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Common Lambsquarters Response to Glyphosate across Environments

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We conducted a series of field experiments to determine the role of several factors that might contribute to the inconsistent control of common lambsquarters with glyphosate. Experiments in 2006 and 2007 determined common lambsquarters response to glyphosate under a wide range of measured environmental conditions. Glyphosate was applied at 0.84 kg ae ha^{-1} plus 3.8 kg ha^{-1} ammonium sulfate (AMS) to 10-cm-tall plants on 18 dates in each year and to 20-cm-tall plants on 18 dates in 2007. Control was less for six application dates relative to control for 48 other dates. Poor control was attributed to rainfall on one of these six dates, but for the other five dates, regression analysis did not identify any significant relationships between environmental conditions (relative humidity, temperature at time of treatment, or minimum and maximum temperature pre- and posttreatment) and control, even though a wide range of conditions occurred. To determine the effects of plant growth stage on control, glyphosate was applied at 0.1 to 3.2 kg ha^{-1} plus 3.8 kg ha^{-1} AMS to 10- and 20-cm-tall plants at four sites. The glyphosate ED_{50} value (the effective dose that reduced shoot mass by 50% relative to nontreated plants) was 1.9 to 3.0 times greater for 20- than 10-cm-tall plants in three site-years, but was not affected by plant height in one site-year. We also conducted experiments to determine the effect of rainfall on glyphosate efficacy. Across years, common lambsquarters control increased from 44 to 75% as the interval between glyphosate application (0.84 kg ha^{-1} + 3.8 kg ha^{-1} AMS) and simulated rainfall increased from 0.5 to 4.0 h, respectively. Our results did not identify environmental conditions that explained reduced glyphosate efficacy in all cases, but they suggest that rainfall after application and plant height can be important factors contributing to the inconsistent control of common lambsquarters.
Nomenclature: Glyphosate; common lambsquarters, *Chenopodium album* L. CHEAL.
Key words: Dose response, plant height, rainfall, resistance, stage of growth, temperature, tolerance.

Realizamos una serie de experimentos de campo para determinar el papel de varios factores que pudieran contribuir a la inconsistencia en el control de *Chenopodium album* con glifosato. Los experimentos en el 2006 y 2007 determinaron la respuesta de *C. album* al glifosato bajo un amplio rango de condiciones ambientales. El glifosato fue aplicado a 0.84 kg ea ha^{-1} más 3.8 kg ha^{-1} de sulfato de amonio (AMS), a plantas de 10 cm de altura en 18 fechas en cada año y a plantas de 20 cm de altura en 18 fechas en el 2007. El control fue menor para seis fechas de aplicación, en relación al control en las otras 48 fechas. El escaso control se atribuyó a la precipitación en una de estas seis fechas, pero para las otras cinco, un análisis de regresión no identificó ninguna relación significativa entre las condiciones ambientales (humedad relativa, temperatura al momento del tratamiento o la temperatura mínima y máxima pre y post tratamiento) y el control, aunque existió un amplio rango de condiciones. Para determinar los efectos de la etapa de crecimiento de la planta en el control, se aplicó glifosato de 0.1 a 3.2 kg ha^{-1} más 3.8 kg ha^{-1} AMS a plantas de 10 y 20 cm de altura en cuatro sitios. El valor ED50 del glifosato, (o sea, la dosis efectiva que redujo la masa de la parte aérea de la planta en un 50% en relación a las plantas no tratadas), fue de 1.9 a 3.0 veces mayor para las plantas de 20 cm de altura que para las de 10 cm en tres sitios-años, pero no fue afectado por la altura de la planta en un sitio-año. También realizamos experimentos para determinar el efecto de la precipitación en la eficacia del glifosato. Promediando los años, el control de *C. album* se incrementó de 44 a 75% al incrementarse de 0.5 a 4.0 h respectivamente, el intervalo entre la aplicación del glifosato (0.84 kg ha^{-1} más 3.8 kg ha$-^{1}$ AMS) y la precipitación simulada. Nuestros resultados no identificaron condiciones ambientales que explicaran la reducción de la eficacia de glifosato en todos los casos, pero sugieren que la precipitación después de la aplicación y la altura de la planta, puedan ser factores importantes que contribuyen al control inconsistente de *C. album.*

Glyphosate use has increased dramatically as conservation tillage practices and the adoption of glyphosate-resistant (GR) crops have become widespread (Givens et al. 2009b; Service 2007). In 2006, 90% of soybean [*Glycine max* (L.) Merr.] and 46% of corn (*Zea mays* L.) hectares in the United States were planted to glyphosate-resistant varieties and hybrids, respectively (Johnson et al. 2007). The rapid and widespread adoption of GR crops has caused glyphosate to become the best-selling herbicide in the world (Service 2007). Simplicity and high efficacy of weed control, along with low cost, have been cited as reasons for the extensive adoption of GR crops (Givens et al. 2009a).

Common lambsquarters is a major problem weed of soybean and corn cropping systems in the upper Midwest (Boerboom 2009; Kruger et al. 2009). It is highly competitive with these crops, and its control with glyphosate can be inconsistent (Boerboom 2009). Common lambsquarters is problematic in many crops because of its high seed production (Harrison 1990), germination under a wide range of environmental conditions (Henson 1970) over an extended period during the growing season (Mulugeta and Stoltenberg 1998), competition for nutrients (Pandy et al. 1971; Vengris

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1955), and seed longevity of up to 20 yr in the soil (Lewis 1973).

Numerous studies have addressed the relationship between glyphosate efficacy and environmental conditions. Glyphosate efficacy has been demonstrated to be greater in conditions of higher relative humidity in some studies (Sharma and Singh 2001; Tanpipat et al. 1997) but not in others (Stewart et al. 2009). Increased soil moisture levels led to greater efficacy or absorption of glyphosate by johnsongrass [*Sorghum halepense* (L.) Pers.] (McWhorter and Azlin 1978) and quackgrass [*Elymus repens* (L.) Gould] (Klevorn and Wyse 1984). A time of day effect on glyphosate efficacy has been observed in velvetleaf (Mohr et al. 2007; Waltz et al. 2004), common lambsquarters, common ragweed, foxtail species (Martinson et al. 2002), and barnyardgrass in some studies (Mohr et al. 2007) but not in others (Stewart et al. 2009). Ambient air temperatures can also affect glyphosate efficacy, absorption, and translocation (Adkins et al. 1998; Jordan 1977; Masiunas and Weller 1988; Reddy 2000; Sharma and Singh 2001; Tanpipat et al. 1997). Although several studies have found increased glyphosate efficacy with higher temperatures (Adkins et al. 1998; Jordan 1977; Masiunas and Weller 1988), others (Tanpipat et al. 1997) have found an inverse relationship between efficacy and air temperature.

Control of common lambsquarters by glyphosate can be affected by plant size, but published reports are mixed. Ziska et al. (1999) reported increased tolerance to glyphosate by common lambsquarters as plant size increased. Schuster et al. (2007) reported 2.5-cm-tall plants to be more susceptible to glyphosate than 7.5- and 15-cm-tall plants. However, Tharp et al. (1999) reported no difference in GR_{50} values (the dose that reduced growth by 50% relative to non-treated plants) for 4- to 8-, 10- to 15-, and 20- to 30-cm-tall common lambsquarters treated with glyphosate under controlled conditions. Similarly, Sikkema et al. (2004) found no difference in control of 2-, 4-, and 6-leaf common lambsquarters by glyphosate.

Although previous research suggests that several factors may affect common lambsquarters response to glyphosate, the importance of these factors under field conditions is not well understood. We conducted a series of field experiments to determine how environmental conditions (relative humidity, temperature at time of treatment, or minimum and maximum temperature pre- and posttreatment), plant height, and rainfall timing affect glyphosate efficacy on common lambsquarters.

Materials and Methods

Environmental Effects on Glyphosate Efficacy. Field experiments were designed to measure the efficacy of glyphosate on common lambsquarters across a wide range of environmental conditions. The experiments were conducted in 2006 and 2007 at the University of Wisconsin Arlington Agricultural Research Station (AARS) near Arlington, WI, on a Plano silt loam soil (fine-silty mesic Typic Ariduoll) with 4.2% organic matter and 6.3 pH. In 2006, the experimental design was a randomized complete block (RCB) in a split-plot arrangement with four replications. The main plot factor was week of glyphosate[1] application. Uniform plant height (10 cm) was achieved across weeks by varying time of tillage to affect time of seedling emergence. The split plot factor was day of glyphosate application within week and included four treatments: glyphosate applied at 0.84 kg ha^{-1} plus 3.8 kg ha^{-1} ammonium sulfate (AMS) on days 1, 3, and 5, plus a nontreated check. Plot size was 3 by 9 m, with 1.2-m-wide alleys between plots. In 2007, common lambsquarters plant height was included as a treatment factor. Consequently, the experimental design was a RCB with four replications of four treatments in a split-split plot arrangement. The main plot factor was week of glyphosate application; the split plot factor was common lambsquarters plant height (10 or 20 cm), and the split-split plot factor was day of glyphosate application within week as described above. Glyphosate was applied with the use of a CO_2-pressurized backpack sprayer and 2.5-m wide boom with XR8003 flat fan nozzles[2] spaced 50-cm apart (3.0 m spray width). The sprayer was calibrated to deliver 187 L ha^{-1} at 159 kPa and a speed of 4.8 km h^{-1}. Glyphosate application dates ranged from June 14 to August 7, 2006, and from June 1 to September 17, 2007. Glyphosate was applied regardless of weather conditions, such as impending rainfall.

At the time of glyphosate application, common lambsquarters plant density and shoot mass were measured in 0.25-m^2 quadrats in each split plot (2006) or split-split plot (2007). Twenty-eight days after glyphosate treatment (DAT), common lambsquarters injury was assessed visually on a scale of 0% (no effect on shoot mass growth) to 100% (total inhibition of shoot mass growth) compared with nontreated plants. A weather station[3] placed within the experiment area recorded air temperature, relative humidity, and precipitation every 15 min for the duration of the experiment. Because of errors in the relative humidity data collected in 2007, relative humidity values were obtained from the AARS weather station located approximately 1 km from the experiment site.

Analysis of variance was performed with the use of the MIXED procedure of SAS[4]. Our intention was to compare glyphosate efficacy as influenced by environmental conditions on each application date; consequently, year, week, and day of application were considered fixed effects, whereas block and interactions with block were considered random effects (Piepho et al. 2003). To compare application dates within week and among weeks, the LSMEANS statement was used with the PDIFF and ADJUST=Tukey options. The Tukey option utilizes Tukey's HSD (Honestly Significant Difference) test to compare means while controlling the family-wise error rate. To determine height main effect, height was considered fixed, whereas week, day of application, and their interactions were considered random. Relationships between injury and environmental conditions were determined by linear regression with the use of PROC GLM in SAS. Data were arcsine transformed to stabilize variances when necessary. Back-transformed means are presented.

Plant Height Effect on Glyphosate Efficacy. Field experiments were conducted at the University of Wisconsin AARS in 2004 and 2005, as described above, at the University of Wisconsin Lancaster Agricultural Research Station on a Fayette silt loam (fine-silty, mixed, superactive, mesic Typic

Hapludalf) in 2004 and in Walworth County, WI, on a Fox silt loam (fine-loamy, mixed, superactive, mesic Typic Hapludalf) in 2004. The experimental design was a RCB in a split plot arrangement with four replications. The main plot factor was common lambsquarters height (10 or 20 cm), and the split plot factor was glyphosate[5] dose (0, 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 kg ha^{-1} + 3.8 kg ha^{-1} AMS). Plot size was 3 by 6 m. Glyphosate was applied as described above. Shoot mass was collected from four 0.25- by 0.25-m quadrats 28 DAT, dried to constant mass in a forced-air oven, and weighed.

Analysis of variance was performed with the use of the MIXED procedure of SAS. Site-year, lambsquarters height, and dose were considered fixed effects. The blocking factor and interactions with block were considered random. Regression analyses were performed with GraphPad Prism.[6] Shoot mass data were normalized (as percentage of the nontreated check) and regressed over dose using a four-parameter log-logistic equation (Stoltenberg and Wiederholt 1995), as shown in Equation 1:

$$Y = (D - C)/\{1 + \exp[b(\log x - \log \mathrm{ED}_{50})]\} + C \qquad [1]$$

where C is the lower asymptote, D is the upper asymptote, ED_{50} is the effective dose that reduced shoot mass 50% relative to nontreated plants, and b is the slope of the curve at the ED_{50}. Extra sum of squares F tests at the 5% significance level were used to test for differences between dose–response curves for 10- and 20-cm-tall plants within site-years, and to test for differences between ED_{50} values for curves that differed (Motulsky and Christopoulos 2004).

Glyphosate Efficacy as Affected by Rainfall. Field experiments were conducted at the University of Wisconsin AARS in 2005 and 2006 as described above. The experimental design was a two-way factorial in a split block arrangement with four replications. The first factor was the time of simulated rainfall (0.5, 1, 2, and 4 h) following glyphosate[7] application (0.84 kg ha^{-1} plus 3.8 kg ha^{-1} AMS). The second factor was the presence or absence of simulated rainfall. Glyphosate was applied as described above. Simulated rainfall was applied using flood nozzles at a rate of 3,550 L ha^{-1}. A total of 42,500 L ha^{-1} was applied, which is equal to a rainfall of approximately 0.4 cm. At the time of treatment application, plants were 30 cm tall or less in 2005 and 25 cm tall or less in 2006. Common lambsquarters injury was visually assessed 25 DAT as described above.

Analysis of variance was conducted using the MIXED procedure of SAS to test for significance of year, rainfall, time between glyphosate application and simulated rainfall, and their interactions on injury ($P < 0.05$). The blocking factor and interactions with block were considered random. Interactions were assessed with the PDIFF and SLICE options of the LSMEANS statement (Littell et al. 2002). Nonlinear regression analyses were conducted by GraphPad Prism. Injury rating was regressed over time using a hyperbolic model (Equation 2; Cousens 1985):

$$Y = Ix/(1 + Ix/A) \qquad [2]$$

where Y is the percentage injury, I is the slope, x is the time between glyphosate application and rainfall, and A is the asymptote of the curve. A replicates test was performed to check for lack of fit of the model to the data (Motulsky and Christopoulos 2004).

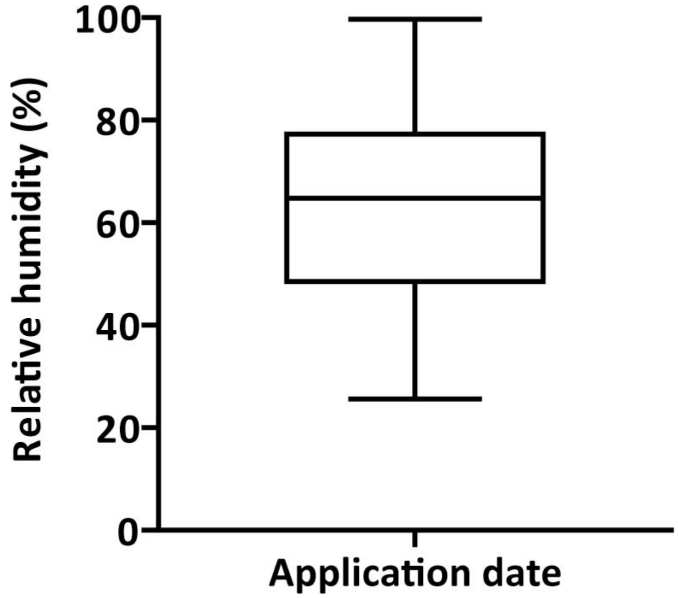

Figure 1. Relative humidity at the time of glyphosate application to common lambsquarters pooled across 54 application dates in 2006 and 2007. Lower and upper boxes represent the second and third quartiles, respectively. Vertical lines extend to the maxima and minima of the data.

Results and Discussion

Environmental Effects on Glyphosate Efficacy. A wide range of environmental conditions occurred across the dates of glyphosate application. Precipitation within 4 h of treatment ranged from 0 to 18 mm, but rainfall occurred on only 6 of 54 treatment dates and averaged 6 mm (data not shown). Relative humidity at the time of treatment varied from 26 to 100%, with a median humidity of 65% across treatment dates (Figure 1). Air temperatures before, after, and during application ranged from 0 to 33 C (Figure 2). Even so, control of common lambsquarters by glyphosate was consistent and high in most environments. A year by week by day of application interaction was observed; therefore, common lambsquarters control was compared within and across weeks. In 2006, control of 10-cm-tall plants did not differ among 17 of 18 dates and was 99% or greater (Figure 3). The failure of glyphosate to control common lambsquarters on one date was attributed to 1 mm of rainfall within 1.5 h of application. In 2007, control of 10-cm-tall plants was less on three dates (93, 83, and 71%) relative to other dates. Control of 20-cm-tall plants in 2007 was less on two dates (88 and 81%) relative to control on other dates.

Except for the one date in 2006, we were not able to determine an environmental cause for decreased common lambsquarters control on the five dates relative to the other 48 dates. Relationships between injury ratings and precipitation, relative humidity, minimum or maximum air temperature within 24 h of treatment, or air temperature at the time of

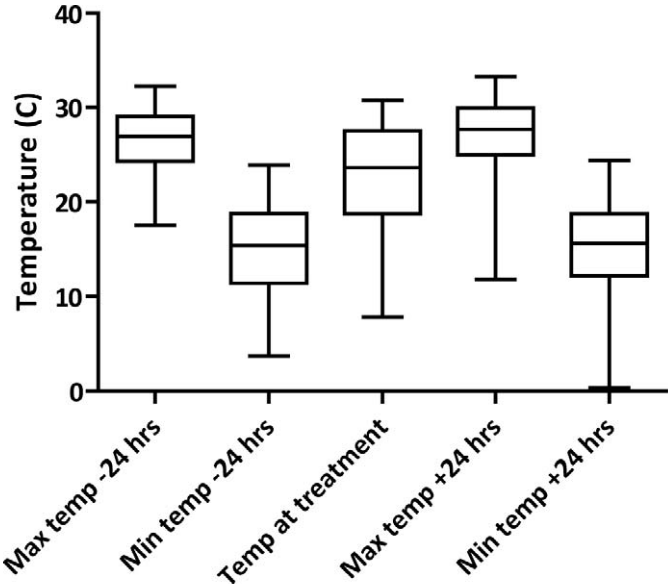

Figure 2. Maximum and minimum air temperature (C) 24 h before (−) and after (+), and the temperature at the time of glyphosate application to common lambsquarters pooled across 54 application dates in 2006 and 2007. Lower and upper boxes represent the second and third quartiles, respectively. Vertical lines extend to the maxima and minima of the data.

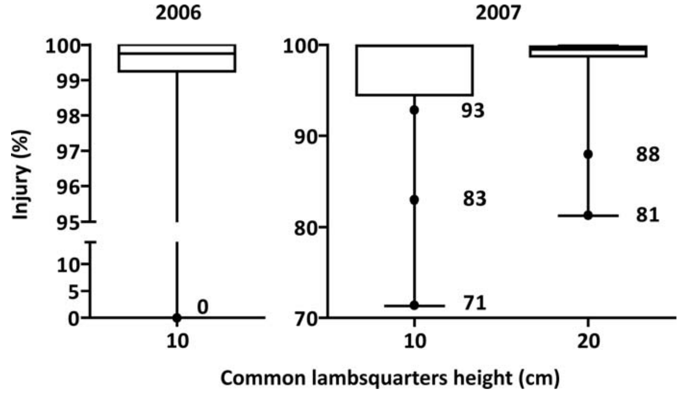

Figure 3. Visual estimates of injury ratings for 10-cm-tall common lambsquarters plants 28 d after treatment with glyphosate (0.84 kg ae ha^{-1} plus 3.8 kg ha^{-1} ammonium sulfate) on 18 dates in 2006 and in 2007 and for 20-cm-tall common lambsquarters on 18 dates in 2007. Injury ratings designated by a black circle differed from injury ratings for other treatments. Lower and upper boxes represent the second and third quartiles, respectively. Vertical lines extend to the maxima and minima of the data.

glyphosate application were not significant, as determined by regression analysis (data not shown).

Results of previous studies concerning the effect of air temperature and relative humidity on glyphosate efficacy are inconsistent. Absorption and activity of glyphosate has been reported to increase under conditions of high relative humidity for liverseedgrass (*Urochloa panichoides* Beauv.) (Adkins et al. 1998), johnsongrass (McWhorter et al. 1980), quackgrass [*Elymus repens* (L.) Gould] (McIntyre and Hsiao 1982), and junglerice [*Echinochloa colona* (L.) Link] (Tanpipat et al. 1997). However, Waltz et al. (2004) found a negative correlation between relative humidity and glyphosate control of velvetleaf in the field. This observation could be more directly a result of the absence of light and the leaf blade position in velvetleaf than the relative humidity because relative humidity tended to be highest at night. Stewart et al. (2009) found no correlation between increased relative humidity and increased control by glyphosate of several weed species, including common lambsquarters.

Many of the studies that report increased glyphosate efficacy due to higher relative humidity were conducted under controlled conditions. Greater efficacy of foliar-applied herbicides on plants grown under controlled conditions compared with field-grown plants has been well documented (Al-Khatib et al. 1992; Hoss et al. 2003; Wanamarta and Penner 1989), with differences attributed to cuticle composition and thickness. In many controlled studies, the differences in relative humidity are profound and maintained for long time periods, typically for the duration of the study. In our study, under field conditions, changes in relative humidity occurred relatively rapidly (data not shown). As the relative humidity values used in our analyses were those recorded at the time of treatment, they reflect only treatment conditions and not the conditions present for the morphological and physiological development of the plants. As such, it may not be surprising that we were not able to detect a relationship between relative humidity and glyphosate efficacy. Because the results of previous studies are mixed, the effect of relative humidity on glyphosate efficacy remains unclear and is likely influenced by interactions with other factors.

Higher air temperatures have been associated with greater glyphosate efficacy in liverseedgrass and wild oat (*Avena fatua* L.) (Adkins et al. 1998), but decreased efficacy in junglerice (Tanpipat et al. 1997). Waltz et al. (2004) reported control of velvetleaf with glyphosate in the field to be correlated with the air temperature at the time of herbicide treatment. However, we did not find a relationship between ambient air temperature and common lambsquarters control by glyphosate. Because control was high across most environments in our study, it is possible a greater temperature effect would be more likely if combined with other environmental conditions less favorable for glyphosate efficacy or under reduced rates of glyphosate. In our study, we applied glyphosate to 10- and 20-cm-tall plants at a rate of 0.84 kg ha^{-1}, the label rate for 30-cm-tall common lambsquarters. Additionally, differences due to temperature might be more readily apparent if temperatures were consistent and maintained for longer periods of time before and after glyphosate application, as they typically are in studies conducted under controlled conditions.

Control of common lambsquarters was not affected by height following treatment with glyphosate at 0.84 kg ha^{-1} in 2007 (data not shown). We attributed this lack of effect to the high level of efficacy associated with a glyphosate rate of 0.84 kg ha^{-1}. Lower rates could result in more differentiation in response between larger and smaller plants to glyphosate because lower rates might still provide adequate control of smaller plants while control of larger plants declines. Other results suggest that a differential response between plant heights is more likely at less than labeled rates (Figure 4,

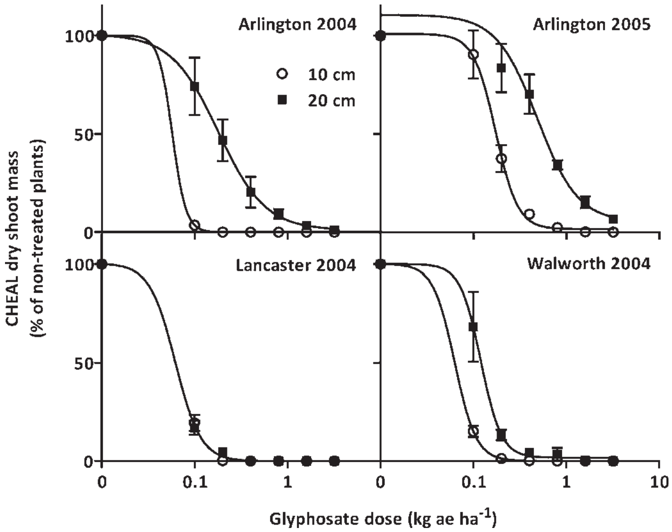

Figure 4. Shoot dry mass (expressed as percent of non-treated plants) of 10- and 20-cm-tall common lambsquarters plants 28 d after treatment with glyphosate. Ammonium sulfate (3.8 kg ha^{-1}) was included with each glyphosate dose. Dose–response analysis was conducted on replicate data. Presented data are mean values ± SE.

discussed below). Results from other studies support this possibility (Krausz et al. 1996).

Plant Height Effect on Glyphosate Efficacy. Because of a significant treatment by site interaction (data not shown), regression analyses were performed separately for each of the four sites (Figure 4). Response to glyphosate varied between sites, with glyphosate ED_{50} values ranging from 0.06 to 0.17 kg ha^{-1} for 10-cm-tall plants and from 0.05 to 0.49 kg ha^{-1} for 20-cm-tall plants (Table 1). ED_{50} values were 1.9-, 3.0-, and 2.8-fold greater for 20-cm-tall plants than for 10-cm-tall plants at Walworth in 2004, Arlington in 2004, and Arlington in 2005, respectively (Table 1). Control was not affected by plant height at the Lancaster site.

The effect of common lambsquarters height on glyphosate efficacy in our study is within the range of previous reports, although the effect of plant height on common lambsquarters susceptibility to glyphosate appears to be inconsistent. Schuster et al. (2007) reported 80% injury to 2.5-cm-tall plants exposed to 1.1 kg ha^{-1} glyphosate under controlled conditions, but only 55% injury to 7.5- and 15-cm-tall plants. They reported ED_{50} values for 15-cm-tall plants that ranged from 2.4 to 5.5 times that of 2.5-cm-tall plants, depending on biotype. Conversely, Tharp et al. (1999) observed no difference in GR_{50} values for 4- to 8-, 10- to 15-, and 20- to 30-cm-tall common lambsquarters treated with glyphosate under controlled conditions. Sikkema et al. (2004) observed no difference in common lambsquarters response to a range of glyphosate doses in the field when plants were at the two-, four-, or six-leaf stages. Krausz et al. (1996) observed greater control of 10-cm than 20-cm-tall common lambsquarters, although differences in control decreased with increased glyphosate dose. In our study, variability of response between sites could be due to interactions between environmental conditions and herbicide response. In addition, some

Table 1. Effective glyphosate dose that reduced shoot mass of 10- and 20-cm-tall common lambsquarters plants 50% (ED_{50}) relative to non-treated plants.

	ED_{50}[a]		
	Plant height		
Site-year	10 cm	20 cm	ED_{50} ratio[b]
	kg ha^{-1}		
Arlington 2004	0.06 ± 0.11	0.18 ± 0.03	3.0
Arlington 2005	0.17 ± 0.01	0.49 ± 0.11	2.8
Lancaster 2004	0.06 ± 0.01	0.06 ± 0.01	nd[c]
Walworth 2004	0.06 ± 0.01	0.12 ± 0.01	1.9

[a] Best fit values ± standard error.
[b] Ratio of ED_{50} values of 20- to 10-cm-tall plant.
[c] nd, ED_{50} values do not differ between plant heights.

differences in response could be due to the natural variability of biotypes present at each site. Schuster et al. (2007) reported that glyphosate GR_{50} values for 15-cm-tall common lambsquarters ranged from 1.0 to 2.8 kg ha^{-1} for biotypes from Kansas, North Dakota, Nebraska, and Ohio.

Glyphosate Efficacy as Affected by Rainfall. Because interactions between treatment and year were not significant, data were pooled over years for analysis. The main treatment effect of simulated rainfall was significant (data not shown); control of common lambsquarters by glyphosate was less for simulated rainfall treatments compared with treatments that did not receive simulated rainfall (Figure 5). In the absence of rainfall, glyphosate provided an average of 92% control of common lambsquarters. In simulated rainfall treatments, glyphosate efficacy increased from 44 to 75% as the interval between application and simulated rainfall increased from 0.5 to 4.0 h, respectively.

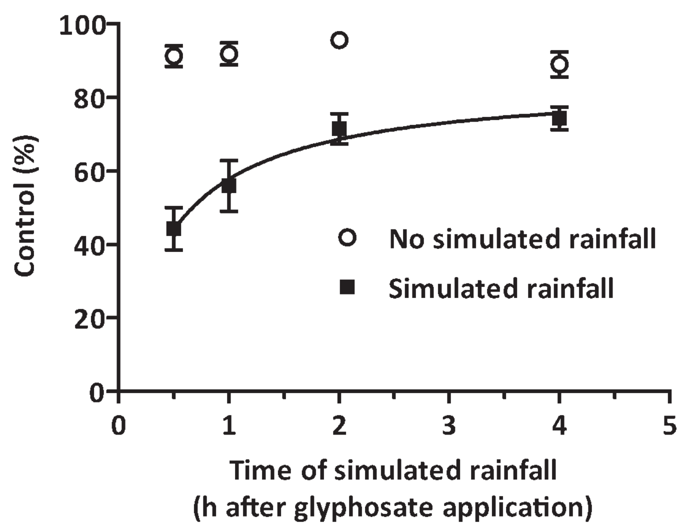

Figure 5. Effect of simulated rainfall on common lambsquarters control by glyphosate for data pooled across 2005 and 2006. Ammonium sulfate (3.8 kg ha^{-1}) was included with each glyphosate dose. Regression analysis was conducted on replicate data. Presented data are mean values ± SE. Common lambsquarters response was described by the equation $y = 184/(1 + 184\,x/84)$ ($r^2 = 0.43$).

Consistent with our results, Miller et al. (1998) observed reduced control of johnsongrass when simulated rainfall occurred 60 min after glyphosate application and was reduced further when the rain-free period was 15 min. Gannon and Yelverton (2008) reported that 30- to 60-min rain-free periods were required for excellent control of tall fescue [*Lolium arundinaceum* (Schreb.) S. J. Darbyshire] with higher glyphosate rates requiring shorter rain-free periods. However, Bariuan et al. (1999) reported simulated rain applied 24 h after glyphosate application reduced efficacy 33% compared with no simulated rain in purple nutsedge (*Cyperus rotundus* L.). Glyphosate rainfastness is likely affected by physiological and morphological differences among species, glyphosate rate, formulation, and additives, as well as environmental factors. However, our results suggest that rainfall soon after glyphosate application can be expected to reduce control of common lambsquarters.

Glyphosate was highly effective in controlling common lambsquarters under a wide range of environmental conditions in our study, with a few exceptions. We were not able to identify specific environmental parameters that reduced efficacy in all cases. However, rainfall after application and plant height at application may be important contributing factors in instances of reduced glyphosate efficacy on common lambsquarters. Subtle interactions of biotic and abiotic factors might be responsible for other instances of reduced glyphosate efficacy on common lambsquarters. Although glyphosate-resistant biotypes were not investigated as a source of variable response in these experiments, resistance should be considered a potential source of reduced efficacy if environmental- or management-related causes are not identified as a reason for reduced efficacy. To reduce the risk of poor efficacy, general recommendations should be followed, such as treating common lambsquarters at earlier growth stages to increase susceptibility to glyphosate, using glyphosate rates that are appropriate for plant size, and using techniques to optimize glyphosate efficacy (i.e., use lower spray volumes, address poor spray water quality, avoid antagonistic tank mixtures). If conditions (i.e., environmental stress) suggest efficacy may be variable, glyphosate application should be altered to increase efficacy, such as avoiding application during early and late times of day or avoiding application during droughty conditions.

Sources of Materials

[1] Roundup Weathermax®, Monsanto Co., St. Louis, MO 63167.

[2] Teejet flat-fan extended range spray tips, Spraying Systems Co., Wheaton, IL 60189.

[3] Hobo Weather Logger, H21-001, Onset Computer Corp., Pocasset, MA 02559-3450, http://www.onsetcomp.com/.

[4] Statistical Analysis Systems, version 9.2, SAS Institute Inc., Cary, NC 27513.

[5] Roundup Ultramax®, Monsanto Co., St. Louis, MO 63167.

[6] GraphPad Prism, version 5.02, GraphPad Software, Inc., La Jolla, CA 92037.

[7] Roundup OriginalMax®, Monsanto Co., St. Louis, MO 63167.

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