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Glyphosate Use for Optimum Field Performance

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Summary

- Glyphosate must contact and be retained on a weed canopy and diffuse through four absorption barriers before being translocated to its sub-cellular target site.
- Environmental conditions, such as extremes in temperature, soil moisture, wind speed, and humidity can enhance or reduce glyphosate absorption and translocation. Long- or short-term droughty conditions most often reduce field performance.
- Although considered a non-selective herbicide, some weed species have an inherently high tolerance to glyphosate. Morningglory species and wild buckwheat are among the most tolerant.
- Ammonium sulfate and a non-ionic surfactant contribute to glyphosate absorption and efficacy; many products include a non-ionic surfactant, however, so carefully consult the appropriate label.
- Only the glyphosate parent acid has herbicidal activity, so acid equivalent (a.e.) concentration should be used for product rate calculation.
- The standard rate of glyphosate is 0.75 lb a.e. per acre. The rate should be increased to 1.13 for weed height ranging from 6 to 12 inches and to 1.50 for weeds > 12 inches tall.
- To maximize crop yield, glyphosate should be applied to weeds < 4 inches tall in corn, and weeds < 6 inches tall in soybean. Timing optima however can vary with weather, weed populations, and cropping management practices.
- Preemerge herbicides followed by foliar glyphosate can increase crop yield and reduce the in-crop timing sensitivity of glyphosate.

Introduction

Glyphosate is one of the most widely used herbicides in North America. The widespread use of glyphosate is due in part to its very broad weed spectrum and high efficacy. Additionally, glyphosate-resistant crops allow the in-crop use of the herbicide without the risk of crop injury. Since their commercial introduction in the U.S. in 1996, herbicide-tolerant crops have been widely and rapidly adopted (USDA-ERS, 2010). Herbicide-tolerant soybean has exceeded 90% of U.S. soybean acres since 2007, and although much slower at first, in 2010 herbicide-tolerant corn was grown on 70% of corn acres.

Foliar-applied herbicides such as glyphosate have the advantage of avoiding the soil environment where colloids, mineral nutrients, and microorganisms can greatly reduce herbicidal activity. Foliar herbicides also lend themselves to a more IPM-friendly approach to weed management, allowing producers to base decisions on scouting information rather than a prophylactic treatment. Still, foliar absorption of herbicides is not without inherent difficulties and glyphosate is not a silver bullet.

Ten weed species in the U.S. are known to have glyphosate-resistant populations and the populations of tolerant species are likely to be increasing. Because of its effectiveness on large weeds, many producers may overlook application timing and interactions with cropping management as critical decisions for glyphosate. Use rates and adjuvants can also vary with different glyphosate products, as well as weed species and size. Glyphosate effectiveness is dependent on a number of factors; growers armed with this information can readily use it to ensure maximum profitability.

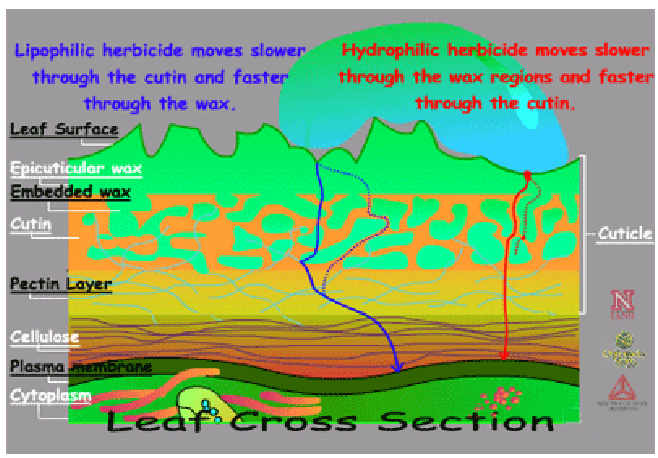

Figure 1. Cross section of leaf depicting routes of herbicide movement through the four absorption barriers which include; epicuticular wax, cuticle, cell wall, and plasma membrane. Source: University of Nebraska, Lincoln.

Absorption Barriers

Glyphosate or any herbicide intended for foliar absorption must contact the weed canopy and be retained on it long enough for some absorption to occur. Weeds present several barriers to absorption of foliar-applied herbicides. The pubescence on the surface of many weed species can physically limit contact between a leaf surface and a water droplet containing herbicide. Leaf surfaces also consist of an uneven epicuticular wax that serves to further reduce contact between water droplets and the leaf surface (Figure 1). Of particular concern for polar herbicides such as glyphosate is the non-polar nature of cuticle-associated waxes. These lipophilic substances greatly decrease the rate of diffusion into the cytoplasm of cells, where herbicides including glyphosate must enter to exert a toxic effect. Before entering the cytoplasm, however, herbicides must diffuse through the cell wall, a primarily hydrophilic environment, and be transported via trans-membrane proteins through the plasma membrane.

Environmental Conditions

Foliar absorption of herbicides occurs in a liquid phase only; once a water droplet has dried on the leaf surface and herbicides have crystallized little to no additional absorption occurs. Therefore, any environmental condition speeding the drying of spray droplets on a leaf surface will reduce absorption. Low humidity and high winds can greatly reduce drying time, thereby allowing little time for absorption to occur. Conversely, high humidity with little wind slows the rate of drying and lengthens absorption time. Rainfall shortly after (< ½ hour) glyphosate application can wash spray droplets from the leaf surface. A foliar application should be "rain fast" once droplets have dried on the leaf surface.

Temperature, soil moisture, and solar radiation that optimize plant growth facilitate absorption and translocation of glyphosate. When photosynthetic rates are high photoassimilate produced in leaf epidermal cells is rapidly loaded into the phloem, other organic molecules like glyphosate are similarly loaded, and both are quickly translocated to sink organs (Figure 2). The rapid removal of glyphosate molecules from epidermal cells maintains a high concentration gradient that increases absorption rate (Figure 3). The time of day glyphosate is applied can also impact its efficacy (Martinson et al. 2005). Applications made between 9:00 a.m. and 6:00 p.m. tend to maximize glyphosate activity. Short-lived temperature spikes (> 90 ºF) can also enhance absorption by reducing cuticle viscosity and allowing easier passage of foliar-applied herbicides.

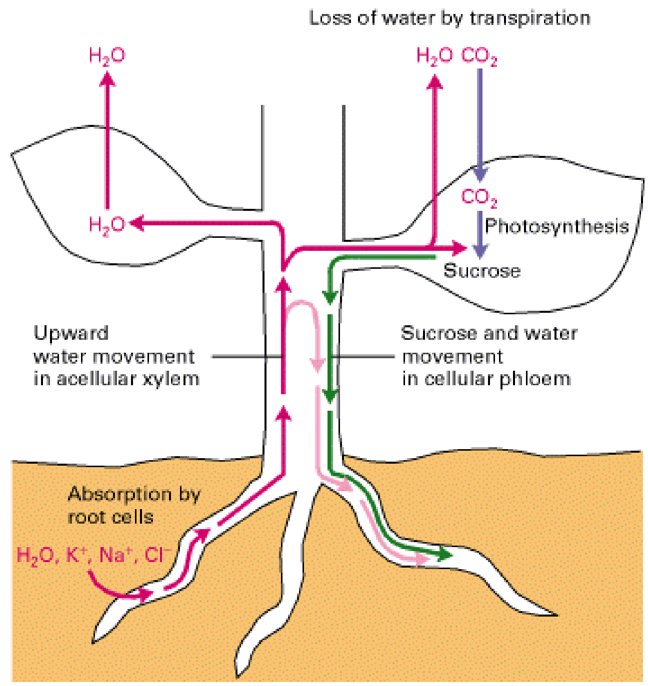

Figure 2. Movement of photoassimilate (sucrose) and water in plant vascular tissue. Glyphosate moves with photoassimilate from source (leaf) to sink meristematic regions such as roots (shown) and the shoot (not shown).

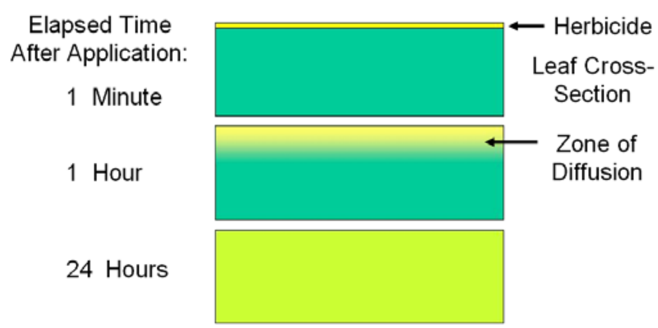

Figure 3. Idealized view of herbicide diffusion into a leaf. Maintaining a large gradient such as occurs during good growing conditions improves herbicide absorption. Source: Iowa State University.

Plants act to conserve available water during droughty times by thickening epicuticular wax and closing stomata. Both responses reduce glyphosate absorption. Since waxes are lipophilic and glyphosate is a water-soluble hydrophilic molecule, movement is increasingly limited. Although little glyphosate is absorbed through stomata, reduced CO_2 absorption lowers photosynthetic rates, translocation, and thus absorption. Certain broadleaf weed species such as velvetleaf are known to orient their leaves more vertically when stresses are applied, decreasing droplet retention time on the leaf and decreasing herbicide efficacy (Zhou et al. 2007). Velvetleaf stressed by drought or flooding had much greater glyphosate tolerance than non-stressed plants. Cold stress also increases tolerance, but the magnitude is much less than drought stress.

Tolerant Species

Although glyphosate is considered a non-selective herbicide there are a number of broadleaf weeds common to the U.S. Midwest that are somewhat tolerant. Reduced susceptibility to glyphosate or tolerance is inherent in a weed species or population and does not indicate a genetic change as resistance does. Table 1 lists 19 weed species considered to have reduced susceptibility to glyphosate.

Table 1. Weed species having some tolerance to glyphosate. Control is considered to be fair to poor at 0.75 lb a.e. per acre. Sources: Illinois Pest Management Handbook, 2008. Weed Control Guide for Ohio and Indiana, 2004.

Common Name	Life Cycle
Bigroot morningglory	Perennial
Dandelion	Perennial
Field bindweed	Perennial
Fleabane, annual	Annual
Fleabane, daisy	Annual/Biennial
Groundcherry	Perennial
Hedge bindweed	Perennial
Hemp dogbane	Perennial
Honeyvine milkweed	Perennial
Horsenettle	Perennial
Ivyleaf morningglory	Annual
Milkweed, common	Perennial
Pitted morningglory	Annual
Pokeweed, common	Perennial
Prickly sida	Annual
Swamp smartweed	Perennial
Tall morningglory	Annual
Wild buckwheat	Annual
Yellow nutsedge	Perennial

One of the most common of these species is annual morningglory species. Morningglory are some of the most glyphosate-tolerant weeds common to the U.S. Corn Belt. This tolerant species also has an extended emergence window, allowing some individuals to completely avoid exposure. Improved control of many tolerant weed species can be obtained by increasing the glyphosate rate and applying to smaller weeds.

Wild buckwheat is another highly tolerant weed. At the standard use rate of 0.75 lb a.e. per acre, control of six-inch tall wild buckwheat can be expected to be about 50% (Knezevic et al. 2006). By tank-mixing a PPO-inhibiting diphenylether or increasing the glyphosate rate, control can be greatly improved.

Adjuvants and Use Rates

Glyphosate is the common name given to the chemical compound N-(phosphonomethyl) glycine; the molecule is a weak acid (parent acid) which can be formulated as any number of salts. Currently manufacturers of glyphosate formulate it as an isopropylamine, ammonium, or potassium salt. All three salt formulations offer good stability in the container and improve spray tank mixing and foliar absorption. Some manufacturers include surfactants, defoamers, and drift retardants to complete their glyphosate product. Products including surfactants are often said to be "fully loaded" and usually don't require the addition of a non-ionic surfactant (NIS), however, manufacturers are not required to provide that information so the product label should be consulted.

For maximum field performance glyphosate applications should be made with ammonium sulfate and an NIS (Hartzler et al. 2006). If a glyphosate product label specifies the addition of an NIS, ensure it contains at least 80% active ingredient (a.i.) and typical use rates are 0.25% by volume. Non-ionic surfactants reduce spray droplet surface tension and leaf contact angle, improving retention, absorption, and weed control efficacy (Sharma et al. 2004). The use of ammonium sulfate is recommended by most product manufacturers; it should be added to the spray solution before glyphosate at 8.5 to 17 lb per 100 gallons of water.

Ammonium sulfate reduces the antagonistic effect of hard water on glyphosate. Water is considered "hard" when it contains various salts such as Ca^{2+}, Mg^{2+}, Fe^{2+}, Na^{+}, and Zn^{2+}. Some of these salts are found in great abundance in rural water supplies and readily bind with glyphosate reducing its solubility, absorption, and field performance (Stahlman and Philips, 1979; Nalewaja et al. 1996). The sulfate anion in ammonium sulfate binds with the salts in hard water and precipitates them out of solution, reducing the antagonistic effect.

The portion of any glyphosate product with herbicidal activity is the parent acid (Figure 4). Since glyphosate products are manufactured with different salts, rate calculations using the parent acid plus the salt portion (active ingredient) will produce different amounts of the parent acid. Therefore, the parent acid or acid equivalent (a.e.) should be utilized to determine product rates.

Glyphosate products also vary in their parent acid concentrations. For example; Roundup WeatherMax® contains 4.5 lb a.e. per gallon, while Gly-4® contains 3 lb. The standard glyphosate application rate is 0.75 lb a.e. per acre; determine the product rate by using 0.75 as the numerator and the parent acid concentration as the denominator to determine gallons of product per acre (0.75/parent acid concentration = gallons/acre * 128 = oz/acre). Rates should be adjusted for weed height by using the standard rate for weeds < 6 inches tall, and increasing the rate by 50 and 100% for weeds between 6 and 12 inches and > 12 inches in height.

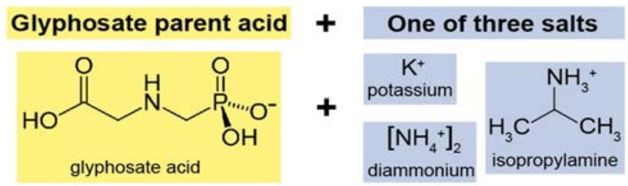

Figure 4. The glyphosate parent acid and potential salts; potassium, diammonium, and isopropylamine.

Recommended spray volumes differ by glyphosate product label; minimum spray volumes range from 3 to 5 gallons per acre and maxima from 20 to 40. Research indicates that glyphosate performance improves with decreasing spray volume to rates as low as 2.5 gallons per acre (Ramsdale et al. 2003). Reduced spray volumes decrease the likelihood of antagonism with hard water and increase glyphosate concentration per droplet. Since foliar-applied herbicides move by simple diffusion, maintaining a high concentration gradient improves absorption. Ultra low carrier volumes may provide insufficient spray coverage in dense weed/crop canopies, however, and the orifice size of spray tips necessary for such volumes are easily plugged. Carrier volumes of 10 to 15 gallons per acre are probably a good range for sufficient performance under a diversity of field conditions.

Application Time and Cropping Management

Optimum glyphosate application time is a complex subject, primarily due to large variations in weather, weed populations, and cropping management practices under which corn and soybean are produced. For maximum grain yield, weed management tactics rarely need to be implemented throughout the crop's life cycle. In fact, weed management tactics need to be concerned with preventing weed interference during the first 4 to 6 weeks after planting (Wood et al. 1996). This *critical weed-free period* or critical period is defined as a period of time in crop development that weeds must be controlled to prevent yield loss. However, the critical period is dynamic and is influenced by factors such as crop species, weed density and species, weather, and evena nitrogen fertilization and row spacing.

Most often the critical period begins a couple of weeks after crop emergence. Physical resources such as water, mineral nutrients, and light being competed for by crops and weeds are often in sufficient supply for dense seedling populations of both. Initial size difference between crops and most Corn Belt weeds due to seed size also tends to delay the onset of the critical period. For corn production the critical period can begin as early as VE to as late as V7, while the end of the period ranges from V5 to VT. These wide ranges have been observed to be caused by weed density, nitrogen fertilization, and drought stress (Evans et al. 2003; Knezevic et al. 2003; Norsworthy and Oliveira 2004; Dalley et al. 2004). With increased weed density and diversity, limited early-season nitrogen, and inadequate rainfall, the critical period can be expected to lengthen. Conversely, low weed density and diversity, well-fertilized corn, and ample rainfall will shorten the critical period.

Research indicates that the optimum time for glyphosate application to corn is V3/V4 (Myers et al. 2005; Gower et al. 2003; Cox et al. 2006). Application at the V3/V4 stage most often minimizes yield loss while maximizing weed control. Producers may have to choose between yield losses due to early-season weed competition and herbicide efficacy when basing weed control on a single glyphosate application. Eliminating early-season yield loss by targeting two-inch weeds invites reinfestation by later germinating weeds, some yield loss, and unacceptable weed control. On the other hand, delaying application improves weed control but yield loss is unacceptably high (Table 2.). A comprise may be to apply glyphosate when weeds are six inches tall, although weed removal at that point may only be marginally acceptable for control and yield loss. Attempting to target a very narrow window for weed removal also poses difficult logistical challenges, especially for large operations and those with additional in-crop field work.

Table 2. Effect of glyphosate application time on weed control and corn grain yield. Adapted from Gower et al. 2003.

Application Timing (Weed Size)	Weed Control	Yield Loss[1] Early Season	Yield Loss[2] Early + Late Season
inches	- - - - - - - - - - - - %	- - - - - - - - - - - - -	
2	73	0	7
4	83	3	6
6	90	6	7
9	93	14	11
12	95	22	21

[1] Weeds emerging after herbicide application controlled with hand weeding.
[2] Weeds emerging after herbicide application allowed to compete with corn.

For some situations a better approach to a single glyphosate application in corn and soybean is to utilize herbicides with soil residual activity. Herbicides with soil activity tank-mixed with postemerge glyphosate have increased soybean yield and weed control (Grey, 2007). Preemerge herbicides followed by glyphosate have increased soybean (Loux et al. 2007) and corn (Tharp et al. 2004) grain yields. Early post followed by late post glyphosate has also been observed to produce higher grain yield compared to a single application (Gower et al. 2003). Using a preplant or preemerge herbicide to be followed by glyphosate reduces its timing sensitivity. Farmers should be aware that whether relying on multiple or single glyphosate applications that include a residual still require a very precisely timed initial application.

Soybean yield is less affected by weed interference when compared to corn (Dalley et al. 2004). This is probably in part due to nitrogen fertilization of corn increasing weed competitiveness (Clay et al. 2005). Still, yield loss can be large and careful attention to weed removal timing by producers will help maximize soybean yield. As with corn, the onset of the critical period will vary with weed communities, weather, and cropping management. Ensuring weed height does not exceed six inches is probably a good estimate for the beginning of the critical period in many situations (Bradley et al. 2007). Reducing soybean row spacing can delay the beginning of the critical period (Knezevic et al. 2003) by reducing the competitiveness of weeds (Hock et al. 2006). Figure 5 depicts soybean yield loss associated with three row widths. Note that at any weed removal time yield loss increases with increasing row width.

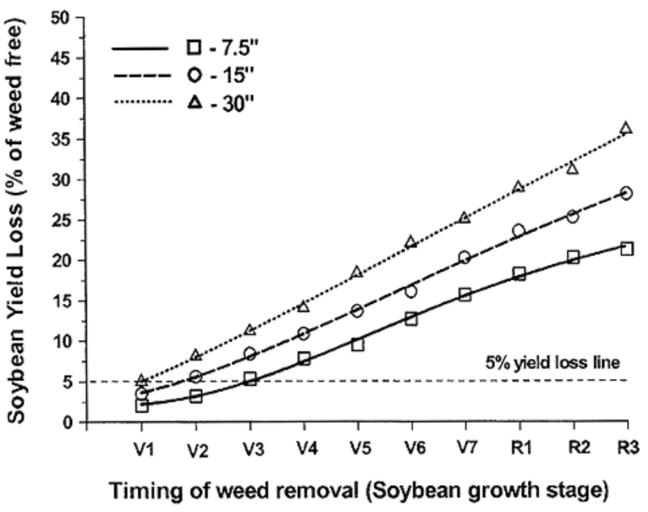

Figure 5. Influence of weed removal timing and row spacing on soybean yield loss. Knezevic et al. 2003.

Narrow-row soybean also reduces weed resurgence, while corn does not share the same benefit (Bradley, 2006). Unlike soybean, reducing corn row spacing does not improve its competitiveness (Norsworthy and Oliveira, 2004) and may even reduce it (Dalley et al. 2004). Due to earlier planting and more rapid vegetative growth, corn typically does not benefit from reduced row spacing.

Glyphosate Resistance

Currently there are 10 weed species with populations resistant to glyphosate in 22 U.S. states (Heap 2010). One of these weed species, common waterhemp, is also resistant to herbicides in two other widely used sites of action (ALS and PPO). Numerous innate biological factors contribute to the occurrence of weed resistance, such as dominance of the resistant allele or fitness of resistant plants, none of which can be affected by farmers (Jeschke 2010). Producers can reduce selection intensity by making fewer glyphosate applications. Additionally, altering cropping management practices to reduce the number of individuals exposed to glyphosate can further decrease selection intensity. Using tillage or preemerge herbicides should reduce weed density prior to a glyphosate application and help maintain the value of herbicide-tolerant crops.

Management Solutions

Poor field performance of glyphosate can be attributed to a number of environmental conditions or management decisions. Ensure the correct rate is used by considering the parent acid concentration or acid equivalent (a.e.) and the height of the dominant weed species in each field. For weeds < 6 inches tall use 0.75 lb a.e. per acre, for 6 to 12 inches use 1.13, and > 12 use 1.50. Ammonium sulfate at a rate of 8.5 to 17 lb per 100 gallons of water should be added to all spray solutions. Species such as morningglory (spp.) and wild buckwheat are difficult to control with glyphosate. Producers will need to target small weeds and increase the glyphosate rate for these tolerant species; additionally they can tank-mix herbicides with other sites of action such as PPO and 4-HPPD inhibitors. For maximum yield glyphosate should be applied to weeds < four inches tall in corn and < six inches for soybean. Producers should also consider the use of preemerge-applied herbicides. The use of an appropriate residual herbicide will reduce the timing sensitivity of glyphosate and provide residual control until a sufficient crop canopy has formed.

Growers can do little to improve glyphosate performance during extended periods of poor plant growth, such as that caused by extensive drought. Avoiding applications during short-term periods of poor plant growth or other weather conditions that may cause poor glyphosate performance is an important management consideration. Glyphosate is and will likely continue to be an important part of weed management for the foreseeable future, fundamental knowledge to optimize its performance will help ensure its effectiveness and longevity.

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