher exposures to diuron had more breast cancer than animals with lower exposures.[19] (See Figure 4.)

In 2002, California's Environmental Protection Agency "formally identified" diuron as a cancer causing chemical.[20]

Diuron can also cause cancer in combination with other chemicals. Scientists from the Industrial Toxicology Research Center (India) showed that applications of diuron to the skin of mice followed by applications of TPA, a skin tumor promoting chemical, led to the development of tumors.[21]

Effects on Reproduction

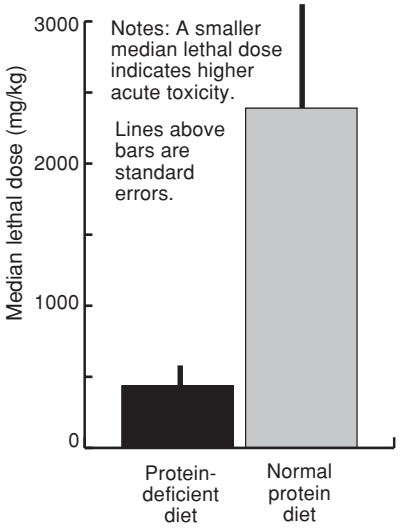
According to a recent review by the California Environmental Protection Agency, there are three laboratory studies that demonstrate effects of diuron exposure on developing fetuses.[22] A 1979 study conducted by scientists at Canada's Bureau of Chemical Safety found that bone formation in the skull[23,24] was delayed in the offspring of rats given 125 mg/kg of Karmex orally during pregnancy.[24] Two more recent studies (submitted to EPA as part of diuron's registration process[25]) found that diuron given orally during pregnancy, or fed continuously during two generations, reduced birth weights (see Figure 5) and delayed bone formation in the offspring. These effects occurred at dose levels of 144 mg/kg and 400 mg/kg. The effects observed in these three studies are described as "typical indications of growth retardation."[22]

In addition, diuron disrupts the normal functioning of male sex hormones; it can displace one form of testosterone from its normal receptors, called androgen receptors.[26] According to the California Environmental Protection Agency "teratology studies (with traditional dosing regimes and assessment periods) and multigenerational reproduction studies fail to clearly identify the hazard of chemicals with antiandrogenic potential" like diuron and "no studies designed to specifically examine such potential effects have been conducted."[22] These kinds of effects have been studied in diuron's chemical relative linuron; linuron exposure caused permanent changes in developing male sex organs resulting in atrophy of testes in adults.[27]

Effect of Malnutrition on Diuron Toxicity

A laboratory study conducted by pharmacologists at Queen's University

Figure 6
Malnutrition Increases Diuron's Acute Toxicity



Source: Boyd, E.M. and V. Krupa. 1970. Protein-deficient diet and diuron toxicity. *J. Agr. Food Chem.* 18:1104-1107.

A low protein diet increased diuron's toxicity.

(Canada) showed that protein deficiency increases the toxicity of diuron. The median acute lethal dose (the amount of a chemical that kills 50 percent of a population of test animals) for rats fed on a diet that was only 3 percent protein was five times less than rats fed a standard diet. (See Figure 6.) In addition, diuron halted sperm production in the protein deficient rats, but did not in rats fed the standard diet.[28]

Dichloroaniline

3,4-Dichloroaniline (DCA) is a chemical used in the manufacturing of diuron.[29] In addition, diuron is transformed into DCA in animals,[30] in soil,[31] and in water.[32]

According to the National Toxicology Program, "Symptoms of exposure to this compound may include irritation of the skin and severe irritation of the eye. It reduces the oxygen carrying capacity of the blood and causes shortness of breath by formation of methemoglobin. It can cause an allergic skin reaction, rash, chloracne, cyanosis, weakness, and blurring of the vision."[33]

DCA is also toxic to the kidney, liver,[34] thymus, and spleen.[35] Exposure to DCA reduced the number of platelets (material that assists in blood clotting[23]) and lymphocytes (white blood cells important in immune responses[23]) in the blood.[35] In addition, DCA exposure reduced the activity of "natural killer" cells, components of the immune system.[36] In a study of human white blood cells, DCA caused a kind of genetic damage called sister chromatid exchanges.[37]

DCA can be transformed in animals to 3,4-dichloroacetanilide (DCAc). Both DCA and DCAc disrupt normal hormone function; they displace one form of testosterone (a male sex hormone) from hormone receptors. DCAc is a potent displacer compared to DCA and diuron.[26] (See Figure 7.)

Tetrachloroazobenzene and Tetrachloroazoxybenzene

3,3',4,4'-Tetrachloroazobenzene and 3,3',4,4'-tetrachloroazoxybenzene (TCAB and TCAOB) are formed during the manufacture of diuron. Neither chemical is produced intentionally, only as contaminants.[38] TCAB is also a transformation product of DCA in both soil and water.[39,40] Their chemical structure is similar to 2,3,7,8-TCDD, the notorious dioxin,[38] and they cause "typical dioxin-like effects."[41]

According to the National Toxicology Program, diuron contains between 6 and 28 parts per million (ppm) TCAB and about 1 ppm TCAOB. Agriculture Canada has analyzed samples of Canadian diuron products and found between 0.15 and 3.38 ppm TCAB.[42]

Both TCAB and TCAOB have caused chloracne, a serious and long lasting skin disease, in exposed workers.[38]

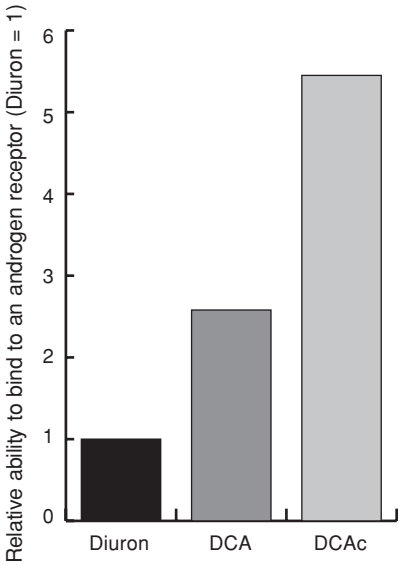
In laboratory tests, TCAB and TCAOB caused an increase in methemoglobin[38] (See "Symptoms of Acute Exposure," p. 12.) They also caused atrophy of the thymus,[38] a gland with important immune system functions.[23] TCAB caused a "sharp decrease" in levels of thyroid hormone at all dose levels tested.[41] TCAB caused genetic damage in blood cells.[41] It also causes porphyria,[43] abnormal metabolism of hemoglobin and similar molecules.[23] In studies of pregnant animals, TCAOB caused cleft palate and fetal death.[38]

Water Contamination

In a national water quality monitoring study conducted by the U.S. Geological Survey (USGS), diuron was a frequent contaminant of rivers and streams. (See Figure 8.) Overall, USGS found diuron in 13 percent of the samples collected in agricultural areas, 22 percent of the samples collected in urban areas, and 20 percent of the samples collected in areas with mixed land uses.[44]

In some areas in Oregon and California, contamination of rivers and streams is even more common. In the Willamette River basin (Oregon) and the San Joaquin River basin (California),

Figure 7
Diuron and Its Transformation Products Bind to Sex Hormone Receptors



Source: Bauer, E.R.S. et al. 1998. Application of an androgen receptor assay for the characterization of the androgenic or antiandrogenic activity of various phenylurea herbicides and their derivatives. *Analyst* 123:2485-2487.

In a laboratory study, diuron and its transformation products were able to bind to sex hormone receptors.

USGS found diuron in over half of the samples collected.[45,46] In California's Sacramento River basin, diuron contaminated water in 68 percent of the samples from agricultural areas, 86 percent of the samples from urban areas, and 54 percent of the samples from areas with mixed land uses.[47]

USGS also found that diuron contaminated groundwater, but not as often as it contaminates rivers and streams. USGS found diuron in between 2 and 4 percent of the wells the agency tested in its nationwide monitoring study.[44] Germany has stopped using diuron on railroad rights of way due to high levels of groundwater contamination.[48,49]

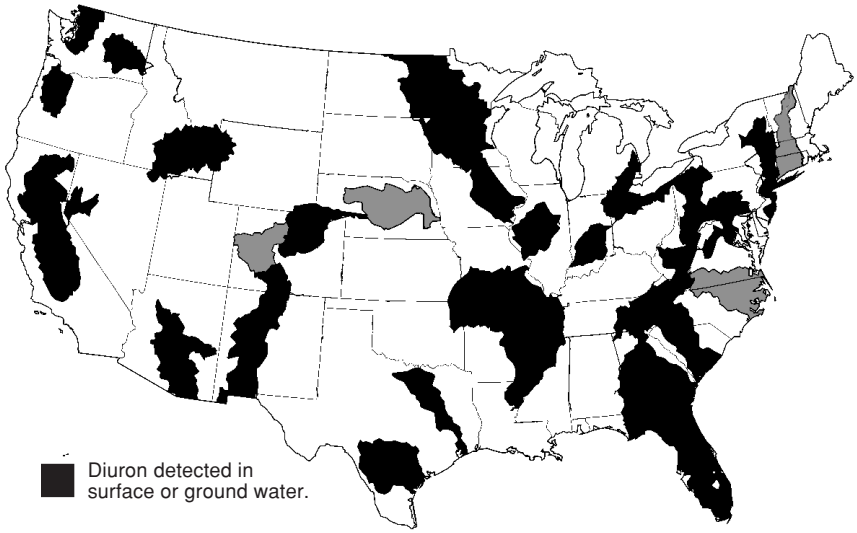
Right of way and other urban uses of diuron contaminate water. In Oregon, a cooperative study by USGS and the Oregon Department of Transportation showed that diuron treatment in September resulted in diuron-contaminated runoff in the roadside drainage ditch following rainstorms. Three months after application (after more than 20 inches of rainfall) diuron was still contaminating the drainage ditch.[50] California's Department of Pesticide Regulation found similar results in a cooperative study with the state Department of Transportation.[51] California's Regional Water Quality Control Board (Central Valley Region) found that urban water bodies were often toxic to algae because of diuron contamination.[52]

Agricultural uses of diuron also contaminate water. A study by the Central California Regional Water Quality Control Board found diuron in levels high enough to be toxic to algae in drainage from alfalfa fields.[53] Agricultural chemists at Oregon State University found diuron following an agricultural application in runoff from the treated field, in a creek that flowed through the field, in the river into which the creek drained, and in the ground water under the treated field.[54] A study of French vineyards found that most diuron-contaminated runoff occurred after significant rainstorms, even when the first rainstorm after treatment did not occur for four months.[55] Botanists at the University of Queensland identified contamination of estuaries by diuron runoff from sugar cane fields (along with runoff of another herbicide) as "the most likely cause" of the worst mangrove dieback in the world.[56]

Effluent from waste water treatment plants can significantly contribute to contamination of rivers. A 1997 study by the Bavarian State Bureau for Water Resources Management found that diuron accounted for about 80 percent of the annual herbicide load in the effluent from an urban treatment plant, and the second largest share of the annual load (only its chemical relative isoproturon had a larger share) in the effluent from a rural plant.[57]

Studies from the U.S. Department of Agriculture, the University of Florida, and the University of California showed that some chemicals used as inert ingredients in pesticides can increase the mobility of diuron in soil.[58-60] These chemical families include surfactants (detergent-like compounds)[58,59] and solvents[60] This suggests that water contamination from commercial diuron products that contain these kinds of ingredients is more likely than if diuron is used without these added chemicals.

Figure 8
Contamination of Water by Diuron



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/.

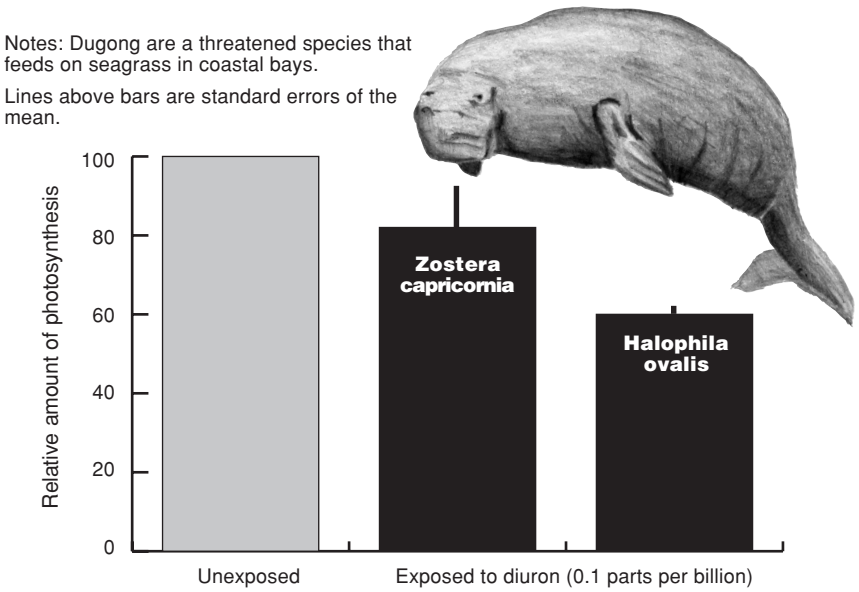
USGS found diuron contamination in all but four of the 36 river basins the agency sampled in its nationwide monitoring program.

Effects on Aquatic Plants and Algae

As is expected from a broad spectrum herbicide, diuron has significant impacts on aquatic plants at low concentrations. Researchers at the University of Reims Champagne-Ardenne (France) showed that a diuron concentration of 5 parts per billion (ppb) reduced growth of duckweed.[61] A National Ocean Service study found that concentration of 20 ppb diuron affected an estuarine community; diuron exposure reduced the amount of chlorophyll produced by plankton as well as the amount of photosynthesis that occurred.[62] Biologists at the University of Bath (England) found that 25 ppb of diuron reduced the growth of a green algae by 50 percent[63] while a study conducted at the Fraunhofer Institute (Germany) showed that a concentration of 36 ppb reduced the growth of another green algae by 50 percent.[64] California's Central Valley Regional Water Quality Control Board identified diuron contamination as the

Dugong drawing by Beth Coddington

Figure 9
Effect of Diuron Contamination on Seagrass Photosynthesis



Source: Haynes, D. et al. 2000. The impact of the herbicide diuron on photosynthesis in three species of tropical seagrass. *Mar. Pollut. Bull.* 41:288-293.

The dugong, a protected species, feeds on seagrasses that are harmed by extremely low concentrations of diuron in seawater.

primary cause of algae growth inhibition at 14 sites in the Sacramento-San Joaquin River delta.[65]

Effects on Fish

Although diuron is described as only "moderately toxic"[66] to fish based on its acute toxicity, low concentrations of diuron affect fish in the following ways:

• **Behavior changes** have been observed at concentrations of 5 ppb. Biologists from the Aquatic Toxicology Laboratory (France) found that goldfish exposed to these low levels of diuron changed their grouping behavior, which can "increase the vulnerability of fish to predation and thus affect survival."[67]

• **Reduction in food sources** can occur at low concentrations of diuron. Algae are the base of the aquatic food web. Often the algae are consumed by zooplankton, which in turn are food for juvenile fish. This means that reduction in algae populations "may result in detrimental effects to higher trophic level species [for example, fish]."[68] As discussed in "Effects on Aquatic Plants," above, diuron at concentrations of 20 ppb can reduce algae growth.

• **Survival of juvenile fish** is reduced at concentrations of 78 ppb. Researchers from the University of Wisconsin found that exposure to diuron increased the percentage of newly-hatched fry that died or were grossly deformed, and decreased the number of juveniles that survived for 60 days.[69]

• **Inhibition of the nervous system and anemia** occur at higher concentrations (approximately 500 ppb). Scientists from the French laboratory mentioned above found that diuron reduced the activity of a nervous system enzyme (acetylcholinesterase) in the brain of goldfish.[70] Biologists at the University of Calgary (Canada) showed that diuron exposure caused anemia in tilapia.[71]

The diuron transformation product DCA is also harmful to fish. DCA reduces growth and reproduction of guppies at a concentration of 2 ppb, and also reduces survival of juvenile zebrafish at the same concentration.[72] Growth of minnows is reduced by a concentration only slightly higher, 7 ppb.[73] Exposure to a mixture of DCA and the insecticide lindane (at higher concentrations - 100 ppb DCA and 40 ppb lindane) irreversibly stops spawning in zebrafish.[74]

Effects on Dugongs

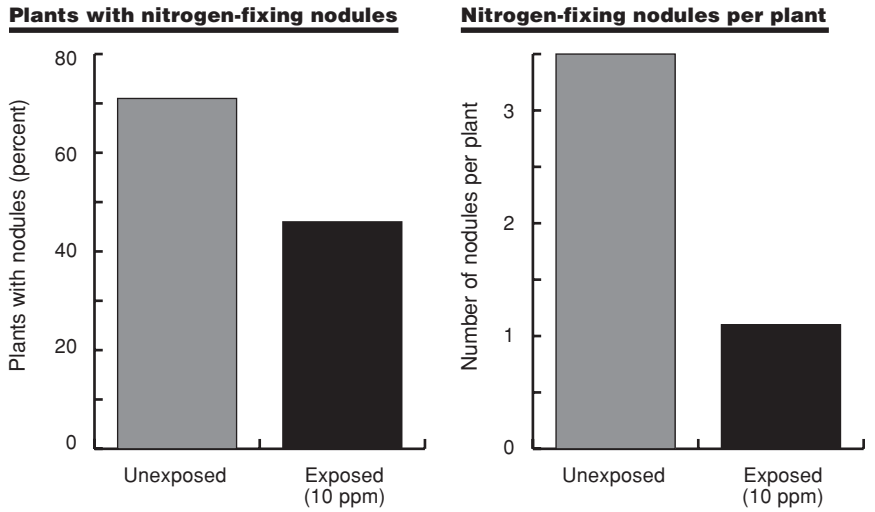
The dugong is an Australian marine mammal related to the elephant and the manatee. It grazes on seagrasses in sheltered coastal waters, and its population has declined dramatically in recent years.[75] Recent research by Australian scientists has implicated diuron as one of the problems facing dugongs. The area where they live is offshore from sugar cane fields that use diuron extensively and diuron has widely contaminated this coastal area. The research showed that extremely low concentrations of diuron (0.1 ppb) reduced photosynthesis by 2 species of seagrass (see Figure 9), and somewhat higher concentrations (10 ppb) reduced photosynthesis by a third species. These are concentrations of diuron that occur along the Queensland coast.[76,77]

Effects on other Aquatic Animals

Diuron's transformation product DCA is toxic to aquatic animals at low concentrations. A biologist at the Organization for Applied Research (The Netherlands) found that DCA reduced sexual reproduction of a water flea (*Daphnia magna*) at all concentrations tested. Water fleas are commonly used as aquatic test species. At the lowest concentration tested (6 ppb) the number of eggs was reduced about 50 percent.[78] A second study from the Netherlands found similar results at a concentration of 10 ppb.[79]

Two studies, one from the University of Sheffield (United Kingdom)[80] and one from Aachen University (Germany),[81] found similar effects on asexual reproduction. In the first study, DCA concentrations between 15 and 20 ppb reduced survival of asexual embryos about 50 percent.[80] In the second study, concentrations between 5 and 20 ppb (depending on the amount of food available) reduced embryo survival. The second study also

Figure 10
Effect of Diuron on Nitrogen-fixing Bacteria



Source: Flores, M. and M. Barbachano. 1992. Effects of herbicides Gramoxone, Diuron and Totacol on growth and nodulation of three strains of *Rhizobium meliloti*. *Sci. Tot. Environ.* 123/124:249-260.

Concentrations of diuron in soil resulting from a typical agricultural application rate decreased the ability of a nitrogen-fixing bacteria to establish on alfalfa roots.

showed that growth was reduced by the same concentrations and that a related water flea (*Ceriodaphnia quadrangula*) was even more sensitive than *Daphnia*.[81]

Reproduction in a marine worm was reduced by 10 ppb of DCA.[79]

Soil Persistence

According to the Extension Toxicology Network, diuron is "moderately to highly persistent in soils."[66] The U.S. Department of Agriculture (USDA) reports a half-life of 90 days for diuron.[82] (The half-life is the time required for half of the applied diuron to break down or move away.)

Field studies showing that diuron is persistent include the following: Agriculture Canada researchers found diuron in peach orchard soil at levels toxic to plants for three years after treatment[83]; University of Hawaii soil scientists measured diuron residues over three years after treatment of a pineapple field[84]; USDA researchers found diuron persisted for over a year in a California cotton field[85]; Oregon State University environmental toxicologists found diuron and one of its breakdown products persisted in a grass seed field from one annual application until the next[86]; and Belgian researchers found that diuron persisted for over 200 days in pear orchard soil.[87]

Laboratory experiments suggest that diuron persists longer in dry soils than wet soils.[88]

Effects on Soil Organisms

Diuron is able to disrupt the complex ecological community of soil microorganisms, including algae and fungi. These effects have been demonstrated in a variety of ecosystems around the world. Biologists at the University of Havana (Cuba) showed that the dominant soil fungus in sugar cane fields did not occur on a diuron-treated field and was replaced by another genus of fungi.[89] Microbiologists at the University of Regina (Canada) found that treatment of soil with diuron in concentrations equivalent to those used by farmers reduced algae populations by 99 percent in the top layer of the soil. The reduction occurred in both clay and sandy loam soil.[90,91] Researchers at the Instituto de Química (Brazil) showed that diuron inhibits microbial activity in soil, even at concentrations as low as several parts per million, causing "conditions adverse to restoring soil fertility."[92]

Effects on Plant Nutrients

Plants rely on a process called nitrogen fixation to convert nitrogen from the atmosphere into a usable form. One place where nitrogen fixation occurs is on plant roots in nodules occupied by nitrogen-fixing bacteria.[93] Microbiologists at the Comlutense University of Madrid (Spain) found that diuron reduced the number of nitrogen-fixing nodules formed by *Rhizobium* bacteria on alfalfa roots. A concentration of 10 ppm (the recommended agricultural application rate) reduced the average number of nodules per plant about 50 percent. Diuron also reduced the number of plants that developed nodules.[94] (See Figure 10.)

Diuron also reduces the ability of certain algae (cyanobacteria) to fix nitrogen. A microbiologist at the University of Bayreuth (Germany) showed that 10 ppm of diuron reduced nitrogen fixation by two strains of *Nostoc* cyanobacteria by 20 percent. One of the strains was more susceptible to a commercial diuron product (80 percent reduction in nitrogen fixation) than to diuron alone.[95]

Canadian microbiologists found that DCA also inhibits bacteria involved in nitrogen cycling. Concentrations of 2.5 ppm inhibited the nitrifying bacteria *Nitrosomonas*.[96]

In addition, diuron reduces the activity of phytase, an enzyme that mineralizes the plant nutrient phosphorus in soil.[97]

Increased Susceptibility of Plants to Disease

Growers of anthurium (a tropical flower) in Hawaii commonly use diuron for weed control. Root rot is widespread in Hawaiian anthurium fields, and plant pathologists from the University of Hawaii demonstrated that diuron "greatly increased"[98] incidence of the root rot by increasing the susceptibility of anthurium to the disease. Exposure to diuron more than doubled the incidence of the rot.[98]

Mutagenicity in Plants

Diuron's ability to damage genetic

material in plant cells was observed shortly after the herbicide came on the market. A 1969 study by biochemists at Rutgers University found that exposing dividing onion cells to diuron's transformation products (DCA and TCAB) caused abnormal chromosomes.[99] A field study in the 1970s from McGill University (Canada) found that a commercial diuron product caused the formation of chromosome fragments in the flower buds of goldenrod and vetch.[100]

A recent study supports these older studies. Biologists at the Industrial Toxicology Research Centre (India) showed, similar to the 1969 study, that diuron exposure caused onion cells to develop abnormal chromosomes.[101]

Weed Resistance to Diuron

According to data compiled by the Weed Science Society of America and cooperating organizations there are twenty weed species that are resistant to diuron and herbicides related to diuron. The earliest reported resistance dates from 1979; resistance has now been reported worldwide, including Asia, Central America, Europe, and North America.[102]

Effects on Beneficial Insects

In Argentina, two species of *Aphytis* wasps are used to control scale insects in citrus orchards. Researchers there found that diuron, also used widely in citrus orchards, is toxic to the two *Aphytis* wasps. In laboratory tests, exposure to diuron caused between 70 and 100 percent mortality.[103]

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