Glyphosate Fact Sheets: Part 1 and Part 2

Glyphosate, Part 1: Toxicology

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Introduction

Glyphosate is a broad-spectrum herbicide widely used to kill unwanted plants both in agriculture and in nonagricultural landscapes. Estimated use in the U.S. is between 19 and 26 million pounds per year.

Most glyphosate-containing products are either made or used with a surfactant, chemicals that help glyphosate to penetrate plant cells.

Glyphosate-containing products are acutely toxic to animals, including humans. Symptoms include eye and skin irritation, cardiac depression, gastrointestinal pain, vomiting, and accumulation of excess fluid in the lungs. The surfactant used in a common glyphosate product (Roundup) is more acutely toxic than glyphosate itself; the combination of the two is yet more toxic.

In animal studies, feeding of glyphosate for three months caused reduced weight gain, diarrhea, and salivary gland lesions. Lifetime feeding of glyphosate caused excess growth and death of liver cells, cataracts and lens degeneration, and increases in the frequency of thyroid, pancreas, and
liver tumors.

Glyphosate-containing products have caused genetic damage in human blood cells, fruit flies, and onion cells.

Glyphosate causes reduced sperm counts in male rats, a lengthened estrous cycle in female rats, and an increase in fetal loss together with a decrease in birth weights in their offspring.

It is striking that laboratory studies have identified adverse effects of glyphosate or glyphosate-containing products in all standard categories of toxicological testing.

Two serious cases of fraud have occurred in laboratories conducting toxicology and residue testing for glyphosate and glyphosate-containing products.

Advertised as herbicides that can "eradicate weeds and unwanted grasses effectively with a high level of environmental safety,"1 glyphosate-based herbicides can seem like a silver bullet to those dealing with unwanted vegetation. However, an independent, accurate evaluation of their health and environmental hazards can draw conclusions very different than those presented by these advertisements. The following summary of glyphosate's hazards is intended to serve that purpose. It will appear in two parts: Part 1 discusses the toxicology of glyphosate, its metabolites, and the other ingredients of glyphosate products and Part 2 will discuss human exposure to glyphosate and its ecological effects.

Glyphosate, N-(phosphonomethyl) glycine (Figure 1), is a post-emergent, systemic, and non-selective herbicide used to kill broad-leaved, grass, and sedge species.2 It has been registered as a broad spectrum herbicide in the U.S. since 1974 and is used to control weeds in a wide variety of agricultural, lawn and garden, aquatic, and forestry situations.3

Most glyphosate herbicides contain the isopropylamine salt of glyphosate. A related chemical, the sodium salt of glyphosate, acts as a growth regulator in sugar cane and peanuts and is marketed for that purpose. The monoammonium salt of glyphosate is also marketed as an herbicide and growth regulator.4

Glyphosate products are manufactured by Monsanto Company worldwide. The herbicide is marketed under a variety of trade names: Roundup (including Roundup D-Pak, Roundup Lawn and Garden Concentrate, and Roundup Ready-to-Use) and Rodeo are the most common U.S. trade names.2 The sodium salt is sold as Quotamaster. The monoammonium salt is sold as Deploy Dry.2 Other brand names used for the isopropylamine salt are Accord,5 Vision, Ranger, and Sting.2

As an herbicidal compound, glyphosate is unusual in that essentially no structurally related compounds show any herbicidal activity.6

Use

Glyphosate is the eighth most commonly used herbicide in U.S. agriculture and the second most commonly used herbicide in nonagricultural situations. Estimated annual use according to
the U.S. Environmental Protection Agency (EPA) is between 15 and 20 million pounds in agriculture and between 4 and 6 million pounds elsewhere.7 The largest agricultural uses are in the production of soybeans, hay and pasture, corn, and oranges.4

About 25 million applications per year are made in U.S. households; most of these are made on lawns or outdoor areas where a total vegetation kill is wanted.8

In California, where pesticide use reporting is more comprehensive than in other states, about 3.4 million pounds were used in 1992; about 25 percent of this was used along rights-of-way, while 15 percent was used on almonds and 10 percent was used on grapes.9

Mode of Action

The mode of action of glyphosate is "not known at this time,"4 according to EPA. However, "herbicidal action probably arises from the inhibition of the biosynthesis of aromatic amino acids."10 These amino acids (phenylalanine, tyrosine, and tryptophan) are used in the synthesis of proteins and are the essential for growth and survival of most plants. One particular enzyme important in aromatic amino acid synthesis, called 5-enolpyruvylshikimate-3-phosphate synthase, is inhibited by glyphosate.10 Glyphosate also "may inhibit or repress"4 two other enzymes, chlorismate mutase and prephrenate hydratase, involved in other steps of the synthesis of the same amino acids. These enzymes are all part of what is called the shikimic acid pathway, present in higher plants and microorganisms but not in animals.11

Two of the three aromatic amino acids (tryptophan and phenylalanine) are essential amino acids in the human diet because humans, like all higher animals, lack the shikimic acid pathway, cannot synthesize these amino acids, and rely on their foods to provide these compounds. Tyrosine is synthesized in animals through another pathway.12

Glyphosate can affect enzymes not connected with the shikimic acid pathway. In sugar cane, it reduces the activity of one of the enzymes involved in sugar metabolism, acid invertase. This reduction appears to be mediated by auxins, plant hormones.13

Glyphosate also affects enzyme systems found in animals and humans. In rats, injection into the abdomen decreases the activity of two detoxification enzymes, cytochrome P-450 and a monooxygenase, and decreases the intestinal activity of the enzyme aryl hydrocarbon hydroxylase (another detoxification enzyme).14

"Inert" Ingredients in Glyphosate-containing Products

Virtually every pesticide product contains ingredients other than what is called the "active" ingredient(s), those designed to provide killing action. Their purpose is to make the product easier to use or more efficient. These ingredients are called "inert," although they are often not biologically, chemically, or toxicologically inert. In general, they are not identified on the label of the pesticide product.

In the case of glyphosate products, many "inerts" have been identified. Roundup contains a polyethoxylated tallowamine surfactant (usually abbreviated POEA), related organic acids of glyphosate, isopropylamine, and water. Both Rodeo and Accord contain glyphosate and water.15 (However, label instructions usually require adding a surfactant during use.15) See "Toxicology of 'Inert' Ingredients of Glyphosate-containing Products," p. 17, for basic information about these "inert" ingredients.

Many of the toxicology studies that will be summarized in this factsheet have been conducted using glyphosate, the active ingredient, alone. Some have been conducted with commercial products containing glyphosate and "inert" ingredients. When toxicology testing is not done with the product as it is actually used, it is impossible to accurately assess its hazards.

We will discuss both types of studies, and will identify insofar as is possible exactly what material was used to conduct each study.

Acute Toxicity to Laboratory Animals

Glyphosate's acute oral median lethal dose (the dose that causes death in 50 percent of a population of test animals; LD50) in rats is greater than 4,320 milligrams per kilogram (mg/kg) of body weight. This places the herbicide in Toxicity Category III (Caution).4 Its acute dermal toxicity (dermal LD50) in rabbits is greater than 2,000 mg/kg of body weight, also Toxicity Category III.4

If animals are given glyphosate in other ways, it is much more acutely toxic. When given intraperitoneally (the dose applied by injection into the abdomen), glyphosate is between 10 and 20 times more toxic to rats (with an LD50 between 192-467 mg/kg)2,16 than it is when given orally. Intraperitoneal injection also caused fever, cessation of breathing, and convulsions.17 While this kind of exposure is not one that would be encountered under conditions of normal use, these studies indicate the kinds of effects glyphosate can potentially cause in mammals.

Commercial glyphosate-containing products are more acutely toxic than glyphosate alone. Two recent (1990 and 1991) studies compared the amount of Roundup required to cause death in rats with the amount of either glyphosate alone or POEA alone that would cause death. The studies found that in combination, the amount of glyphosate and POEA required to kill was about 1/3 of a lethal dose of either compound separately. The Roundup formulation tested was also more toxic than POEA alone.18,19

As with glyphosate alone, glyphosate-containing products are more toxic when administered other ways than orally. Inhalation of Roundup by rats caused "signs of toxicity in all test groups,"20 even at the lowest concentration tested. These signs included a dark nasal discharge, gasping, congested eyes, reduced activity, hair standing erect,21 and body weight loss following exposure.20 Lungs were red or blood-congested.21 The dose required to cause lung damage and mortality following pulmonary administration of Roundup Lawn and Garden Concentrate or Roundup-Ready-to-Use (the glyphosate product is directly forced into the trachea, the tube carrying air into the lungs) was only 1/10 the dose causing damage through oral administration.18

Effects on the Circulatory System: When dogs were given intravenous injections of glyphosate, POEA, or Roundup so that blood concentrations were approximately those found in humans who ingested glyphosate, a variety of circulatory effects were found. Glyphosate increased the ability of the heart muscle to contract. POEA reduced the output of the heart and the pressure in the arteries. Together (Roundup), the result was cardiac depression.22

Eye Irritation: Glyphosate is classified as a mild eye irritant by EPA, with effects lasting up to seven days4 although more serious effects were found by the World Health Organization. In two of the four studies they reviewed, glyphosate was "strongly irritating"2 to rabbits' eyes and a third test found it "irritating."2 In tests of glyphosate-containing products, all eight products tested were irritating to rabbit eyes, and four of the products were "strongly" or "extremely" irritating.2

Skin Irritation: Glyphosate is classified as a slightly irritating to skin. Roundup is a "moderate skin irritant" and causes redness and swelling on both intact and abraded rabbit skin. Recovery can take more than two weeks.20

Acute Toxicity to Humans

The acute toxicity of glyphosate products to humans was first widely publicized by physicians in Japan who studied 56 cases of Roundup poisoning. Most of the cases were suicides or attempted suicides; nine cases were fatal. Symptoms of acute poisoning in humans included gastrointestinal pain, vomiting, excess fluid in the lungs, pneumonia, clouding of consciousness, and destruction of red blood cells.23 They calculated that the mean amount ingested in the fatal cases was slightly more than 200 milliliters (about 3/4 of a cup). They believed that POEA was the cause of Roundup's toxicity.23 More recent reviews of glyphosate poisoning incidents have found similar symptoms, as well as lung congestion or dysfunction,24-26, erosion of the gastrointestinal tract,24,26 abnormal electrocardiograms,26 massive gastrointestinal fluid loss,27 low blood pressure,23,26 and kidney damage or failure.24,25,27

Smaller amounts of Roundup also cause adverse effects. In general these include the skin or eye irritation documented in animal studies, as well as some of the symptoms seen in humans following ingestion. For example, rubbing of Roundup in an eye caused swelling of the eye and lid, rapid heartbeat, palpitations, and elevated blood pressure. Wiping the face with a hand that had contacted leaky Roundup spray equipment caused a swollen face and tingling of the skin. Accidental drenching with Roundup (horticultural strength) caused recurrent eczema of the hands and feet lasting two months.25

Different symptoms have been observed when a different type of exposure has occurred. In Great Britain, a study compared the effects of breathing dust from a flax milling operation that used flax treated with Roundup with the effects of dust from untreated flax. Treated flax dust caused a decrease in lung function and an increase in throat irritation, coughing, and breathlessness.28

Subchronic Toxicity

Experiments in which glyphosate was fed to laboratory animals for 13 weeks showed a variety of effects. In experiments conducted by the National Toxicology Program (NTP), microscopic salivary gland lesions were found in all doses tested in rats (200 - 3400 mg/kg per day) and in all but the lowest dose tested in mice (1,000-12,000 mg/kg per day). Both the parotid and submandibular salivary glands were affected in rats; in mice the lesions were confined to the parotid gland. Based on further experiments, NTP concluded the lesions were mediated by the adrenal hormone adrenalin.29

The NTP study also found evidence of effects on the liver: increases in bile acids as well as two liver enzymes were found in both males and females. Other effects found in this study were reduced weight gain in male and female rats and mice; diarrhea in male and female rats; and changes in the relative weights of kidney, liver and thymus in male rats and mice.29

Other subchronic laboratory tests found decreased weight gains (using doses of 2500 mg/kg per day)30 along with an increase in the weights of brain, hearts, kidney, and livers in mice.2 In rats, blood levels of potassium and phosphorus increased at all doses tested (60-1600 mg/kg/day) in both sexes. There was also an increase in pancreatic lesions in males.4

As in acute toxicity tests, glyphosate-containing products are more toxic than glyphosate alone in subchronic tests. In a 7 day study with calves, 790 mg/kg of Roundup caused labored breathing, pneumonia, and death of 1/3 of the animals tested. At lower doses decreased food intake and diarrhea were observed.2

Chronic Toxicity

Glyphosate is also toxic in long-term studies. The following effects were found in lifetime glyphosate feeding studies using mice: decreased body weight, excessive growth of particular liver cells, death of the same liver cells, and chronic inflammation of the kidney. Effects were significant only in males and at the highest dose tested (about 4800 mg/kg of body weight per day). In females, excessive growth of some kidney cells occurred.31 At a lower dose (814 mg/kg of body weight per day) excessive cell division in the urinary bladder occurred.2

Lifetime feeding studies with rats found the following effects: decreased body weight in females; an increased incidence of cataracts and lens degeneration in males; and increased liver weight in males. These effects were significant at the highest dose tested (900-1200 mg/kg of body weight per day).4 At a lower dose (400 mg/kg of body weight per day) inflammation of the stomach's mucous membrane occurred in both sexes.2

Carcinogenicity

The potential of glyphosate to cause cancer has been a controversial subject since the first lifetime feeding studies were analyzed in the early 1980s. The first study (1979-1981) found an increase in testicular interstitial tumors in male rats at the highest dose tested (30 mg/kg of body weight per day).32 as well as an increase in the frequency of a thyroid cancer in females.33 The second study (completed in 1983) found dose-related increases in the frequency of a rare kidney tumor in male mice.34 The most recent study (1988-1990) found an increase in the number of pancreas and liver tumors in male rats together with an increase of the same thyroid cancer found in the 1983 study in females.35

All of these increases in tumor incidence are "not considered compound-related"35 according to EPA. In each case, different reasons are given for this conclusion. For the testicular tumors, EPA accepted the interpretation of an industry pathologist who said that the incidence in treated groups (12 percent) was similar to those observed in other control (not glyphosate-fed) rat feeding studies (4.5 percent).36 For the thyroid cancer, EPA stated that it was not possible to consistently distinguish between cancers and tumors of this type, so that the incidences of the two should be considered together. The combined data are not statistically significant.33 For the kidney tumors, the registrants reexamined slides of kidney tissue, finding an additional tumor in untreated mice so that statistical significance was lost. This was despite a memo from EPA's pathologist stating that the lesion in question was not really a tumor.34 For the pancreatic tumors, EPA stated that there was no dose-related trend and no progression to malignancy. For the liver tumors and the thyroid tumors, EPA stated that pairwise comparisons between treated and untreated animals were not statistically significant and there was no progression to malignancy.35

EPA concluded that glyphosate should be classified as Group E, "evidence of non-carcinogenicity for humans."35 They added that this classification "is based on the available evidence at the time of evaluation and should not be interpreted as a definitive conclusion that the agent will not be a carcinogen under any circumstances." 35 From a public health perspective, the results of the laboratory tests leave many questions unanswered. An EPA statistician wrote in a memo concerning one of the carcinogenicity studies, "Viewpoint is a key issue. Our viewpoint is one of protecting the public health when we see suspicious data."36 Unfortunately, EPA has not taken that conservative viewpoint in its assessment of glyphosate's cancer-causing potential.

There are no studies available to NCAP evaluating the carcinogenicity of Roundup or other glyphosate-containing products. Without such tests, the carcinogenicity of glyphosate-containing products is unknown.

Mutagenicity

Laboratory studies of a variety of organisms have shown that glyphosate-containing products cause genetic damage:

* In fruit flies, Roundup and Pondmaster (an aquatic herbicide consisting of glyphosate and a trade secret surfactant)37 both increased the frequency of sex-linked, recessive lethal mutations. (These are mutations that are usually visible only in males because two damaged genes are required in order to be expressed in females.) In this study, the frequency of lethal mutations was between 3 and 6 times higher in fruit flies that had been exposed to glyphosate products during their larval development than in unexposed flies.38

* A laboratory study of human lymphocytes (one type of white blood cell) showed an increase in the frequency of sister chromatid exchanges following exposure to high doses of Roundup.39 (Sister chromatid exchanges are exchanges of genetic material during cell division between members of a chromosome pair. They result from point mutations.)

* In Salmonella bacteria, Roundup was weakly mutagenic at high concentrations. In onion root cells, Roundup caused an increase in chromosome aberrations.40

Glyphosate alone has rarely caused genetic damage in laboratory tests. None of the mutagenicity studies required for registration of glyphosate have shown it to be mutagenic. Tests included studies of mutations in hamster ovary cells, bacteria, and mouse bone marrow cells.4 Glyphosate was also not mutagenic in other studies of rats, mice,2 and onion cells40 but caused chromosome stickiness and fragmentation in water hyacinth root cells.41

Reproductive Effects

Laboratory studies have demonstrated a number of effects of glyphosate on reproduction,including effects on mothers, fathers, and offspring.

In rat feeding studiess, glyphosate reduced sperm counts (at the two highest doses tested) andlengthened the estrous cycle, how often a female comes into heat (at the highest dose tested).29 Other effects on mother rats in laboratory tests include soft stools, diarrhea, breathing rattles, red nasal discharge, reduced activity, growth retardation, decreased body weights, and increased mortality.2 Effects on offspring included an increase in fetal loss, a decrease in the number of embryos successfully implanted into the uterus, a decrease in the number of viable fetuses, a slight decrease in litter size, a decrease in fetal and pup weights, and an increase in problems with breast bone formation.2 Effects were observed at the highest doses tested (1500 and 3500 mg/kg of body weight per day).2

In a study of rabbits using doses that were lower than those used in the rat studies above, glyphosate caused diarrhea, nasal discharge, and death in mothers.2 The only effect on offspring was a decrease in fetal weight in all treated groups.42

A study in which glyphosate was fed to rats for three generations after which the offspring were examined for birth defects found kidney damage at a relatively low dose (30 mg/kg of body weight). However, a second study (only two generations long) did not find similar effects, and EPA called the damage in the first study "spurious."4 From a public health perspective, however, a new three generation study is crucial.

Toxicology of Glyphosate's Major Metabolite

In general, studies of the breakdown of glyphosate find only one metabolite,aminomethylphosphonic acid (AMPA).2 (See Figure 5.) Although AMPA has low acute toxicity (its LD50 is 8,300 mg/kg of body weight in rats)20 and is only slightly irritating to eyes,43 it causes a variety of toxicological problems. In subchronic tests on rats, AMPA caused decreased weight gain in males; an increase in the acidity of urine in both males and females; an increase in the activity of an enzyme, lactic dehydrogenase, in both sexes; a decrease in liver weights in males at all doses tested; and excessive cell division in the lining of the urinary bladder and in part of the kidney in both sexes.20 AMPA is much more persistent than glyphosate; studies in eight states found that the half-life in soil (the time required for half of the original concentration of a compound to break down or dissipate) were between 119 and 958 days.2

Quality of Toxicology Testing

Tests done on glyphosate to meet registration requirements have been associated with fraudulent practices.

Laboratory fraud first made headlines in 1983 when EPA publicly announced that a 1976 audit had discovered "serious deficiencies and improprieties" in toxicology studies conducted by Industrial Biotest Laboratories (IBT).44 Problems included "countless deaths of rats and mice that were not reported," "fabricated data tables," and "routine falsification of data."44

IBT was one of the largest laboratories performing tests in support of pesticide registrations.44 About 30 tests on glyphosate and glyphosate-containing products were performed by IBT, including 11 of the 19 chronic toxicology studies.45 A compelling example of the poor quality of IBT data comes from an EPA toxicologist who wrote, "It is also somewhat difficult not to doubt the scientific integrity of a study when the IBT stated that it took specimens from the uteri (of male rabbits) for histopathological examination."46 (Emphasis added.)

In 1991, laboratory fraud returned to the headlines when EPA alleged that Craven Laboratories, a company that performed contract studies for 262 pesticide companies including Monsanto, had falsified test results.47 "Tricks" employed by Craven Labs included "falsifying laboratory notebook entries" and "manually manipulating scientific equipment to produce false reports."48 Roundup residue studies on plums, potatoes, grapes, and sugarbeets were among the tests in question.49

The following year, the owner/president of Craven Laboratories and three employees were indicted on 20 felony counts. A number of other employees agreed to plead guilty on a number of related charges.50 The owner was sentenced to five years in prison and fined $50,000; Craven Labs was fined 15.5 million dollars, and ordered to pay 3.7 million dollars in restitution.48

Although the tests of glyphosate identified as fraudulent have been replaced, these practices cast shadows on the entire pesticide registration process.

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Glyphosate, Part 2:
Human Exposure and Ecological Effects

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Overview

Residues of the commonly-used herbicide glyphosate have been found in a variety of fruits and vegetables. Residues can be detected long after glyphosate treatments have been made. Lettuce, carrots, and barley planted a year after glyphosate treatment contained residues at harvest.

In California, where reporting of pesticide-caused illnesses is more comprehensive than in other states, glyphosate exposure was the third most commonly-reported cause of pesticide illness among agricultural workers. For landscape maintenance workers, glyphosate ranked highest.

Glyphosate can drift away from the site of its application. Maximum drift distance of 400 to 800 meters (1300-2600 feet) have been measured.

Glyphosate residues in soil have persisted over a year.

Although not expected for an herbicide, glyphosate exposure damages or reduces the population of many animals, including beneficial insects, fish, birds, and earthworms. In some cases glyphosate is directly toxic; for example, concentrations as low as 10 parts per million can kill fish and 1/20 of typical application rates caused delayed development in earthworms. In other cases, (small mammals and birds, for example) glyphosate reduces populations by damaging the vegetation that provides food and shelter for the animals.

Glyphosate reduces the activity of nitrogen-fixing bacteria. These bacteria transform nitrogen, an essential plant nutrient, into a form that plants can use. Glyphosate reduces the growth of mycorrhizal fungi, beneficial fungi that help plants absorb water and nutrients. Glyphosate also increases the susceptibility of plants to diseases, including Rhizoctonia root rot, take-all disease, and anthracnose.

Glyphosate is a widely-used, broad-spectrum herbicide that is used to kill unwanted plants in a wide variety of agricultural, lawn and garden, aquatic, and forestry situations. It ranks among the top ten herbicides used in the U.S., both in agricultural and nonagricultural situations. Common brand names are Roundup, Rodeo, Accord, and Vision. This is the second part of a summary of glyphosate's hazards. Part 1 (JPR 15(3):14-20) discussed the toxicology of glyphosate, its breakdown products, and the other ingredients in glyphosate-containing products. This part discusses human exposure to glyphosate and its ecological effects.

Human Exposure

The most important ways that people are exposed to glyphosate are through workplace exposure (for people who use glyphosate products on the job), eating of contaminated food, exposure caused by off-target movement following application (drift), contact with contaminated soil, and drinking or bathing in contaminated water. The next five sections of this factsheet summarize information about these five routes of exposure. The third section, discussing drift, also covers impacts on plants.

Contamination of Food

Analysis of glyphosate residues is "in general laborious, complex, and costly."1 For this reason, it is not included in government monitoring of pesticide residues in food.1 The only information available about contamination of food comes from research situations. Such studies demonstrate several important points:

* First, glyphosate can be taken up by plants and moved to parts of the plant that are used for food. For example, glyphosate has been found in strawberries,2 wild blueberries and raspberries,3 lettuce, carrots, barley,4 and fish5,6 following treatment.

* Second, pre-harvest use of glyphosate on wheat (to dry out the grain prior to harvest) results in "significant residues in the grain,"1 according to the World Health Organization. Bran contains between 2 and 4 times the amount on whole grains. Residues are not lost during baking.1

* Third, glyphosate residues can be found in food long after treatments have been made. For example, lettuce, carrots, and barley contained glyphosate residues at harvest when planted a year after treatment.4

Occupational Exposure

Workers in a variety of occupations are exposed to glyphosate. Researchers have documented exposure for forestry workers in Finland7 and the southeastern U.S., palm plantation workers in Malaysia1 and conifer nursery workers in Mississippi and Oregon.8 All of these studies generally found low, but consistent, exposure rates.

Physicians, however, paint a different picture. In California, the state with the most comprehensive program for reporting of pesticide-caused illness, glyphosate was the third most commonly-reported cause of pesticide illness among agricultural workers.9 Among landscape maintenance workers, glyphosate was the most commonly reported cause.10 (Both these statistics come from reviews of illness reports collected between 1984 and 1990.) Even when glyphosate's extensive use in California is considered, and the illness statistics presented as "number of acute illnesses reported per million pounds used in California," glyphosate ranked twelfth.9

Drift

In general, movement of a pesticide through unwanted drift is "unavoidable."11 Drift of glyphosate is no exception. Glyphosate drift, however, is a particularly significant problem. Its wide use means that there is a correspondingly large potential for drift.12 When drift does occur, "damage is likely to be much more extensive and more persistent than with many other herbicides. "13 This is because glyphosate translocates (moves) within plants readily so that even unexposed parts of a plant can be damaged. Damage to perennial plants (when not exposed to enough glyphosate to kill them) is persistent, with some symptoms lasting several years.13 In addition, plant susceptibility varies widely. Some wildflowers are almost a hundred times more sensitive than others; small amounts of drift will damage these species.14

A fundamental question about drift is "How far can I expect glyphosate to travel off-site?" Unfortunately, the question is difficult to answer, since drift is "notoriously variable."15 Factors that increase drift are aerial application techniques, high wind speeds (over 10 kilometers, or 6 miles, per hour), spray nozzles that produce a high proportion of fine droplets, and calm conditions (without enough turbulence to drive the glyphosate droplets onto plant foliage).15 Drift distances that have been measured for the major application techniques include the following:

* Ground Applications: Between 14 and 78 percent of glyphosate applied as ground sprays moves off-site.15 Seedling mortality has been demonstrated 20 meters (66 feet) downwind when using a tractor-mounted sprayer. Sensitive species were killed at 40 meters (131 feet).16 Models indicate that even more sensitive species would be killed at distances approaching 100 meters (328 feet).14 Glyphosate residues have been measured 400 meters (1312 feet) downwind from ground applications.17

* Helicopter applications: Between 41 and 82 percent of glyphosate applied from helicopters moves off the target site.15 Two studies done in Canada18,19 measured glyphosate residues 200 meters (656 feet) from target areas following helicopter applications to forest sites. In both studies, 200 meters was the farthest distance at which samples were taken, so the longest distance glyphosate travelled is not known.18,19 A third study (from California) found glyphosate 800 meters (2624 feet) downwind following a helicopter application. Again, this was the farthest distance at which measurements were made. Plant injury was recorded 400 meters (1312 feet) downwind.17

Fixed-wing aircraft: Long drift distances occur following applications of glyphosate made from fixed-wing airplanes. Three studies on forested sites conducted by Agriculture Canada (the Canadian agricultural ministry) showed that glyphosate was consistently found at the farthest distance from the target areas that measurements were made (200, 300, and 400 meters, or 656, 984, and 1312 feet).20-22 A California study found glyphosate 800 meters downwind of an airplane application. Again, this was the farthest distance at which measurements were made. Plant injury was observed at 100 meters (328 feet). Unlike the first three studies, this study used a grass field as the test site.17

One of the Canadian studies22 calculated that buffer zones of between 75 and 1200 meters (246 feet - 0.75 miles) would be required to protect nontarget vegetation.

Soil Contamination

Persistence: Glyphosate's persistence in soil varies widely, so giving a simple answer to the question "How long does glyphosate persist in soil?" is not possible. Half-lives (the time required for half of the amount of glyphosate applied to break down or move away) as low as 3 days and as long as 141 days have been measured by glyphosate's manufacturer.4 Initial degradation (breakdown) is faster than the subsequent degradation of what remains, resulting in long persistence.23 Long persistence has been measured in the following studies: 55 days on an Oregon Coast Range forestry site24; 249 days on Finnish agricultural soils25; between 259 and 296 days on eight Finnish forestry sites23; 335 days on an Ontario (Canada) forestry site26; 360 days on 3 British Columbia forestry sites27; and, from 1 to 3 years on eleven Swedish forestry sites.28 These are minimum estimates because, in all but two of these studies, glyphosate was detected on the last date samples were analyzed.

Glyphosate is thought to be "readily bound to many soils and clay minerals"1 and therefore "immobile or slightly immobile in many soils."1 This means that the glyphosate will be unlikely to move away from the application site and contaminate water or soil elsewhere. However, a new study29 paints a different picture. The researchers found that glyphosate bound readily to the four soils studied. However, desorption, when glyphosate unbinds from soil particles, also occurred readily. In one soil, 80 percent of the added glyphosate desorbed in a two hour period. The study concludes that "this herbicide can be extensively mobile in the soil environment.."29

Water Contamination

Based on the prevailing view that glyphosate binds readily to soil particles, it does not have the chemical characteristics of a pesticide that is likely to leach into either ground or surface water.1 (If it readily desorbs, as described above, this picture would change.) In either case, glyphosate can move into surface water when the soil particles to which it is bound are washed into streams or rivers.4 How often this happens is not known, because routine monitoring for glyphosate in water is infrequent.1

However, glyphosate has been found in both ground and surface water. Examples include two farm ponds in Ontario, Canada, contaminated by run-off from an agricultural treatment (one pond) and a spill (the other pond)30; the run-off from a watersheds treated with Roundup during production of no-till corn and fescue31; contaminated surface water in the Netherlands1; and seven U.S. wells (one in Texas, six in Virginia) contaminated with glyphosate.32

Glyphosate's persistence in water is shorter than its persistence in soils. Two Canadian studies found glyphosate persisted 12 to 60 days in pond water following direct application.33,34 Glyphosate persists longer in sediments. For example, a study of Accord applied to forest ponds found glyphosate residues in sediment 400 days after application.1 The half-life in pond sediments in a Missouri study was 120 days; persistence was over a year in pond sediments in Michigan and Oregon.4

Ecological Effects

Glyphosate can impact many organisms not intended as targets of the herbicide. The next two sections describe both direct mortality and indirect effects, through destruction of food or shelter.

Effects on Nontarget Animals

Beneficial insects: Glyphosate-containing products pose hazards to insects that are economically beneficial because they kill pest insects. The International Organization for Biological Control found that exposure to freshly dried Roundup killed over 50 percent of three species of beneficial insects: a parasitoid wasp, a lacewing, and a ladybug.35 Over 80 percent of a fourth species, a predatory beetle, was killed.

Similar impacts on beneficial insects have been shown in field studies. In North Carolina winter wheat fields, populations of large carabid beetles declined after treatment with a commercial glyphosate product and did not recover for 28 days.36 A study of Roundup treatment of pasture hedgerows in the United Kingdom showed a similar decline in carabid beetles.37

Roundup treatment of a Maine clear-cut caused an 89 percent decline in the number of herbivorous (plant-eating) insects. While these are not usually considered beneficial insects, they serve as an important food resource for birds and insect-eating small mammals.38

Aquatic insects can also be affected by glyphosate. Midge larvae (important food for breeding waterfowl39) are killed by glyphosate in amounts that vary widely. For example, one study found that 55 parts per million (ppm) of glyphosate killed midge larvae6 while other studies found that 65040 -560039 ppm of Rodeo (containing glyphosate and water) were required to kill the larvae. Part of the variability is related to water hardness.39

The U.S. Fish and Wildlife Service has identified one endangered species of insect, a longhorn beetle, that would be jeopardized by use of glyphosate.41

Other arthropods: Glyphosate and glyphosate-containing products kill a variety of other arthropods. For example, over 50 percent of test populations of a predatory mite that is an important predator of pest mites was killed by exposure to Roundup.35 In another laboratory study, Roundup exposure caused a decrease in survival and a decrease in body weight of woodlice. These arthropods are important in humus production and soil aeration.42 Roundup treatment of pasture hedgerows reduced the number of spiders, probably by killing the plants they preferred for web-spinning.37 The water flea Daphnia pulex is killed by concentrations of Roundup between 3 and 25 ppm.6,43,44 Young Daphnia are more susceptible than mature individuals, and suspended sediments in the water increased the toxicity.43 The red swamp crawfish, a commercial species, was killed by 47 ppm of Roundup.45

Fish: Both glyphosate and the commercial products that contain glyphosate are acutely toxic to fish. In general, glyphosate alone is less toxic than the common glyphosate product, Roundup, and other glyphosate products have intermediate toxicity. Part of these differences in toxicity to fish can be explained by the toxicity of the surfactant (detergent-like ingredient) in Roundup. It is about 30 times more toxic to fish than glyphosate itself.44

Acute toxicities of glyphosate vary widely: median lethal concentrations (LC50s; the concentrations killing 50 percent of a population of test animals) from 10 ppm to over 1000 ppm have been reported depending on the species of fish and test conditions.1 In soft water there is little difference between the toxicities of glyphosate and Roundup.

Acute toxicities of Roundup to fish range from an LC50 of 3.2 ppm to an LC50 of 52 ppm.1 Acute toxicities of Rodeo (used with the surfactant X-77 per label recommendations) vary from 120 to 290 ppm.46

Factors important in determining the toxicity of glyphosate or glyphosate-containing products to fish include the following:

* First, different species of fish have different susceptibilities. For example, coho and chinook salmon are more tolerant of glyphosate than pink or chum salmon.47

* Water quality is important: glyphosate in soft water was 20 times more toxic to rainbow trout than was glyphosate in hard water. For Roundup, the reverse is true: it is more toxic in hard water than in soft.47,48

* Age affects the susceptibility of fish because juveniles are often more susceptible than adults. For example, Roundup was four times more toxic to rainbow trout fry and fingerlings than it was to larger fish.6

* Nutrition also can determine toxicity. Hungry fish are more susceptible to glyphosate than fed fish. For example, fed flagfish were 10 times more tolerant of glyphosate than unfed fish.49

* Finally, glyphosate toxicity increases with increased water temperature. In both rainbow trout and bluegills, toxicity about doubled between 7 and 17!C (45 and 63!F).6 Treatment of riparian areas with glyphosate causes water temperatures to increase for several years following treatment 50 because the herbicide kills shading vegetation. This means that repeated use of glyphosate in a watershed could favor its increased toxicity to fish. In addition, the temperature increase itself could be critical for fish, like juvenile salmon, that are sensitive to water temperature.

Sublethal effects of glyphosate on fish are also significant and occur at low concentrations. Studies of rainbow trout and Tilapia found that concentrations of about 1/2 and 1/3 of the LC50 (respectively) caused erratic swimming.51,52 The trout also exhibited labored breathing.51 Behavioral effects can increase the risk that the fish will be eaten, as well as affecting feeding, migration, and reproduction.52

Birds: Glyphosate is acutely toxic to birds, but only in large amounts. The LC50, the amount in food that kills 50 percent of a population of test animals, is often above 4000 milligrams per kilogram of food.1

Glyphosate also has indirect impacts on birds. Because glyphosate kills plants, its use creates a dramatic change in the structure of the plant community. This affects bird populations, since the birds depend on the plants for food, shelter, and nest support.

For example, a study of four glyphosate-treated clear-cuts (and an unsprayed control plot) in Nova Scotia found that the densities of the two most common species of birds (white-throated sparrow and common yellowthroat) decreased for two years after glyphosate treatment. By the fourth year post-spray, densities had returned to normal for these two species. However, the unsprayed plot had by then been colonized by new species of birds (warblers, vireos, and a hummingbird). These species did not appear on the sprayed plots.53

An earlier three year study of songbird abundance following glyphosate treatment of clear-cuts in Maine forests showed similar results. Abundances of the total number of birds (Figure 2) and three common species decreased. The decrease in bird abundance was correlated with decrease in the diversity of the habitat.54

Black grouse avoided glyphosate-treated clear-cuts in Norway for several years after treatment.55 Researchers recommended that the herbicide not be used near grouse courtship areas.

Small mammals: In field studies, small mammals have also been indirectly affected when glyphosate kills the vegetation they (or their prey) use for food or shelter. This was first shown in studies of clear-cuts in Maine.38 Insect-eating shrews declined for three years post-treatment; plant-eating voles declined for two. A second study in Maine56 found similar results for voles, but not shrews. A British Columbia study found that deer mice populations were dramatically (83 percent) lower following glyphosate treatment.57 While some other studies have found no affect on mice, this may have occurred because treated areas were small.1 This suggests that effects are more severe when large areas are treated.

In Norway, there was a "strong reduction" in use of sprayed clear-cuts by mountain hare.58

Earthworms: A study of the most common earthworm found in agricultural soils in New Zealand showed that glyphosate significantly affects growth and survival of earthworms. Repeated biweekly applications of low rates of glyphosate (1/20 of typical rates) caused a reduction in growth, an increase in the time to maturity, and an increase in mortality.59

Effects on Nontarget Plants

As a broad-spectrum herbicide, glyphosate has potent acutely toxic effects on most plant species. However, there are other kinds of serious effects. These include effects on endangered species, reduction in the ability to fix nitrogen, increased susceptibility to plant diseases, and reduction in the activity of mycorrhizal fungi.

Endangered species: Because essentially all plants are susceptible to glyphosate-caused damage or mortality, glyphosate can seriously impact endangered plant species. The U.S. Fish and Wildlife Service has identified 74 endangered plant species that it believes could be jeopardized by use of glyphosate. This list is based on the use of glyphosate on 9 crops, and does not include over 50 other uses.41

Nitrogen fixation: Nitrogen is important because of its "near omnipresence" in membranes, proteins, and genetic material of living things. Most living things cannot use nitrogen in its common form and instead use ammonia and nitrates, much rarer compounds. The processes by which ammonia and nitrates are created are called nitrogen fixation and nitrification. They are carried out by certain bacteria.60

A number of studies (from Iowa,61 Australia,62 eastern Canada,63 and Ontario (Canada)64,65) have shown that commercial glyphosate products can reduce nitrogen-fixing or nitrification activity of soils. The amount of glyphosate that produces inhibitory effects varies from 262 to 200063 ppm. Effects can be persistent; the formation of nitrogen-fixing nodules on clover roots was inhibited 120 days after treatment. 62

In addition, tests of cultured nitrogen-fixing bacteria have also shown that glyphosate inhibits nitrogen-fixation. These studies included the nitrogen-fixing species in roots of soybeans66 and clover.67-68

Given the importance of nitrogen-fixation to agriculture, more research is crucial.

Mycorrhizal fungi: Mycorrhizal fungi are beneficial fungi that live in and around plant roots. They help plants absorb nutrients and water and can protect them from cold and drought.69 Glyphosate is toxic to many species of mycorrhizal fungi. Effects, mostly growth inhibition, have been observed at concentrations between 1 and 100 ppm.70-73

Plant diseases: Glyphosate treatment increases the susceptibility of crop plants to a number of diseases. For example, glyphosate reduced the ability of bean plants to defend themselves against the disease anthracnose.74 Glyphosate increased the growth of take-all disease in soil from a wheat field. In addition, the proportion of soil fungi which was antagonistic to the take-all fungus decreased.75 Bean seedlings also survived glyphosate treatment when grown on sterile soil, but not when grown on normal (not sterilized) soil.76 Spraying of Roundup prior to planting barley increased the severity of Rhizoctonia root rot and decreased barley yield.77 In addition, Roundup injection of lodgepole pine inhibited the defensive response of the tree to blue stain fungus.78

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