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Weed Management—Major Crops

Response of Rice to Drift Rates of Glyphosate Applied at Low Carrier Volumes

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Field studies were conducted near Crowley, LA in 2005 through 2007 to evaluate the effects of simulated herbicide drift on 'Cocodrie' rice. Each application was made with the spray volume varying proportionally to herbicide dosage based on a constant spray volume of 234 L ha^{-1} and a glyphosate rate of 863 g ae ha^{-1}. The 6.3%, 54–g ha^{-1}, herbicide rate was applied at a spray volume of 15 L ha^{-1}, and the 12.5%, 108–g ha^{-1}, herbicide rate was applied at a spray volume of 29 L ha^{-1}. Compared with the nontreated, glyphosate applied at one tiller, panicle differentiation (PD), and boot resulted in increased crop injury. The greatest injury was observed on rice treated at the one-tiller timing. Applications of glyphosate at one tiller, PD, and boot reduced plant height at harvest and primary and total crop yield. Rice treated at primary crop maturity was not affected by glyphosate applications.

Nomenclature: Glyphosate; rice, *Oryza sativa* L. 'Cocodrie'.

Key words: Simulated herbicide drift, sublethal herbicide rates.

Se realizaron estudios de campo cerca de Crowley, LA desde 2005 hasta 2007 para evaluar los efectos de la deriva simulada de herbicidas sobre arroz 'Cocodrie'. Cada aplicación fue hecha con un volumen de aspersión que varió proporcionalmente a la dosis del herbicida con base en un volumen constante de aspersión de 234 L ha^{-1} y una dosis de glyphosate de 863 g ae ha^{-1}. La dosis de 6.3%, 54 g ha^{-1}, fue aplicada a un volumen de aspersión de 15 L ha^{-1}, y la de 12,5%, 108 g ha^{-1}, fue aplicada a un volumen de aspersión de 29 L ha^{-1}. Al compararse con el testigo no-tratado, glyphosate aplicado en los estados de un hijuelo, diferenciación de panícula (PD), y engrosamiento de la vaina de la hoja bandera, resultó en un mayor daño al cultivo. El mayor daño fue observado en arroz tratado en el estado de un hijuelo. Las aplicaciones de glyphosate en los estados de un hijuelo, PD y engrosamiento de la vaina de la hoja bandera, redujeron la altura de la planta al momento de la cosecha y el rendimiento primario y total del cultivo. El arroz tratado al momento de la madurez primaria del cultivo no fue afectado por las aplicaciones de glyphosate.

Glyphosate is a nonselective, foliar-applied, POST-applied herbicide used to control annual and perennial weeds in preplant burndown applications and for weed control in glyphosate-resistant crops (Senseman 2007). The use of glyphosate has greatly increased with the introduction and extensive acceptance of glyphosate-resistant canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Shaner 2000).

The mechanism of action of glyphosate is the inhibition of 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase (EC 2.5.1.19), which produces EPSP from shikimate-3-phosphate and phosphoenolpyruvate in the shikimic acid pathway (Amrhein et al. 1980, 1983; Boocock and Coggins 1983; Herrmann and Weaver 1999; Hollander-Czytko and Amrhein 1987; Jakeman et al. 1998; Schonbrunn et al. 2001; Senseman 2007). The symptoms expressed in plants from the inhibition of EPSP synthase are growth inhibition soon after application, followed by general foliar chlorosis and necrosis within 4 to 7 d in highly susceptible species or longer for less susceptible species (Senseman 2007). Visual symptoms appear first and are most pronounced in immature leaves and growing points in the form of chlorosis. Regrowth of treated perennial and woody species often appears deformed and multiple shoots may develop at the nodes.

Rice is a major crop produced in the four-state region of Arkansas, Louisiana, Mississippi, and Texas, with these states accounting for 75% of the 1.5 million total hectares of rice planted in the United States and 68% of the $3.1 billion of total value of rice produced in the United States in 2010 (NASS 2011a,b). That same year, approximately 98% of Louisiana's 417,150 ha of soybean were planted in glyphosate-resistant soybean cultivars (Ronald J. Levy, Jr., personal communication). Because many of the rice-producing parishes in Louisiana also produce glyphosate-resistant soybean, corn, and cotton (NASS 2011c), the potential exists for off-target herbicide drift from one of these crops to rice.

Wind speed and direction are the two most important meteorological factors affecting spray droplets in the atmosphere; a stable atmosphere may be the third most important factor (Thistle 2004). A stable atmosphere, commonly referred to as an inversion, is an atmosphere that has an increase in temperature with an increase in elevation in the atmosphere. In this stable atmosphere, warm air overlies cool air. If air in a particular layer is displaced upward or downward in a stable atmosphere it will be colder or warmer, respectively, than the immediately adjacent layer it enters, and

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thus return to its layer of origin. This is the inverse of an unstable atmosphere, where temperature decreases with an increase in elevation, allowing mixing of layers as warmer air rises and cooler air falls through adjacent layers. If an herbicide application is made during an inversion scenario, the fine droplets may remain in the air layer in which they are applied, where they may remain concentrated and may horizontally move off target great distances.

Ultra-low-volume applications made during an inversion produced 35% more herbicide drift than applications made during turbulent atmosphere with light wind speeds (Crabbe et al. 1994). The conditions in which the greatest drift occurred were in moderately stable conditions with wind at 3 m s^{-1}, resulting in off-target drift of 71% at 400 m and 50% at 2,200 m from the application site and in slightly stable conditions with wind at 5 m s^{-1} resulting in off-target drift of 77% at 400 m and 27% at 2,200 m from the application site. It is recommended that herbicide applications be avoided during the early morning and late evening, as these times are most favorable for the development of inversion conditions (Crabbe et al. 1994; Thistle 2004).

Through the use of simulated herbicide drift studies or reduced herbicide rate studies, the potential effects of glyphosate drift to rice can be evaluated. In previous research, simulated drift studies conducted employing reduced spray volume proportionally with reduced herbicide rates resulted in increased crop injury compared with the same lower herbicide rates at a higher spray volume (Banks and Schroeder 2002; Ellis et al. 2002; Ramsdale et al. 2003; Roider et al. 2008). Banks and Schroeder (2002) reported low spray volume proportionally with lower herbicide dosage, thus maintaining constant herbicide concentration in the spray, would change the response of sweet corn to glyphosate when compared with a constant spray volume where a low herbicide rate would be more dilute in the carrier. The no-effect glyphosate rate for sweet corn was 0.046 kg ae ha^{-1} when using a proportionally lower spray volume of 12 L ha^{-1}; however, the no-effect glyphosate rate was four times greater, 0.185 kg ha^{-1}, when glyphosate was applied in a constant spray volume of 281 L ha^{-1}. Ellis et al. (2002) reported glyphosate applied to corn at 12.5 and 6.3% of the labeled use rate of 1,120 g ai ha^{-1} in a proportional spray volume and a constant spray volume of 234 L ha^{-1} produced results similar to those observed by Banks and Schroeder (2002). The use of a constant spray volume in drift research may underestimate the effects of off-target drift to susceptible crops.

Others have reported contradictory results depending on plant species evaluated. With data averaged over active ingredient, Ellis et al. (2002) reported constant vs. proportional spray volume differed for glufosinate and glyphosate on corn; however, the impact of glufosinate and glyphosate on soybean did not change with constant vs. variable carrier volume. Everitt and Keeling (2009) and Marple et al. (2008) reported the reduced carrier volume may be unrealistic in drift research and/or may confound results. Sawchuck et al. (2006) suggested that extrapolating or generalizing results for one specific herbicide–plant species interaction should not and cannot be applicable to all situations. Pesticide spray drift occurs when small concentrated spray droplets are deposited in a non-uniform pattern on non-target plants, and it is unlikely that concentrated droplets will give similar results for all herbicides (Sawchuck et al. 2006). Each herbicide will behave independently under proportional spray volumes.

Simulated drift applications of glyphosate applied to rice at the two- to three-leaf and panicle differentiation growth stages in a constant spray volume reduced rice yield 67 to 99% and 29 to 54%, respectively (Ellis et al. 2003). Kurtz and Street (2003) reduced rice yield with simulated glyphosate drift applied to rice at midtiller, panicle initiation, and boot growth stages.

Even though published studies evaluating the effects of simulated glyphosate drift on rice exist (Davis et al. 2011; Ellis et al. 2003; Koger et al. 2005; Kurtz and Street 2003), none of these studies were conducted using spray volumes that vary proportionally with reduced herbicide dosage and, therefore, may have underestimated the effects of glyphosate drift on rice. The objectives of this research were to evaluate the effects of simulated glyphosate drift applied to rice during the primary rice crop on the crop response and yield of treated rice in the primary and ratoon rice crops.

Materials and Methods

A study was conducted on rice grown in 2005 through 2007 at the LSU Agricultural Rice Research Station near Crowley, LA on a Crowley silt loam with pH 5.5 and 1.2% organic matter. Field preparation consisted of a fall and spring disking and two passes in opposite directions with a two-way bed conditioner equipped with rolling baskets and S-tine harrows 15 cm deep. The long-grain rice cultivar 'Cocodrie' was drill seeded March 28 to April 17 in 2005 through 2007. Plots consisted of 12 to 18–cm spaced rows 6 m long.

The experimental design was two-factor factorial arrangement of treatments in a randomized complete block with a nontreated added for comparison and four replications. Factor A consisted of glyphosate (Roundup Weathermax®, 540 g ae L^{-1}, Monsanto Co., 800 N. Lindbergh Blvd., St. Louis, MO 63167) applied at simulated drift rates of 6.3 and 12.5% of the labeled usage rate of 863 g ae ha^{-1}, or 54 and 108 g ha^{-1}, respectively. Factor B consisted of application timings at different growth stages: one-tiller, panicle differentiation (PD), boot, and physiological maturity. Each herbicide application was made with the spray volume reduced proportionally with herbicide dosage based on a constant spray volume of 234 L ha^{-1}. The 12.5% herbicide rate was applied at a spray volume of 29 L ha^{-1} and the 6.3% herbicide rate was applied at a spray volume of 15 L ha^{-1}. Each application was made with a tractor-mounted CO_2-pressurized sprayer calibrated to deliver a constant carrier volume with speed adjusted to vary application rate and equipped with Teejet® TX-2 Conejet® 800033 nozzles (Teejet® Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187). A ratoon rice crop was not produced in 2006 because of unfavorable weather following primary crop harvest.

The study area was maintained weed free with the use of clomazone at 420 g ai ha^{-1} applied PRE followed by propanil at 4,480 g ai ha^{-1} plus halosulfuron at 53 g ai ha^{-1} applied POST. For the primary rice crop, a preplant application of 280 kg ha^{-1} of 8-24-24 ($N–P_2O_5–K_2O$) fertilizer and a preflood application of 365 kg ha^{-1} 46-0-0 urea fertilizer were applied to the study area and for the ratoon rice crop a

Table 1. Effects of simulated glyphosate drift application timing and rating date on primary crop rice injury 7, 14, 21, and 28 d after treatment (DAT), 2005 through 2007, Crowley, LA.[a]

	Rice plant injury			
Glyphosate timing[b]	7 DAT	14 DAT	21 DAT	28 DAT
	%			
One tiller	34 c	51 a	41 b	42 b
PD	8 f	15 e	22 d	24 d
Boot	6 f	10 ef	10 ef	11 ef
Maturity	0 g	0 g	0 g	0 g
Nontreated	0 g	0 g	0 g	0 g

[a] Means followed by the same letter, within and across columns, were not statistically different according to the *t* test on difference of least-square means at P = 0.05.

[b] Data averaged across glyphosate application rates of 54 and 108 g ae ha^{-1} applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

Table 2. Effects of simulated glyphosate drift application rate and timing on primary crop rice plant height at harvest, 2005 through 2007, Crowley, LA.[a]

	Rice plant height[b]	
Glyphosate timing	54 g ae ha^{-1}	108 g ae ha^{-1}
	cm	
One-tiller	83 b	83 b
PD	85 b	80 b
Boot	84 b	83 b
Maturity	94 a	96 a
Nontreated	94 a	

[a] Means followed by the same letter, within and across columns, were not statistically different according to the *t* test on difference of least-square means at P = 0.05.

[b] Glyphosate at 54 and 108 g ha^{-1} was applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

preflood application of 100 kg ha^{-1} 46-0-0 urea fertilizer was applied to the study area to maintain proper fertility and to maximize yields in the primary and ratoon crops. Standard agronomic and pest management practices were implemented throughout the growing season to maximize yield.

Rice plant height (data not shown) and rice injury in the primary rice crop were obtained 7 d after herbicide treatment (DAT) and continued weekly for 28 DAT. Rice plant height was obtained by measuring four plants per plot from the soil surface to the tip of the extended uppermost emerged leaf or extended rice panicle. Rice injury was evaluated based on chlorosis and necrosis of foliage and reduced plant height using a scale of 0 to 100%, where 0 = no injury and 100 = plant death. Rice plant height at primary crop harvest and rough rice yield and stem and panicle counts for the primary and ratoon crop were also obtained. Whole plots were harvested with the use of a mechanical plot harvester and rough rice yield was adjusted to 12% moisture. Total stem and panicle counts were calculated by hand harvesting a 0.46-m section of row and determining the number of stems present at the midheight of the plants and the number of panicles with bases emerged beyond the sheath of the flag leaf, the last leaf to emerge prior to the panicle.

All data were subjected to the Mixed Procedure of SAS (SAS 2003). Year and replications (nested within year) were considered random effects. Application timing, rate, and evaluation date were considered fixed effects. Considering year as a random effect permits inferences about treatments over a range of environments (Blouin et al. 2011). Type III statistics were used to test all possible effects of fixed factors and least-square means were used for mean separation at the 5% probability level ($P \leq 0.05$).

Results and Discussion

An application timing by rating date interaction was observed in the primary crop-injury data; therefore, data were averaged across application rate (Table 1). Visually rated rice crop injury ranged from 34 to 51% when glyphosate was applied to rice at the one-tiller stage, representing more injury than any other timing evaluated in this study. At the one-tiller stage some recovery or regrowth was observed at later rating dates. When treatments were delayed to the PD and boot timings, visually rated injury was below 20% except for the 21 and 28 DAT evaluation for rice treated at the PD timing. Glyphosate applications at one tiller and PD resulted in increased injury at later rating dates beyond the 7 DAT rating date. Applications of glyphosate to rice at maturity had no effect on rice-crop injury, compared with the nontreated. As with actual drift events, identifying drift based on visual injury is more difficult as rice matures. Similar findings were reported by Ellis et al. (2003) and Kurtz and Street (2003), where visual injury symptoms were more severe in rice treated with glyphosate during early vegetative growth stages than rice treated during late reproductive growth stages.

This reduction in visually rated injury during reproductive growth stages may be due to the translocation of glyphosate to meristematic tissue (Martin and Edgington 1981). This tissue is located in the internal portions of the rice plant during the reproductive stages of growth and would not be expressed on foliar tissue.

The injury symptoms observed in this study on plants treated at the one-tiller timing ranged from general chlorosis in the uppermost leaves to plant death. The newest leaf to emerge following treatment often emerged tightly rolled. An overall stunting of plants was observed on plants treated at the one-tiller, PD, and boot timings (Table 2).

Visual symptomology observed on plants treated with glyphosate at PD and boot were various forms of foliar and inflorescence malformations. Foliar symptoms included plants having multiple shoots arising from the secondary nodes of the main stem, and the flag leaf on the main stem and secondary shoots also would often appear wrinkled, contorted, or rolled (Figures 1 and 2). Davis et al. (2011) reported similar characteristics with rice treated with reduced rates of glyphosate. In some instances, secondary shoots were stunted or both stunted and malformed. At maturity, some panicles failed to fully exert beyond the flag-leaf sheath or emerged from the side of the sheath (Figure 3). Some of the inflorescence malformations were due to malformed panicle axis and partially emerged panicles due to fusing with the flag-leaf sheath. Individual floret malformations that were observed were florets that were void of a developing grain with only a bleached lemma and palea remaining and individual florets with tips of the lemma excessively curved toward the palea (Figure 4), causing an

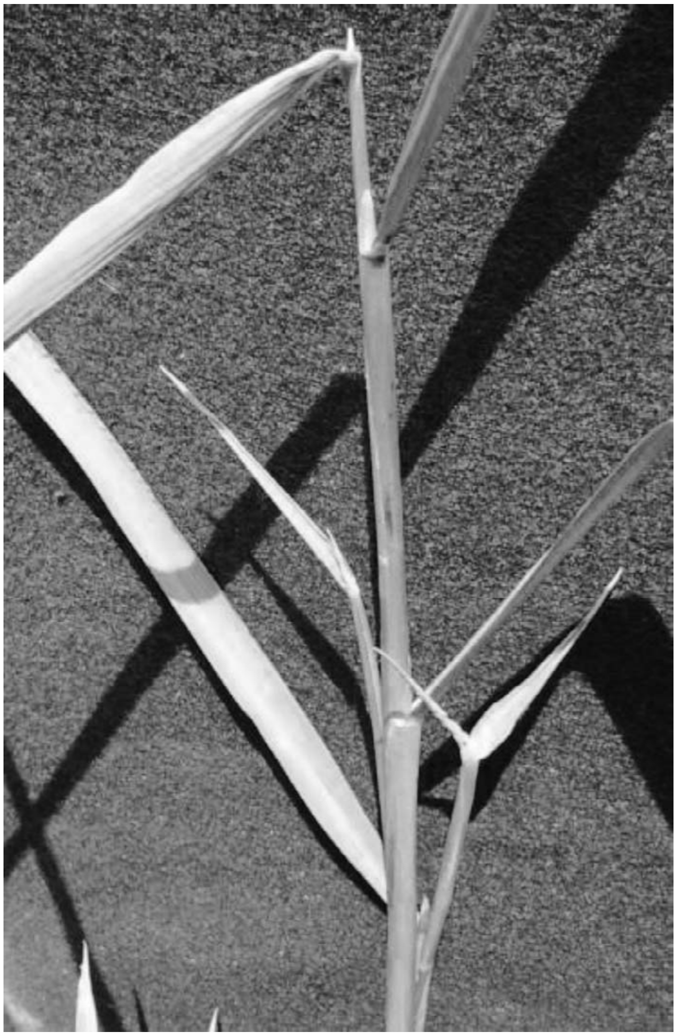

Figure 1. Secondary stems in upper plant nodes observed with glyphosate drift to rice.

Figure 2. Flag-leaf malformation observed with glyphosate drift to rice.

appearance often referred to as "parrot beaked" when observed in association with the straight-head physiological disorder of rice (Groth et al. 2009).

Analysis of rice plant height at harvest data resulted in an application timing by rate interaction (Table 2). Glyphosate applied to rice at one-tiller, PD, and boot timings resulted in reduced rice plant height at primary crop harvest, 80 to 85 cm, compared with a nontreated height of 94 cm. Glyphosate applied to mature rice had no effect on rice plant height. These results are similar to the visual-rated injury data. Davis et al. (2011) also reported reduced mature plant height when evaluating glyphosate drift rates applied to rice at growth stages similar to those evaluated in this study.

There was an application timing by rate interaction in the primary and ratoon crop stem and panicle counts (Table 3). Except when applied at 54 g ha^{-1} at one tiller, glyphosate applied at one tiller, PD, and boot increased secondary plant stems in the primary crop, resulting in an increased stem count, compared with the nontreated. However, panicle count was only increased in the primary crop when glyphosate was applied at the PD timing, regardless of application rate. In the ratoon rice crop, an increase in stem and panicle counts was only observed in rice treated at the boot stage.

An application timing by rate interaction was observed in the primary, ratoon, and total crop yield data (Table 4). Glyphosate applied at one tiller, PD, and boot reduced primary crop yield, compared with the nontreated. Within application rates, the primary crop yield reduction resulting from an application of glyphosate at the boot timing was more severe than applications at the PD growth stage, but similar to applications at the one-tiller timing evaluated in this study. Glyphosate applications of 54 and 108 g ha^{-1} at boot and 108 g ha^{-1} at one tiller resulted in a primary crop yield of 35 to 52% of the nontreated. However, glyphosate applied at boot resulted in an increased ratoon crop yield of 141 to 142% of the nontreated. This increase in ratoon crop yield was due to glyphosate causing an excess of secondary stems to be produced on the main-stem upper plant nodes in the primary rice crop (Table 3). This excess of secondary stems did not produce panicles in the primary crop, but did produce panicles in the ratoon crop. This response was not observed with rice treated at any other timings evaluated in this study.

Figure 3. Partially exerted panicle observed with glyphosate drift to rice.

Figure 4. Panicle floret malformations observed with glyphosate drift to rice.

However, when primary and ratoon crop yields were combined, the increase in ratoon crop yield did not compensate for the primary crop yield loss (Table 4). These data indicate that a glyphosate application at the growth stages evaluated in this study would reduce primary crop yield at the 54– and 108–g ha^{-1} glyphosate rates evaluated. Total yield was also reduced when glyphosate was applied at the one-tiller, PD, and boot timings, compared with the nontreated. Glyphosate applications at maturity had no effect on primary, ratoon, or total crop rough rice yield, compared with the nontreated. Rice producers may have the ability to recover some yield loss from a drift event occurring to rice during the boot growth stage by increasing ratoon crop yield; however, the reduction in total crop yield from a glyphosate drift event at the one-tiller, PD, or boot growth stages of rice can be significant. Hensley et al. (2012) reported similar results with drift rates of imazethapyr in rice.

In conclusion, simulated glyphosate drift applications at the one-tiller, PD, and boot timings resulted in reduced plant height at harvest and primary and total crop yield losses, with the greatest reduction in primary crop yield resulting from a simulated glyphosate drift application at 108 g ha^{-1} at one tiller

Table 3. Effects of simulated glyphosate drift application rate and timing on primary crop rice stem and panicle counts, 2005 through 2007, and ratoon crop rice stem and panicle counts, 2005 and 2007, Crowley, LA.[a]

		Primary crop counts		Ratoon crop counts	
Glyphosate rate[b]	Timing	Stem	Panicle	Stem	Panicle
g ae ha^{-1}		Stems per 0.46 m of row			
54	One tiller	35 c	28 d	36 bc	29 b
	PD	56 b	53 ab	44 b	24 b
	Boot	60 b	33 cd	86 a	78 a
	Maturity	38 c	36 cd	48 b	31 b
108	One tiller	56 b	42 bc	22 c	16 b
	PD	72 a	62 a	49 b	33 b
	Boot	74 a	31 cd	87 a	76 a
	Maturity	37 c	35 cd	47 b	31 b
Nontreated		39 c	35 cd	44 b	32 b

[a] Means within a column followed by the same letter were not statistically different according to the *t* test on difference of least-square means at P = 0.05.

[b] Glyphosate at 54 and 108 g ha^{-1} was applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

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Table 4. Effects of simulated glyphosate drift application rate and timing on primary crop rice yield, 2005 through 2007, and ratoon and total crop rice yield, 2005 and 2007, Crowley, LA.[a]

Glyphosate rate[c]	Timing	Yield[b]		
		Primary crop	Ratoon crop	Total crop
g ae ha^{-1}		kg ha^{-1}		
54	One tiller	4,280 bc	780 d	5,060 cd
	PD	5,230 b	890 cd	6,120 bc
	Boot	3,650 cd	1,830 a	5,480 cd
	Maturity	6,850 a	1,100 bcd	7,950 ab
108	One tiller	3,620 cd	1,050 bcd	4,670 cd
	PD	3,800 c	1,110 bcd	4,910 cd
	Boot	2,410 d	1,840 a	4,250 d
	Maturity	6,640 a	1,170 bc	7,810 ab
Nontreated		6,990 a	1,300 b	8,290 a

[a] Means within a column followed by the same letter were not statistically different according to the *t* test on difference of least-square means at P = 0.05.

[b] Rough rice yield adjusted to 12% moisture.

[c] Glyphosate at 54 and 108 g ha^{-1} was applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

and the 54– and 108–g ha^{-1} rates at the boot growth stage. Simulated glyphosate drift applications to mature rice had no effect on rice plant height or yield.

The potential for a reduced rice yield exists if a glyphosate drift event occurs to a rice field in the one-tiller, PD, and boot stages of growth. Rice in the vegetative growth stages, one leaf to one tiller, receiving a drift event can often recover if stand is maintained at recommended densities. Little or no visible foliar injury may be observed on rice receiving a drift event in the reproductive growth stages, and often symptoms may not appear until rice plants near crop maturity. This undetected reduction in yield may lead to reduced profitability due to the cost of continuing to supply inputs to a rice crop that has an already reduced yield potential.

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