Weed Technology 2016 30:99–105

Rice Crop Response to Simulated Drift of Imazamox

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Field studies were conducted near Crowley, LA, to evaluate the effects of simulated herbicide drift on 'Cocodrie' rice. Each treatment was made with the spray volume varying proportionally to herbicide dosage based on a spray volume of 234 L ha^{-1} and an imazamox rate of 44 g ai ha^{-1}. The 6.3%, 2.7-g ha^{-1}, herbicide rate was applied at a spray volume of 15 L ha^{-1} and the 12.5%, 5.5-g ha^{-1}, herbicide rate was applied at a spray volume of 29 L ha^{-1}. Rice was treated at the one-tiller, panicle differentiation, boot, and physiological maturity growth stages. Injury was observed with imazamox applied at the one-tiller timing. Injury was not observed until 21 and 28 d after treatment (DAT) when imazamox was applied at the panicle differentiation and boot timings. The greatest reduction in plant height resulted from applications at the one-tiller timing at 7 and 14 DAT; however, when evaluated at harvest, plant height was reduced no more than 10%. Imazamox, averaged over rate, applied to rice at the boot timing reduced primary crop yield 66% compared with the nontreated. Applications at the boot timing resulted in an increased ratoon crop yield; however, the yield increase did not compensate for the loss in the primary crop yield.
Nomenclature: Imazamox; rice, *Oryza sativa* L. 'Cocodrie'.
Key words: Simulated herbicide drift, sublethal herbicide rates.

Estudios de campo fueron realizados cerca de Crowley, Louisiana, para evaluar los efectos de la deriva simulada de herbicidas en el arroz 'Cocodrie'. Cada tratamiento fue hecho con un volumen de aspersión que se varió proporcionalmente a la dosis del herbicida con base en un volumen de aspersión de 234 L ha^{-1} y una dosis de imazamox de 44 g ai ha^{-1}. La dosis de herbicida de 6.3%, 2.7 g ha^{-1}, fue aplicada con un volumen de aspersión de 15 L ha^{-1}. y la dosis de 12.5%, 5.5 g ha^{-1}, fue aplicada con un volumen de aspersión de 29 L ha^{-1}. El arroz fue tratado en los estadios de crecimiento de un hijuelo, diferenciación de panícula, emergencia de tallo floral, y madurez fisiológica. Se observó daño con imazamox aplicado en el estadio de un hijuelo. No se observo daño hasta 21 y 28 d después del tratamiento (DAT) cuando imazamox fue aplicado en los estadios de diferenciación de panícula y de emergencia de tallo floral. La mayor reducción en la altura de las plantas se debió a aplicaciones en el estadio de un hijuelo a 7 y 14 DAT. Sin embargo, cuando se evaluó en el momento de la cosecha, la altura de planta se redujo en no más de 10%. Imazamox, promediando las dosis, aplicado al arroz en el momento de la emergencia del tallo floral, redujo el rendimiento del cultivo primario 66% comparado con el testigo sin tratamiento. Las aplicaciones al momento de la emergencia del tallo floral resultaron en un incremento en el rendimiento de la soca. Sin embargo, el aumento del rendimiento no compensó la pérdida de rendimiento del cultivo primario.

Imazamox is a selective imidazolinone herbicide used to control annual and perennial weeds in soybean [*Glycine max* (L.) Merr.], edible legumes, and imidazolinone-resistant crops (Shaner 2014). The mechanism of action for imazamox is inhibition of acetolactase synthase, a key enzyme in the biosynthesis of the branched-chain amino acids isoleucine, leucine, and valine (Muhitch et al. 1987; Shaner 1991; Stidham and Singh 1991). Growth of susceptible plants treated with an imidazolinone herbicide is inhibited within a few hours of application; meristematic areas become chlorotic within 7 to 14 d, followed by a slow general foliar chlorosis and necrosis (Shaner 1991).

In 1993, imidazolinone-resistant rice was developed and the first commercially available imidazolinone-resistant rice cultivars were 'CL 121' and 'CL 141' which were derived from the imidazolinone-resistant parent line 'IMI-tolerant 93AS-3510' (Carlson et al. 2002; Croughan 1994, 1998; Gealy

DOI: 10.1614/WT-D-15-00024.1
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et al. 2003; Pellerin st al. 2004, Tan et al. 2005; Webster and Masson 2001). Imazethapyr was the herbicide targeted for use with commercial imidazolinone-resistant rice varieties.

Imazamox (Beyond®, 120 g ai L^{-1}, BASF Corporation, Research Triangle Park, NC 27709) is currently labeled for use in imidazolinone-resistant rice cultivars and hybrids. Imazamox can only be applied following an imazethapyr application for control of red rice (*Oryza sativa* L.) plants that survived previous imazethapyr applications, and because of its limited soil activity (Meins et al. 2004; Webster et al. 2012).

Rice is a major crop produced in the five-state region of Arkansas, Louisiana, Mississippi, Missouri, and Texas, with these states accounting for 79% of the 963,000 total hectares of rice planted in the United States (USDAERS 2014). In 2013, approximately 166,290 ha of rice were planted in Louisiana (LSUA 2014), and 57% of the rice planted were Clearfield cultivars or hybrids (LSUA 2013). With roughly half of the hectares planted to Clearfield rice the potential for off-target drift of imazamox to non–imidazolinone-resistant rice exists.

From 2009 to 2014, the Louisiana Department of Agriculture and Forestry (LDAF) processed 44 Pesticide Investigation Reports per year, and approximately six reports per year involved rice (R. Mulberry, personal communication). However, in 2009 to 2014, at least 25 to 50 rice fields affected by off-target drift of imazethapyr or glyphosate were not reported to the LDAF (J.K. Saichuk, personal communication). Therefore, the number of rice fields actually affected by drift each year may be underrepresented by the number of official complaints processed by the LDAF.

It has been reported that fine spray droplets less than 150 µm in size have a greater potential to drift than coarse droplets greater than 150 µm (Hanks 1995; SDTF 1997). The use of adjuvants and selection of proper spray nozzle type, size, and application pressure can be beneficial in reducing the amount of fine spray droplets in the spray cloud (Hanks 1995; Jones et al. 2007; Nuyttens et al. 2007; VanGessel and Johnson 2005). Although increasing droplet size can reduce the potential for off-target drift, environmental conditions at the time of herbicide application can drastically impact the off-target drift of spray solutions (Bouse et al. 1976; Crabbe et al. 1994; Thistle 2004).

Simulated herbicide drift trials can be used to evaluate the potential effects of imazamox drift to rice. In previous research, simulated drift studies with varying spray volume proportionally with reduced herbicide rates to simulate herbicide drift have resulted in increased crop injury compared to those examining the lower herbicide rates at a constant high spray volume (Banks and Schroeder 2002; Ellis et al. 2002; Ramsdale et al. 2003; Roider et al. 2008). The no-effect glyphosate rate for sweet corn (*Zea mays* var. *rugosa* Bonaf.) was four times lower when using a spray volume proportional to the reduced glyphosate rate compared with reduced glyphosate rates applied in a constant spray volume (Banks and Schroeder 2002). Other researchers suggest the reduced carrier volume may be unrealistic in drift research, may confound results, or both (Everitt and Keeling 2009; Marple et al. 2008). Preliminary research indicated that reduced carrier volume impacted damage of rice observed when exposed to reduced rates of imazamox.

The objective of this research was to evaluate reduced rates of imazamox applied to rice during the primary crop and its impact on the primary and ratoon rice crops.

Materials and Methods

A field study was conducted on rice grown in 2005 through 2007 at the Louisiana State University Agricultural Center 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 S-tine harrows 15 cm deep and rolling baskets. The long-grain rice cultivar 'Cocodrie' was drill-seeded from March 28 to April 17 in 2005 through 2007. Cocodrie is commonly grown long-grain rice in the mid-South, and growth characteristics are similar to other long grains released from the Louisiana State University Agricultural Center rice breeding program (S.D. Linscombe, personal communication).

The experimental design was an augmented two-factor factorial arrangement of treatments in a randomized complete block with four replications. Factor A consisted of imazamox applied at reduced

https://doi.org/10.1614/WT-D-15-00024.1 Published online by Cambridge University Press

rates of 2.7 and 5.5 g ha^{-1}, or 6.3 and 12.5% of the labeled rate, respectively. Factor B consisted of application timings at different rice growth stages: one-tiller, panicle differentiation (PD), boot, and physiological maturity. A nontreated plot was added for comparison. Each herbicide application was made with the spray volume varying proportionally to 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 treatment was applied with a tractor-mounted CO_2-pressurized sprayer calibrated to deliver a constant carrier volume with speed adjusted to vary application rate. The spray boom was equipped with six Teejet® TX-2 Conejet® 800033 nozzles (Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187) with a 38-cm spacing. Plots consisted of 12 18-cm-spaced rows 6 m long.

The study area was maintained weed-free using clomazone (Command®, 360 g ai L^{-1}, FMC Corporation, Philadelphia, PA 19103) at 420 g ai ha^{-1} applied PRE followed by propanil (RiceShot®, 480 g ai L^{-1}, RiceCo LLC, Memphis, TN 38137) at 4,483 g ai ha^{-1} plus halosulfuron (Permit®, 75% DF, Gowan Company, Yuma AZ 85364) 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 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 preflood application of 100 kg ha^{-1} 46–0–0 urea fertilizer was applied.

Rice plant height and rice injury data in the primary rice crop was collected 7, 14, 21, and 28 DAT. Plant height was obtained by averaging the height of four plants per plot. Plant height was measured from the soil surface to the tip of the extended uppermost emerged leaf for the one-tiller, PD, and boot application timings, and from the soil surface to the tip of the extended rice panicle for the rice treated at the physiological maturity. Rice injury was evaluated based on chlorosis and necrosis of foliage and reduced plant height using a scale of 0 to 100%, where 0% represents no injury and 100% represents plant death. Rice plant height at primary crop harvest and rough rice yield and stem and panicle counts for the primary and ratoon crops were also recorded. Immediately prior to harvest, total stem counts were determined by hand-harvesting a 0.5-m section of row and determining the number of stems present at the midheight of the plant, approximately 40 cm above the ground. The number of panicles with bases emerged beyond the sheath of the flag leaf were also determined. Whole plots were harvested using a mechanical plot harvester and rough rice yield was adjusted to 12% moisture.

All data were subjected to the Mixed Procedure of SAS (version 9.2, SAS, Cary, NC). The design was a replicated (by year) with a factorial arrangement of treatments in a randomized block design with repeated measures. Blocks were nested within year, imazamox application timings and rates were the treatments, plots within each block were the experimental units for the treatments, and DAT were the repeated measures effects in time for crop injury. Rice plant height was analyzed by DAT. The fixed effects for the model were timing, rate, DAT, and all interactions. The random effects for the model were year, blocks within year, and plots. Type III statistics were used to test all possible effects of fixed factors (application timing by rate by rating date) and least square means were used for mean separation at the 5% probability level ($P \leq 0.05$). Normality of plot effects over all DAT was checked using the UNIVARIATE procedure of SAS (version 9.3, SAS). Significant normality problems were not observed.

Results and Discussion

An application timing by imazamox rate by rating date interaction occurred for injury in the primary crop (Table 1). Regardless of rate, rice treated with imazamox at one-tiller resulted in the greatest amount of injury at 7, 14, and 21 DAT, 25 to 36%. Hensley et al. (2012, 2013) reported increased injury when one-tiller rice was treated with reduced rates of imazethapyr and glyphosate. Imazamox at 2.7 and 5.5 g ha^{-1} applied to rice at PD and boot resulted in 5 to 14% injury 21 DAT, and this was lower than rice treated at the one-tiller timing. At 28 DAT, imazamox at either rate at one-tiller and boot and 5.5 g ha^{-1} at PD resulted in 15 to 26% injury. Rice treated with imazamox at the boot stage resulted in increased injury from 21 to 28 DAT. The increased injury was due to necrosis of the flag leaf, which had emerged by 28 DAT. This was similar to results reported by Hensley et al. (2012). No crop injury was observed on rice treated

https://doi.org/10.1614/WT-D-15-00024.1 Published online by Cambridge University Press

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

Imazamox rate[b]	Timing	Injury 7 DAT	14 DAT	21 DAT	28 DAT
g ai ha^{-1}		%			
2.7	One-tiller	25 a	27 a	25 a	20 a
	PD	2 bc	8 bc	5 bc	5 c
	Boot	7 bc	8 bc	9 bc	23 a
	Maturity	0 c	0 c	0 c	0 c
5.5	One-tiller	32 a	36 a	33 a	26 a
	PD	3 bc	11 b	14 b	15 ab
	Boot	7 bc	8 b	11 b	23 a
	Maturity	0 c	0 c	0 c	0 c

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

[b] The 2.7 and 5.5 g ha^{-1} imazamox rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

Table 2. Effects of simulated imazamox drift application rate and timing on primary crop rice plant height at 7, 14, 21, and 28 days after treatment (DAT) and at harvest, 2005 through 2007, as percent of the nontreated, Crowley, LA.[a]

Imazamox rate[b]	Timing	Rice plant height[c] 7 DAT	14 DAT	21 DAT	28 DAT	Harvest
g ai ha^{-1}		% of nontreated				
2.7	One-tiller	80 c	91 de	87 e	86 cd	93 b
	PD	99 a	96 cd	96 cd	97 ab	100 a
	Boot	98 ab	96 cd	96 cd	91 bc	92 b
	Maturity	95 ab	102 ab	108 a	101 a	100 a
5.5	One-tiller	66 d	82 f	85 e	83 d	90 b
	PD	93 b	89 e	88 e	88 cd	92 b
	Boot	97 ab	94 d	94 d	91 bc	91 b
	Maturity	98 ab	106 a	105 ab	103 a	100 a

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

[b] The 2.7 and 5.5 g ha^{-1} imazamox rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

[c] Actual height (cm) of nontreated rice at primary crop harvest was 95 cm.

with imazamox at maturity. This data suggests that injury to rice is more severe when imazamox is applied during the early, vegetative growth stage of rice. The results are similar to earlier research of imazethapyr on selected weed species; visual injury symptoms were more severe on plants treated at earlier growth stages (Hoss et al. 2003; Shaw et al. 1990).

Injury symptoms observed in this study on plants treated at the one-tiller timing ranged from interveinal chlorosis in the uppermost leaves to plant death. Leaves of treated plants often exhibited small, narrow reddish-brown leaf lesions similar to those associated with leaf blast disease of rice (Groth et al. 2014). Subsequent tillers on recovering treated plants often emerged along a single plane causing a flat, fan-shaped appearance. Similar symptoms were observed when rice was treated with reduced rates of imazethapyr (Hensley et al. 2012).

An imazamox rate by imazamox timing by rating date interaction occurred for plant height in the primary crop. With the exception of a boot application at 7 DAT, 5.5 g ha^{-1} imazamox applied at one-tiller, PD, and boot reduced rice plant height at 7, 14, 21, and 28 DAT (Table 2). Imazamox applied at 2.7 g ha^{-1} to one-tiller rice reduced plant height 7 to 20% across all rating dates. Imazamox applied at 5.5 g ha^{-1} resulted in the greatest reduction in height at 7 and 14 DAT when applied at one-tiller, 66 and 82% of the nontreated, respectively. At primary crop harvest, plant height was 90 to 100% of the nontreated, regardless of imazamox application rate or timing. Imazamox applied to mature rice had no effect on plant height. These results support the trend of increased crop injury at earlier application timings. Similar results were reported by Bond et al. (2006) and Hensley et al. (2012).

An imazamox application timing interaction occurred for stem and panicle counts in the primary and ratoon crops; therefore, data were averaged over imazamox rate. Imazamox applied to rice in the PD and boot stages increased secondary plant stems in the primary crop resulting in an increase in stem count (Table 3). This increase was due to imazamox causing an excess of secondary stems to be produced on the upper plant nodes in the primary rice crop. However, this increase in stems did not translate into an increase in the number of panicles in the primary crop. In the ratoon crop, an increase in stem counts was observed when imazamox was applied to rice at the boot stage, and the increased number of stems resulted in an increase in panicle numbers (Table 3). These results are similar to those reported with imazethapyr and glyphosate (Hensley et al. 2012, 2013).

https://doi.org/10.1614/WT-D-15-00024.1 Published online by Cambridge University Press

Table 3. Effects of simulated imazamox drift application timing on primary crop rice stem and panicle counts, 2005 through 2007, and ratoon crop rice stem and panicle counts, 2005 and 2007, as percentage of the nontreated, Crowley, LA.[a]

Imazamox timing	Primary crop counts		Ratoon crop counts	
	Stem	Panicle	Stem	Panicle
	% of nontreated[b]			
One-tiller	92 c	86 b	123 b	103 b
PD	112 b	112 a	112 bc	99 b
Boot	141 a	90 b	156 a	188 a
Maturity	97 c	96 ab	110 bc	103 b
Nontreated[c]	38	35	38	30

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

[b] Data averaged across application rates of 2.7 and 5.5 g ai ha^{-1} imazamox applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

[c] Actual nontreated primary crop stem and panicle counts and nontreated ratoon crop stem and panicle counts. Counts obtained from 0.5 m of row.

An imazamox application rate by imazamox timing interaction occurred for primary crop, ratoon crop, and total crop yield. Primary crop yield was 79 and 83% of the nontreated when imazamox was applied to rice at 2.7 g ha^{-1} at one-tiller and 5.5 g ha^{-1} at PD, respectively (Table 4). Imazamox applied to rice at 5.5 g ha^{-1} at one-tiller and 2.7 g ha^{-1} at boot resulted in a primary crop yield of 54 to 58% of the nontreated. The highest reduction in primary crop yield occurred when rice was treated with 5.5 g ha^{-1} imazamox at boot, 66% reduction. However, imazamox applied at 2.7 and 5.5 g ha^{-1} to rice in the boot stage resulted in a ratoon crop rice yield of 135 and 156%, respectively. This increase was due to imazamox causing high numbers of secondary stems to be produced on the upper plant nodes in the primary rice crop (Table 3). The secondary stems did not produce panicles in the primary crop but did produce panicles in the ratoon crop. This increase in ratoon crop panicles was not observed with rice treated at the other timings. When primary and ratoon crop yields were combined, the increase in ratoon crop yield did not compensate for the primary crop yield loss. Total crop yield loss was 40 to 53% when imazamox was applied to rice in the boot stage. Imazamox had no effect on primary, ratoon, or total crop yield when applied to mature rice. Similar

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

Imazamox rate[b]	Timing	Yield		
		Primary crop	Ratoon crop	Total crop
g ai ha^{-1}		% of nontreated		
2.7	One-tiller	79 b	96 b	72 b
	PD	100 a	100 b	101 a
	Boot	58 c	135 a	60 bc
	Maturity	99 a	99 b	101 a
5.5	One-tiller	54 c	103 b	62 bc
	PD	83 b	97 b	89 a
	Boot	34 d	156 a	47 c
	Maturity	102 a	104 b	101 a
Nontreated[c]		5,900	1,300	7,200

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

[b] The 2.7 and 5.5 g ha^{-1} imazamox rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

[c] Actual yield (kg ha^{-1}) of nontreated rice for the primary, ratoon, and total crops.

results were reported for imazethapyr (Hensley et al. 2012), glyphosate (Hensley et al. 2013), and glufosinate (Webster et al. 2015).

In conclusion, reduced rates of imazamox applied at the one-tiller, PD, and boot timings resulted in reduced plant height and primary-crop yield losses. Total crop yield was reduced when imazamox was applied at one-tiller and boot with the greatest reduction in primary and total crop yield resulting from a simulated imazamox drift applied at the boot growth stage. Simulated imazamox drift to mature rice had no effect on rice plant height or yield.

Imazamox drift on to a producer's field at the one-tiller, PD, or boot growth stages of rice can reduce yield; however, this study suggests that an imazamox drift event occurring to rice at the boot stage may be the most detrimental. Rice exposure to imazamox in the vegetative growth stages, one-leaf to one-tiller, can often recover if the stand is not reduced. However, an imazamox drift event on rice in the reproductive stage of growth may have little to no visual foliar injury and often symptoms may not appear until rice is near crop maturity. This may lead to loss of yield and profitability due to continuing to supply crop inputs, such as increased fertilizer, insecticide, and fungicide applications, to

https://doi.org/10.1614/WT-D-15-00024.1 Published online by Cambridge University Press

a crop that has an already reduced yield potential. Unfortunately, due to the use of imazamox for late-season red rice control following imazethapyr applications, the potential for off-target drift of imazamox is greater during the reproductive growth stages of rice.

Acknowledgments

Published with the approval of the Director of the Louisiana Agricultural Experiment Station, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, under manuscript number 2014-306-18806. The authors would like to thank Dr. Steve Linscombe and the staff of the Louisiana State University Agricultural Center Rice Research Station. Louisiana Rice Research Board provided partial funding for this project.

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Received February 23, 2015, and approved September 20, 2015.

Associate Editor for this paper: William Johnson: Purdue University.