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Impact of Drift Rates of Imazethapyr and Low Carrier Volume on Non-Clearfield Rice

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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 an imazethapyr rate of 70 g ai ha^{-1}. The 6.3%, 4.4 g ha^{-1}, herbicide rate was applied at a spray volume of 15 L ha^{-1} and the 12.5%, 8.7 g ha^{-1}, herbicide rate was applied at a spray volume of 29 L ha^{-1}. An application of imazethapyr at one-tiller, panicle differentiation (PD), and boot resulted in increased crop injury compared with the nontreated rice. The most injury observed occurred on rice treated at the one-tiller timing. Imazethapyr at one-tiller, PD, and boot reduced plant height at harvest and primary and total (primary plus ratoon) crop yield, with the greatest reduction in primary crop yield resulting from imazethapyr applied at boot. Imazethapyr did not affect rice treated at primary crop maturity.
Nomenclature: Imazethapyr; rice, *Oryza sativa* L. 'Cocodrie'.
Key words: Simulated herbicide drift, sub-lethal herbicide rates.

Estudios de campo se realizaron cerca de Crowley, Louisiana del 2005 al 2007 para evaluar los efectos de la deriva de herbicida simulada sobre arroz 'Cocodrie'. Cada aplicación se hizo con un volumen que varió proporcionalmente a la dosis del herbicida con base en un volumen constante de 234 L ha^{-1} y una dosis de imazethapyr de 70 g ai ha^{-1}. La dosis de herbicida de 6.3%, 4.4 g ha^{-1}, fue aplicada a un volumen de 15 L ha^{-1}, y la de 12.5%, 8.7 g ha^{-1}, se aplicó con un volumen de 29 L ha^{-1}. Una aplicación de imazethapyr a 1-retoño, diferenciación de la panícula (PD), y engrosamiento de la vaina, resultó en un aumento en el daño del cultivo en comparación con el plantas no tratadas. El mayor daño observado ocurrió en arroz tratado en la etapa de 1-retoño. Imazethapyr a 1-retoño, PD y engrosamiento de la vaina redujo la altura de la planta al momento de la cosecha y el rendimiento primario y total (primario más soca), con una reducción mayor en el rendimiento primario como resultado del imazethapyr aplicado durante el engrosamiento de la vaina. El imazethapyr no afectó el arroz tratado en la madurez del cultivo primario.

In 1993, imidazolinone-resistant rice (*Oryza sativa* L.) was developed and exhibited tolerance to the imidazolinone class of herbicides (Croughan 1994; Pellerin et al. 2004; Webster and Masson 2001). Imazethapyr is a selective herbicide used to control annual and perennial weeds in soybean [*Glycine max* (L.) Merr.], edible legumes, and imidazolinone-resistant crops (Senseman 2007).

The mechanism of action for imazethapyr is inhibition of acetolactate synthase (ALS) (EC 4.1.3.18) also called acetohydroxyacid synthase (AHAS), a key enzyme in the biosynthesis of the branched-chain amino acids isoleucine, leucine, and valine (Muhitch et al. 1987; Senseman 2007; Shaner 1991; Shaner et al. 1984; Stidham 1991; Stidham and Singh 1991). Plant death results from events occurring in response to ALS inhibition, specifically the inhibition of isoleucine, leucine, and valine, but the actual sequence of phytotoxic processes is unclear (Shaner 1991; Stidham and Singh 1991). Some secondary effects may include disruption of photosynthate translocation, hormone imbalance due to interruption of source/sink relationships, and interference in DNA synthesis and cell growth.

Symptoms expressed from this toxicity are that growth is inhibited within a few hours of herbicide application and meristematic areas become chlorotic, followed by a slow general foliar chlorosis and necrosis (Shaner 1991). This injury to meristematic areas can be attributed to inhibition of branched-chain amino acids in the meristematic region. Even though plants have the ability to scavenge amino acids from preexisting proteins, the meristematic region lacks the protein reserve pools that are available in mature regions of the plant. Injury symptoms usually appear within 7 to 14 d for susceptible species.

Rice is a major crop produced in the four-state region of Arkansas, Louisiana, Mississippi, and Texas, with these states accounting for 78% of the 1.5 million total hectares of rice planted in the United States and 68% of the $3.1 billion value of rice produced in the United States in 2010 (NASS 2011a,b). Louisiana planted approximately 214,000 ha of rice in 2010 with approximately 71% planted to imidazolinone-resistant rice cultivars or hybrids (LSUA 2010). Since many of the rice-producing parishes in Louisiana produce imidazolinone-resistant and conventional rice, the potential exists for off-target drift of imazethapyr to conventional rice.

It has been reported that fine spray droplets less than 150 μm in size have a greater potential to drift off-target (Hanks 1995; SDTF 1997). The use of adjuvants and

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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). This increase in droplet size can reduce the potential for off-target drift from droplets larger than 150 μ m; however, environmental conditions at the time of herbicide application can also impact the off-target drift of spray solutions (Bouse et al. 1976; Crabbe et al. 1994; Thistle 2004). It is recommended that herbicide applications should be avoided during the early morning and late evening because 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, the potential effects of imazethapyr drift to rice can be evaluated. In previous research, simulated drift studies varying the spray volume proportionally with reduced herbicide rates to simulate herbicide drift has resulted in increased crop injury compared with the same 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). Banks and Schroeder (2002) reported varying spray volume proportionally with herbicide dosage, thus maintaining constant herbicide concentration in the spray, would change the response of sweet corn (*Zea mays* L.) to glyphosate when compared with a constant spray volume where herbicide rate would vary and be more dilute in the carrier. The no-effect glyphosate rate for sweet corn was 0.046 kg ae ha^{-1} when using a spray volume proportional to the reduced glyphosate rate; however, the no-effect glyphosate rate was four times greater when glyphosate was applied in a constant spray volume. However, others have reported differing results. Ellis et al. (2002) reported constant vs. variable spray volume differed for glufosinate and glyphosate on corn; however, data was averaged over active ingredient. The impact of glufosinate and glyphosate on soybean did not differ with constant vs. variable carrier volume. Everitt and Keeling (2009) and Marple et al. (2008) reported that reduced carrier volume may be unrealistic in drift research andmay confound results. Pesticide spray drift occurs when small concentrated spray droplets are deposited in a nonuniform pattern, and it is unlikely these droplets will enhance activity for all herbicides on all plant species (Sawchuck et al. 2006). 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.

A simulated drift application of the commercial herbicide premix of imazethapyr plus imazapyr affected rice plant height and yield; however, simulated drift of the imazethapyr plus imazapyr premix did not affect yield when applied to corn (Bond et al. 2006). Al-Khatib et al. (2003) reported imazethapyr applied at various times within 30 d of planting resulted in reduced grain sorghum (*Sorghum bicolor* L.) yield.

Even though published studies evaluating the effects of simulated imazethapyr drift exist (Al-Khatib et al. 2003; Bond et al. 2006), none of these studies were conducted using reduced spray volumes proportional with herbicide dosage. The objectives of this research were to evaluate the effects of simulated imazethapyr drift applied to rice in the primary rice crop on the crop response and yield on 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 Louisiana State University AgCenter Rice Research Station near Crowley, LA, on a Crowley silt loam (fine montmorillonitic, thermic Typic Albaqualf) 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 18-cm-spaced rows 6 m long.

The experimental design was an augmented two-factor factorial arrangement of treatments in a randomized complete block with four replications. Factor A consisted of imazethapyr (Newpath®, 240 g ai L^{-1}, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709) applied at simulated drift rates of 6.3 and 12.5% of the labeled usage rate of 70 g ai ha^{-1}, or 4.4 and 8.7 g ha^{-1}, respectively. Factor B consisted of application timings at different growth stages: one-tiller, 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 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 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 due to unfavorable weather following primary crop harvest.

The study area was maintained weed-free using clomazone (Command®, 360 g ai L^{-1}, FMC Agricultural Corporation, Philadelphia, PA) 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 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 and rice injury in the primary rice crop were obtained 7 d after herbicide treatment (DAT) and continued weekly until 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, rough rice yield, and stem and panicle

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

Imazethapyr timing[b]	Rice plant injury			
	7 DAT	14 DAT	21 DAT	28 DAT
	%			
One-tiller	32 a	36 a	35 a	32 a
Panicle differentiation	13 cd	14 c	14 c	14 c
Boot	7 d	8 cd	11 cd	24 b
Maturity	0 e	0 e	0 e	0 e
Nontreated	0 e	0 e	0 e	0 e

[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 application rates of 4.4 and 8.7 g ha^{-1} imazethapyr applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

counts for the primary and ratoon crop were obtained. Whole plots were harvested using 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 Version 9.1, Cary, NC). 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

A timing by rating date interaction occurred when primary crop injury was evaluated; therefore, data were averaged across application rates. Imazethapyr applied at 4.4 and 8.7 g ha^{-1} at one-tiller resulted in crop injury of 32 to 36% at 7, 14, 21, and 28 DAT (Table 1). When applications were delayed to the PD and boot stages crop injury was 14% or less except for rice treated at the boot stage at 28 DAT with 24% injury. An increase in injury from 21 to 28 DAT with rice treated with imazethapyr at boot was noted because necrosis of the flag leaf was observed at 28 DAT that was not present at 21 DAT. No response was observed on rice treated with imazethapyr at maturity. These data indicate that injury to rice is more severe when a simulated imazethapyr drift application is applied during the early, vegetative growth stage of rice. As with actual drift events, identifying drift based on injury is more difficult as rice matures. Davis et al. (2011) and Kurtz and Street (2003) also reported similar trends of increased injury at earlier application timings when evaluating simulated glyphosate drift on rice. When evaluating the efficacy of imazethapyr on selected weed species, injury symptoms were more severe on plants treated at earlier timings (Hoss et al. 2003; Shaw et al. 1990).

Figure 1. Interveinal chlorosis observed with imazethapyr drift to rice.

This reduction in injury during reproductive growth stages may be due to the translocation of imazethapyr to meristematic tissue (Shaner et al. 1984). 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 interveinal chlorosis in the uppermost leaves (Figure 1) 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. 2009). Subsequent tillers on recovering treated plants often emerged along a single plane resulting in a flat, fan-shaped appearance in plants. Also, an overall stunting of plants was observed on plants treated at the one-tiller and PD timings (data not shown).

Symptomology observed on plants treated with imazethapyr at PD and boot, often beyond the rating dates evaluated in this study, were various forms of foliar and inflorescence malformations. Foliar symptoms were plants having multiple shoots arising from the secondary nodes of the main stem (Figure 2). The flag leaf on the main stem and secondary

Figure 2. Secondary panicle emergence observed with imazethapyr drift to rice.

Figure 3. Malformed panicle observed with imazethapyr drift to rice.

shoots would often appear malformed, wrinkled, contorted, or rolled, and this is similar to results observed with glyphosate applications to rice (Davis et al. 2011). In some instances, secondary shoots were stunted or both stunted and malformed. Panicles may partially extend beyond the flag leaf sheath or emerge from the side of the sheath (Figure 3). Often panicles failed to initiate emergence from the flag leaf sheath and decomposed in the leaf sheath causing necrosis of the flag leaf when treated at the boot stage (Figure 4). Some of the inflorescence malformations were due to a malformed panicle axis and partial emergence of the panicle due to fusing of the panicle with the flag leaf sheath. Individual florets were sometimes malformed with the tips of the lemma excessively curved toward the palea (Figure 3), which results in an appearance often referred to as "parrot-beaked" when observed in association with the straighthead physiological disorder of rice (Groth et al. 2009).

A timing by rate interaction was observed for primary rice crop height at harvest. Rice plant height at harvest was reduced in the primary rice crop when a simulated imazethapyr drift application was applied to rice (Table 2). At primary crop harvest, compared with a nontreated rice plant height of 96 cm, applications at one-tiller, PD, and boot resulted in a reduced rice plant height of 85 to 87 cm, with the exception of 4.4 g ha^{-1} imazethapyr applied at PD, which resulted in a rice plant height of 92 cm. Imazethapyr applications at maturity had no effect on primary crop rice plant height. Davis et al. (2011) reported reduced plant height following applications of low rates of glyphosate to rice at growth stages similar to those evaluated in this study.

A timing by rate interaction occurred for stem and panicle counts. Imazethapyr applied at PD and boot increased secondary plant stems in the primary crop resulting in an increase in stem count compared with the nontreated rice (Table 3). This increase was due to imazethapyr causing the production of an excess of secondary stems on the upper plant nodes. However, panicle count was only increased in the primary crop when imazethapyr was applied at PD at the 8.7 g ha^{-1} rate. In the ratoon crop, an increase in stem and panicle counts was only observed in rice treated at the boot stage (Table 3).

A timing by rate interaction was observed for the primary, ratoon, and total crop yield data. Applications of imazethapyr

Figure 4. Necrosis of flag leaf observed with imazethapyr drift to rice.

applied at one-tiller, PD, and boot timings resulted in reduced primary crop rice yield (Table 4). Imazethapyr applied at 8.7 g ha^{-1} at one-tiller and PD and 4.4 g ha^{-1} at one-tiller resulted in a primary crop rice yield 59 to 75% of the nontreated rice. The primary crop yield reduction resulting from an application of imazethapyr at the boot timing is more severe than when applied to the earlier growth stages of rice, and this is similar to low rates of glyphosate applied to rice (Davis et al. 2011). Regardless of rate, imazethapyr applied at the boot timing resulted in a primary crop yield 31 to 44% of the nontreated. However, the ratoon crop yield was 131 to 146% of the nontreated with the same boot timing. This increase was due to imazethapyr causing an excess of secondary stems to be produced on the upper plant nodes in the ratoon 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 the other timings. However, when primary and ratoon crop yields were combined, the increase in ratoon crop yield did not compensate for the primary crop yield loss. Either rate of imazethapyr applied at the boot or one-tiller timing resulted in a total crop yield 49 to 64% of the nontreated (Table 4). Imazethapyr applied at 8.7 g ha^{-1} at PD reduced total crop yield to 75% of the nontreated. Simulated imazethapyr drift applications applied to rice at maturity and at 4.4 g ha^{-1} at PD had no effect on primary, ratoon, or total crop rice yield compared with the nontreated rice.

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

Imazethapyr timing	Rice plant height: 4.4 g ai ha^{-1} [b]	Rice plant height: 8.7 g ai ha^{-1}
	cm	
One-tiller	87 b	86 b
Panicle differentiation	92 a	85 b
Boot	87 b	87 b
Maturity	95 a	96 a
Nontreated	96 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] The 4.4 and 8.7 g ha^{-1} imazethapyr rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

Although primary crop rice yield was reduced by simulated imazethapyr drift applications at the one-tiller, PD, and boot timings, it appears that rice is most susceptible to imazethapyr during the boot growth stage. Similar results were reported when evaluating simulated glyphosate drift on rice (Hensley 2009). Rice producers in Louisiana may have the ability to recover some yield loss from an imazethapyr drift event occurring to rice during the boot growth stage by increasing ratoon crop yield; however, the reduction in total crop yield

Table 3. Effects of simulated imazethapyr 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]

Imazethapyr rate[b]	Timing	Primary crop counts: Stem	Primary crop counts: Panicle	Ratoon crop counts: Stem	Ratoon crop counts: Panicle
g ai ha^{-1}		Stems per 0.46 m of row			
4.4	One-tiller	32 d	30 b	44 b	47 b
	Panicle differentiation	44 c	34 b	38 b	29 b
	Boot	60 ab	28 b	66 a	77 a
	Maturity	33 d	27 b	45 b	31 b
8.7	One-tiller	29 d	29 b	50 b	47 b
	Panicle differentiation	56 b	51 a	47 b	35 b
	Boot	67 a	30 b	71 a	89 a
	Maturity	37 cd	31 b	38 b	28 b
Nontreated		33 d	32 b	39 b	27 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] The 4.4 and 8.7 g ha^{-1} imazethapyr rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

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Table 4. Effects of simulated imazethapyr 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]

Imazethapyr rate[b]	Timing	Yield[c]		
		Primary crop	Ratoon crop	Total crop
g ai ha^{-1}		kg ha^{-1}		
4.4	One-tiller	4,150 cd	1,090 b	5,240 cd
	Panicle differentiation	6,160 ab	1,150 b	7,310 ab
	Boot	2,980 de	1,740 a	4,720 d
	Maturity	6,550 a	1,120 b	7,670 ab
8.7	One-tiller	3,980 cd	1,110 b	5,190 d
	Panicle differentiation	5,130 bc	980 b	6,110 bc
	Boot	2,100 e	1,870 a	3,970 d
	Maturity	6,690 a	1,230 b	7,920 ab
Nontreated		6,840 a	1,320 b	8,160 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] The 4.4 and 8.7 g ha^{-1} imazethapyr rates were applied at spray volumes of 15 and 29 L ha^{-1}, respectively.

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

from an imazethapyr drift event at the boot growth stage of rice has the potential to be significant. These data also indicate an increased susceptibility to imazethapyr drift occurring at the one-tiller timing compared to the PD timing. This may be due to the reduced plant biomass at this growth stage compared to the later PD growth stage. Shaw et al. (1990) reported an increased susceptibility to imazethapyr in smaller plants when evaluating its effects on johnsongrass (*Sorghum halepense* L.) at 15-, 30-, and 60-cm plant heights. Even though rice has the ability to recover from imazethapyr drift occurring at the vegetative one-tiller stage, combinations of herbicide drift and climatic conditions unsuitable for growth that hinder recovery may result in significant yield losses.

In conclusion, simulated imazethapyr drift applications at the one-tiller, PD, and boot timings result in reduced plant height at primary crop harvest and primary and total crop yield losses, with the greatest reduction in primary crop yield resulting from a simulated imazethapyr drift application applied at the boot growth stage. Simulated imazethapyr drift applications to mature rice had no effect on rice plant height or yield.

The ability to identify imazethapyr drift on rice can be helpful to producers, cooperative extension service personnel, crop consultants, and state regulatory agencies in distinguishing between herbicide drift and injury associated with soil fertility issues, diseases, and other disorders affecting rice. Misidentification of herbicide drift symptoms as injury associated with other factors can reduce profitability if growers apply inputs unnecessarily to correct these factors when the symptoms present are actually a result of herbicide drift. The ability to correlate symptoms with imazethapyr drift also may assist state regulatory agencies in identifying the source of a herbicide drift event. If imazethapyr can be identified by observation of plant symptoms, this can reduce the cost associated with confirmation of a herbicide drift event through the use of diagnostic testing of foliar residue since most analytical facilities charge per evaluation and the diagnostic tests involved are often herbicide-specific.

An imazethapyr drift event occurring to a field at the one-tiller, PD, or boot growth stages of rice can reduce yield; however, this study indicates that a drift event occurring at the boot stage may be the most detrimental to yield. Rice receiving a drift event in vegetative growth stages, one-leaf to one-tiller, can often recover if stand is maintained at recommended densities. However, an imazethapyr drift event on rice in the reproductive stage of growth may cause little to no detectable foliar injury, and often, symptoms may not appear until rice plants near crop maturity. This may lead to a loss of yield and profitability due to costs of supplying inputs such as fertilizer, insecticide, and fungicide to a crop that has already incurred irrecoverable yield loss.

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