Glyphosate Stewardship

Optimizing and Preserving Glyphosate Performance

K-STATE
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Kansas State University
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Glyphosate is one of the most widely used herbicides in Kansas and around the world. It is highly effective for broad-spectrum weed control and has been especially important to the development and sustainability of chemical-fallow and no-till crop production systems in the Great Plains.

Glyphosate was first registered and introduced as Roundup herbicide in 1974. It injures or kills many plant species when applied postemergence to the foliage at labeled field rates. Glyphosate is systemic and readily translocates in plant xylem and phloem. It kills plants by interfering with enolpyruvylshikimate phosphate synthase (EPSPS) enzyme activity needed for plant growth and development. Glyphosate has low mammalian toxicity because mammals do not possess the EPSPS enzyme.

Although glyphosate is somewhat persistent in soil, it has little or no activity on plants once it contacts the soil because it is tightly bound to soil particles and organic matter. Because of its low mammalian toxicity and limited soil activity, glyphosate is considered an environmentally friendly herbicide.

Glyphosate use initially was limited to noncropland, fallow, and no-till burndown treatments because of its nonselectivity on crops. Another factor that limited early use was its high cost. Over the years, glyphosate use gradually increased as an alternative to tillage in fallow and no-till crop production. Replacing tillage with herbicide treatments maintains plant residues, which reduces erosion and conserves soil moisture. Burndown and fallow treatments generally had lower use rates to minimize cost and often included a tank-mix partner such as 2,4-D and/or dicamba for enhanced broadleaf weed control.

Following the introduction of Roundup Ready crops and a subsequent reduction in glyphosate price, glyphosate use dramatically increased in the late 1990s. Introduction of genetically engineered crops with resistance to glyphosate allowed in-crop broadcast application of glyphosate for broad-spectrum weed control. Roundup Ready weed-control programs are cost-effective and simple compared to conventional weed-control programs. Roundup Ready crops and glyphosate use have helped growers manage herbicide-resistant weeds, such as ALS- and triazine-resistant waterhemp, Palmer amaranth, shattercane, and kochia. Roundup Ready soybeans were quickly adopted, and within a few years more than 90 percent of all soybeans grown in Kansas were Roundup Ready. In many cases, the only herbicide used to control weeds in Roundup Ready soybeans is glyphosate. Roundup Ready cotton, corn, canola, and alfalfa are also available. Almost all cotton grown in Kansas is Roundup Ready, and acreage of Roundup Ready corn and other crops continues to increase.

Glyphosate use in fallow and burndown also has increased because of the continuing shift to less tillage. In some cases, tank-mix herbicide partners have been replaced by higher rates of glyphosate because of low cost, lack of planting restrictions, and lower potential for drift damage to nearby crops compared to many other herbicides. Consequently, glyphosate has become an important, even primary, method of controlling weeds in many areas. Unfortunately, heavy reliance on glyphosate has led to shifts in weed species and development of glyphosate-resistant weeds in some areas. Therefore, it should be used judiciously and managed carefully to optimize and maintain its performance.

Factors Affecting Glyphosate Performance

Although glyphosate is relatively nonselective and acts on many weed species, a number of factors affect performance and weed control, including application methods, environmental conditions, and weed species. Understanding these factors and their interactions can help optimize weed control with glyphosate.

Factors associated with glyphosate application that can affect performance, include use rate, presence of dust, applicator wheel tracks, spray water quality, spray volume, spray adjuvants, and tank-mix combinations.

Table 1. Glyphosate product comparisons.

Trade Name	Formulated Salt[a]	Concentration[b] lb ai/gal	Concentration[b] lb ae/gal	0.75 lb ae Product Rate (oz/a)
Roundup Original	IPA	4	3	32
Roundup Power Max	K	5.5	4.5	22
Roundup WeatherMax	K	5.5	4.5	22
Touchdown Total	K	5	4.2	23
Touchdown HiTech	K	6	5	19
Durango DMA	DMA	5.1	4	24
Cornerstone 5	IPA	5.4	4	24
Credit	$K+NH_4$	3.4	3	32
Many Generics	IPA	4	3	32

[a] Glyphosate is generally formulated as one of the following salt molecules: IPA = isopropylamine; K = potassium; NH_4 = ammonium; or DMA = dimethylamine.

[b] The concentration of glyphosate salts can be expressed in terms of pounds of glyphosate salt (ai) per gallon or pound of glyphosate acid (ae) per gallon. Because the various salts have different weights, comparing glyphosate on an acid equivalence (ae) basis provides a better comparison of the herbicidal component of the different salts.

Weed control with glyphosate and no ammonium sulfate additive.

Weed control with glyphosate plus ammonium sulfate at 2 percent by weight (17 pounds per 100 gallons of spray)

Weed control with glyphosate plus a low rate ammonium sulfate replacement.

Formulations

Glyphosate products are formulated as different salts, such as isopropylamine (IPA), potassium (K), and dimethylamine (DMA) salts of glyphosate. Different salts have different molecular weights, which influences how much glyphosate can be concentrated into a formulated product.

Herbicide concentrations often are presented on the label in terms of pounds of active ingredient (lb ai) or pounds of acid equivalent (lb ae) per gallon of product. Because glyphosate salts have different weights, and it is the glyphosate acid that is important for weed control, the best measure to compare product concentrations is pounds acid equivalent per gallon (lb ae/gal).

The concentration of current glyphosate agricultural products on the market ranges from 3 to 5 lb ae/gal. Consequently, the amount of product required to provide the same amount of glyphosate will vary depending on the concentration. Refer to Table 1 for examples of various glyphosate products, concentrations, and equivalent product rates. Refer to *Chemical Weed Control for Field Crops, Pastures, Rangeland, and Noncropland* from K-State Research and Extension for a current list of glyphosate products.

Surfactants

Glyphosate absorption by plants is maximized by including nonionic surfactant in the spray solution. Glyphosate products are formulated with varying concentrations of surfactant, so some products require additional surfactant, while others do not. It is important to read product labels for surfactant recommendations for each product.

Water Quality and Conditioning

Glyphosate can bind to cations or other charged surfaces. Glyphosate molecules that bind to cations in hard water can reduce absorption into plants, so weed control with glyphosate is often reduced when mixed and applied with hard water. Adding ammonium sulfate (AMS) to the solution helps counteract effects of hard water on glyphosate. The sulfate component of AMS binds to the cations in hard water to minimize binding to the glyphosate. In addition, the ammonium component of AMS will bind with the glyphosate and enhance absorption and control of certain weeds. The recommended rate of AMS to add to glyphosate solutions is 1 to 2 percent AMS by weight, which is equal to 8.5 to 17 lb AMS per 100 gallons of spray solution. Liquid AMS products are also available and are as effective as dry AMS. The equivalent amounts of liquid AMS are 2.5 to 5 gallons of AMS per 100 gallons of spray solution. K-State Research and Extension recommends adding AMS to all glyphosate applications. AMS should be added and thoroughly dissolved in spray water before adding the glyphosate product.

A number of products are sold as alternatives to AMS. These are often recommended at much lower rates and may or may not include AMS. They are appealing because of the low use rates and ease of handling. However, research at Kansas State University (Table 2) has shown that these materials often do not enhance glyphosate performance as well as AMS, especially under less than ideal conditions.

Spray Volume

Spray carrier volume may have several different effects on glyphosate activity. In general, weed control with glyphosate has been better at volumes of less than 10 gallons per acre than at higher spray volumes. Better glyphosate activity at lower spray volumes could be from fewer cations in the spray solution, smaller spray droplets, improved absorption from more concentrated droplets, or a

Table 2. Weed control at 4 weeks after treatment as influenced by labeled rates of ammonium sulfate replacement adjuvants with a reduced rate of glyphosate at Manhattan, Kansas, in 2005.

Treatment	Application Rate	Velvetleaf	Sorghum	Corn	Common sunflower
	(per 100 gal.)	---------------------(% control)---------------------			
Roundup WeatherMax with:					
AMS	17 lb or 5 gal	77	90	83	92
Class Act NG	2.5 gal	72	90	82	90
Alliance	1.25 gal	65	83	77	90
Alliance	3 qt	60	82	72	87
Choice	2 qt	30	47	42	60
Request	2 qt	37	58	50	75
Speedway	2 qt	42	50	50	85
Blendmaster	1 gal	43	57	53	80
US500	1 qt	33	50	47	70
Citron	2.2 lb	37	40	40	78
None		40	60	52	73
LSD 10%*		7	9	7	7

**Least Significant Difference. If the difference between two treatments is greater than the LSD value, then the difference is significant.*

combination of factors. However, it is important to remember that spray drift becomes more likely with low spray volumes and smaller spray droplets, and that adequate spray coverage of plants throughout the canopy is still necessary to achieve good weed control.

Dust and Wheel Tracks

When glyphosate comes in contact with dust or organic residue, it becomes tightly bound and is unavailable for uptake by plants. Consequently, once glyphosate contacts soil, it no longer has herbicidal activity. Likewise, individual molecules in a spray droplet that contact dust particles in the air or on a plant surface become deactivated, reducing the effectiveness of the spray.

The sprayer wheels sometimes generate dust, reducing weed control in the wheel tracks. Reduced weed control in wheel tracks also could result from physical damage to weeds as they are run over or by rubbing the plants in soil. Applicators sometimes compensate for this by using a larger spray tip directly in line with the wheels, which results in a higher application rate and improved weed control. This should only be done if the application rate in the wheel track area is still within the label guidelines.

Tank Mixes

Tank mixes of other pesticides with glyphosate sometimes have a similar effect to dust or cations. Herbicide tank mixes may interfere with absorption or translocation and reduce glyphosate activity. Tank-mix partners that have antagonized glyphosate activity on certain weeds include atrazine, Sencor, Aim, Spartan, Cobra, Ultra Blazer, and Flexstar.

Make separate applications or increase the glyphosate application rate to minimize the antagonistic effects of various tank-mix partners on glyphosate. Although certain herbicide tank mixes can be antagonistic to glyphosate, it still may be beneficial to improve the control of certain weed species and help reduce the risk of developing herbicide resistance.

Environmental Factors

Environmental conditions influence the activity and weed control achieved with any herbicide. Optimal conditions for plant growth usually result in the best weed control and the least risk of crop injury. Any environmental conditions that cause plant stress may reduce herbicide uptake and performance. Environmental factors that may influence weed control with glyphosate include drought, temperature, relative humidity, presence of dew, rainfall following application, and light.

Weed control and the speed of control with glyphosate generally increase as air temperatures increase, as long as the plant is still actively growing. However, high temperatures that place plants under stress, or when combined with dry conditions, likely will result in reduced weed control. Glyphosate applied during cool periods before, during, or after treatment will result in a slower plant response and may result in decreased weed control.

Herbicide absorption and weed control generally are greater with higher humidity levels. Lower humidity conditions, which are common in the Great Plains, may result in reduced herbicide absorption and weed control. Relative humidity levels often fluctuate with the time of day, being highest at night and in the morning and lowest during the midday hours.

High nighttime and early morning humidity may result in heavy dew, which may have a negative effect on weed control. These conditions may reduce glyphosate activity by causing spray droplet runoff and decreasing the concentration of glyphosate on the leaf surface.

Rainfall soon after an application can wash herbicide off plant foliage and reduce weed control. The interval required between application and rainfall depends on a number of factors. Consult product labels for recommended intervals between

6:00 a.m. *10:00 a.m.* *9:00 p.m.*

Weed control with glyphosate as influenced by application time of day.

application, and pay close attention to rainfall forecasts.

Changes in light with the time of day also seem to influence control. Even though environmental conditions may seem more favorable in the morning or evening, research at several universities has demonstrated that weed control with glyphosate is often lower early in the morning or in the evening as compared to midday applications (Figure 1).

This phenomenon is not completely understood, but several possible contributing factors include interactions with dew, diurnal leaf movement patterns, and interactions with plant physiological processes. Some plants, such as velvetleaf and morningglory, fold their leaves down at night. Consequently, if the leaves are more vertical when the herbicide is applied, there is less spray coverage and herbicide uptake by the plant.

Fluctuation in control due to application time seems to correlate closely with light intensity and daily plant photosynthetic cycles. Glyphosate absorption, translocation, and metabolic activity may be affected by the photosynthetic cycle. Light seems to be the key factor in the effect of time of day on glyphosate activity. Applications after sunrise and before the sun starts to set have generally provided the best control. Wind also is an important consideration: spray to avoid herbicide drift. Consult with local weather forecasts and plan applications to minimize drift and optimize herbicide performance.

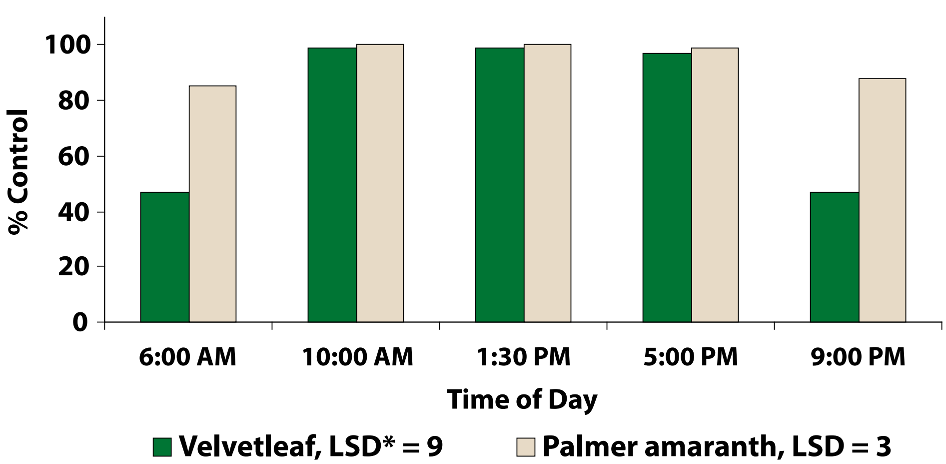
Weed Spectrum Shifts

Weed communities are dynamic and species composition is a result of past events. Shifts in weed species and density occur as a result of selection forces imposed when agricultural practices are modified and alter the habitat. Species able to survive the new practice flourish, reproduce, and eventually may completely displace lesser-adapted species.

Methods of weed management are among the most common and powerful selective forces imposed on agricultural weed communities. The weed management method could be herbicide, tillage, crop rotation, or other agronomic factors used continuously throughout the cropping system to cause a shift in the weed population.

Weed shifts typically occur more rapidly when herbicides are the control method because of the

Figure 1. Velvetleaf and Palmer amaranth control with glyphosate as influenced by application time of day at Manhattan, Kansas.



**Least Significant Difference. If the difference between two treatments is greater than the LSD value, then the difference is significant.*

greater selection they impose on the population. Just as weed shifts develop when a system is constantly exposed to herbicides with similar modes of action, repeated selection may influence genetic adaptation and lead to herbicide resistant biotypes. Weed resistance is not the result of a mutation caused by herbicides; rather it arises from the selection of a natural mutation or small pre-existing population of resistant plants.

Weed-control programs need to be adjusted in fields where weed shifts occur. In some cases, adjusting application rate or timing may help improve control. Other cases may require the addition or rotation of other herbicide programs, changes in the crop rotation, or perhaps judicious use of tillage.

Kansas weeds that have been difficult to control with glyphosate include prairie cupgrass, tumble windmillgrass, yellow nutsedge, annual spurge species, wild buckwheat, horseweed (marestail), lambsquarters, giant ragweed, kochia, Russian thistle, velvetleaf, and morningglory.

Early season weed competition with cotton from delayed application of glyphosate in the left plot compared to timely applications of glyphosate in the right plot.

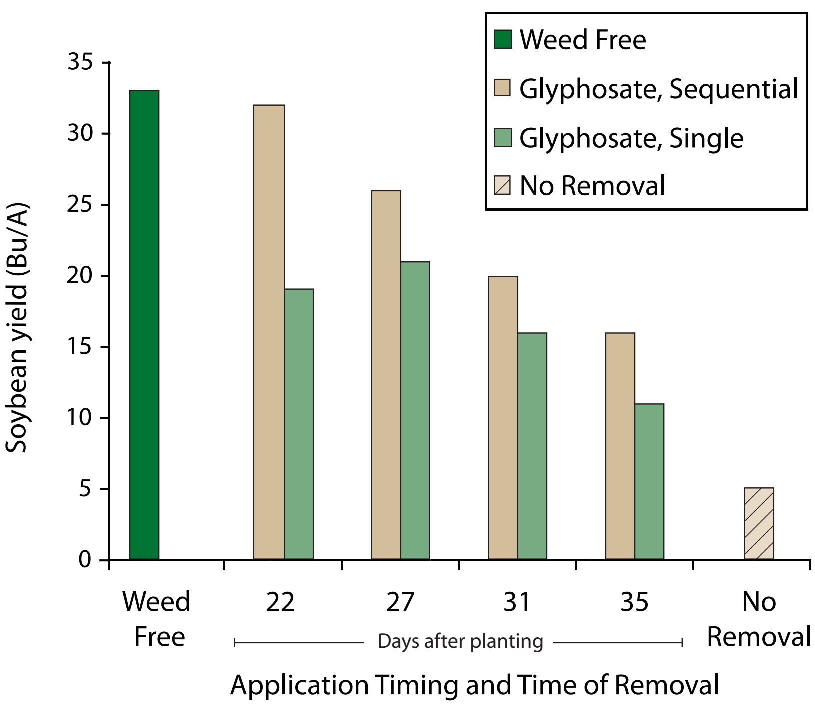
Application Timing

Growth stage also is important in herbicide susceptibility. Although glyphosate is more effective than most herbicides for controlling large plants, weeds are generally most susceptible to herbicides in the seedling stage. The tendency to delay applications of glyphosate in Roundup Ready crops, waiting for later flushes of weeds, may be effective on low weed densities, but is risky with more dense weed populations.

Delayed applications may result in spray coverage problems, poor weed control, and early season weed competition and yield loss. Early emerging weeds are the most competitive with crops and need to be controlled in a timely manner to avoid yield loss. Weeds controlled by 3 to 4 weeks after planting generally do not cause yield loss, but waiting longer than 4 weeks will often reduce yields (Figure 2).

It is important to follow the herbicide label regarding application time and rate for optimum control. Application at reduced rates or incorrect growth stage may result in poor control and increase the risk of yield loss and weed shifts.

Figure 2. Soybean yield as influenced by time of glyphosate application and weed removal, Manhattan, Kansas in 1998.



Weed Resistance to Glyphosate

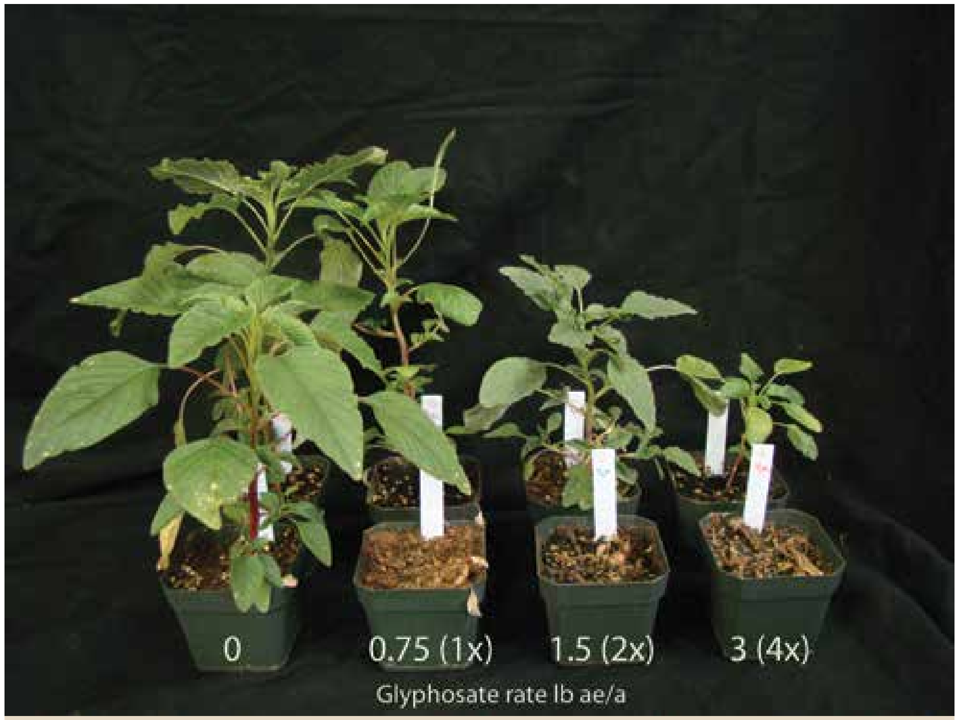
Weed resistance is defined by the Weed Science Society of America as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the native wild type." Even though glyphosate has been used for many years, development of glyphosate-resistant weeds was not an issue during its first 20 years. However, a number of glyphosate-resistant weed species have been documented, including six species in Kansas (Table 3). Increased occurrence of glyphosate-resistant weeds probably relates mostly to increased reliance on glyphosate during the last two decades, especially when used exclusively. Selection pressure for herbicide resistance increases as the frequency of use increases.

Glyphosate-resistant weeds seem to be somewhat different than most other examples of herbicide resistance. ALS and triazine resistance is often regulated by a single gene, which results in an altered site of action with a high degree of resistance. Glyphosate resistance generally occurs at a lower level, is slower to develop, and may be a result of multiple genes, rather than a single dominant gene. It is harder to identify and quantify glyphosate-resistant weeds compared to ALS- or triazine-resistant weeds. The degree of glyphosate resistance is highly variable and seems to increase over time with continued selection pressure.

Poor weed control does not mean weeds are resistant, as previously discussed factors can affect herbicide performance. However, glyphosate resistance may be possible if the following criteria exist.

1. Glyphosate normally provides good control of the weed species in question.
2. Other glyphosate-susceptible weeds were controlled as usual.
3. Environmental conditions were favorable for glyphosate performance.
4. The rate was correct for the species being controlled and there were no application errors.
5. Glyphosate has been used frequently and often exclusively in the field.

If resistance is suspected, contact your local K-State Research and Extension agent or weed researcher for further examination. Weeds of greatest concern for developing glyphosate resistance in Kansas include Palmer amaranth, common waterhemp, kochia, horseweed (marestail), lambsquarters, giant ragweed, and Russian thistle. These species have a history of developing resistance to glyphosate and other classes of herbicides, and glyphosate has become a primary tool to control them in Kansas croplands.



Resistant (back row) and susceptible (front row) Palmer amaranth treated with increasing rates of glyphosate

A key factor in the development of resistant weeds appears to be frequent and exclusive use of glyphosate for weed control. Consequently, a key practice to prevent development of glyphosate resistance is to avoid exclusive use of glyphosate.

Management practices that diversify cropping systems and weed-control programs help reduce the risk of developing herbicide resistance, including:

1. Rotation of competitive crops, including glyphosate-resistant and conventional crop varieties.
2. Using herbicides with different modes of action in sequence or in tank mixes where practical.
3. Using residual herbicides in the weed-control program, especially preemergence treatments.
4. Using tillage occasionally when it fits into the cropping system.
5. Applying glyphosate with appropriate adjuvants, at the

Table 3. Weed species with confirmation of glyphosate-resistance in Kansas.

Weed	Distribution in Kansas	Prevalence
Horseweed (marestail)	Statewide	Common
Common ragweed	East central	Isolated
Palmer amaranth	Central	Increasing
Common waterhemp	Eastern half	Common
Kochia	Western half	Common
Giant ragweed	Eastern third	Scattered

proper rate and application stage, and under optimal conditions to maximize performance.

Evidence is building that use of lower glyphosate rates may increase the risk of weed shifts and selection for glyphosate-resistant weeds. With low glyphosate prices, it is not worth sacrificing performance by cutting the glyphosate rate.

Glyphosate has been an extremely valuable tool for weed control and has even helped shape current cropping systems. It is important to use glyphosate wisely to maintain its value for the future. Scout and monitor fields regularly for evolving weed problems and address them accordingly.

Horseweed (marestail) escapes in Roundup Ready Cotton.

This publication was initiated and is endorsed by the Kansas State University Weed Science Forum

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