Weed Technology 2014 28:443–453

Soybean Sensitivity to Drift Rates of Imazosulfuron

Sandeep S. Rana, Jason K. Norsworthy, and Robert C. Scott*

Imazosulfuron is a sulfonylurea herbicide recently labeled in U.S. rice at a maximum rate of 336 g ai ha^{-1}. Soybean is prone to drift of herbicides from rice fields in the southern United States because these crops are often grown in close proximity. Field trials were conducted to determine the effect of low rates of imazosulfuron applied to nonsulfonylurea-resistant soybean at different growth stages. Soybean was treated at the vegetative cotyledonary (VC); vegetative second trifoliate (V2); vegetative sixth trifoliate (V6); and reproductive full bloom (R2) growth stages with 1/256 (1.3 g ha^{-1}) to 1/4 (84.1 g ha^{-1}) times (X) the maximum labeled rate of imazosulfuron. Soybean was injured regardless of application rate or timing. At 2 wk after treatment (WAT), imazosulfuron injured soybean 23 to 79, 44 to 76, 32 to 68, and 14 to 50% when applied at the VC, V2, V6, and R2 growth stages, respectively, where the highest injury was caused by the highest imazosulfuron rate (1/4X). However, by 20 wk after planting (WAP), soybean treated with imazosulfuron at the VC and V2 growth stages had only 0 to 17% and 8 to 53% injury, respectively. At higher rates [1/8 (42 g ha^{-1}) and 1/4X] of imazosulfuron, soybean treated at the VC growth stage recovered more from injury than did soybean treated at the V2 growth stage. Soybean treated with imazosulfuron at the V6 and R2 growth stages had better recovery from the injury at the lower two rates [1/256 and 1/128X (2.6 g ha^{-1})] than at the higher rates [1/64 (5.3 g ha^{-1}) to 1/4X]. Imazosulfuron, at all rates tested, delayed soybean maturity by 1 to 4, 2 to 6, 1 to 12, and 3 to 16 d for the VC, V2, V6, and R2 growth stages, respectively. Yield loss was greater when imazosulfuron was applied at V6 and R2 compared to applications at VC and V2. Results from this research indicate that imazosulfuron can severely injure soybean regardless of the growth stage at which drift occurs; however, soybean injured by imazosulfuron at early growth stages (VC and V2) has a better chance of recovery over time compared to drift at later growth stages (V6 and R2).

Nomenclature: Imazosulfuron; rice, *Oryza sativa* L.; soybean, *Glycine max* (L.) Merr.
Key words: Herbicide drift, off-target movement, sulfonylurea herbicides.

Imazosulfuron es un herbicida del grupo sulfonylurea que fue recientemente registrado para uso en arroz en Estados Unidos a una dosis máxima de 336 g ai ha^{-1}. La soya tiende a estar expuesta a deriva de herbicidas provenientes de campos de arroz en el sur de los Estados Unidos porque estos cultivos se encuentran generalmente cerca. Se realizaron experimentos de campo para determinar el efecto de dosis bajas de imazosulfuron aplicado a soya no-resistente a sulfonylurea en diferentes estadios de desarrollo. La soya fue tratada en los estadios de desarrollo vegetativo-cotiledonario (VC), vegetativo-segunda hoja trifoliada (V2), vegetativo-sexta hoja trifoliada (V6), y reproductivo-floración completa (R2) con 1/256 (1.3 g ha^{-1}) a 1/4 (84.1 g ha^{-1}) veces (X) la dosis máxima de imazosulfuron según la etiqueta. La soya sufrió daño sin importar la dosis o el momento de aplicación. A 2 semanas después del tratamiento (WAT), imazosulfuron dañó la soya 23 a 79, 44 a 76, 32 a 68, y 14 a 50% cuando se aplicó en los estadios VC, V2, V6, y R2, respectivamente, y en donde el mayor daño fue causado por la dosis mayor (1/4X) de imazosulfuron. Sin embargo, a 20 semanas después de la siembra (WAP), la soya tratada con imazosulfuron en los estadios VC y V2 tuvieron solamente 0 a 17% y 8 a 53% de daño, respectivamente. Con las dosis más altas de imazosulfuron [1/8 (42 g ha^{-1}) and 1/4X], la soya tratada en el estadio VC se recuperó más del daño que la soya tratada en el estadio V2. La soya tratada con imazosulfuron en los estadios V6 y R2 tuvo una mejor recuperación del daño en las dos dosis más bajas [1/256 and 1/128X (2.6 g ha^{-1})] que en las dosis más altas [1/64 (5.3 g ha^{-1}) to 1/4X]. Con todas las dosis evaluadas, imazosulfuron retrasó la madurez de la soya en 1 a 4, 2 a 6, 1 a 12, y 3 a 16 d para los estadios VC, V2, V6, y R2, respectivamente. La pérdida de rendimiento fue mayor cuando imazosulfuron fue aplicado en V6 y R2 en comparación con las aplicaciones en VC y V2. Los resultados de esta investigación indican que imazosulfuron puede dañar severamente a la soya sin importar el estadio de desarrollo en el que ocurre la deriva. Sin

DOI: 10.1614/WT-D-13-00138.1

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https://doi.org/10.1614/WT-D-13-00138.1 Published online by Cambridge University Press

embargo, la soya dañada por imazosulfuron en estadios tempranos de desarrollo (VC y V2) tiene mejores oportunidades de recuperarse con el tiempo, en comparación con deriva causa daño en estadios tardíos de desarrollo (V6 y R2).

Weed control in rice is highly dependent on herbicides. Halosulfuron is the current standard of sulfonylurea herbicides used in rice and is reported to drift on to soybean fields grown in close proximity to rice in the southern United States (Nandula et al. 2009). Depending on the crop variety and the growth stage, injury from the off-target movement of herbicides to nonlabeled or susceptible crops ranges from sub-lethal to severe. Glyphosate injures nonglyphosate-resistant soybean when applied from vegetative through reproductive stages; however, plants often recover better from injury at vegetative than at reproductive growth stages (Norsworthy 2004). Halosulfuron at 4.3 to 69 g ha^{-1} applied to four-trifolilate (V4) soybean caused 78 to 89% injury at 28 d after treatment (DAT) (Nandula et al. 2009). At the same rates, halosulfuron applied to full bloom (R2) soybean injured plants 70 to 75% at 28 DAT. Imazosulfuron, another sulfonylurea herbicide, applied at 168 g ha^{-1} (1/2X) caused more than 80% injury when applied at the VC, vegetative third trifoliate (V3), V6, and R2 growth stages of soybean (Norsworthy et al. 2010).

Imazosulfuron is a new sulfonylurea herbicide marketed under the trade name of League by Valent Corporation (Walnut Creek, CA 94596) for weed control in drill- and water-seeded rice at a maximum field use rate of 336 g ha^{-1}. In rice, sequential applications (PRE fb POST) of imazosulfuron at 336 g ha^{-1} provided effective control of broadleaf weeds and sedges (Godara et al. 2012; Riar and Norsworthy 2011). Imazosulfuron acts by inhibiting acetolactate synthase (ALS) (EC 4.1.3.18) activity and hinders biosynthesis of the branched-chain amino acids valine, leucine, and isoleucine, resulting in rapid cessation of plant cell division and growth (Brown 1990; Usui 2001). Injury to nontarget crops from imazosulfuron is generally in the form of chlorosis, purple veins, and stunting that is characteristic of sulfonylurea herbicide (ALS-inhibiting herbicide) injury to soybean (Brown 1990; Norsworthy et al. 2010). In addition, severely injured soybean usually fails to produce seed (Norsworthy et al. 2010).

There is little information available for the sensitivity of soybean to drift rates of imazosulfuron. Therefore, research was conducted to understand the potential of imazosulfuron to injure soybean via off-target movement from rice.

Material and Methods

Field trials were conducted at the University of Arkansas, Agricultural Research and Extension Station, Fayetteville and the Pine Tree Experiment Station, Pine Tree, in summer 2011 to evaluate the effect of low rates of imazosulfuron applied to nonsulfonylurea-resistant soybean at different growth stages. Soybean was planted May 7, 2011, and May 10, 2011, and emerged on May 16, 2011, and May 19, 2011, at Fayetteville and Pine Tree, AR, respectively. Soybean was planted at 30 seeds m^{-1} of row and 0.91-m row spacing with a four-row John Deere 7100 plate-type planter at Fayetteville and with an eight-row John Deere vacuum planter at Pine Tree. At both locations, the experimental area was cultivated twice prior to planting. The soybean variety used for the experiment was AG 4703, which was a nonsulfonylurea-resistant, glyphosate-resistant, indeterminate, maturity group IV soybean cultivar. Soybean was irrigated twice weekly with lateral-moving irrigation system at Fayetteville and approximately once weekly with poly-irrigation tube (Delta Plastics, 10801 Executive Center Drive, Ste 201, Little Rock, AR 72211) at Pine Tree. The soil was a Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) composed of 12% sand, 70% silt, 18% clay, with 1.3% organic matter and a pH of 7.5 at Pine Tree. At Fayetteville, the soil was characterized as a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults) composed of 27% sand, 54% silt, 19% clay, with 1.9% organic matter and a pH of 5.8. Plots at both locations were kept weed-free with broadcast applications of glyphosate (Roundup PowerMax™, Monsanto Co., 800 N. Lindbergh Blvd. St. Louis, MO 63167) at 870 g ae ha^{-1}.

At Fayetteville, plots were 1.5 m wide and 7.6 m long with 1.5-m alleys between replications. At Pine

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Tree, plots were 1.5 m wide and 9.1 m long with 1.5-m alleys between replications. The experimental arrangement used was a factorial in a randomized complete block design with four replications; factor A was four application timings and factor B was seven imazosulfuron rates. The four application timings were the vegetative cotyledonary (VC), two-trifoliolate soybean (V2), six-trifoliolate soybean (V6), and R2 growth stages (Fehr and Caviness 1977). Imazosulfuron was applied at 1/256 (1.31 g ha^{-1}), 1/128 (2.6 g ha^{-1}), 1/64 (5.3 g ha^{-1}), 1/32 (10.5 g ha^{-1}), 1/16 (21 g ha^{-1}), 1/8 (42 g ha^{-1}), and 1/4 (84.1 g ha^{-1}) times (X) its labeled rate, 336 g ha^{-1}. Imazosulfuron rates used in this experiment cover the range of herbicide drift rates, 0.1 to 10%, that most often occurs in the field (Al-Khatib and Peterson 1999; Snipes et al. 1992). Treatments also included a non-treated control. Soybean at the VC, V2, V6, and R2 growth stages was treated on May 28, June 8, June 22, and July 6, 2011, respectively, at Fayetteville and on May 31, June 6, June 21, and July 13, 2011, respectively, at Pine Tree. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with 11001 XR flat-fan spray nozzles (Teejet Technologies, 1801 Business Park Drive, Springfield, IL 62703) calibrated to deliver 93 L ha^{-1} spray solution.

Imazosulfuron injury to soybean was rated visually on a weekly basis on a scale of 0 to 100%, where 0 is no injury and 100 is plant death. Injury to soybean was in the form of chlorosis, purple veins, and stunting. Plant height at harvest was determined by randomly selecting five plants within the two center rows, each from ground to the tip of the top-most fully expanded leaf. Delay in days to maturity was recorded for every plot. At maturity, a random sample of five plants was hand harvested and threshed to determine the number of seeds per five plants and 100-seed weight. Soybean plots at Fayetteville were harvested on October 15, 2011 and at Pine Tree on October 31, 2011. At both locations, only the two center rows of the four-row plot were harvested with a small-plot combine and plot seed yield, moisture content adjusted to 13%, was weighed.

All data, except delay in days to maturity, were presented as the percent of non-treated check for the respective parameters measured. The delay in days to maturity data are presented as the additional number of days to mature with respect to the soybean in the non-treated check. Data were first tested for normality to comply with the assumptions of homogeneous variance. The data were normal and needed no transformation. All data were regressed with the nonlinear modeling function of SAS JMP v.10 software (JMP, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513) and graphs were made using Sigmaplot v12.5 (Systat Software Inc., 1735 Technology Drive, Suite 430 San Jose, CA 95110). A three-parameter Gompertz model (Rawlings et al. 1998) was used for nonlinear regression, which is indicated as below:

$$Y = a^*\exp\{-\exp[-b^*(X - c)]\}$$

where Y is the response (e.g. injury at 2 WAT), a is the asymptote, b is the growth rate, c is the inflection point, and X is the imazosulfuron rate. The three-parameter Gompertz model is commonly used for nonlinear regression of visible estimates of injury against the herbicide rate. Crooks et al. (2003 a,b) used the Gompertz three-parameter model for nonlinear regression of injury estimates of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot] against herbicide rates.

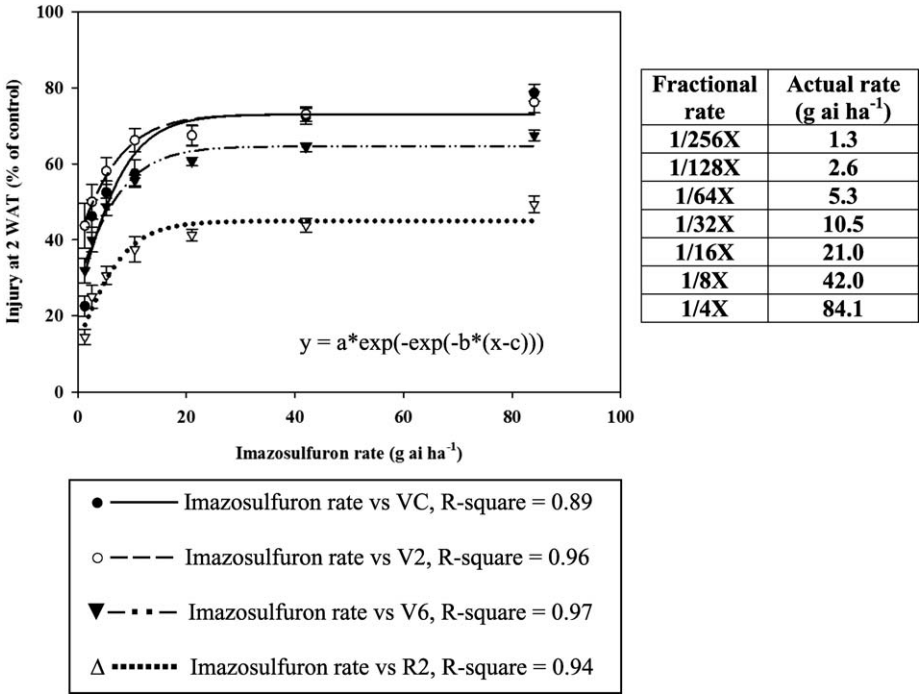
In addition, data were subjected to the multivariate and correlation function of SAS JMP v.10 software to determine pairwise correlations among injury at 2 WAT, late-season injury, delay in days to maturity, height reduction, and yield reduction. Comparison of means was performed with the use of Fisher's protected LSD at 5% level of significance.

Locations were considered random. Both locations had the same silt-loam soil series and similar air-temperature conditions till the R2 application timing. Differences in rainfall were compensated with timely irrigation at both locations. Moreover, the response of soybean to imazosulfuron for the measured parameters was comparable between locations. Therefore, data were pooled for locations to obtain better predictions of soybean response to imazosulfuron at different application timings.

Results and Discussion

Injury at 2 WAT. At 2 WAT, injury to soybean from imazosulfuron increased with increasing application rates, till 1/16X (21 g ha^{-1}) rate, regardless of application timing (Figure 1). Injury

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1/256X	1.3
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1/64X	5.3
1/32X	10.5
1/16X	21.0
1/8X	42.0
1/4X	84.1

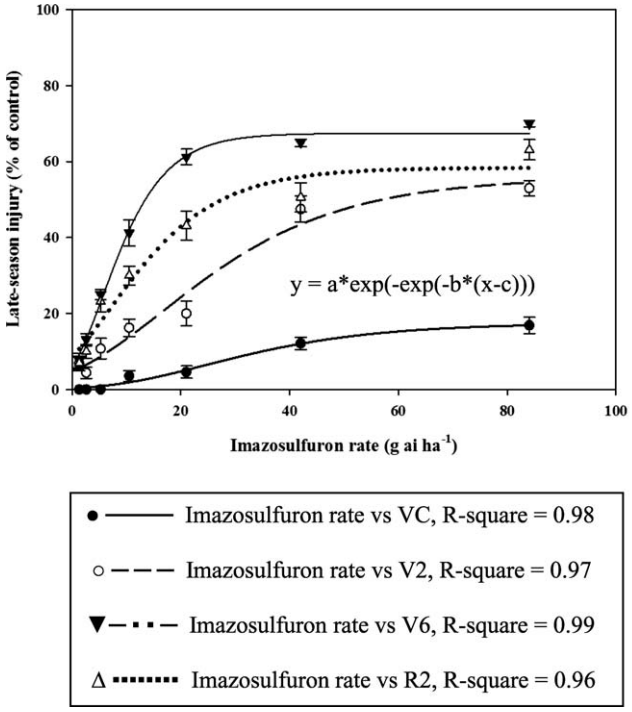
Figure 1. Soybean injury at 2 wk after treatment (WAT) as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

from imazosulfuron at 2 WAT was greater for early (VC and V2) than the later growth stages (V6 and R2). Imazosulfuron at 1/4 X (84.1 g ha^{-1}) rate resulted in soybean injury of 73% when applied at VC growth stage, 73% at the V2 stage, 65% at the V6 stage, and 46% at the R2 stage. The sensitivity of early growth stages of soybean to imazosulfuron is attributed to higher herbicide absorbance by young and rapidly growing plants than mature plants (Devine 1989; Wanamarta and Penner 1989). The response of soybean to imazosulfuron applied at early vegetative growth stages (VC and V2) was quite similar for imazosulfuron rates $\geq$ 1/16X (21 g ha^{-1}). Across the application timings, injury to soybean increased by $>$ 35% when imazosulfuron rate was increased from 1/256 (1.3 g ha^{-1}) to 1/16X (21 g ha^{-1}), but injury increased only $<$ 10% when imazosulfuron rates were increased further (Figure 1).

Late-season Injury. When observed late in the growing season (at 20 WAP), soybean injury was greatest for the V6 growth stage followed by R2, V2, and VC growth stages (Figure 2). The pattern of injury to soybean late in the season is almost opposite to that observed at 2 WAT, except soybean applied at the V6 growth stage showed more injury than at the R2 growth stage. The higher injury at V6 than at the R2 growth stage may be because of higher sensitivity of soybean during vegetative growth to sulfonylurea herbicides than reproductive stages as found in other research (Bailey and Kapusta 1993). There is less time for recovery of soybean when drift occurs late in the season compared to early growth stages (VC and V2). For the same reason, late-maturing soybean varieties often have a better chance for recovery from herbicide injury compared with the early-maturing soybean varieties (Davis et al. 2011). At the 1/4X (84.1 g ha^{-1}) rate, imazosulfuron applied at the V6 growth stage was still causing 67% injury to soybean at 20 WAP. Imazosulfuron rates of 1/256 (1.3 g ha^{-1}) to 1/16X (21 g ha^{-1}) applied to VC soybean resulted in low levels ($<$ 5%) of injury at 20 WAP (Figure 2).

In Arkansas, soybean can be planted from May 1 to July 15 contingent on climatic conditions and varietal maturity groups of soybean, and rice can be planted from March 15 to May 31 (Ashlock et. al. 2013; Wilson et. al. 2013). Imazosulfuron can be

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1/16X	21.0
1/8X	42.0
1/4X	84.1

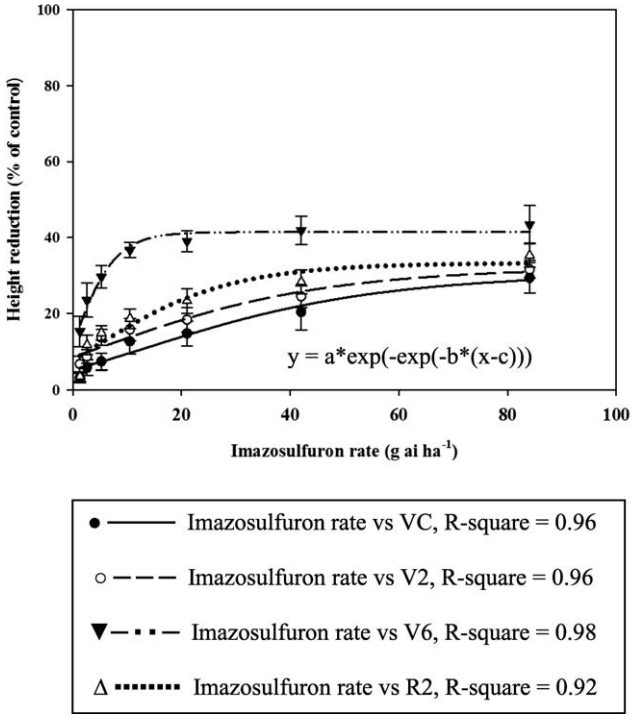
Figure 2. Soybean late-season injury as affected by rate of imazosulfuron applied at VC, V2, V6 and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

used in rice for both PRE and POST weed control, where POST applications must not be made any sooner than 21 days after PRE application (Riar and Norsworthy 2011). Therefore, depending upon the climatic conditions and choice of variety, imazosulfuron applied to rice fields has the potential to injure soybean from early vegetative to early reproductive stages.

Height Reduction. Soybean plants that received no imazosulfuron treatment were 81 cm tall at harvest (data not shown). The reduction in plant height increased with increasing imazosulfuron rate at all application timings, except for the V6 growth stage where height reduction did not increase further above the 1/16X (21 g ha^{-1}) rate of imazosulfuron (Figure 3). At the highest imazosulfuron rate, a height reduction of 42% occurred from applications at the V6 growth stage. Greater height reduction at the V6 growth stage than at the R2 growth stage is attributed to greater early-season (2 WAT) injury to soybean treated with imazosulfuron at the V6 than at the R2 growth stage. In addition, the injury to soybean treated at the V6 growth stage persisted till late in the season, which coincides with the time at which plant height was measured. Moreover, the fact that the determinate soybean had completed most of its growth in height by the R2 growth stage probably contributed to less height reduction from the late-season injury. Bailey and Kapusta (1993) also documented greater height reduction at the vegetative than the reproductive growth stages of soybean when primisulfuron was applied at 10 to 50% of the labeled rate. Similar to injury, height reductions were less apparent for the VC and V2 compared to the V6 application because of the greater recovery time for the earlier applications (Figure 3).

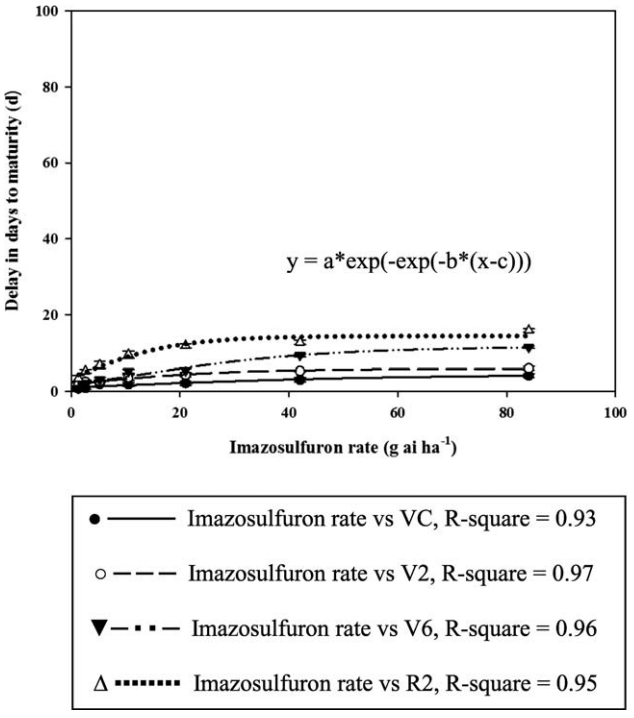
Days to Maturity. Delay in maturity increased with increasing imazosulfuron rates, regardless of the application timing (Figure 4). The greatest delay in maturity of 15 d was observed for soybean treated with the 1/4X (84.1 g ha^{-1}) rate of imazosulfuron at the R2 growth stage followed by a delay in maturity of 12, 6, and 4 d for the V6, V2, and VC growth stages, respectively, at the same rate. Maturity was delayed more when imazosulfuron was applied at the R2 stage than the vegetative growth stages because of less time available for soybean to recover from injury from imazosulfuron applied at R2 growth stage compared to early vegetative stages.

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1/64X	5.3
1/32X	10.5
1/16X	21.0
1/8X	42.0
1/4X	84.1

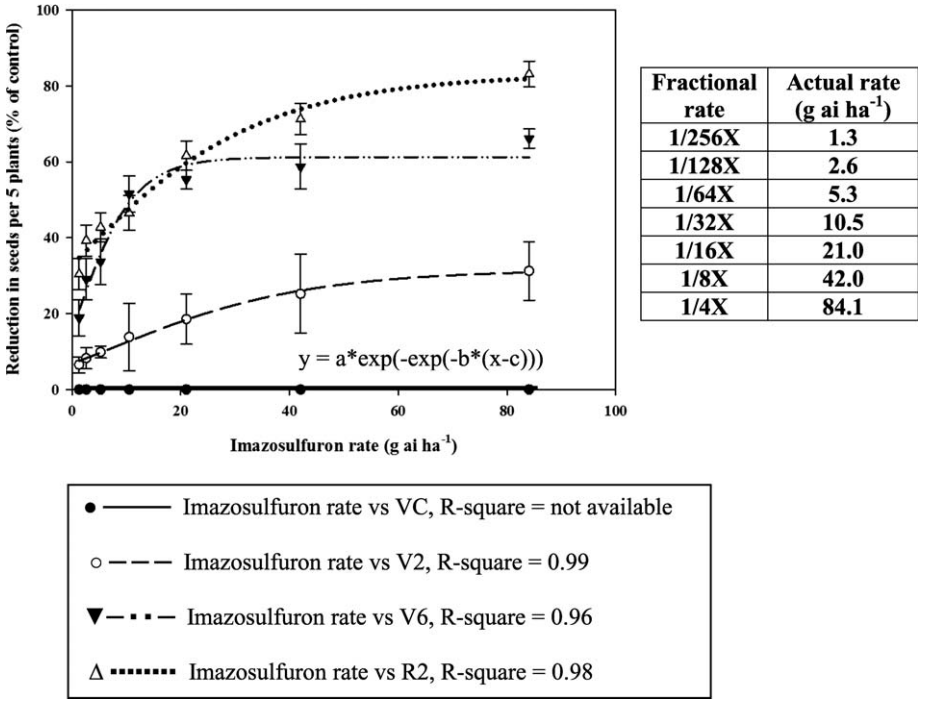
Figure 3. Soybean-plant height reduction as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.



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1/64X	5.3
1/32X	10.5
1/16X	21.0
1/8X	42.0
1/4X	84.1

Figure 4. Delay in days to maturity of soybean as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

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1/16X	21.0
1/8X	42.0
1/4X	84.1

Figure 5. Reduction in number of seeds per five soybean plants as affected by rate of imazosulfuron applied at at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

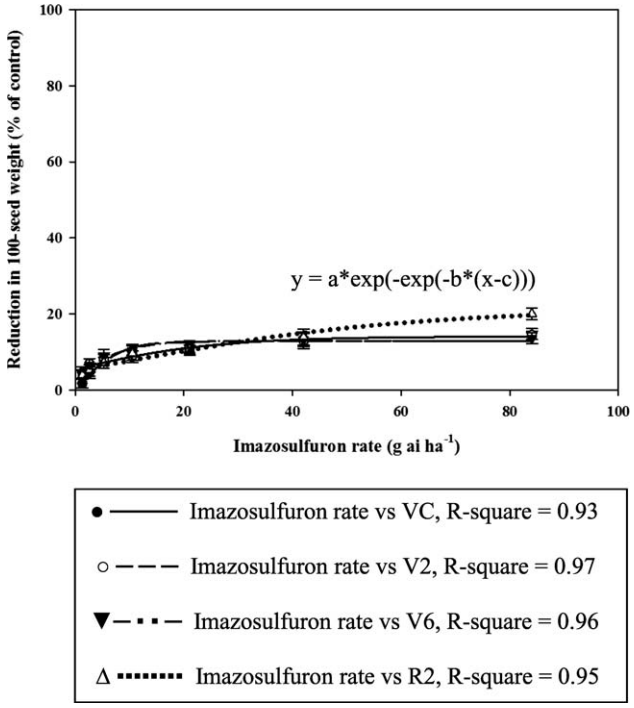
Davis et al. (2011) documented a 2- to 5-d delay in soybean maturity following simulated glufosinate drift at approximately a 1/8 to 1/2X rate (label rate of 594 g ai ha^{-1}) across vegetative and reproductive growth stages, indicating that imazosulfuron is more likely to delay maturity; consequently, posing risk for lower seed quality and difficulty in harvesting.

Seed Count. Soybean plants in non-treated checks produced 630 seeds per five plants (data not shown). The highest reduction in seed number of 84% occurred for the soybean treated with the 1/4X (84.1 g ha^{-1}) rate of imazosulfuron at the R2 growth stage followed by 61 and 32% for the V6 and V2 growth stages, respectively (Figure 5). This indicates that imazosulfuron applied to soybean at later growth stages decreases yield by reducing the number of seeds produced per plant, which is probably the result of lack of production, death, or abortion of flowers or pods following imazosulfuron application (Figure 5). Weidenhamer et al. (1989) reported a decrease in soybean seed number per plant with increasing rates of dicamba.

Hundred-Seed Weight. Non-treated soybean plants had a hundred-seed weight of 16 g (data not shown). Reduction in seed weight was less responsive to imazosulfuron rate than seed number per plant, but seed weight did decline with increasing imazosulfuron rates (Figure 6). The decrease in seed weight for the V2 and V6 growth stages was most notable with the increase in imazosulfuron rates from 1/256 (1.3 g ha^{-1}) to 1/16X (21 g ha^{-1}). At the R2 growth stage, seed weight decreased with each successive imazosulfuron rate. The reduction in soybean seed weight for imazosulfuron is different from that observed for contact herbicide glufosinate, where applications at the V3, R1, and R5 stages of soybean did not reduce seed weight (Davis et al. 2011).

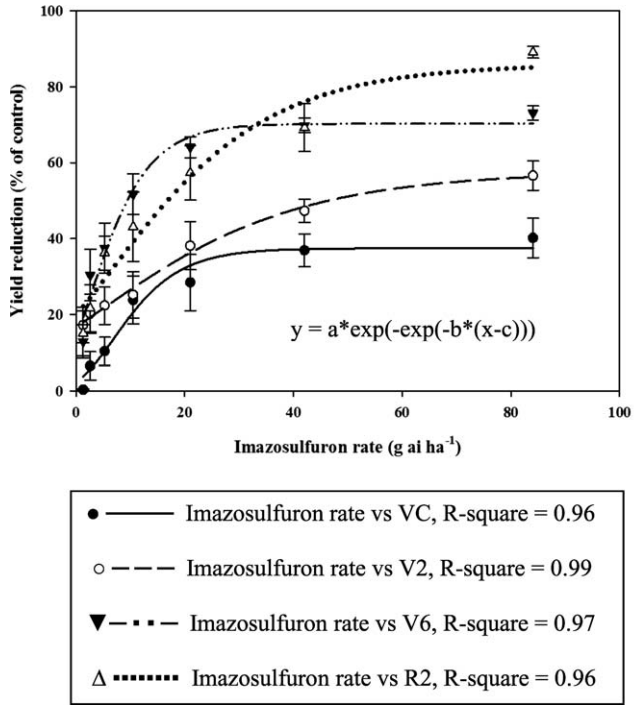
Yield Reduction. The non-treated check produced soybean seed yield of 2,760 kg ha^{-1} (data not shown). Yield loss increased with increasing rates of imazosulfuron for the V2 and R2 application timings (Figure 7). For the VC and V6 growth stages, yield decreased with increasing imazosulfuron rates up to the 1/16X (21 g ha^{-1}) rate. Imazosulfuron at 1/4X (84.1 g ha^{-1}) rate reduced soybean yield 88% when applied at the R2 growth stage.

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1/4X	84.1

Figure 6. Reduction in 100 soybean-seed weight as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.



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1/8X	42.0
1/4X	84.1

Figure 7. Soybean grain yield reduction as affected by imazosulfuron drift at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011. Abbreviations: VC, vegetative cotyledonary; V2, vegetative second trifoliate; V6, vegetative sixth trifoliate; R2, reproductive full bloom; a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

https://doi.org/10.1614/WT-D-13-00138.1 Published online by Cambridge University Press

Table 1. Correlation of injury at 2 wk after treatment (WAT) and late-season injury with delay in days to maturity; and injury at 2 WAT, late-season injury, delay in maturity, and height reduction with yield reduction at the VC, V2, V6, and R2 application timings, and across the application timings.

				Confidence interval		
	Variable	By variable	Correlation	Lower 95%	Upper 95%	P-value
Overall	Delay in days to maturity	Injury at 2 WAT	0.09	−0.04	0.22	0.1654
	Delay in days to maturity	Late-season injury	0.73	0.66	0.79	< .0001
	Yield reduction	Injury at 2 WAT	0.37	0.25	0.48	< .0001
	Yield reduction	Late-season injury	0.82	0.76	0.86	< .0001
	Yield reduction	Delay in days to maturity	0.67	0.58	0.73	< .0001
	Yield reduction	Height reduction	0.72	0.65	0.78	< .0001
VC	Delay in days to maturity	Injury at 2 WAT	0.61	0.41	0.76	< .0001
	Delay in days to maturity	Late-season injury	0.58	0.36	0.74	< .0001
	Yield reduction	Injury at 2 WAT	0.68	0.50	0.80	< .0001
	Yield reduction	Late-season injury	0.80	0.67	0.88	< .0001
	Yield reduction	Delay in days to maturity	0.37	0.10	0.58	0.0077
	Yield reduction	Height reduction	0.77	0.63	0.86	< .0001
V2	Delay in days to maturity	Injury at 2 WAT	0.72	0.57	0.83	< .0001
	Delay in days to maturity	Late-season injury	0.61	0.41	0.76	< .0001
	Yield reduction	Injury at 2 WAT	0.56	0.35	0.72	< .0001
	Yield reduction	Late-season injury	0.56	0.34	0.72	< .0001
	Yield reduction	Delay in days to maturity	0.42	0.17	0.61	0.0013
	Yield reduction	Height reduction	0.55	0.33	0.71	< .0001
V6	Delay in days to maturity	Injury at 2 WAT	0.85	0.76	0.91	< .0001
	Delay in days to maturity	Late-season injury	0.86	0.76	0.91	< .0001
	Yield reduction	Injury at 2 WAT	0.82	0.71	0.89	< .0001
	Yield reduction	Late-season injury	0.89	0.81	0.93	< .0001
	Yield reduction	Delay in days to maturity	0.75	0.61	0.85	< .0001
	Yield reduction	Height reduction	0.65	0.46	0.78	< .0001
R2	Delay in days to maturity	Injury at 2 WAT	0.79	0.66	0.87	< .0001
	Delay in days to maturity	Late-season injury	0.80	0.68	0.88	< .0001
	Yield reduction	Injury at 2 WAT	0.79	0.67	0.88	< .0001
	Yield reduction	Late-season injury	0.84	0.74	0.91	< .0001
	Yield reduction	Delay in days to maturity	0.72	0.55	0.83	< .0001
	Yield reduction	Height reduction	0.80	0.67	0.88	< .0001

Correlation of Delay in Days to Maturity with Injury. Correlation values for different variables were significant at $P \leq 0.05$, except for the overall correlation of injury at 2 WAT with delay in days to maturity across application timings ($P = 0.16$). However, for an individual timing, estimates of visible injury at 2 WAT were a good indicator of expected delay in maturity and suggest a delay in maturity as soybean injury from imazosulfuron increases. Lack of correlation between injury at 2 WAT and delay in days to maturity, averaged across application timing, was probably because of partial recovery of treated soybean at the early growth stages (VC and V2), indicating that the greater injury at early growth stages (VC and V2) is less likely to delay maturity than injury at late stages (V6 and R2) (Figures 1, 2, 4).

Correlation of delayed maturity with late-season injury (0.73) was significant across application timings (Table 1), which was primarily a function of late-season assessment being closer to maturity than the injury assessment at 2 WAT, giving soybean less time to recover from imazosulfuron injury before maturity. Not only do these correlations suggest that injury at later growth stages is a better indication than injury at early stages for expected delay in days to maturity (Figures 1, 2, 4), they could also help to somewhat accurately predict the delay in days to maturity from injury data if the soybean growth stage when the imazosulfuron drift event occurred is known.

https://doi.org/10.1614/WT-D-13-00138.1 Published online by Cambridge University Press

Correlation of Yield Reduction with Injury, Delay in Days to Maturity, and Height Reduction. Correlation values for different variables were significant at $P \leq 0.05$ (Table 1). The correlation of yield reduction with injury at 2 WAT across application timings was lower (0.37) than at individual application timings of VC (0.68), V2 (0.56), V6 (0.82), and R2 (0.79) (Table 1). Why the correlation of yield reduction with injury was lower at the V2 than the VC application timing is not known.

Injury at 2 WAT resulted in lower yield loss than late-season injury, even though injury at 2 WAT was more severe than injury from late-season applications of imazosulfuron (Figures 1, 2, 7). It appears that injury soon after application and late-season injury are good indicators of expected yield loss; however, late-season injury can predict the expected yield loss somewhat more accurately than injury at V2. Hence, severe early-season injury may lead to overestimation of yield loss. Similarly, Everitt and Keeling (2009) reported that estimates of injury early in the season often lead to overestimation of yield reduction in cotton.

Yield loss was also significantly correlated with delayed maturity and height reduction at each application timing (Table 1). As soybean maturity is delayed, soybean yield loss increases. These results indicate that late-season drift events would likely cause more of a delay in soybean maturity and greater soybean yield loss than would injury from early-season off-target imazosulfuron movement. Yield reduction was positively correlated with reduction in plant height (Table 1). Soybean height reduction probably had a greater impact than delayed maturity on yield reduction. This might be a function of fewer pods, hence less seed, on the smaller-stature soybean plants.

Results from this experiment show that soybean is highly sensitive to imazosulfuron within the range of 1/256 (1.3 g ha^{-1}) to 1/4X (84.1 g ha^{-1}) rates, regardless of growth stage at application. Furthermore, visible estimates of injury are a good indicator of delay in days to maturity and yield reduction, although late-season injury is a better predictor of delayed maturity and yield reduction. Based on this study, nonsulfonylurea-resistant soybean should not be planted in close proximity to rice where off-target movement of imazosulfuron is likely. However, if off-target injury to soybean from imazosulfuron occurs during the early vegetative stages, the chances for recovery and consequently, chances for no yield loss increases compared to injury during later stages of growth contingent upon soybean being irrigated throughout the remainder of the growing season. Under irrigated conditions, soybean will grow vigorously without drought stress, making soybean grow out of injury from imazosulfuron compared to nonirrigated soybean.

Further research is needed to determine the response of soybean to imazosulfuron under different production systems such as dryland vs. irrigated, early vs. late maturity groups, early vs. late planted, drilled vs. bedded, and narrow vs. wide row spacing. Planting soybean under dryland conditions may add an extra stress factor to the plant other than herbicide injury compared to irrigated soybean. Similarly, changing the row spacing can impact the competition from weeds, where soybean planted in narrow rows can compete with weeds in a more effective manner because of early crop canopy closure compared to soybean planted in wide rows (Nelson and Renner 1998). Additionally, wide-row soybean may need more time to compensate from early-season injury to achieve a dense crop canopy which is essential to maximize yield potential. Finally, varying the planting dates and using different maturity groups of soybean can make soybean become either more or less sensitive to drift from rice herbicides. This could happen by changing the growth stage of soybean to the corresponding herbicide application timings in nearby rice fields and by impacting the length of vegetative growth which would impact the ability of soybean to recover from injury. Again, based on this research, it is suggested that growers should use extreme caution when planting nonsulfonylurea-resistant soybean adjacent to a rice field where imazosulfuron will be applied. Sulfonylurea-resistant cultivars can be a good option for growers to protect against off-target movement of imazosulfuron.

Acknowledgments

The authors would like to thank fellow graduate students and postdoctoral fellows for their help and support with this research. Appreciation also extended to Andy Mauromaustakos for his guidance with the statistical analysis. Lastly, the authors would also like to thank Valent Corporation, USA, the Arkansas Rice Research and Promotion Board,

https://doi.org/10.1614/WT-D-13-00138.1 Published online by Cambridge University Press

and the Arkansas Soybean Promotion Board for funding this research.

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Received September 11, 2013, and approved February 16, 2014.

https://doi.org/10.1614/WT-D-13-00138.1 Published online by Cambridge University Press