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Glyphosate Stewardship: Maintaining the Effectiveness of a Widely Used Herbicide

TIM MILLER, Mount Vernon Research and Extension Center, Mount Vernon, Washington; BRAD HANSON, UC Cooperative Extension Weed Specialist, Department of Plant Sciences, University of California, Davis; ED PEACHEY, Department of Horticulture, Oregon State University, Corvallis; RICK BOYDSTON, USDA Agricultural Research Service, Prosser, Washington; KASSIM AL-KHATIB, UC Cooperative Extension Weed Specialist and Director of Statewide IPM Program, Department of Plant Sciences, University of California, Davis

Glyphosate has been used since it was registered in 1974 under the trade name Roundup. It is a foliar-applied herbicide that readily moves throughout the plant, both in phloem (tissue that moves carbohydrates) and xylem (tissue that moves water). Because of its net negative charge, it tightly binds to phosphate sorption sites on soil and organic matter; therefore, glyphosate very rarely exhibits soil activity. It is an effective herbicide for burndown treatments to control weeds before planting. In addition, it is widely used in orchards and glyphosate-resistant crops.

Glyphosate kills plants by inhibiting a particular enzyme, 5-enolpyruvyl shikimate-3-phosphate (EPSP) synthase. This enzyme is one of several in the shikimic acid pathway, which is how plants produce the aromatic amino acids phenylalanine, tyrosine, and tryptophan. Amino acids are building blocks for the plant, so a plant not able to manufacture all amino acids is unable to grow and develop normally. Plants also use these three specific amino acids to synthesize more complex structural compounds (such as lignin) and a host of plant defense molecules (such as alkaloids, cyanogenic glycosides, coumarins, and flavonoids), which together can make up 60 percent of a plant's dry weight. Consequently, inhibition of this pathway causes serious consequences for a plant, and it helps to explain why glyphosate is such an effective herbicide. It is also an herbicide with a very low mammalian toxicity, as mammals do not have the EPSP synthase enzyme.

Using Glyphosate Effectively

While glyphosate effectively controls many weedy species, including annual and perennial grass and broadleaf weeds, many factors play a role in how well it controls these weeds.

Formulation

Glyphosate is normally formulated as a salt, which is a compound that can split into positively and negatively charged portions when mixed with water. Glyphosate salts include potassium, diammonium, isopropylamine, trimethylsulfonium, and sesquisodium. Formulations differ in how much glyphosate ends up in the final product, due to the chemistry of the salt and the different adjuvants used by the various manufacturers. The amount of the glyphosate salt in the formulation is listed on the herbicide label as the active ingredient (a.i.). In the case of glyphosate, however, only the glyphosate portion of the salt is actually herbicidal; the other portion of the salt is nonherbicidal. Why would a manufacturer formulate glyphosate as a salt? Glyphosate salts are better able to enter into plant tissues than is the free glyphosate acid, so these formulations provide better weed control.

Since different salts have different molecular weights, it would be difficult to determine how much actual glyphosate is contained in different formulated products if we just look at the a.i. content, usually listed as pounds of a.i. per gallon (lbs a.i./gal) or grams of a.i. per liter (g a.i./l). When comparing different formulations of glyphosate, it is better to look at the acid equivalent (a.e.), which is the amount of glyphosate in the negatively charged or acid portion of the salt, the part of the a.i. that binds with EPSP synthase. Therefore, using the a.e. is also the best way to select the appropriate application rate for various formulations, since the a.e. represents the amount of glyphosate needed to control certain weed species (table 1).

Table 1. Glyphosate product comparisons

Trade name	Formulated salt*	Concentration†		0.75 lb a.e. product rate (oz/ac)
		lb a.i./gal	lb a.e./gal	
Roundup Original	IPA	4	3	32
Roundup Original Max	K	5.5	4.5	22
Roundup PowerMax	K	5.5	4.5	22
Roundup Ultra	IPA	4	3	32
Roundup WeatherMax	K	5.5	4.5	22
Touchdown	DA	3.75	3	32
Touchdown Total	K	5	4.2	24
Touchdown HiTech	K	6	5	19
Durango	IPA	5.4	4	26
Glyphomax XRT	IPA	5.4	4	26
most generics	IPA	4	3	32

Source: Peterson, D., B. Olson, K. Al-Khatib, R. Currie, J. A. Dille, J. Falk, P. Geier et al. 2007. Glyphosate stewardship. Kansas State University publication MF-2767, Kansas State Research and Extension website, http://www.ksre.k-state.edu/bookstore/pubs/MF2767.pdf.

Notes:

*Glyphosate is generally formulated as one of the following salt molecules: IPA = isopropylamine; K = potassium; or DA = diammonium.

†The concentration of glyphosate salts can be expressed in terms of pounds of glyphosate salt (a.i.) per gallon or pounds of glyphosate acid equivalent (a.e.) per gallon. Because the various salts have different molecular weights, comparing glyphosate on an a.e. basis provides a better comparison of the herbicidal component of the different salts.

Adjuvants

Adjuvants are products mixed with a formulated herbicide to improve its performance. Surfactants are the most commonly used adjuvants; they modify the surface tension of water and, when in mixture with an herbicide, cause applied droplets to spread out on leaves and improve herbicide uptake. Most agricultural surfactants are nonionic, although crop oils are also widely used; other surfactants are organosilicon based. Most glyphosate formulations contain an adequate concentration of surfactant for general use, so additional surfactant is usually not necessary. Exceptions occur when applying glyphosate to weeds with dense hairs or thick cuticles on their leaves or when using a formulation that does not contain added surfactant, such as aquatic formulations of glyphosate. Read the label to determine whether adding a surfactant to a particular glyphosate formulation, or for a particular weed species, is necessary.

Water-conditioning agents are another major type of adjuvant. Because glyphosate can exist as a negatively charged molecule after the herbicide is mixed with water, it can react with positively charged ions (also called cations) or molecules in the water. Water containing a high concentration of cations is commonly called hard water. Some common cations in hard water include sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and iron (Fe^{2+} or Fe^{3+}). Cations with more than one positive charge bind strongly to glyphosate and reduce its ability to be absorbed into plant leaves.

Water conditioners, such as ammonium sulfate (AMS) or other proprietary adjuvants, help to soften hard water. When AMS is added to water, the compound splits into two ammonium ions (NH_4^+) and one sulfate ion (SO_4^{2-}). This ionized AMS helps improve glyphosate performance in two ways. First, if glyphosate binds to ammonium, the resultant molecule is much more easily absorbed through the leaf cuticle, through the cell wall, or across the plasma membrane of certain weed species than when glyphosate is bound to other cations, resulting in more herbicide penetrating the weed. Second, sulfate preferentially binds to calcium, magnesium, and iron cations in the water, thus removing them from the solution and leaving more glyphosate free to move into the weed. Studies show that translocation of glyphosate is increased when AMS is added, due to improved phloem mobility, probably because more glyphosate in plant cells increases phloem loading and translocation of the herbicide in the weed. The general recommendation is to add 1 to 2 percent of AMS by weight to glyphosate mixtures, which is equivalent to 8.5 to 17 pounds dry AMS or 2.5 to 5 gallons of liquid AMS per 100 gallons of spray solution. (For converting U.S. customary units to metric units, see the table at the end of this publication.)

Buffering agents are another type of adjuvant. The pH of water is a measure of the hydrogen ion (H^+) and hydroxide ion (OH^-) concentration. As the number of H^+ increases relative to OH^-, water becomes more acidic and pH decreases. As noted above, when glyphosate is unbound, it has a net negative charge and is absorbed more slowly across cuticles and cellular membranes than when it is bound to certain cations as a salt. At a lower pH, more glyphosate exists as a salt than as a free acid, so plant uptake of the sprayed solution is improved. Consequently, slightly acidic water (with a pH of 4 to 6) is most suitable for mixing with glyphosate. When water pH exceeds 7, consider adding buffers or acidifiers to lower the pH.

Dust and Wheel Tracks

Since glyphosate binds tightly to soil particles, its application to dusty plants results in inactivation of much of the herbicide before uptake can occur. Glyphosate activity is usually poorer on weeds growing in wheel tracks, probably due to dust or mud on the surface of the plant foliage. Also, weeds that have been run over by sprayers or other vehicles may not be healthy enough to translocate absorbed glyphosate to their growing points, resulting in poor control. For optimal weed control with glyphosate, weeds should be relatively dust free at the time of application. Applications are therefore best made prior to the onset of dusty conditions in the summer. If weeds are already dusty, irrigation may be an option to wash dust off the foliage, followed by glyphosate application after the foliage has dried.

Spray Volume

Weed control with glyphosate has sometimes been observed to be better when applied at low volumes than at high volumes. This may occur if the low volumes are achieved by using nozzles with small orifices, resulting in the production of smaller droplets and increased foliar coverage. Perhaps, too, lower volumes of hard water contain fewer cations to bind with glyphosate in the mixture. Also, smaller droplets are more likely to drift, reducing coverage of weed foliage and increasing the chance of crop injury, particularly when glyphosate is applied when the crop is bearing leaves and is actively growing.

Tank Mixtures

When other pesticides or additives such as fertilizers are mixed with glyphosate solutions, an opportunity exists for the chemicals to bind with otherwise-inactive glyphosate. Sometimes the mode of action of certain herbicides may also slow or prevent translocation of glyphosate. Metribuzin (Sencor and other trade names), carfentrazone (Aim or Shark), and sulfentrazone (Spartan or Authority) are herbicides that antagonize glyphosate activity on certain weed species, while certain anti-drift agents have also antagonized glyphosate. The best way to avoid antagonism is to mix glyphosate formulations only with other products listed on the glyphosate label. Applying herbicides in separate applications rather than in a tank mixture may also reduce antagonism between herbicides. Since tank mixtures may offer improved control of other weed species, however, antagonism observed in certain weed species may be an acceptable trade-off.

Environmental Factors

Glyphosate absorption through treated foliage is affected by environmental conditions shortly before, during, and after glyphosate application. Glyphosate must translocate from foliage to the site in plant cells where shoots or roots are being actively produced. Therefore, weeds under stress due to cold, heat, or improper amounts of soil moisture or weeds displaying symptoms from plant disease or previous herbicide application are usually not actively growing and may not respond as quickly or as completely to glyphosate application. Excess leaf moisture from dew or rainfall too close to the time of application can also reduce glyphosate performance. Conversely, glyphosate activity is usually improved with higher relative humidity. Leaf cuticles are usually more hydrated under humid conditions, resulting in better herbicide uptake, provided that leaf surfaces are dry during and after the application.

Application Timing

The stage of growth and the life cycle of targeted weed species are important to consider if maximal control with glyphosate is to be achieved. Annual weeds are best controlled when they are small, when less glyphosate is necessary for a lethal dose. If killed prior to flowering, seed production will also be prevented. Glyphosate is strictly a foliar herbicide and does not exhibit residual soil activity. Weeds that have not emerged at the time of application are not controlled, so multiple applications are usually necessary to fully control both early- and late-emerging seedlings. Tank mixtures or sequential applications with soil-residual herbicides may improve weed control while reducing the number of herbicide applications necessary to fully control weeds. Perennial weed species frequently become more problematic the longer a perennial crop is kept in production. Directed sprays or spot applications of glyphosate are usually necessary to gain adequate control while preventing crop injury. Perennial weeds are usually most susceptible to glyphosate in the bud stage of growth immediately prior to flowering and in the fall when weed foliage is still green. Both stages represent times when weeds are translocating most of their photosynthates from leaves to roots. Since glyphosate primarily moves in the same direction as sugar in phloem tissues, glyphosate translocation to perennial roots is maximized when applied at these timings.

It is also important to consider the stage of growth and age of the crop prior to using glyphosate. In woody perennial crops, most glyphosate formulations can be safely applied as a directed spray to the base of dormant plants. Use extreme care on smooth-barked crops, however, as certain formulations or surfactants may allow glyphosate to be absorbed through the bark, resulting in injury or death of treated crop plants. Shielded nozzles and low sprayer pressure may aid in preventing accidental glyphosate application or drift to crop plants, whether dormant or not.

Summary

Glyphosate is a broad-spectrum foliar herbicide that, when applied at the proper rate, is able to control emerged annual, biennial, and perennial broadleaf and grass weeds. It is available in a wide variety of formulations and from multiple manufacturers, so most growers have ready access to glyphosate to use in their farming operations. To get the most consistent weed control with this herbicide, adjuvants (such as surfactants, water conditioners, fertilizers, drift control agents, and buffers) should be added to the spray mixture as necessary. Target weeds should be inspected to determine whether they are actively growing or are species best controlled at a different stage of growth. Physically damaged weeds or weeds that are stressed by drought or excess water may not be fully controlled. Foliage should be clean and dry at the time of application, and environmental conditions should be favorable for herbicide application and optimal uptake into the plant. Mixtures or sequential application of glyphosate with other herbicides may enhance control of difficult weed species and potentially delay onset of herbicide resistance in the weed population. If these factors are considered and any necessary corrective actions taken prior to application, glyphosate can remain a very effective herbicide for years to come.

Measurement Conversion Table

U.S. customary	Conversion factor for U.S. customary to metric	Conversion factor for metric to U.S. customary	Metric
ounce (oz)	28.35	0.035	gram (g)
gallon (gal)	3.785	0.264	liter (l)
pound (lb)	0.454	2.205	kilogram (kg)
acre (ac)	0.4047	2.47	hectare (ha)

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Agriculture and Natural Resources
Communication Services
1301 S. 46th Street
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Richmond, CAalifornia 94804-4600

Telephone 1-800-994-8849
510-665-2195
FAX 510-665-3427
E-mail: anrcatalog@ucanr.edu

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