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# A comparative ecological risk assessment for herbicides used on spring wheat: the effect of glyphosate when used within a glyphosate-tolerant wheat system

Robert K. D. Peterson
Corresponding author. Agricultural and Biological Risk Assessment, Department of Entomology, Montana State University, Bozeman, MT 59717-3020; bpeterson@montana.edu

Andrew G. Hulting
Department of Crop and Soil Sciences, Pennsylvania State University, University Park, PA 16802.

Glyphosate-tolerant spring wheat currently is being developed and most likely will be the first major genetically engineered crop to be marketed and grown in several areas of the northern Great Plains of the United States. The public has expressed concerns about environmental risks from glyphosate-tolerant wheat. Replacement of traditional herbicide active ingredients with glyphosate in a glyphosate-tolerant spring wheat system may alter ecological risks associated with weed management. The objective of this study was to use a Tier 1 quantitative risk assessment methodology to compare ecological risks for 16 herbicide active ingredients used in spring wheat. The herbicide active ingredients included 2,4-D, bromoxynil, clodinafop, clopyralid, dicamba, fenoxaprop, flucarbazone, glyphosate, MCPA, metsulfuron, thifensulfuron, tralkoxydim, triallate, triasulfuron, tribenuron, and trifluralin. We compared the relative risks of these herbicides to glyphosate to provide an indication of the effect of glyphosate when it is used in a glyphosate-tolerant spring wheat system. Ecological receptors and effects evaluated were avian (acute dietary risk), wild mammal (acute dietary risk), aquatic vertebrates (acute risk), aquatic invertebrates (acute risk), aquatic plants (acute risk), nontarget terrestrial plants (seedling emergence and vegetative vigor), and groundwater exposure. Ecological risks were assessed by integrating toxicity and exposure, primarily using the risk quotient method. Ecological risks for the 15 herbicides relative to glyphosate were highly variable. For risks to duckweed, green algae, groundwater, and nontarget plant seedling emergence, glyphosate had less relative risk than most other active ingredients. The differences in relative risks were most pronounced when glyphosate was compared with herbicides currently widely used on spring wheat.

**Nomenclature:** Bromoxynil; clodinafop; clopyralid; dicamba; 2,4-dichlorophenoxy acetic acid; fenoxaprop; flucarbazone; glyphosate; MCPA; metsulfuron; spring wheat; thifensulfuron; tralkoxydim; triallate; triasulfuron; tribenuron; trifluralin; spring wheat, *Triticum aestivum* L.

**Key words:** Biotechnology, exposure assessment, genetically engineered crops, herbicide exposure, herbicide toxicity.

Wheat is the primary cereal crop in the northern Great Plains of the United States (Minnesota, North Dakota, South Dakota, Wyoming, and Montana) and Pacific Northwest (Idaho, Oregon, and Washington). Based on 2003 production data, Minnesota, North Dakota, Washington, Montana, Idaho, and South Dakota were ranked in the top 10 total wheat-producing states (USDA 2003a). For spring wheat, Minnesota, North Dakota, Montana, South Dakota, Idaho, Washington, and Oregon were the top seven producing states.

Glyphosate-tolerant spring wheat most likely will be the first major genetically engineered crop to be marketed and grown in many areas of the northern Great Plains and Pacific Northwest. Regulatory approvals and marketing of seed in the United States are not expected until at least the 2005 growing season (D. Gigax, Monsanto, personal communication). Even though glyphosate-tolerant spring wheat is not being grown commercially, the public has expressed concerns about environmental, agronomic, and human health risks from the technology (Center for Food Safety 2003; Northern Plains Resource Council 2002).

Science-based risk assessment can provide a valuable framework from which to measure, communicate, and make decisions about the environmental impacts from agricultural biotechnology (Peterson 2002; Wolt and Peterson 2000; Wolt et al. 2003). Risk assessment can be defined as a formalized basis for the objective evaluation of risk in which assumptions and uncertainties are clearly considered and presented. The risk assessment framework practiced most frequently today largely follows the "Red Book" paradigm (NRC 1983). Risk assessment flows in a logical, stepwise fashion that includes the following procedures: (1) problem formulation, (2) hazard identification, (3) dose–response relationships, (4) exposure assessment, and (5) risk characterization. Hazard is considered in juxtaposition with exposure to determine risk or to determine what additional data are needed to calculate or refine risk estimates. The five stages of risk assessment can be categorized more simply as representing three major phases: problem formulation, data analysis, and risk characterization (USEPA 1999).

Ecological risk can be described in quantitative terms as a function of exposure and effect (USEPA 1999). Ecological risk assessment uses a tiered modeling approach extending from deterministic field-scale models (Tier 1) based on very conservative assumptions to probabilistic regional-scale models (Tier 4) using refined assumptions (SETAC 1994). In risk assessment, "conservative assumptions" in lower-tier assessments represent overestimates of hazard and exposure. Consequently, the resulting quantitative risk value typically is itself conservative and, therefore, errs on the side of environmental safety.

After regulatory approval and commercialization, glyphosate-tolerant spring wheat potentially could be planted on thousands of hectares. Indeed, if grower acceptance of other glyphosate-tolerant crops is an indication of adoption rate, glyphosate-tolerant spring wheat may be planted on the majority of spring wheat hectares in the United States. Consequently, herbicide use in spring wheat may shift from primarily tank-mix combinations of grass and broadleaf active ingredients to glyphosate as the primary, if not the sole, herbicide input during the growing season.

Herbicides containing the active ingredient glyphosate are used in agriculture, industrial, and residential weed management (Giesy et al. 2000). Formulations of glyphosate for nonselective weed management were first commercialized in 1974, and, currently, glyphosate-based herbicides are among the most widely used herbicides in the world (Franz et al. 1997). Glyphosate underwent reregistration in the United States in 1993 and, at that time, the United States Environmental Protection Agency (USEPA) concluded that glyphosate and its associated formulations when used according to the label will not pose unreasonable risks or adverse effects (USEPA 1993).

If regulatory approval of glyphosate-tolerant spring wheat is granted, recent field trials indicate that the technology has the potential to be a useful weed management tool for spring wheat producers. Blackshaw and Harker (2002) found that glyphosate when used in a glyphosate-tolerant spring wheat system provided similar or better control of several problem weed species compared with other commonly used spring wheat herbicides. They also reported that crop safety was excellent at the glyphosate rates and application timings tested. Another potential value of the technology would be the addition of a previously unavailable incrop mode of action that would be useful to manage weed populations resistant to several herbicide classes.

Replacement of traditional active ingredients with glyphosate in a glyphosate-tolerant spring wheat system may alter ecological risks associated with weed management. Therefore, the objective of this study was to use a Tier 1 quantitative risk assessment methodology to compare ecological risks for 16 herbicide active ingredients used in spring wheat in the United States. In particular, we compared the relative risks of these herbicides to glyphosate to provide an indication of the effect of glyphosate when it is used in a glyphosate-tolerant spring wheat system.

The Tier 1 approach provides a useful standardized basis for considerations of comparative risks, as considered here. However, the risk associated with any particular product and use would need to be clarified with higher tiered assessments that more completely describe actual use and exposure scenarios.

## Materials and Methods

Tier 1 ecological risk assessments were conducted for 15 herbicide active ingredients commonly used in spring wheat in the United States. The herbicide active ingredients included 2,4-D, bromoxynil, clodinafop, clopyralid, dicamba, fenoxaprop, flucarbazone, MCPA, metsulfuron, thifensulfuron, tralkoxydim, triallate, triasulfuron, tribenuron, and trifluralin. These active ingredients were chosen because they are widely on spring wheat in the United States. Ecological risk associated with glyphosate was evaluated because of its use, on appropriate registrations, within a glyphosate-tolerant spring wheat system.

Ecological effects, exposures, and risks from direct exposure to herbicides were evaluated in this study. Indirect risks from changes in weed populations as mediated by herbicides, such as shifts in species diversity and abundance, were not assessed. Ecological receptors and effects evaluated were avian (acute dietary risk), wild mammal (acute dietary risk), aquatic vertebrates (acute risk), aquatic invertebrates (acute risk), aquatic plants (acute risk), nontarget terrestrial plants (seedling emergence and vegetative vigor), and groundwater exposure.

Chronic dietary risks to avian and mammalian species are not presented because chronic toxicities to the herbicides evaluated in this assessment were low. In addition, exposures to the herbicides were not expected to be chronic. Chronic risks to aquatic vertebrates and invertebrates are not presented because chronic toxicity information only was publicly available for 6 of the 16 herbicides. Moreover, for the six herbicides for which information was publicly available, chronic risks were lower than the acute risks, and no chronic risks exceeded USEPA levels of concern (LOC).

Risk to estuarine and marine organisms was not assessed because those species were not expected to be exposed to the herbicides when used on spring wheat in the United States. In addition, risk to nontarget insect pollinators was not evaluated because each herbicide is considered practically nontoxic to the surrogate species, honey bee (*Apis mellifera* L.).

For all ecological receptors, the most sensitive toxicity endpoints that were publicly available were used for this assessment. Data sources for toxicity for each ecological receptor are referenced in each table.

### Avian Acute Dietary Risk

*Toxicity*

Acute dietary toxicities to herbicide active ingredients were compared between the mallard duck (*Anas platyrhynchos* L.) (a waterfowl surrogate species) and the bobwhite quail [*Colinus virginianus* (L.)] (an upland game bird surrogate species). To determine the acute dietary $LC_{50}$, the surrogate species typically are fed a pesticide-treated diet for 5 d, and morbidity and mortality data are recorded (USEPA 1996a). The lowest $LC_{50}$ for each herbicide from either species was used as the toxicological endpoint in the risk characterization. For all herbicides except bromoxynil, an $LC_{50}$ was not established, and the highest dose tested was used to conservatively represent the $LC_{50}$.

*Exposure*

The herbicide residues expected on potential dietary food items immediately after application of the maximum single-use rate for wheat for each herbicide were compared with

$LC_{50}$ values to predict acute dietary risks to birds. The food items for which residues were estimated included short grasses, long grasses, broadleaf plants, insects, fruits, and pods. Herbicide residues on food items immediately after application were estimated based on the methods of Hoerger and Kenaga (1972) and Fletcher et al. (1994). Briefly, Hoerger and Kenaga (1972) and Fletcher et al. (1994) estimated maximum pesticide residues based on application rate and surface area of the food item. They derived a linear relationship between application rate and maximum residues on the different food items. In this assessment, the maximum single-use application rate for each herbicide in spring wheat was used to estimate the residue of the herbicide active ingredient on the food items.

## Wild Mammal Acute Dietary Risk

*Toxicity*

Acute dietary toxicities and exposures to the meadow vole [*Microtus pennsylvanicus* (Ord)], mouse (*Mus musculus* L.), and least shrew [*Cryptotis parva* (Say)]) were used to characterize risk to wild mammals. Acute dietary toxicities to these wild mammals were determined by converting the acute oral $LD_{50}$ in the rat (*Rattus norvegicus* Berkenhout) to an estimated $LC_{50}$ value for dietary exposure (USEPA 1998). The estimated $LC_{50}$ was derived using the following formula:

$$LC_{50} = LD_{50} * \text{body weight (g)} \div \text{food consumed per day (g)} \qquad [1]$$

*Exposure*

The herbicide residues expected on potential dietary food items immediately after application of the maximum single-use rate for wheat for each herbicide were compared with the estimated $LC_{50}$ values to predict acute risks to wild mammals. The mammalian species and associated food items for which residues were estimated included meadow vole consuming short grasses, adult field mouse consuming seeds, and least shrew consuming insects. Herbicide residues on food items immediately after application were estimated based on the methods of Hoerger and Kenaga (1972) and Fletcher et al. (1994) as discussed above.

## Nontarget Terrestrial Plants

*Toxicity*

Nontarget terrestrial plants were considered plants that inhabit nonaquatic areas, which typically are well drained (methods for nontarget aquatic plants are discussed below). Toxicological effects for seedling emergence and vegetative vigor were used in this assessment. Typically, six species of at least four dicotyledonous families (one of which is soybean [*Glycine max* (L.) Merr.] and one of which is a root crop) and four species of at least two monocotyledonous families (one of which is corn [*Zea mays* L.]) are used in toxicology studies. The soil is treated or the pesticide is applied to the foliage at the maximum rate, and effects such as root length, plant height, dry plant weight, morphological changes, and percentage germination are assessed (USEPA 1996b). For nonendangered plant species, the $EC_{25}$ for the most sensitive species and factor was used as the toxicological endpoint. For endangered plant species, the no-observed effect level for the most sensitive species was used.

*Exposure*

A simple total loading rate model based on application rate (1% spray drift) was used to estimate exposure for vegetative vigor effects of nontarget terrestrial plants. A total loading rate (5% runoff + 1% spray drift) was used to estimate exposure for seedling emergence effects.

## Aquatic Risk

*Toxicity*

*Nontarget aquatic plants.* Toxicological effects for green algae (*Selenastrum capricornutum* Printz) (a nonvascular plant surrogate species) and duckweed (*Lemna gibba* L.) (a vascular plant surrogate species) were used in this assessment. In a typical toxicology study, a suitable medium, containing a population of each species is dosed with the active ingredient with a range of concentrations and growth inhibition is determined. For nonendangered aquatic plant species, the $EC_{50}$ is used as the toxicological endpoint (USEPA 1996c, 1996d). For endangered aquatic plant species, the no observed effect concentration is used.

*Aquatic invertebrates.* Acute toxicities of water flea (*Daphnia magna* Straus) to herbicide active ingredients were used in this assessment. This species traditionally has been the preferred test organism to assess freshwater invertebrate toxicity and risk from pesticides. To determine acute effects, newly hatched water flea are exposed to varying concentrations of the active ingredient, and the concentration necessary to immobilize 50% of the individuals is considered the $EC_{50}$. The 48- or 96-h $EC_{50}$ typically is used as the acute toxicity endpoint (USEPA 1996e). Both the glyphosate active ingredient and formulation (Roundup®) toxicity and risk were assessed because the formulation is more toxic to aquatic invertebrates and vertebrates than the active ingredient. For the other active ingredients, it was assumed that the toxicity of the active ingredient was representative of the formulation toxicity.

*Aquatic vertebrates.* Acute toxicities of the rainbow trout [*Oncorhynchus mykiss* (Walbaum)] (a cold-water surrogate species) and the bluegill sunfish (*Lepomis macrochirus* Rafinesque) (a warm-water surrogate species) to herbicide active ingredients were used. These two species historically have been used to establish the toxicity of a pesticide active ingredient to aquatic fishes. To determine acute effects, the surrogate species are exposed to varying concentrations of the active ingredient. The 96-h $LC_{50}$ is used as the acute toxicity endpoint (USEPA 1996f). The lowest $LC_{50}$ for each herbicide from either fish species was used as the toxicological endpoint in the risk characterization. As with the aquatic invertebrate assessment, both the glyphosate active ingredient and formulation (Roundup®) toxicity and risk were assessed. For the other active ingredients, it was assumed that the toxicity of the active ingredient was representative of the formulation toxicity.

*Surface water exposure.* The Tier 1 screening model, the Generic Expected Environmental Concentration Program (GENEEC v. 1.2), was used in this assessment to provide conservative estimates of surface water concentrations of the herbicides (USEPA 2002a). The model was developed by USEPA and primarily uses the chemical application rate, soil adsorption partition coefficient, and degradation half-life values to estimate runoff from a 10-ha field into a 1-ha by 2-m-deep static pond. The model calculates conservative or high-end exposure values after pesticide application to a highly erosive and steep upland slope, with heavy rainfall occurring within 2 d. GENEEC calculates both acute and chronic generic expected environmental concentration values. It considers reduction in dissolved pesticide concentration due to adsorption of pesticide to soil or sediment, incorporation, degradation in soil before washoff to a water body, direct deposition of spray drift into the water body, and degradation of the pesticide within the water body.

For this assessment, maximum single-use application rates in spring wheat and average reported values for the soil adsorption coefficient (Koc) and aerobic soil degradation half-life were used as input values in the model. Where available, water solubility, aerobic aquatic metabolic half-life, and photolysis half-life were used as input values, but GENEEC does not require those data to estimate surface water concentrations.

### Groundwater Concentrations

The Tier 1 screening model, Screening Concentrations in Groundwater, (SCI-GROW v. 2.2) was used in this assessment (USEPA 2002b). It was developed by USEPA and is used to estimate pesticide concentrations in vulnerable ground water. The estimated concentration is based on environmental fate properties of the pesticide (aerobic soil degradation half-life and linear adsorption coefficient normalized for soil organic carbon content [Koc]), the maximum application rate, and existing data from small-scale prospective groundwater monitoring studies at sites with sandy soils and shallow groundwater.

The pesticide concentration estimates provided by SCI-GROW represent conservative or high-end exposure values because the model is based on ground-water monitoring studies, which were conducted by applying pesticides at maximum labeled rates and frequency to vulnerable sites, such as shallow aquifers, sandy, permeable soils, and ensuring substantial rainfall or irrigation to maximize leaching. The EPA states that the SCI-GROW estimate is "usually only likely to be exceeded under exceptional circumstances in a small percentage of the use area." For this reason, the EPA states that "it is not appropriate to use SCI-GROW concentrations for national or regional exposure estimates" (USEPA 2002b). However, for the purposes of this comparison, SCI-GROW is used to assess relative risk of groundwater contamination.

For this assessment, maximum single-use application rates on spring wheat and average reported values for soil adsorption coefficient (Koc) and aerobic soil degradation half-life were used as input values in the model.

### Risk Characterization

Ecological risks in this study were assessed by integrating toxicity and exposure. To do this, risks to ecological receptors were assessed using the risk quotient (RQ) method. For each ecological receptor, an RQ was calculated by dividing the estimated environmental concentration (EEC) by the appropriate toxicity endpoint (e.g., the $LC_{50}$). The general equation used was

$$RQ = EEC \div \text{Toxicity Endpoint} \qquad [2]$$

The toxicity endpoints and EECs for each ecological receptor are discussed above.

Herbicide concentrations in groundwater were not compared with an ecological toxicity endpoint because organisms were not expected to be exposed to groundwater. Instead, estimated concentrations of herbicides in groundwater were considered to represent potential degradation of a water resource. Therefore, estimated concentrations of the herbicides in groundwater served as comparison values.

RQs were compared with USEPA LOCs to indicate potential risk to nontarget organisms. The nonendangered and endangered species LOCs for each ecological receptor assessed are presented in Tables 1–8.

Risks of herbicides compared with the risks of glyphosate for each ecological receptor were determined by dividing the herbicide RQ by the corresponding glyphosate RQ. For example, the nontarget terrestrial plant (seedling emergence) RQ for bromoxynil was 0.25, and the RQ for glyphosate was 0.005. Therefore, the relative risk is 50. The relative risk value, based on Tier 1 toxicity and exposure information, then was used to assess whether the nonglyphosate herbicide presented more or less risk than glyphosate (within the context of the conservatively based Tier 1 assumptions). A relative risk $< 1.0$ presented less risk, and a relative risk $> 1.0$ presented more risk than glyphosate.

## Results and Discussion

### Avian Acute Dietary Risk

All but one herbicide, bromoxynil, were essentially nontoxic at the highest dose tested. Therefore, none of the herbicides exceeded USEPA LOCs for acute avian dietary risk (Table 1). Only two herbicides, MCPA and bromoxynil, exceeded the endangered species LOC. Three herbicides had higher relative risks than glyphosate. However, relative risk values for acute avian risk are of limited value because all herbicides except for bromoxynil were not acutely toxic at the highest dose tested.

### Wild Mammal Acute Dietary Risk

Eleven of the 16 herbicides were not acutely toxic at the highest dose tested None of the herbicides exceeded USEPA LOCs (Table 2). Bromoxynil and 2,4-D exceeded endangered species LOCs. Bromoxynil, 2,4-D, MCPA, triallate, and trifluralin had greater relative risks than glyphosate. As with acute avian risk, the relative risk approach is of limited value because of the number of herbicides that were not acutely toxic at the highest dose tested.

### Nontarget Terrestrial Plants

*Seedling Emergence*

Triallate, 2,4-D, and MCPA exceeded LOCs (Table 3). Eight of the 13 herbicides for which data were available exceeded LOCs for endangered species. All 12 active ingredients for which data were available had greater relative risks

TABLE 1. Avian acute dietary risk from spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $LC_{50}$[b] | Toxicity class[c] | Acute dietary RQ[d,e] | RR[f] | Toxicity data source |
|---|---|---|---|---|---|---|---|
| | g ai $ha^{-1}$ | ppm | ppm | | range | | |
| Glyphosate | 840 | 11–180 | > 4,640 | ST | < 0.002–0.04 | 1 | USEPA 1993 |
| Bromoxynil | 560 | 8–120 | 1,150 | ST | 0.007–**0.1** | **2.5** | USEPA 1998 |
| 2,4-D | 1,100 | 15–240 | > 5,620 | PNT | < 0.003–0.04 | 1 | USEPA 2003 |
| Clodinafop | 67 | 1–19 | > 5,200 | PNT | < 0.0002–0.003 | 0.1 | USEPA 2003 |
| Clopyralid | 146 | 2–31 | > 4,640 | ST | < 0.0004–0.006 | 0.2 | USEPA 2003 |
| Dicamba | 280 | 4–60 | > 10,000 | PNT | < 0.0004–0.006 | 0.2 | USEPA 2003 |
| Fenoxaprop | 90 | 1–19 | > 5,620 | PNT | < 0.0002–0.003 | 0.1 | USEPA 2003 |
| Flucarbazone | 34 | 0.5–7.2 | > 4,621 | ST | < 0.0001–0.002 | 0.1 | USEPA 2003 |
| MCPA | 1,457 | 20–312 | > 2,000 | ST | < 0.01–**0.16** | **4** | USEPA 2003 |
| Metsulfuron | 9 | 0.12–2 | > 5,620 | PNT | < 0.00002–0.0004 | 0.01 | USEPA 2003 |
| Thifensulfuron | 22 | 0.3–4.8 | > 5,620 | PNT | < 0.00005–0.008 | 0.2 | DuPont 2002a |
| Tralkoxydim | 280 | 4–60 | > 6,237 | PNT | < 0.0006–0.01 | 0.3 | USEPA 2003 |
| Triallate | 1,100 | 15–240 | > 5,620 | PNT | < 0.003–0.04 | 1 | USEPA 2003 |
| Triasulfuron | 34 | 0.5–7.2 | > 5,000 | PNT | < 0.00009–0.0014 | 0.04 | USEPA 2003 |
| Tribenuron | 16 | 0.2–3.4 | > 5,620 | PNT | < 0.00004–0.0006 | 0.02 | USEPA 2003 |
| Trifluralin | 1,100 | 15–240 | > 5,000 | PNT | < 0.003–0.05 | **1.3** | USEPA 2003 |

[a] Abbreviations: EEC, estimated environmental concentrations on food sources; PNT, practically nontoxic; ST, slightly toxic; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk.
[b] $LC_{50}$ for the most sensitive species between mallard duck and bobwhite quail. Toxicity sign ">" signifies that the $LC_{50}$ is greater than the highest dose tested.
[c] USEPA Toxicity Class (USEPA 1985a).
[d] $RQ = EEC \div LC_{50}$.
[e] Value in bold indicates the risk exceeds EPA levels of concern for nonendangered ($RQ \geq 0.5$) or endangered ($RQ \geq 0.1$) species.
[f] RR compared with glyphosate (nonendangered species); value in bold indicates greater risk relative to glyphosate.

than glyphosate, which was not unexpected given that glyphosate was the only herbicide assessed that is practically nontoxic with respect to seedling emergence.

*Vegetative Vigor*

MCPA exceeded RQ LOCs (Table 4). Seven herbicides exceeded LOCs for endangered species. Six of the 12 herbicides for which data were available had greater relative risks than glyphosate.

## Nonvascular Aquatic Plants

None of the herbicides exceeded RQ LOCs (Table 5). Twelve of the 15 active ingredients had greater relative risks than glyphosate, with relative risks ranging from 1.4 to 1,870.

## Vascular Aquatic Plants

Metsulfuron and triasulfuron exceeded LOCs (Table 6). Twelve of the 13 herbicides for which toxicity data were available had greater relative risks than glyphosate, with relative risks ranging from 1.6 to 54,002.

## Aquatic Invertebrates

None of the herbicides exceeded LOCs, even though six were moderately toxic, highly toxic, or very highly toxic to water flea (Table 7). Triallate and 2,4-D exceeded endangered species LOCs. Four of the 15 active ingredients had greater relative risks than Roundup®. When the 15 active ingredients were compared with the active ingredient glyphosate and not the formulated product, Roundup®, 12 had greater relative risks.

## Aquatic Vertebrates

None of the herbicides exceeded LOCs, even though seven were moderately toxic, highly toxic, or very highly toxic to rainbow trout or bluegill sunfish (Table 8). Bromoxynil and trifluralin exceeded endangered species LOCs. Five of the 15 active ingredients had greater relative risks than the formulated herbicide, Roundup®. When the 15 active ingredients were compared with the active ingredient glyphosate and not the formulated product, Roundup®, 10 had greater relative risks.

## Herbicide Concentrations in Groundwater

SCI-GROW predicted low groundwater concentrations for all the herbicides (Table 9). All herbicides had modeled groundwater concentrations ≤ 0.1 ppb, except for flucarbazone (0.2 ppb) and MCPA (0.26 ppb). In Europe, 0.1 ppb in groundwater often is used as a nonrisk based regulatory threshold for pesticides in drinking water (European Council 1980). Ten of 15 herbicides had higher predicted groundwater concentrations than glyphosate. Seven herbicides with lower maximum single-use rates than glyphosate had higher predicted groundwater concentrations.

Based on Tier 1 risk assessment methods, few herbicides exceeded USEPA LOCs. RQs greater than LOCs for all ecological receptors ranged from 0.69 to 7.8 for nonendangered species and from 0.06 to 13 for endangered species. Because of the conservative hazard and exposure data used in this Tier 1 assessment, RQ's in this assessment most likely would be considerably below LOCs using a higher tiered assessment. Based on RQ's calculated in this Tier 1 assessment, currently labeled herbicides and glyphosate most likely will not produce unacceptable ecological risks—as defined by USEPA—when used in spring wheat.

Table 2. Wild mammal acute dietary risk from spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $LC_{50}$[b] | Toxicity class[c] | Acute dietary RQ[d,e] | RR[f] | Toxicity data source |
|---|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | ppm | ppm | | range | | |
| Glyphosate | 840 | 11–180 | > 5,000 | PNT | < 0.0004–0.02 | 1 | USEPA 1993 |
| Bromoxynil | 560 | 7–120 | 238 | MT | 0.005–0.31 | **16** | USEPA 1998 |
| 2,4-D | 1,100 | 15–240 | 375 | MT | 0.006–**0.4** | **20** | EXTOXNET 1996 |
| Clodinafop | 67 | 0.9–14.4 | > 2,276 | PNT | < 0.0006–0.004 | 0.2 | Syngenta 2002a |
| Clopyralid | 146 | 2–31.2 | > 4,300 | PNT | < 0.00007–0.005 | 0.3 | Information Ventures 1995 |
| Dicamba | 280 | 4–60 | 1,707 | ST | 0.0004–0.02 | 1 | EXTOXNET 1996 |
| Fenoxaprop | 90 | 1–19 | > 3,254 | PNT | < 0.00005–0.004 | 0.2 | Bayer CropScience 2002 |
| Flucarbazone | 34 | 0.45–7.2 | > 5,000 | PNT | < 0.00002–0.0009 | 0.05 | Bayer CropScience 2001 |
| MCPA | 1,457 | 19.5–312 | 700 | ST | 0.005–**0.28** | **14** | EXTOXNET 1996 |
| Metsulfuron | 9 | 0.12–2 | > 5,000 | PNT | < 0.000004–0.0002 | 0.01 | EXTOXNET 1996 |
| Thifensulfuron | 22 | 0.3–4.8 | > 5,000 | PNT | < 0.00001–0.0006 | 0.03 | DuPont 2002a |
| Tralkoxydim | 280 | 3.75–60 | > 5,000 | PNT | < 0.0001–0.007 | 0.4 | Syngenta 2002b |
| Triallate | 1,100 | 15–240 | 3,382 | PNT | 0.0007–0.04 | **2** | USEPA 2001 |
| Triasulfuron | 34 | 0.45–7.2 | > 2,276 | PNT | < 0.00003–0.002 | 0.1 | Syngenta 1998 |
| Tribenuron | 16 | 0.21–3.36 | > 5,000 | PNT | < 0.000007–0.0004 | 0.02 | DuPont 2002b |
| Trifluralin | 1,100 | 15–240 | > 5,000 | PNT | < 0.0004–0.03 | **1.5** | USEPA 1996g |

[a] Abbreviations: EEC, estimated environmental concentrations on food sources; PNT, practically nontoxic; ST, slightly toxic; MT, moderately toxic; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk.
[b] $LC_{50}$ for the most sensitive species between mallard duck and bobwhite quail. Toxicity sign ">" signifies that the $LC_{50}$ is greater than the highest dose tested.
[c] USEPA Toxicity Class.
[d] $RQ = EEC \div LC_{50}$.
[e] Value in bold indicates the risk exceeds EPA levels of concern for nonendangered ($RQ \geq 0.5$) or endangered ($RQ \geq 0.1$) species.
[f] RR compared with glyphosate (nonendangered species); value in bold indicates greater risk relative to glyphosate.

There were quantitative differences in ecological risks among the 16 spring wheat herbicides evaluated in this study. Ecological risks for the 15 herbicides relative to glyphosate were highly variable, ranging from 0.001 to 54,002 across all ecological receptors. Despite the variation in relative risks, several conclusions can be drawn. For risks to duckweed, green algae, groundwater, and nontarget plant seedling emergence, glyphosate had less relative risk than most other active ingredients. The differences in relative risks were most pronounced when comparing glyphosate with active ingredients currently with substantial market share in terms of percentage of total area treated, such as 2,4-D, MCPA, triallate, dicamba, and bromoxynil.

Currently, the broadleaf herbicides 2,4-D, MCPA, dicam-

Table 3. Nontarget terrestrial plant risk (seedling emergence) to spring wheat herbicides.

| Active ingredient | Application rate | EEC[a] | $EC_{25}$[b] | NOEL[b] | RQ[c,d] | Endangered species RQ[c,d] | RR[e] | Toxicity data source |
|---|---|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | g ai/ha | g ai/ha | g ai/ha | | | | |
| Glyphosate | 840 | 50.4 | > 11,208 | > 11,208 | < 0.005 | 0.005 | 1 | USEPA 2003 |
| Bromoxynil | 560 | 33.6 | 134 | 22.4 | 0.25 | **1.5** | **50** | USEPA 1998 |
| 2,4-D | 1,100 | 66 | 33.6 | 16.8 | **2** | **4.0** | **400** | USEPA 2003 |
| Clodinafop | 67 | 4 | 33.6 | 25.8 | 0.12 | 0.16 | **24** | USEPA 2003 |
| Clopyralid | 146 | 8.8 | 11.2 | 1.4 | 0.78 | **6.2** | **156** | USEPA 2003 |
| Dicamba | 280 | 16.8 | 44.8 | 2.2 | 0.375 | **7.5** | **75** | USEPA 2003 |
| Fenoxaprop | 90 | 5.4 | NA | NA | | | | |
| Flucarbazone | 34 | 2 | 11.2 | 0.25 | 0.18 | **8.2** | **36** | USEPA 2003 |
| MCPA | 1,457 | 87.4 | 11.2 | 6.7 | **7.8** | **13** | **1,560** | USEPA 2003 |
| Metsulfuron | 9 | 0.5 | NA | NA | | | | |
| Thifensulfuron | 22 | 1.3 | NA | NA | | | | |
| Tralkoxydim | 280 | 16.8 | 22.4 | 15.7 | 0.75 | **1.1** | **150** | USEPA 2003 |
| Triallate | 1,100 | 66 | 22.4 | 11.2 | **3** | **6.0** | **600** | USEPA 2003 |
| Triasulfuron | 34 | 2 | 22.4 | 2.5 | 0.09 | 0.8 | **18** | USEPA 2003 |
| Tribenuron | 16 | 1 | 11.2 | 3.4 | 0.084 | 0.3 | **17** | USEPA 2003 |
| Trifluralin | 1,100 | 66 | 370 | 146 | 0.18 | 0.5 | **36** | USEPA 2003 |

[a] Abbreviations: EEC, estimated environmental concentration; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk; NOEL, no-observed effect level.
[b] $EC_{25}$ or NOEL for the most sensitive surrogate species. Toxicity sign ">" signifies that the $EC_{25}$ or NOEL is greater than the highest dose tested.
[c] $RQ = EEC \div EC_{25}$ (nonendangered species) or NOEL (endangered species).
[d] Value in bold indicates the risk exceeds EPA levels of concern ($RQ \geq 1$).
[e] RR compared with glyphosate (nonendangered species); value in bold indicates greater risk relative to glyphosate.

Table 4. Nontarget terrestrial plant risk (vegetative vigor) to spring wheat herbicides.

| Active ingredient | Application rate | EEC[a] | $EC_{25}$[b] | NOEL[b] | RQ[c,d] | Endangered species RQ[c,d] | RR[e] | Toxicity data source |
|---|---|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | g ai/ha | | lb ai/a | | | | |
| Glyphosate | 840 | 8.4 | 100.9 | 39.2 | 0.08 | 0.21 | 1 | USEPA 2003 |
| Bromoxynil | 560 | 5.6 | 19.1 | 16.8 | 0.29 | 0.33 | **3.5** | USEPA 1998 |
| 2,4-D | 1,100 | 11 | 11.2 | 2.2 | 1.0 | **5** | **12** | USEPA 2003 |
| Clodinafop | 67 | 0.67 | 22.4 | 6.3 | 0.03 | 0.11 | 0.4 | USEPA 2003 |
| Clopyralid | 146 | 1.46 | 11.2 | 0.56 | 0.13 | **2.6** | **1.6** | USEPA 2003 |
| Dicamba | 280 | 2.8 | 11.2 | 0.56 | 0.25 | **5** | **3** | USEPA 2003 |
| Fenoxaprop | 90 | 0.09 | NA | NA | | | | |
| Flucarbazone | 34 | 0.34 | 11.2 | 0.25 | 0.03 | **1.4** | 0.4 | USEPA 2003 |
| MCPA | 1,457 | 0.013 | 11.2 | 4.5 | **1.3** | **3.3** | **16** | USEPA 2003 |
| Metsulfuron | 9 | 0.09 | NA | NA | | | | |
| Thifensulfuron | 22 | 0.22 | NA | NA | | | | |
| Tralkoxydim | 280 | 2.8 | 11.2 | 3 | 0.25 | 0.9 | **3** | USEPA 2003 |
| Triallate | 1,100 | 11 | 40 | 10.1 | 0.3 | **1.1** | **3.6** | USEPA 2003 |
| Triasulfuron | 34 | 0.34 | 11.2 | 0.34 | 0.03 | **1** | 0.4 | USEPA 2003 |
| Tribenuron | 16 | 0.16 | 22.4 | 0.02 | 0.007 | **7** | 0.08 | USEPA 2003 |
| Trifluralin | 1,100 | 11 | 751 | 280 | 0.01 | 0.04 | 0.18 | USEPA 2003 |

[a] Abbreviations: EEC, estimated environmental concentration; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk; NOEL, no-observed effect level.
[b] $EC_{25}$ or NOEL for the most sensitive surrogate species. Toxicity sign ">" signifies that the $EC_{25}$ or NOEL is greater than the highest dose tested.
[c] RQ = EEC ÷ $EC_{25}$ (nonendangered species) or NOEL (endangered species).
[d] Value in bold indicates the risk exceeds EPA levels of concern (RQ ≥ 1).
[e] RR compared with glyphosate (nonendangered species); value in bold indicates greater risk relative to glyphosate.

ba, tribenuron, and bromoxynil are used on approximately 58, 26, 23, 20, and 13%, respectively, of total spring wheat area in the United States (USDA 2003b). The herbicides 2,4-D, MCPA, and bromoxynil had higher relative risks than glyphosate for eight of the nine ecological receptors evaluated. Dicamba and tribenuron had higher relative risks than glyphosate for five and three of the nine receptors, respectively.

The grass weed management herbicides fenoxaprop, triallate, trifluralin, and tralkoxydim currently are used on approximately 58, 12, 9, and 6%, respectively, of spring wheat hectares in the United States (A. M. Kirk, unpublished data, USDA 2003b). Triallate and trifluralin had higher relative risks than glyphosate for eight of the nine ecological receptors. Tralkoxydim had higher risks relative to glyphosate for six of the nine receptors. However, fenoxaprop had higher relative risks than glyphosate only for one of the six ecological receptors for which data were available.

Conventional weed management programs in wheat typically involve applications of soil-applied or postemergence

Table 5. Nontarget nonvascular aquatic plant risk to spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $EC_{50}$[b] | RQ[c] | RR[d] | Toxicity data source |
|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | ppb | ppm | | | |
| Glyphosate | 840 | 2.96 | 12.54 | 0.0002 | 1 | USEPA 2003 |
| Bromoxynil | 560 | 3.11 | 0.051 | 0.0610 | **258** | USEPA 1998 |
| 2,4-D | 1,100 | 37.26 | 33.2 | 0.0011 | **4.8** | USEPA 2003 |
| Clodinafop | 67 | 0.459 | 5.41 | 0.0001 | 0.36 | USEPA 2003 |
| Clopyralid | 146 | 6.12 | 6.9 | 0.0009 | **3.8** | USEPA 2003 |
| Dicamba | 280 | 12.41 | > 3.7 | < 0.0034 | **14.2** | USEPA 2003 |
| Fenoxaprop | 90 | 0.21 | 0.65 | 0.0003 | **1.4** | USEPA 2003 |
| Flucarbazone | 34 | 1.42 | > 89.2 | < 0.00002 | 0.07 | USEPA 2003 |
| MCPA | 1,457 | 47.15 | 122 | 0.0004 | **1.6** | USEPA 2003 |
| Metsulfuron | 9 | 0.371 | 0.285 | 0.0013 | **5.5** | USEPA 2003 |
| Thifensulfuron | 22 | 0.808 | 0.0157 | 0.0515 | **218** | USEPA 2003 |
| Tralkoxydim | 280 | 9.47 | 7.7 | 0.0012 | **5.2** | USEPA 2003 |
| Triallate | 1,100 | 10.5 | 0.14 | 0.0750 | **318** | USEPA 2003 |
| Triasulfuron | 34 | 1.21 | 0.018 | 0.0672 | **285** | USEPA 2003 |
| Tribenuron | 16 | 0.576 | 4.9 | 0.0001 | 0.5 | USEPA 2003 |
| Trifluralin | 1,100 | 3.32 | 0.00752 | 0.4415 | **1,870** | USEPA 1996g |

[a] Abbreviations: EEC, estimated environmental concentration; RQ, risk quotient; RR, relative risk.
[b] $EC_{50}$ for *Selenastrum capricornutum*. Toxicity sign ">" signifies that the $EC_{50}$ is greater than the highest dose tested.
[c] RQ = EEC ÷ $EC_{50}$.
[d] RR compared with glyphosate; value in bold indicates greater risk relative to glyphosate.

Table 6. Nontarget vascular aquatic plant risk to spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $EC_{50}$[b] | RQ[c,d] | RR[e] | Toxicity data source |
|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | ppb | ppm | | | |
| Glyphosate | 840 | 2.96 | 25.1 | 0.0001 | 1 | USEPA 2003 |
| Bromoxynil | 560 | 3.11 | 0.219 | 0.0142 | **120** | USEPA 1998 |
| 2,4-D | 1,100 | 37.26 | 0.7 | 0.0532 | **451** | USEPA 2003 |
| Clodinafop | 67 | 0.459 | 2.4 | 0.0002 | **1.6** | USEPA 2003 |
| Clopyralid | 146 | 6.12 | NA | | | |
| Dicamba | 280 | 12.41 | > 3.25 | < 0.0038 | **32** | USEPA 2003 |
| Fenoxaprop | 90 | 0.21 | NA | | | |
| Flucarbazone | 34 | 1.42 | > 12.6 | < 0.0001 | 1 | USEPA 2003 |
| MCPA | 1,457 | 47.15 | 0.17 | 0.2774 | **2,352** | USEPA 2003 |
| Metsulfuron | 9 | 0.371 | 0.00036 | **1.03** | **8,739** | USEPA 2003 |
| Thifensulfuron | 22 | 0.808 | 0.00159 | 0.5082 | **4,309** | USEPA 2003 |
| Tralkoxydim | 280 | 9.47 | 2.6 | 0.0036 | **31** | USEPA 2003 |
| Triallate | 1,100 | 10.5 | > 10 | < 0.0011 | **8.9** | USEPA 2001 |
| Triasulfuron | 34 | 1.21 | 0.00019 | **6.4** | **54,002** | USEPA 2003 |
| Tribenuron | 16 | 0.576 | 0.0042 | 0.1371 | **1,163** | USEPA 2003 |
| Trifluralin | 1,100 | 3.32 | 0.0435 | 0.0763 | **647** | USEPA 1996g |

[a] Abbreviations: EEC, estimated environmental concentration; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk.
[b] $EC_{50}$ for *Lemna gibba*. Toxicity sign ">" signifies that the $EC_{50}$ is greater than the highest dose tested.
[c] $RQ = EEC \div EC_{50}$.
[d] Value in bold indicates the risk exceeds EPA levels of concern ($RQ \geq 1$).
[e] RR compared with glyphosate; value in bold indicates greater risk relative to glyphosate.

broadleaf and grass herbicides. These herbicides are applied sequentially or often simultaneously as tank-mix combinations. Common tank-mix programs in spring wheat can include (1) tralkoxydim + thifensulfuron + tribenuron; (2) triallate + metsulfuron + 2,4-D; (3) fenoxaprop or clodinafop + bromoxynil + MCPA; or (4) tribenuron + fenoxaprop (A. M. Kirk, unpublished data). For example, in North Dakota these active ingredients in various combinations were applied to approximately 126% of the total wheat hectares planted that were treated with herbicides in 2000 (Glogoza et al. 2002). Results from this assessment indicate that glyphosate when used alone would produce less ecological risk overall than triallate + metsulfuron + 2,4-D, fenoxaprop or clodinafop + bromoxynil + MCPA, and tralkoxydim + thifensulfuron + tribenuron.

Although this study assessed most of the ecological risks

Table 7. Aquatic invertebrate risk to spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $EC_{50}$[b] | Toxicity class[c] | RQ[d,e] | RR[f] | Toxicity data source |
|---|---|---|---|---|---|---|---|
| | g ai ha$^{-1}$ | ppm | | | | | |
| Roundup® | 840 | 2.96 | 11.3 | ST | 0.0003 | 1 | USEPA 2003 |
| Glyphosate | 840 | 2.96 | 780 | PNT | 0.000004 | 0.014 | USEPA 2003 |
| Bromoxynil | 560 | 3.11 | 0.032 | VHT | 0.097 | **371** | USEPA 2003 |
| 2,4-D | 1,100 | 37.26 | 0.054 | VHT | **0.69** | **2,634** | USEPA 2003 |
| Clodinafop | 67 | 0.459 | 59.5 | ST | 0.00001 | 0.03 | USEPA 2003 |
| Clopyralid | 146 | 6.12 | 225 | PNT | 0.00003 | 0.10 | USEPA 2003 |
| Dicamba | 280 | 12.41 | 110 | PNT | 0.0001 | 0.43 | USEPA 2003 |
| Fenoxaprop | 90 | 0.21 | 3.18 | MT | 0.0001 | 0.25 | USEPA 2003 |
| Flucarbazone | 34 | 1.42 | > 109 | PNT | < 0.00001 | 0.05 | USEPA 2003 |
| MCPA | 1,457 | 47.15 | > 180 | PNT | < 0.0003 | 1 | USEPA 2003 |
| Metsulfuron | 9 | 0.371 | > 150 | PNT | < 0.000002 | 0.01 | USEPA 2003 |
| Thifensulfuron | 22 | 0.808 | > 1000 | PNT | < 0.000001 | 0.003 | PAN 2003 |
| Tralkoxydim | 280 | 9.47 | > 110 | PNT | < 0.0001 | 0.33 | USEPA 2003 |
| Triallate | 1,100 | 10.5 | 0.091 | VHT | **0.11** | **440** | USEPA 2001 |
| Triasulfuron | 34 | 1.21 | > 100 | PNT | < 0.00001 | 0.05 | USEPA 2003 |
| Tribenuron | 16 | 0.576 | 720 | PNT | 0.000001 | 0.003 | USEPA 2003 |
| Trifluralin | 1,100 | 3.32 | 0.56 | HT | 0.006 | **23** | USEPA 2003 |

[a] Abbreviations: EEC, estimated environmental concentration; PNT, practically nontoxic; ST, slightly toxic; MT, moderately toxic; HT, highly toxic; VHT, very highly toxic; RQ, risk quotient; EPA, Environmental Protection Agency; RR, relative risk.
[b] $EC_{50}$ for *Daphnia magna*. Toxicity sign ">" signifies that the $EC_{50}$ is greater than the highest dose tested.
[c] USEPA Toxicity Class (USEPA 1985b).
[d] $RQ = EEC \div EC_{50}$.
[e] Value in bold indicates the risk exceeds EPA levels of concern for nonendangered ($RQ \geq 0.5$) or endangered ($RQ \geq 0.05$) species.
[f] RR compared with Roundup® herbicide (nonendangered species); value in bold indicates greater risk relative to Roundup® herbicide.

Table 8. Aquatic vertebrate risk to spring wheat herbicides.

| Active ingredient | Application rate | Peak EEC[a] | $LC_{50}$[b] | Toxicity class[c] | RQ[d,e] | RR[f] | Toxicity data source |
|---|---|---|---|---|---|---|---|
| | g ai $ha^{-1}$ | ppm | | | | | |
| Roundup® | 840 | 2.96 | 5.4 | MT | 0.0005 | 1 | USEPA 2003 |
| Glyphosate | 840 | 2.96 | 86 | ST | 0.00003 | 0.06 | USEPA 1993 |
| Bromoxynil | 560 | 3.11 | 0.053 | VHT | **0.06** | **107** | USEPA 1998 |
| 2,4-D | 1,100 | 37.26 | 110 | PNT | 0.0003 | 0.62 | USEPA 2003 |
| Clodinafop | 67 | 0.459 | 0.21 | HT | 0.002 | **4** | Syngenta 2002a |
| Clopyralid | 146 | 6.12 | 103.5 | PNT | 0.0001 | 0.11 | USEPA 2003 |
| Dicamba | 280 | 12.41 | 130 | PNT | 0.0001 | 0.17 | USEPA 2003 |
| Fenoxaprop | 90 | 0.21 | 0.46 | HT | 0.0005 | 0.83 | USEPA 2003 |
| Flucarbazone | 34 | 1.42 | 96.7 | ST | 0.0000 | 0.03 | USEPA 2003 |
| MCPA | 1,457 | 47.15 | 91 | ST | 0.0005 | 0.95 | USEPA 2003 |
| Metsulfuron | 9 | 0.371 | > 150 | PNT | < 0.000002 | 0.005 | DuPont 2003 |
| Thifensulfuron | 22 | 0.808 | > 100 | PNT | < 0.00001 | 0.01 | DuPont 2002a |
| Tralkoxydim | 280 | 9.47 | 7.7 | MT | 0.001 | **2.2** | USEPA 2003 |
| Triallate | 1,100 | 10.5 | 1.2 | MT | 0.009 | **16** | USEPA 2001 |
| Triasulfuron | 34 | 1.21 | > 100 | PNT | < 0.00001 | 0.02 | USEPA 2003 |
| Tribenuron | 16 | 0.576 | > 1,000 | PNT | < 0.000001 | 0.001 | USEPA 2003 |
| Trifluralin | 1,100 | 3.32 | 0.041 | VHT | **0.08** | **148** | USEPA 2003 |

[a] Abbreviations: EEC, estimated environmental concentration; PNT, practically nontoxic; ST, slightly toxic; MT, moderately toxic; HT, highly toxic; VHT, very highly toxic; RQ, risk quotient; RR, relative risk; EPA, Environmental Protection Agency.
[b] $EC_{50}$ for the most sensitive species between rainbow trout and bluegill sunfish. Toxicity sign ">" signifies that the $LC_{50}$ is greater than the highest dose tested.
[c] USEPA Toxicity Class (USEPA 1985c).
[d] $RQ = EEC \div LC_{50}$.
[e] Value in bold indicates the risk exceeds EPA levels of concern for nonendangered ($RQ \geq 0.5$) or endangered ($RQ \geq 0.05$) species.
[f] RR compared with Roundup® (nonendangered species); value in bold indicates greater risk relative to Roundup®.

to receptors for which data were publicly available, it could be argued that glyphosate poses risks to other nontarget organisms that exceed the risks presented here. In an ecological risk assessment, Giesy et al. (2000) presented ecotoxicological and exposure data for numerous nontarget organisms and concluded that the risks were not significant. Besides bobwhite quail and mallard duck, the only other avian species for which toxicological responses have been assessed after exposure to glyphosate has been the zebra finch (*Peophila guttata* Vieillot). In a dietary toxicity study, Evans and Batty (1986) showed that the NOEC after exposure to Roundup® herbicide was 8,064 mg $kg^{-1}$ diet, which was greater than either avian surrogate species discussed above. In the mouse the acute oral $LD_{50}$ was > 5,000 mg Roundup $kg^{-1}$ diet,

Table 9. Predicted groundwater concentrations of active ingredients based on SCI-GROW modeling.[a]

| Active ingredient | Application rate | Groundwater value | RR[b] | Koc[c,d] | Aerobic soil half-life | Model input data source |
|---|---|---|---|---|---|---|
| | g ai $ha^{-1}$ | ppb | | | d | |
| Glyphosate | 840 | 0.0005 | 1 | 2,100 | 2 | USDA 2003 |
| 2,4-D | 560 | 0.005 | **10** | 48 | 5.5 | USDA 2003 |
| Bromoxynil | 1,100 | 0.0004 | 0.8 | 1,003 | 2 | USEPA 1998 |
| Clodinafop | 67 | 0.00003 | 0.06 | 252 | 1 | Syngenta 2002a |
| Clopyralid | 146 | 0.06 | **120** | 36 | 26 | USDA 2003 |
| Dicamba | 280 | 0.1 | **220** | 13 | 18 | USDA 2003 |
| Fenoxaprop | 90 | 0.000006 | 0.01 | 9,490 | 1 | USDA 2003 |
| Flucarbazone | 34 | 0.2 | **400** | NA | NA | USEPA 2000 |
| MCPA | 1,457 | 0.26 | **520** | 110 | 25 | USDA 2003 |
| Metsulfuron | 9 | 0.004 | **8** | 42 | 28 | USDA 2003 |
| Thifensulfuron | 22 | 0.0001 | 0.2 | 28 | 6 | USDA 2003 |
| Tralkoxydim | 280 | 0.001 | **2** | 30 | 5 | Syngenta 2002b |
| Triallate | 1,100 | 0.04 | **80** | 1,601 | 54 | USEPA 2001 |
| Triasulfuron | 34 | 0.05 | **100** | 105 | 114 | USDA 2003 |
| Tribenuron | 16 | 0.00003 | 0.06 | 52 | 2 | USDA 2003 |
| Trifluralin | 1,100 | 0.009 | **18** | 7,200 | 169 | USDA 2003 |

[a] Abbreviations: RR, relative risk; NA, not available.
[b] RR, relative risk compared with glyphosate; value in bold indicates greater risk relative to glyphosate.
[c] Koc, soil adsorption coefficient.
[d] NA, model input data not publicly available for flucarbazone; groundwater value obtained from USEPA 2000.

the highest dose tested. For both the hopping mouse [*Notomys mitchelli* (Ogilby)] and stripe-faced dunnart marsupial [*Sminthopsis macroura* (Gould)] the dietary no-observed-adverse-effect-level was $> 15{,}000$ mg Roundup® kg diet$^{-1}$ (equivalent to $> 4{,}650$ mg glyphosate kg diet$^{-1}$). In the goat (*Capra hircus* L.), toxicological testing on glyphosate and the Roundup® formulation produced acute oral $LD_{50}$'s that ranged from 3,500 to 5,700 mg kg body weight$^{-1}$ (Giesy et al. 2000).

Giesy et al. (2000) concluded that earthworms (*Eisenia foetida* Savigny) were at minimal risk from the use of glyphosate. Two recent studies examined the effects of glyphosate and glyphosate-tolerant crops on insects in field plots. Bitzer et al. (2002) did not observe the deleterious short-term effects of glyphosate-tolerant soybean weed management systems on abundance of springtail species. McPherson et al. (2003) did not observe the differences in seasonal abundance of insect pests between conventional and glyphosate-tolerant soybean.

Thirteen fish species in addition to rainbow trout and bluegill sunfish have been evaluated for acute toxicity to glyphosate and the Roundup® formulation (Giesy et al. 2000). The most sensitive species to glyphosate or the formulated product was the rainbow trout. Similarly, acute toxicity studies conducted on five species of amphibians revealed sensitivities to glyphosate and the formulated product less than that of the rainbow trout. Of 15 species of aquatic invertebrates listed by Giesy et al. (2000), only crayfish [*Orconectes nais* (Faxon)] was more sensitive to Roundup® than water flea (Mayer and Ellersieck 1986).

Tier 1 risk assessment approaches are limited for accurate quantifications of risk because of their hazard and exposure assumptions. These assumptions, which are highly conservative and err on the side of environmental safety, typically are used for screening out negligible risks in decision making. However, because of their standardized effects and exposure assumptions we believe that the Tier 1 approach is valuable for making direct comparisons of quantitative risk between pesticides. Indeed, the methodology we have used in this study is similar to approaches used by USEPA to evaluate petitions for reduced risk represented by the registration of new pesticide active ingredients (USEPA 1997).

Previously, many pesticide risk comparisons primarily have focused on hazard comparisons (Higley and Wintersteen 1992; Kovach et al. 1992; Nelson and Bullock 2003). Although these approaches can be used to compare pesticide risks, we believe that without incorporating environmental exposures and integrating them with hazards, hazard comparisons alone are more limited. For example, in this assessment, toxicity considerations alone would indicate that numerous herbicides are moderately, highly, or very highly toxic to aquatic vertebrates and invertebrates (Tables 7 and 8). However, when conservative estimates of environmental exposures to pesticides in surface waters were incorporated with hazard information to produce RQ's, those RQ's did not exceed nonendangered species LOCs.

The Tier 1 risk assessment methodology allows for standardized comparisons between pesticides because it is possible to determine relative risks between active ingredients with publicly available information. The difference in risks between two herbicide active ingredients most likely would not change if higher tiers are incorporated for each pesticide (i.e., relative risks between pesticides may be proportionally similar at any tier). However, to our knowledge, risk comparisons between pesticides at higher tiers have not occurred or have not been reported in the literature. Therefore, our hypothesis about the proportional similarity among pesticides at different risk assessment tiers should be tested.

Even though all the herbicides discussed here most likely do not represent unacceptable ecological risks—as defined by EPA—when used according to their respective labels in spring wheat, this assessment shows that there are quantitative differences in risk among the 16 active ingredients. Therefore, this assessment provides a potential mechanism for decision makers to choose between herbicides and weed management systems with different ecological risks. Although many of the RQ's determined in this study were below USEPA LOCs, we believe that the differences in risk between the herbicides are valuable for decision makers. The USEPA regulates pesticides in the United States, but clearly that agency is not the sole arbiter of decisions about the risks from pesticides. Therefore, discriminations of ecological risks between herbicides using different techniques are potentially valuable for decision making.

Ideally, the ecological risk assessment presented here would be considered in juxtaposition with other needed assessments for glyphosate-tolerant spring wheat, such as human health risks from herbicides, agronomic risks and benefits, and ecological and human risks posed by the transgenic product (i.e., glyphosate-tolerant wheat). The resulting assessments then would form an information base from which decision makers, such as individual growers, could make decisions based on quantitative differences in risk.

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