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Soybean (Glycine max) Response to Imazosulfuron Drift and Carryover from Rice (Oryza sativa)

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SOYBEAN (*Glycine max*) RESPONSE TO IMAZOSULFURON DRIFT AND CARRYOVER FROM RICE (*Oryza sativa*)

SOYBEAN (*Glycine max*) RESPONSE TO IMAZOSULFURON DRIFT AND CARRYOVER FROM RICE (*Oryza sativa*)

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Crop, Soil, and Environmental Sciences

By

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ABSTRACT

In the Midsouth, soybean is often grown in close proximity to rice or in rotation with rice. Herbicides used in rice can injure soybean via drift or carryover. Consequently, field trials were conducted to determine the response of soybean (cv. AG 4703) to imazosulfuron drift and carryover (at Fayetteville, Marianna, Keiser, and Pine Tree, AR) from rice. To assess the potential for carryover, soybean was planted into rice fields treated the previous year with imazosulfuron (rotation study). To evaluate in-season sensitivity of soybean to imazosulfuron (tolerance study) relative to halosulfuron, a common sulfonylurea herbicide applied to rice, both imazosulfuron and halosulfuron were applied preemergence (PRE) at varying rates and soybean was immediately seeded into treated plots. For the drift study, imazosulfuron was applied at the VC, V2, V6, and R2 growth stages of soybean at 1/256 to 1/4 times (X) the labeled rate of imazosulfuron (336 g ai ha^{-1}). To evaluate carryover potential, imazosulfuron was applied PRE to rice at 112 to 672 g ha^{-1} for the rotation study; whereas for the tolerance study, imazosulfuron and halosulfuron were applied at 1/256 to 1/4X the labeled rate of imazosulfuron and halosulfuron (52 g ha^{-1}). Soybean was highly sensitive to imazosulfuron drift, with injury (stunting and purple veins, typical of acetolactate synthase-inhibiting herbicides) resulting at all rates and application timings. At 2 weeks after treatment (2 WAT), topical application of the highest (1/4X) rate of imazosulfuron caused more than 73% injury at the VC application timing. Soybean recovered from the injury, with little to no injury observed from the lowest four rates of imazosulfuron applied at the VC and V2 growth stages by the end of the growing season. For the carryover trial at 2 weeks after planting (2 WAP), soybean exhibited 3 and 13% injury at Keiser (silty clay soil with 1.0% organic matter content and a pH of 8.3) and Pine Tree (silt loam soil with 2.3% organic matter content and a pH of 7.1), respectively, when imazosulfuron was applied to rice the previous year at 672 g ha^{-1}, a 2X rate. Injury to soybean was transient and not apparent by the end of the growing season. For the tolerance study, sulfonylurea-tolerant (STS) soybean was not injured. Moreover, no injury was observed on non-STS soybean by PRE-applied imazosulfuron or halosulfuron regardless of herbicide rate, and yield was comparable to the non-treated control. Results of this research indicate that imazosulfuron should be applied with extreme caution to rice as off-target movement will likely cause injury to non-STS soybean (cv. AG 4703) in adjacent fields and applications of imazosulfuron may carryover to non-STS (cv. AG 4703) soybean on silt loam soils having low organic matter and a high soil pH, especially in fields where overlap of an imazosulfuron spray occurred in the preceding rice crop. Under conditions conducive for imazosulfuron to injure soybean via off-target movement or carryover, planting of STS soybean is recommended to avoid possible risks of soybean injury.

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DEDICATION

Dedicated to my wife and family

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INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important crops grown in Arkansas. Rice production in Arkansas began in 1902 with only 0.40 ha of land under cultivation in Lonoke County (Slaton 2001). At present, rice cultivation has increased to 1.09 M ha, and Arkansas alone contributes about 48% of the total area planted to rice in the U.S. (0.52 M ha) (NASS 2012a). Rice is grown in 40 of the 75 counties in Arkansas, with the major counties being Arkansas, Poinsett, Cross, Lawrence, and Jackson (Wilson and Branson 2005). Rice ranks first among the top three crop commodities as far as cash receipts for Arkansas farmers (Slaton 2001).

Soybean [*Glycine max* (L.) Merr.] is also an important crop in the U.S. and contributes a large share of the national agricultural economy. Currently, soybean covers an area of 31.24 M ha in the U.S. (NASS 2012b). In 2012, U.S. soybean production reached 82.05 billion kg, with a total value of 43.19 billion dollars (NASS 2012b). Arkansas ranked eleventh in the total value of production of soybean in the U.S. (NASS 2012c). In 2012, Arkansas alone contributed 4.12, 4.51, and 4.53% of total area, production, and value of production, respectively, of soybean to the national pool (NASS 2012b).

In rice, sulfonylurea herbicides are applied for the control of broadleaf weeds and sedges (Obrigawitch et al. 1998). The popularity of sulfonylurea herbicides in rice is basically due to their relatively low use rate, low mammalian toxicity, excellent selectivity, and high efficacy (Saari et al. 1994). The injury caused by sulfonylurea herbicides to non-target crops has been studied and reported in the past two decades (Al-Khatib et al. 1992, 1999a, 1999b, 2003; Bailey and Kapusta 1993; Mallory-Smith and Thill 1993; Wall 1994). Sulfonylurea herbicides cause no damage via vapor drift due to their extremely low-volatile nature (Degiorgio and King 2003). Additional factors causing the exposure of plants to herbicides are spray drift, soil residues, surface run-off, and improper cleaning of application equipment (Obrigawitch et al. 1998). Since most sulfonylurea herbicides are effective at extremely low rates, improper cleaning of application equipment can result in enough herbicide exposure to injure soybean (Bailey and Kapusta 1993; Brown 1990; Brown and Cotterman 1994). Nandula et al. (2009) reported soybean injury from halosulfuron applied at very low rates, 4.3 to 69 g ha^{-1}. Halosulfuron is the current standard of sulfonylurea herbicides applied to rice, but imazosulfuron (V-10142), 1-(2-chloroimidazo [1, 2-*a*] pyridin-3-ylsulfonyl)-3-(4, 6-dimethoxypyrimidin-2-yl) urea, is a new sulfonylurea herbicide recently registered for use in rice by Valent U.S.A. (Godara et al. 2012; Morrica et al. 2002; Riar et al. 2011).

Imazosulfuron is targeted for use in drill- and water-seeded rice (Godara et al. 2012; Riar et al. 2011). Imazosulfuron was launched for use in U.S. rice in spring 2011 under the trade name League. This compound controls several broadleaf weeds and has good activity on sedges (Godara et al. 2012; Riar et al. 2011; Sondhia 2008; Still et al. 2009). Imazosulfuron inhibits acetolactate synthase (ALS), thereby blocking the biosynthesis of branched-chain amino acids valine, leucine, and isoleucine (Brown 1990; Brown and Cotterman 1994), which results in cessation of plant cell division and growth due to lack of amino acids (Tanaka and Yoshikawa 1994).

In the southern USA, soybean is often grown in close proximity to rice, either in adjacent fields or in rotation to rice. Therefore, preemergence- and postemergence-applied herbicides in rice have the tendency to injure soybean either via in-season drift or via carryover the following year.

Herbicide drift occurs when an herbicide is moved by air from the target site to an area that is not intended for treatment. Off-target movement of herbicides can injure adjacent crops

(Bailey and Kapusta 1993). Therefore, it is imperative to study physical drift of herbicides to non-target crops for understanding the contamination potential and potential economic injury to non-target crops (Banks and Schroeder 2002).

The problem of herbicide drift in soybean becomes more severe when herbicides are applied under environmental conditions favoring volatilization and redeposition (Hanks 1995; Wall 1994). Injury to soybean from herbicide drift depends on many factors, including crop cultivar, growth stage, herbicide used, herbicide formulation, environmental conditions (wind, temperature, etc.), droplet size, spray additive, pressure of spray, type of nozzle, and height of release of herbicide above the ground (Auch and Arnold 1978; Bode 1987; Fribourg and Johnson 1955; Hanks 1995; Miller 1993; Wax et al. 1969). In addition, the appropriate height of boom at the time of application is approximately 40 cm for ground-application equipment and approximately 46 m for aerial-application equipment, and the working pressure of herbicide spraying should not exceed 2 to 5 x 10^5 bar (Grundy and Bennett 1960; Nordby and Skuterud 1974). Moreover, at high air temperatures, injury to soybean is generally greatest due to increased diffusion through the cuticle and cell membranes (Wanamarta and Penner 1989).

Characteristics of sulfonylurea herbicides, including being highly active at low rates, persistent in nature, and having potential for carryover, are considered important for planning crop rotational programs (Jordan et al. 1993; Renner et al. 1988). Several sulfonylurea herbicides are reported to injure rotational crops (Barnes et al. 1989; Jordan et al. 1993; Monks and Banks 1991; and Renner et al. 1988). However, injury to a rotational crop is not solely a function of herbicide persistence, but also depends on sensitivity of the rotational crop.

Sensitivity of the rotational crop to an herbicide differs among cultivars of a crop. Sulfonylurea-tolerant soybean (STS), a genetically modified soybean cultivar, has an enhanced tolerance for sulfonylurea herbicides and is an option for reducing injury to soybean (Nandula et al. 2009). However, non-sulfonylurea-tolerant soybean (non-STS) can be severely injured when they come into contact with sulfonylurea herbicides. STS soybean has also shown tolerance to PRE-applied pyrithiobac, a non-sulfonylurea herbicide that inhibits ALS (Medlin et al. 1998).

The susceptibility of soybean to direct applications of halosulfuron suggests that carryover and injury from residues of sulfonylurea herbicides may occur (Nandula 2009). Therefore, the objectives of this research were to evaluate soybean sensitivity to drift rates of imazosulfuron applied at different growth stages and to determine the carryover potential of imazosulfuron to soybean from rice.

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CHAPTER I

SOYBEAN (*Glycine max*) SENSITIVITY TO DRIFT RATES OF IMAZOSULFURON

ABSTRACT

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 U.S. because the two crops are often grown in close proximity. Therefore, field trials were conducted to determine the effect of low rates of imazosulfuron applied at different growth stages of non-sulfonylurea-tolerant soybean. Soybean was treated at the VC, V2, V6, and R2 growth stages with 1/256 to 1/4 times (X) the maximum labeled rate of imazosulfuron. Soybean was injured regardless of herbicide rate or application timing. At 2 wk after treatment (WAT), imazosulfuron at the 1/256 to 1/4X rates 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, at 20 wk after planting (WAP), soybean treated with 1/256 to 1/4X rates of imazosulfuron at the VC and V2 growth stages had only 0 to 17% and 8 to 53% visible injury, respectively. At higher rates (1/8 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) than at the higher rates (1/64 to 1/4X). Imazosulfuron applied at 1/256 to 1/4X rates 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. Injury resulted in greater yield loss when imazosulfuron was applied at V6 and R2 than 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 injury by imazosulfuron at early growth stages (VC and V2) has a better chance of recovery over time compared to 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.

INTRODUCTION

Imazosulfuron is a new sulfonylurea herbicide labeled for use in rice (Godara et al. 2012; Riar et al. 2011). Imazosulfuron acts by inhibiting acetolactate synthase (ALS) (EC 4.1.3.18) activity at very low concentrations and hinders biosynthesis of the branched-chain amino acids valine, leucine, and isoleucine, thereby resulting in rapid cessation of plant cell division and growth (Brown 1990; Usui 2001; Riar et al. 2011). Imazosulfuron is 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 ai ha^{-1}. In rice, sequential applications (PRE fb POST) of imazosulfuron at 336 g ha^{-1} provided excellent control of broadleaf weeds and sedges (Godara et al. 2012; Riar et al. 2011).

Rice is one of the most important crops grown in Arkansas. In 2012, 0.52 M ha of land was planted to rice in Arkansas, contributing 48% of the total rice ha in the U.S. (NASS 2012). Weed control in rice is highly dependent on use of herbicides; halosulfuron is the current standard of sulfonylurea herbicides used in rice (Nandula et al. 2009). In the southern U.S., soybean is also an important crop and is often grown in close proximity to rice. Halosulfuron, when applied to rice, is reported to injure soybean through off-target movement or drift (Nandula et al. 2009). The normal drift rates of herbicide during application can range from 0.01 to 10% of the applied rate (Al-Khatib and Peterson 1999; Snipes et al. 1992). However, depending on the crop variety and the growth stage, injury from the off-target movement of herbicides to non-labeled or susceptible crops ranges from sub-lethal to severe.

Glyphosate injures non-glyphosate-resistant soybean when applied from vegetative through reproductive stages; however, soybean have better chances to recover when injury occurs at the vegetative growth than the reproductive growth stages (Norsworthy 2004).

Therefore, soybean is considered more sensitive to glyphosate applications made later in the season because there is less time to recover from the injury. Halosulfuron at 4.3 to 69 g ha^{-1} applied to 4-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 soybean 70 to 75% at 28 DAT. Imazosulfuron at as little as 5.26 g ha^{-1} (1/64X) injured non-STS soybean from cotyledonary (VC) through R2 growth stages (Norsworthy 2010). Moreover, imazosulfuron applied at 168 g ha^{-1} (1/2X) caused more than 80% injury to soybean. In the same work, soybean treated with 5.26 and 10.52 g ha^{-1} of imazosulfuron at emergence (VE) and at the 3-trifoliolate (V3) soybean growth stages recovered from the injury and resulted in no yield reduction compared with the non-treated control. Recovery of soybean plants treated at early growth stages with lower imazosulfuron rates was because of ample time available for early-season-treated soybean to recover from the injury. For the same reason, the late-maturing soybean varieties have a better chance of recovery from imazosulfuron injury compared with the early-maturing soybean varieties (Davis 2011). Injury 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 fails to produce grain (Norsworthy et al. 2010).

There is little information available for the sensitivity of soybean to drift rates of imazosulfuron. Therefore, it is imperative to conduct research to understand the potential of imazosulfuron to injure soybean via off-target movement from rice. Since imazosulfuron has same chemistry as that of halosulfuron, we hypothesized that imazosulfuron, like halosulfuron, will drift from rice fields to injure soybean in the nearby fields. To test our hypothesis, field studies were conducted with an objective of evaluating the effect of low rates of imazosulfuron applied at different growth stages to non-sulfonylurea-tolerant soybean.

MATERIALS AND METHODS

Field trials were conducted at the University of Arkansas Agricultural Research and Extension Station, Fayetteville, and the Pine Tree Experiment Station, Arkansas, in summer 2011 to evaluate the effect of low rates of imazosulfuron applied at different growth stages of non-sulfonylurea-tolerant soybean. Soybean was planted May 7, 2011, and May 10, 2011, and emerged on May 16, 2011, and May 19, 2011, at the Fayetteville and the Pine Tree stations, respectively. Soybean at Fayetteville was planted with a four-row John Deere 7100 plate-type planter set on 0.91-m row spacing to deliver 30 seeds m^{-1}. At Pine Tree, soybean was planted with an eight-row John Deere vacuum planter set on 0.76-m row spacing to deliver 30 seeds m^{-1}. 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 non-sulfonylurea-tolerant, glyphosate-resistant, indeterminate, maturity group IV soybean cultivar. Soybean was irrigated twice weekly with an overhead lateral moving irrigator at Fayetteville, and approximately once weekly with poly-irrigation tube (Delta Plastics, 10801 Executive Center Drive, Ste 201, Little Rock, AR 72211) at the Pine Tree station. The soil was Calloway silt loam (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs) composed of 11.7% sand, 69.8% silt, 18.5% clay, with 1.25% organic matter and a pH of 7.5 at the Pine Tree station. At Fayetteville, the soil was characterized as a Leaf silt loam (Fine, mixed, active, thermic Typic Albaquults), composed of 27.1% sand, 54.4% silt, 18.5% clay, with 1.87% organic matter and a pH of 5.8. Plots at both locations were kept weed-free with timely broadcast applications of glyphosate (Roundup PowerMax^{TM}, 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 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 VC, 2-trifoliolate soybean (V2), 6-trifoliolate soybean (V6), and R2 growth stages. Imazosulfuron was applied at 1/256 (1.31 g ha^{-1}), 1/128 (2.62 g ha^{-1}), 1/64 (5.25 g ha^{-1}), 1/32 (10.51 g ha^{-1}), 1/16 (21.02 g ha^{-1}), 1/8 (42.03 g ha^{-1}), and 1/4 (84.06 g ha^{-1}) times (X) its labeled rate, 336 g ai ha^{-1}. The reason for using imazosulfuron rates ≤1/4X is because herbicide drift most often occurs in the range of 0.1 to 10% (Al-Khatib and Peterson 1999; Snipes et al. 1992) and the rate used in this experiment covers this range. Treatments also included a non-treated control. At Fayetteville, soybean at the VC, V2, V6, and R2 growth stages were sprayed on May 28, June 8, June 22, and July 6, 2011, respectively. At Pine Tree, soybean at the VC, V2, V6, and R2 growth stages were sprayed on May 31, June 6, June 21, and July 13, 2011, respectively. 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. Crop oil concentrate at 1% v/v (Agri-Dex, Helena Chemical Company, 225 Schilling Boulevard, Suite 300, Collierville, TN 38017) was added to each treatment.

Visual estimates of soybean injury caused by imazosulfuron were rated on a weekly basis on a scale of 0 to 100%, where 0 is no injury and 100 is plant death. Injury ratings were based on chlorosis, purple veins, and stunting. The height of five plants per plot was recorded at harvest.

Plant height 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. Before harvesting the plots with a small-plot combine, 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 October 31, 2011 at Pine Tree. At both locations, only the two center rows of the four-row plot were harvested and moisture content adjusted to 13%.

All data except delay in days to maturity data were presented as the percent of non-treated check for all the parameters measured, and data from the non-treated check were not included in the analysis. The delay in days to maturity data were presented as number of days for soybean in treated plots to mature with respect to the soybean in the non-treated check, where delay in days to maturity for soybean in the non-treated check was zero days. Data were first tested for normality in order to comply with the assumptions for statistical analysis. Normality of data was tested with the distribution of residuals. The data were normal (normal distribution of residuals) and needed no transformation. All data were regressed with the nonlinear modeling function of SAS JMP v.10 software and graphs were made using Sigmaplot v12.5 (Systat Software, Inc. 1735 Technology Drive, Suite 430 San Jose, CA 95110 USA) using. The three-parameter Gompertz model (Rawlings et al. 1998) was used for non-linear 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 non-linear regression of visible injury against the herbicide rate. Crooks et al.

(2003 a,b) used Gompertz model for non-linear regression of visible injury estimates of large crabgrass and Italian ryegrass 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. Pairwise correlations were then utilized to predict the yield reduction from the observed levels of injury at 2 WAT and late in the season, delay in days to maturity, and height reduction; and to predict delay in days to maturity and height reduction from the observed levels of injury at 2 WAT and late-season injury by subjecting data to further analysis using the fit model function of SAS JMP v.10 software. Comparison of means was performed with the use of Fisher's Protected LSD at 5% level of significance.

RESULTS AND DISCUSSION

Locations were randomly selected. Both locations have same silt loam series and similar air-temperature conditions till the R2 application timing and for majority of growing season (Table 1). The differences in the rainfall (Table 1) were compensated with the timely irrigation at both locations. Moreover, the response of soybean to imazosulfuron was comparable among response parameters across locations. Therefore, data were pooled across the locations to obtain better predictions of soybean response to imazosulfuron at different application timings.

Imazosulfuron injury to soybean was noticeable within a week after treatment and peaked at 2 WAT. At 2 WAT, injury symptoms, which were purple veins and stunting, were more severe at higher imazosulfuron rates applied at early growth stages (VC and V2) than lower imazosulfuron rates at later growth stages (V6 and R2).

Berti et al. 1996 has described nonlinear models as a functional approach to determine relationships between plant injury and herbicide rates. Moreover, nonlinear regression models have also been recommended for weed control and crop injury studies (Knezevic et al. 2002, 2007).

Injury at 2 WAT. At 2 WAT, injury to soybean from imazosulfuron increased with increasing application rates regardless of application timing (Figure 1). Imazosulfuron at 2 WAT injured early growth stages, VC and V2, more than the later growth stages, V6 and R2. Imazosulfuron at 1/4 X rate resulted in soybean injury of 73% when applied at VC growth stage, followed by V2 (73%), V6 (65%), and R2 (46%) growth stages, respectively. However, the response of soybean to imazosulfuron applied at early vegetative growth stages (VC and V2) was quite similar for imazosulfuron rates ≥1/16X. 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). Injury to soybean increased a great deal when imazosulfuron rate was increased from 1/256 to 1/16X, but injury did not increase much 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 vegetative growth stages of soybean to sulfonylurea herbicides than reproductive stages (Bailey and Kapusta 1993). There is less time in the growing season for recovery of soybean when drift occurs during reproductive development. The early growth stages (VC and V2) have more opportunity to recover from injury than the later growth stages (V6 and R2). At the 1/4X rate, imazosulfuron caused the highest injury of 67% at the V6 growth stage followed by the R2 (59%), V2 (57%), and VC (17%) growth stages. Conversely, lower imazosulfuron rates, 1/256 to 1/16X, at the VC growth stage resulted in extremely low levels (<5%) injury to soybean (Figure 2).

Height Reduction. Soybean that received no imazosulfuron treatment was 81 cm tall (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 significantly after 1/16 X rate of imazosulfuron. At the highest imazosulfuron rate, the maximum height reduction of 42% occurred at the V6 growth stage followed by the R2 (34%), V2 (32%), and VC (30%) growth stages, respectively. The greater height reduction at the V6 growth stage than the R2 growth stage is a function of 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, and was greater than at the R2 growth stage. Moreover, the greater plant height reduction at the V6 growth stage than at R2 growth stage was probably because of reason that the soybean treated with imazosulfuron at the R2 growth stage has already completed most of its vegetative growth and does not grow much more in height. Here again, greater height reduction was observed for soybean plants treated at later growth stages because of the less time available for them to recover from the injury than those treated earlier in the growing season (Figure 3). 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. Moreover, the soybean treated at the V3 growth stage recovered more rapidly than soybean treated at the R1 growth stage, and recovery for both growth stages was more rapid for soybean treated with 10 to 20% rates of primisulfuron than those treated with higher rates (Bailey and Kapusta 1993). At the end of growing season, soybean plants treated with prosulfuron at 13 g ha^{-1}, prosulfuron plus primisulfuron at 8 + 8 g ha^{-1}, and rimsulfuron plus thifensulfuron at 46 + 23 g ha^{-1} resulted in stunted plants (Al-Khatib and Peterson 1999).

Days to Maturity. Delay in maturity increased with increasing imazosulfuron rates, regardless of the application timing; the greatest delay in maturity of 15 d was observed for soybean treated with the 1/4X 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 (Figure 4). Maturity was delayed more when imazosulfuron was applied at the R2 stage than the vegetative growth stages because injury at the R2 growth stage generally results in flower and pod abortion, whereas at the vegetative growth stages, the major impact of imazosulfuron was in terms of purple veins, chlorosis, and stunting (Figure 4). The longer the crop stays in the field after the optimum time for harvest, the less would be the quality and yield. Furthermore, delays in harvest could constrain other harvest operations since differing planting dates and maturity groups are commonly grown to spread out maturity and harvest. Similar to imazosulfuron, Davis et al. (2011) documented a 2- to 5-d delay in soybean maturity following simulated glufosinate drift at 77 to 308 g ai ha^{-1}.

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 at the R2 growth stage with the 1/4X rate of imazosulfuron followed by 61 and 32% for the V6 and V2 growth stages, respectively. 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 or death or abortion of flowers or pods following imazosulfuron application (Figure 5). Weidenhamer et al. (1989) reported that increasing rates of dicamba can result in a decrease in number of seeds per plant in soybean as high as 95 to 100%.

Hundred-Seed Weight. Non-treated soybean plants had a hundred-seed weight of 16 g (data not shown). Seed weight declined with increasing imazosulfuron rates for the R2 growth stage, showing that soybean had smaller seeds as the rate of imazosulfuron increases (Figure 6). However for the V2 and V6 growth stages, the decrease in hundred-seed weight increased with the increase in imazosulfuron rates from 1/265 to 1/16X, and further increase in rates did not decrease the hundred-seed weight significantly. The reduction in 100-seed weight for each corresponding rate was somewhat similar for all individual timings, except for the 20% reduction in 100-seed weight at the R2 growth stage when soybean was treated with the 1/4X rate of imazosulfuron. For the VC, V2, and V6 growth stages, the 100-seed weight reductions for the two highest imazosulfuron rates were similar. For 1/256 to 1/8X imazosulfuron rates, the reduction in 100-seed weight ranged from 2 to 13% across the application timings, indicating that imazosulfuron causes the yield reduction more by reducing the number of seeds produced per soybean plant rather than producing smaller-sized grain (Figure 6). The reduction in soybean seed weight for imazosulfuron is different from that observed for 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 grain yield of 2760 kg ha^{-1}. Yield loss increased with increasing rates of imazosulfuron for the V2 and R2 application timings (Figure 7). However, yield did not decrease significantly for imazosulfuron rates >1/16X applied at the VC and V6 growth stages. The greatest yield reduction of 88% percent occurred for soybean treated with the 1/4X rate of imazosulfuron at the R2 growth stage. There was no significant difference in yield reduction between the V6 and R2 soybean growth stages when treated with imazosulfuron rates of ≤1/8X, but imazosulfuron at the 1/4X rate reduced yield more at the R2 than the V6 growth stage. Across application timings, the yield reduction was greatest for the soybean treated at V6 growth stage followed by the R2, V2, and VC growth stages. At the 1/4X imazosulfuron rate, yield reductions of 70, 50, and 37% were measured for the V6, V2, and VC growth stages, respectively (Figure 7). These results followed the late-season injury assessments where maximum injury from imazosulfuron occurred at the V6 growth stage followed by the R2, V2, and VC growth stages (Figure 2 and 7).

One possible explanation for the observed trend in yield reduction is that by the time soybean reaches the V6 growth stage plants have already completed their vegetative growth and assimilates are used primarily for flower and pod formation, which results in pod fill and finally crop yield. Hence, soybean injured at the V6 and later growth stages had a shorter period from application to maturity along with the greatest delay in maturity (Figure 4). Soybean plants treated at the VC and V2 growth stages had ample time to recover from the injury; whereas soybean at V6 and R2 growth stages had comparatively less time to recover from injury.

Correlations and Predictions. All the correlation values between different variables were significant with a P-value <0.05, except for the correlation of injury at 2 WAT with delay in days to maturity across the application timings (P = 0.17) (Table 3). There was very poor correlation (0.09) between injury at 2 WAT and delay in days to maturity when measured across application timings; however for individual timings, correlation values were much higher. This indicates that visible estimates of injury at 2 WAT are a good indicator of expected delay in maturity only when growth stage of soybean, at which injury occurred, is known. At the V6 growth stage, the injury at 2 WAT was correlated with delay in days to maturity with a correlation value of 0.85

followed by correlation value of 0.79, 0.72, and 0.61 for the R2, V2, and VC growth stages (Table 3). The positive values of these correlation coefficients imply that as soybean injury from imazosulfuron increases, delay in maturity of soybean increases. For individual application timings, the absolute values of correlation coefficient being greater than 0.6 suggests that imazosulfuron injury at 2 WAT is a good indicator of soybean delay in maturity (Ott and Longnecker 2001). Lack of correlation between injury at 2 WAT and delay in days to maturity across the application timings compared to individual application timing was because of partial recovery of soybean treated at the early growth stages (VC and V2), indicating that higher levels of injury observed at early growth stages may not result in a noticeable delay in days to maturity.

For individual application timing, the predictions of soybean delay in maturity and yield loss were made from the highest levels of injury observed at 2 WAT and late in the season (Figures 8, 9, 10, 11). Similarly, predictions of yield loss from delay in maturity and height reductions were made by taking into account the highest levels of delay in days to maturity and height reductions observed at each application timing (Figures 12, 13).

At 2 WAT, imazosulfuron injury to soybean of 85, 85, 70, and 55% resulted in a predicted delay in maturity of 6, 7, 8, and 12 d when treated at the VC, V2, V6, and R2 growth stages, respectively (Figure 8 a,b,c,d). Although imazosulfuron caused greater injury to early (VC and V2) than later (V6 and R2) growth stages, consequent delay in days to maturity was greater for later than early growth stages, indicating the ability of indeterminate growth habit of soybean treated early in the season to recover partially from imazosulfuron injury over time.

Contrary to correlation of delay in days to maturity with injury at 2 WAT, correlation was greater with late-season injury (0.73), which was primarily a function of having dates of late-season injury assessment and delay in days to maturity closer to each other compared to injury at

2 WAT. Moreover, correlation of late-season injury with delay in days to maturity across the application timings was higher than those at early application timings (VC and V2) and lower than those at later application timings (V6 and R2) (Table 3). At the V6 growth stage, late-season injury was correlated with delay in days to maturity with a correlation value of 0.86 followed by correlation values of 0.80, 0.61, and 0.58 for the R2, V2, and VC growth stages, respectively (Table 3). Both injury at 2 WAT and late-season injury had higher correlation with delay in days to maturity when measured at later than early growth stages, which is because of ability of soybean to recover from imazosulfuron injury over time. In addition, soybean plants treated at early growth stages have more time to recover from the injury than those treated late in the season.

Correlation values observed in this research suggest that degree of injury observed at later growth stages is a better indication of the expected delay in days to maturity than at early growth stages. Also, the observed correlation indicates that one can 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.

Late in the season, the injury of 25, 60, 70, and 70% resulted in delay in maturity of 5, 9, 9, and 12 d at the VC, V2, V6, and R2 growth stages, , respectively (Figure 9 a,b,c,d). This indicates that even though late-season injury and injury at 2 WAT were almost equally correlated with delay in days to maturity, late-season injury assessment is a better predictor of delayed maturity than the injury observed at 2 WAT.

Correlation of yield reduction with injury at 2 WAT and late-season injury followed the same pattern as that of correlation of delay in days to maturity with injury at 2 WAT and late-season injury. Correlation of yield reduction with injury at 2 WAT across the application timings was lower (0.37) than at the VC (0.68), V2 (0.56), V6 (0.82), and R2 (0.79) application timings individually (Table 3). However, correlation of yield reduction with late-season injury (across the application timing) was higher (0.82) than with injury at 2 WAT, and was comparable to correlations values at the VC (0.80), V6 (0.89), and R2 (0.84) application timings (Table 3). It was unclear why the correlation of yield reduction with injury at 2 WAT and late-season injury was significantly lower (0.56) at the V2 application timing than at other timings, especially the VC.

At 2 WAT, predicted reduction in yield was highest for the R2 (68%) growth stage followed by the V6 (57%), V2 (56%), and VC (51%) growth stages (Figure 10 a,b,c,d). For the V6 and R2 growth stages, injury persisted till the end of the growing season; whereas soybean treated at VC and V2 growth stages partially recovered from injury by end of the growing season. Consequently, the highest levels of late-season injury observed at the VC, V2, V6, and R2 growth stages resulted in corresponding predicted yield losses of 38, 67, 76, and 82%, respectively (Figure 11 a,b,c,d). These results suggest that injury soon after application and late-season estimates of injury are good indicators of expected yield loss; however, late-season injury can predict the expected yield loss somewhat more accurately. If high levels of injury to soybean persist till the end of growing season, greater yield loss will result than when soybean visibly recovers from high levels of early-season injury by season's end. Moreover, yield loss was predicted to be lower for injury at 2 WAT than late-season injury even when injury at 2 WAT was more severe than injury resulting from late-season applications of imazosulfuron, indicating that early-season injury may overestimate the expected yield loss. Similarly, Everitt and Keeling (2009) reported that visible estimates of injury early in the season often overestimate yield reduction in cotton.

Yield loss at end of the growing season is also a function of delayed maturity and height reduction. Yield reduction was correlated with delay in days to maturity, with correlation values of 0.37, 0.42, 0.75, 0.72, and 0.67 at the VC, V2, V6, R2 application timings, and across all application timings (Table 3). As soybean maturity is delayed, soybean yield loss increases. However, at the rates evaluated, delays in days to maturity were only observed at the V2, V6, and R2 application timings. The greatest delay in maturity was 7, 9, 12, and 17 d at the VC, V2, V6, and R2 application timings, which resulted into corresponding predicted yield reductions of 43, 57, 79, and 82%, respectively (Figure 12 a,b,c,d). 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.

Soybean height reduction was a better predictor of yield reduction than delayed maturity. This is probably because of fewer pods and hence less seed on the smaller-stature soybean plants. Yield reduction was correlated with reduction in plant height, with the correlation values of 0.77, 0.55, 0.65, 0.80, and 0.72 at the VC, V2, V6, R2 application timings, and across the application timings (Table 3). In addition, the highest levels of height reduction were 45, 40, 55, and 50% when soybean was treated at the VC, V2, V6, and R2 growth stages, which resulted in corresponding predicted yield losses of 66, 65, 79, and 89%, respectively. These results suggest that even though the height reduction observed was similar across application timing, the expected yield loss is greater when height reduction occurs from imazosulfuron applications late in the season.

Results from this experiment indicate that soybean is highly sensitive to imazosulfuron within the range of 1/256 to 1/4X 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, yet late-season injury is a better predictor of delayed maturity and yield reduction. Based on this study, non-sulfonylurea-tolerant 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 no yield loss increases compared to injury during later stages of growth, contingent upon soybean being irrigated throughout the remainder of the growing season.

Further research is needed to determine response of soybean to imazosulfuron under different production systems such as dryland vs. irrigated conditions, early vs. late maturity groups, early vs. late planted, and drilled vs. bedded or 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 in order 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 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 should impact the ability of soybean to recover from injury. Again, based on this research, it is suggested that growers use extreme caution when planting non-sulfonylurea-resistant soybean adjacent to a rice field where imazosulfuron will be applied. Furthermore, growers may opt to plant a sulfonylurea-resistant cultivar as a partial measure to protect against off-target movement of imazosulfuron.

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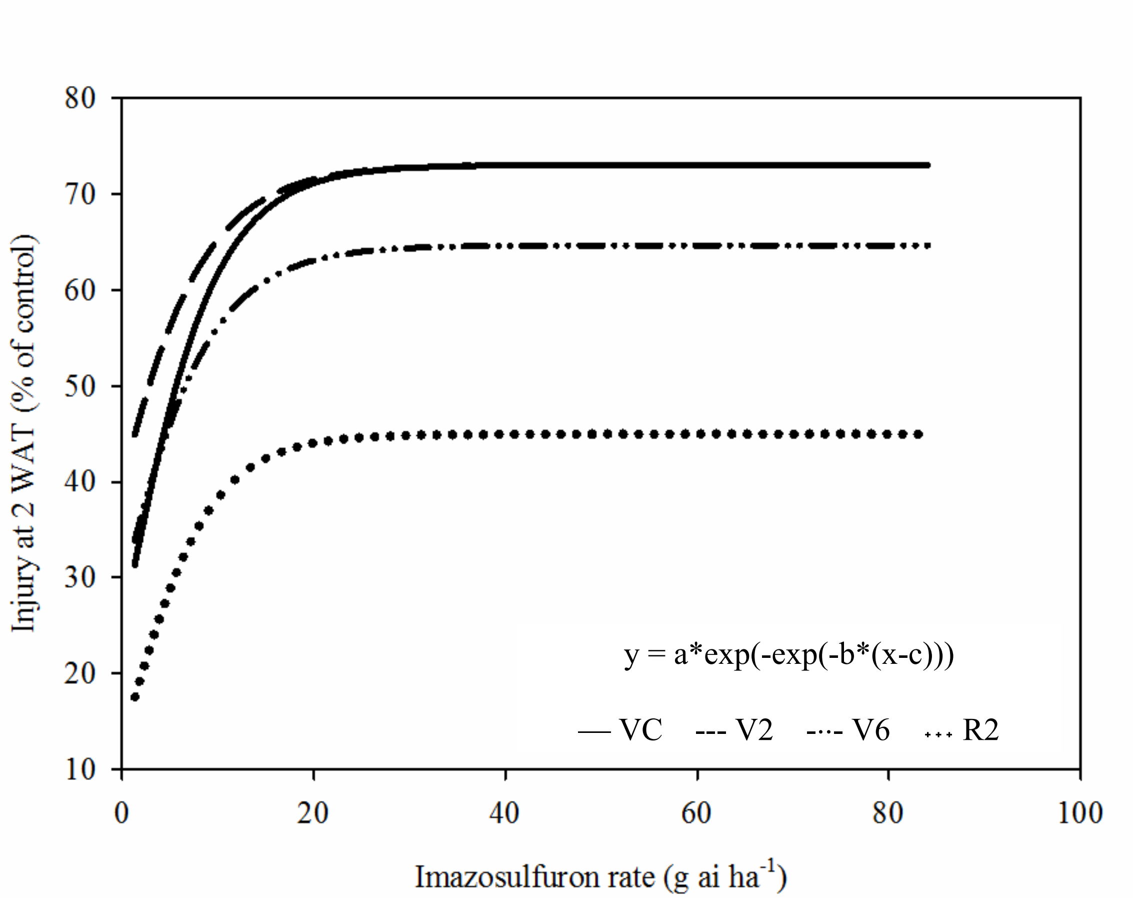


Figure 1. Soybean injury at 2 week after treatment (WAT) as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

[*]Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

[*]Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

[*]The equations and regression parameters of each curve is listed in Table 2.

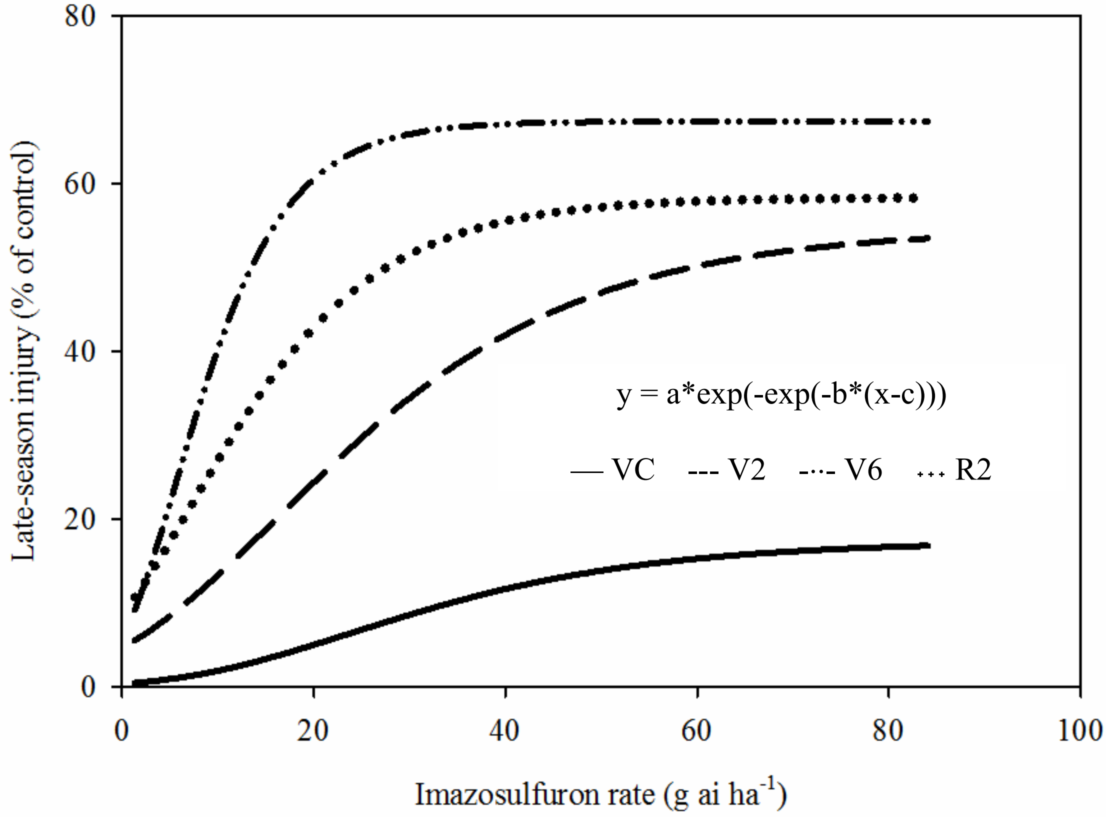


Figure 2. Soybean late-season injury as affected by rate of imazosulfuron applied at VC, V2, V6 and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

*Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

*The equations and regression parameters of each curve is listed in Table 2.

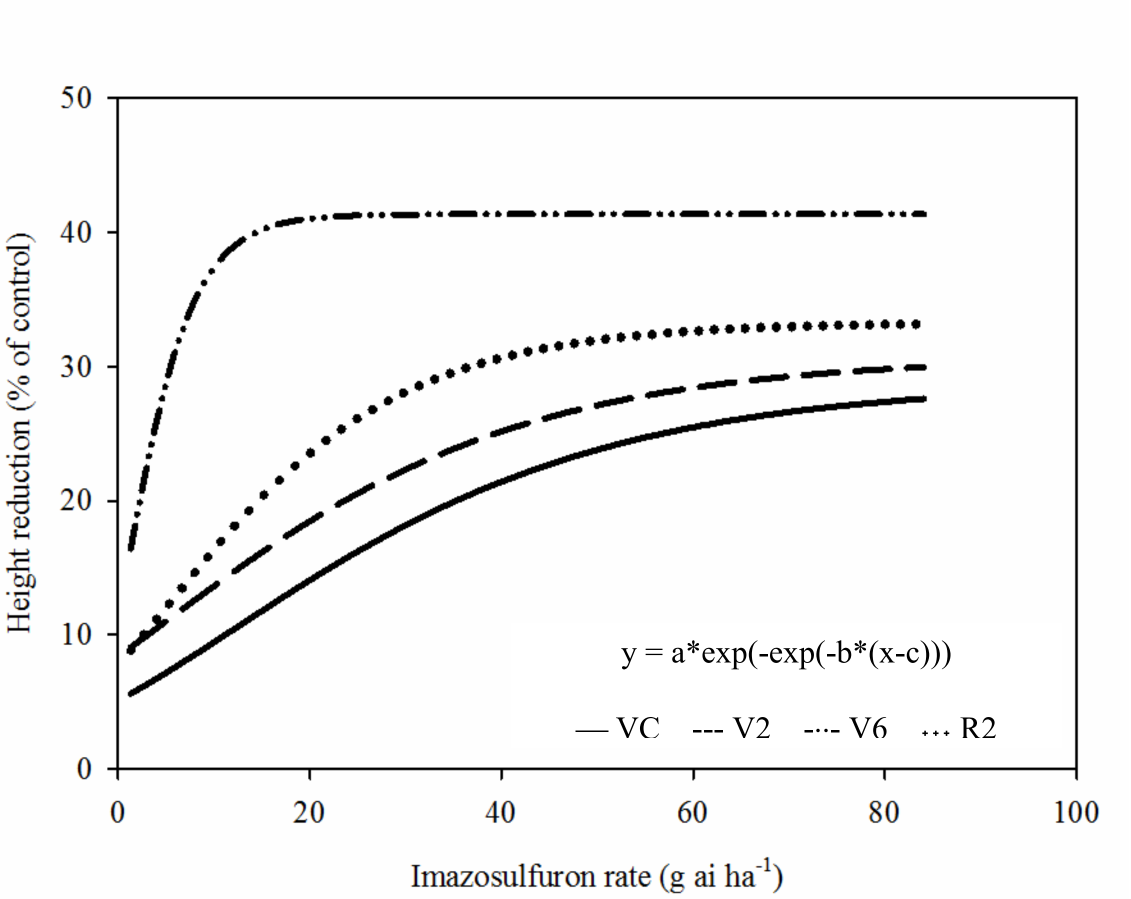


Figure 3. Soybean-plant height reduction as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

*Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

*The equations and regression parameters of each curve is listed in Table 2.

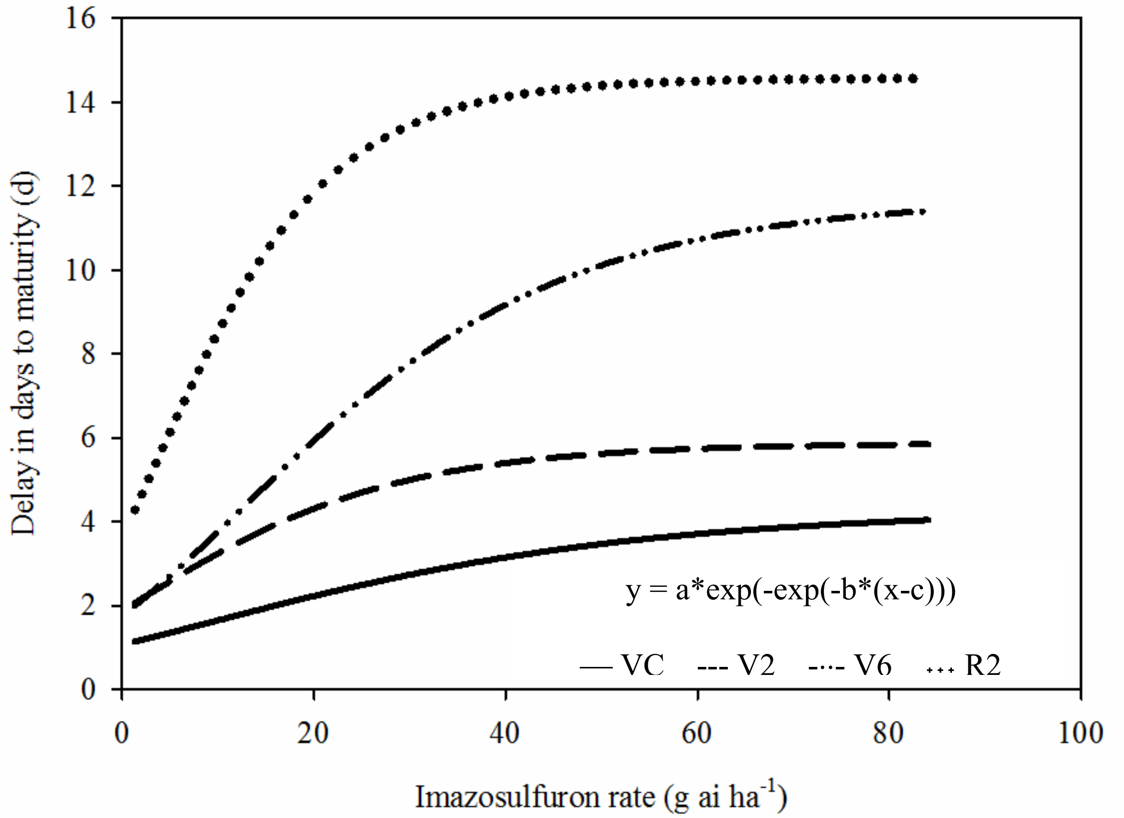


Figure 4. Delay in days to maturity of soybean as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

[*] Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

[*] Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

[*] The equations and regression parameters of each curve is listed in Table 2.

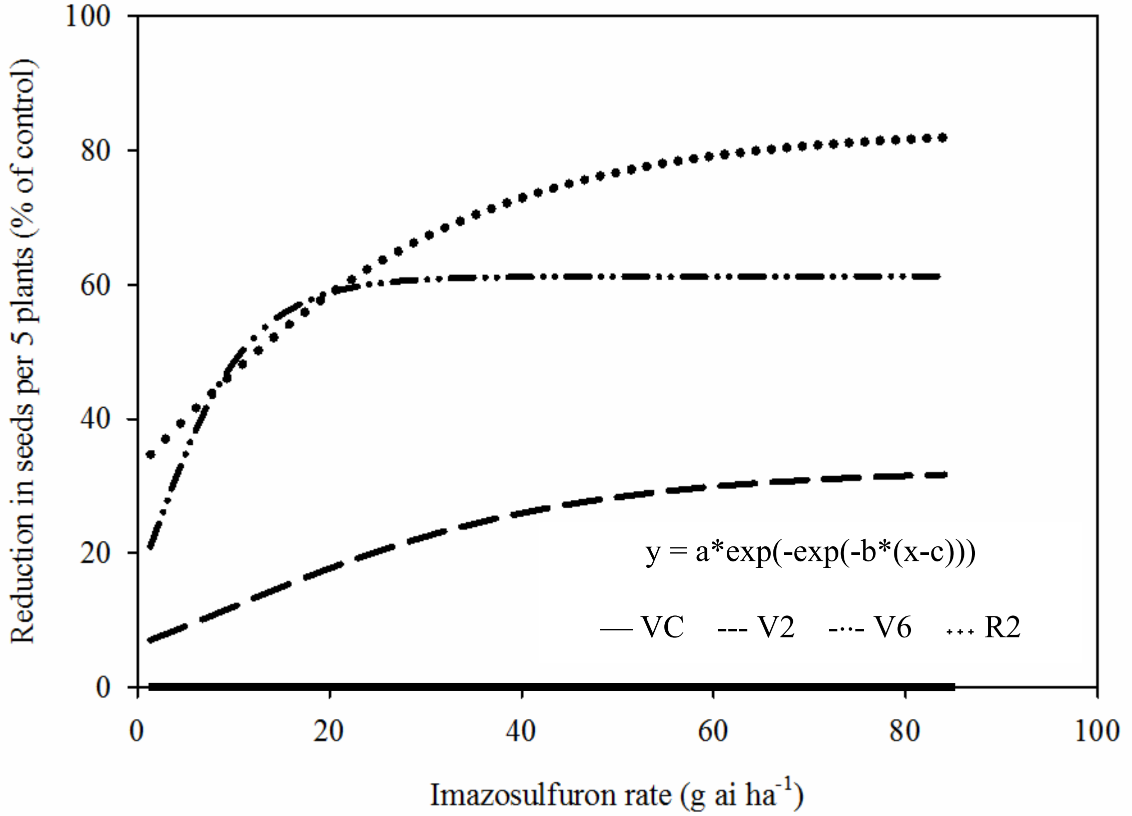


Figure 5. Reduction in number of seeds per five soybean plants as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

[*] Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

[*] Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

[*] The equations and regression parameters of each curve is listed in Table 2.

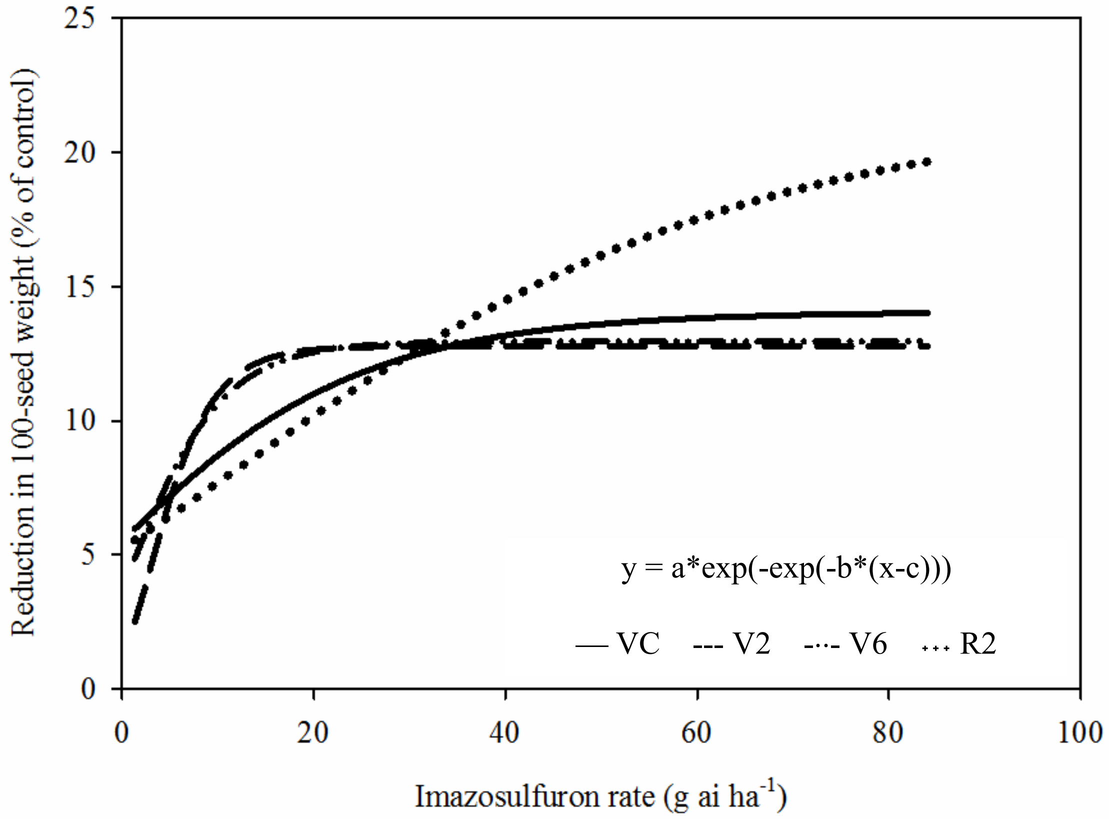


Figure 6. Reduction in 100 soybean-seed weight as affected by rate of imazosulfuron applied at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

*Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

*The equations and regression parameters of each curve is listed in Table 2.

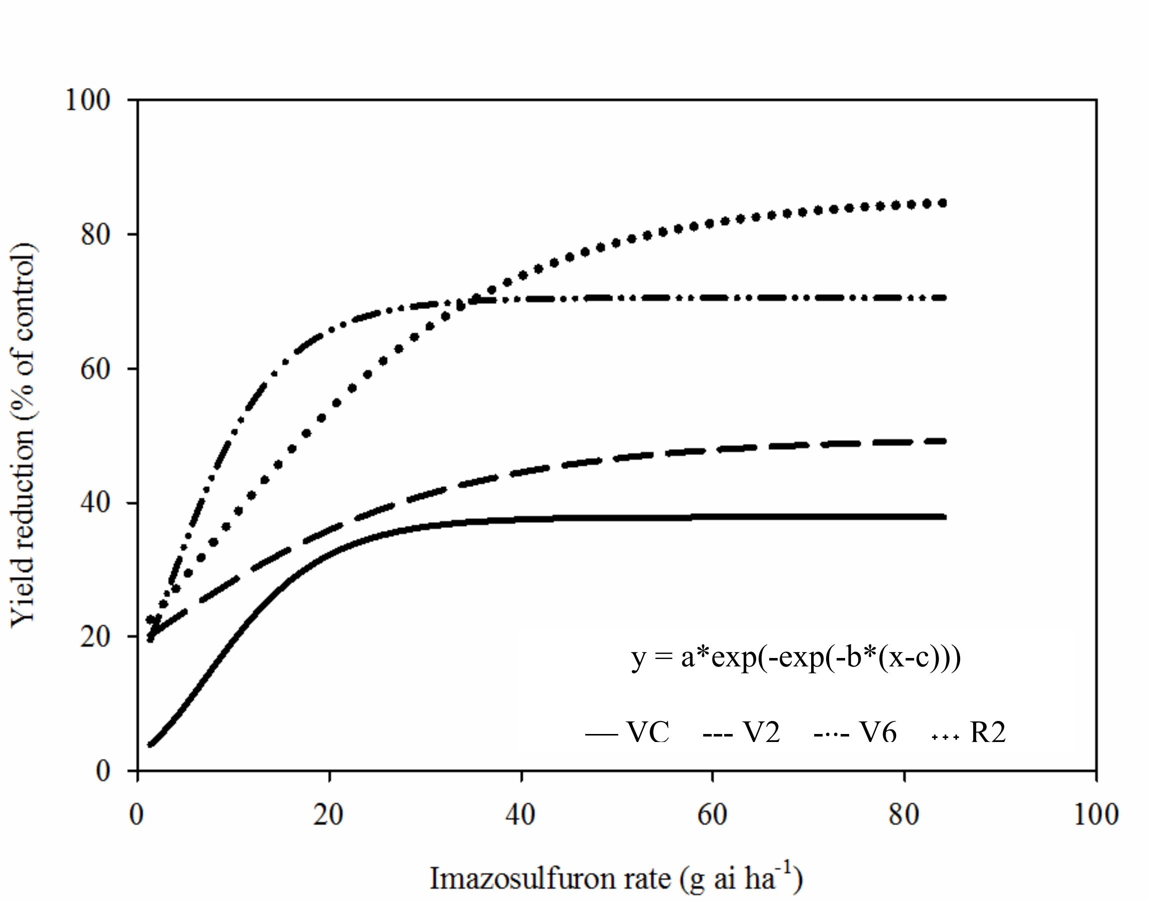


Figure 7. Soybean grain yield reduction as affected by imazosulfuron drift at VC, V2, V6, and R2 growth stages at Fayetteville and Pine Tree, AR, in 2011.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

*Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve.

*The equations and regression parameters of each curve is listed in Table 2.

Table 1. Total monthly rainfall and average monthly temperature at Fayetteville and Pine Tree, AR, 2011.

	Rainfall (cm)		Temperature (^oC)	
Month	Fayetteville	Pine Tree	Fayetteville	Pine Tree
May	0.70	24.18	19	20
June	0.08	6.53	28	28
July	0.04	0.89	31	29
August	0.26	9.07	29	27
September	0.46	4.62	16	21
October	0.20	4.50	10	16

Table 2. Regression parameter estimates and R-square values for regression of injury at 2 WAT, late- season injury, delay in days to maturity, height reduction, reduction in seeds per 5 plants, reduction in 100-seed weight, and yield reduction with imazosulfuron rate using Gompertz-3P model.

		Regression parameters (± SE)			
Variable	Application timing	a	b	c	R-square
Injury at 2 WAT	VC	73.05 (1.91)	0.19 (0.03)	0.42 (0.58)	0.8
	V2	73.08 (1..94)	0.17 (0.05)	-2.96 (1.57)	
	V6	64.67 (1.93)	0.18 (0.05)	-1.17 (1.06)	
	R2	45.83 (2.07)	0.14 (0.04)	0.64 (1.05)	
Late-season injury	VC	17.45 (2.95)	0.06 (0.02)	24.58 (6.33)	0.93
	V2	56.78 (3.46)	0.05 (0.01)	17.02 (1.96)	
	V6	67.47 ((1.55)	0.16 (0.02)	5.73 (0.40)	
	R2	59.07 (1.95)	0.09 (0.01)	7.92 (0.83)	
Delay in days to maturity	VC	4.40 (1.14)	0.03 (0.02)	10.57 (9.77)	0.86
	V2	5.87 (0.56)	0.07 (0.03)	2.02 (2.62)	
	V6	11.70 (0.71)	0.05 (0.01)	12.47 (2.02)	
	R2	14.47 (0.45)	0.10 (0.02)	3.26 (0.67)	
Height reduction	VC	30.09 (5.09)	0.04 (0.02)	13.61 (5.95)	0.68
	V2	31.58 (4.89)	0.04 (0.02)	6.19 (4.47)	
	V6	41.46 (1.73)	0.24 (0.08)	0.82 (0.78)	
	R2	34.03 (2.93)	0.06 (0.02)	6.43 (2.36)	
Reduction in seeds per 5 plants	VC	NA	NA	NA	0.75
	V2	31.62 (5.96)	0.05 (0.03)	8.75 (6.09)	
	V6	61.20 (2.92)	0.18 (0.05)	1.70 (0.83)	

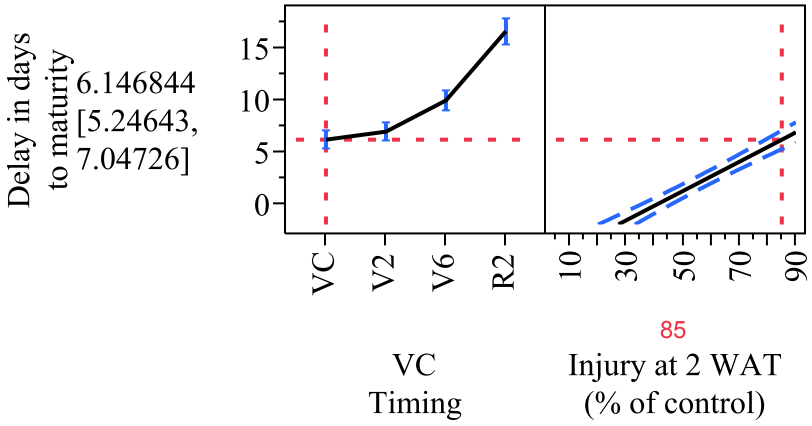
	R2	83.63 (5.63)	0.05 (0.01)	-1.63 (2.34)	
Reduction in 100- seed weight	VC	12.84 (0.90)	0.25 (0.10)	3.03 (0.86)	0.48
	V2	14.09 (1.42)	0.07 (0.03)	-0.53 (3.37)	
	V6	12.94 (0.95)	0.19 (0.09)	1.22 (1.34)	
	R2	21.82 (3.43)	0.03 (0.01)	12.27 (6.28)	
Yield reduction	VC	36.96 (3.87)	0.15 (0.06)	6.83 (1.83)	0.69
	V2	49.66 (5.69)	0.05 (0.03)	0.64 (3.80)	
	V6	70.30 (3.45)	0.17 (0.04)	2.89 (0.79)	
	R2	87.49 (5.72)	0.06 (0.01)	7.70 (1.91)	

[*] Abbreviations: a, asymptote of the curve; b, growth point of the curve; c, inflection point of the curve; SE. standard error; WAT, weeks after treatment. Imazosulfuron was applied with Agri-Dex at 1% v/v.

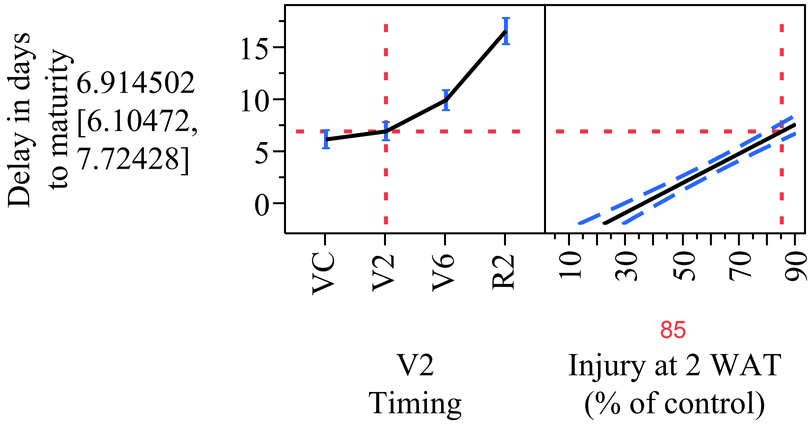
Table 3. Correlation of injury at 2 WAT and late-season injury with delay in days to maturity; and injury at 2 WAT, late-season injury, delay in maturity, and height reduction with yield reduction at the VC, V2, V6, and R2 application timings, and across the application timings

				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

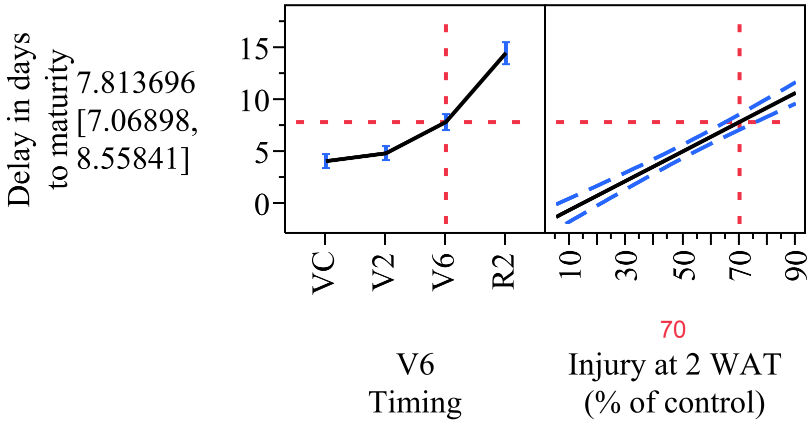
	Yield reduction	Late-season injury	0.89	0.81	0.93	<.0001
	Yield reduction	Delay in days to maturity	0.75	0.61	0.85	<.0001
	Yield reduction	Height reduction	0.65	0.46	0.78	<.0001
R2	Delay in days to maturity	Injury at 2 WAT	0.79	0.66	0.87	<.0001
	Delay in days to maturity	Late-season injury	0.80	0.68	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


Delay in days
to maturity
6.146844
[5.24643,
7.04726]
15
10
5
0
VC
V2
V6
R2
10
30
50
70
90
85
VC
Timing
Injury at 2 WAT
(% of control)

a)


Delay in days
to maturity
6.914502
[6.10472,
7.72428]
15
10
5
0
VC
V2
V6
R2
10
30
50
70
90
85
V2
Timing
Injury at 2 WAT
(% of control)

b)


Delay in days
to maturity
7.813696
[7.06898,
8.55841]
15
10
5
0
VC
V2
V6
R2
10
30
50
70
90
70
V6
Timing
Injury at 2 WAT
(% of control)

c)

d)

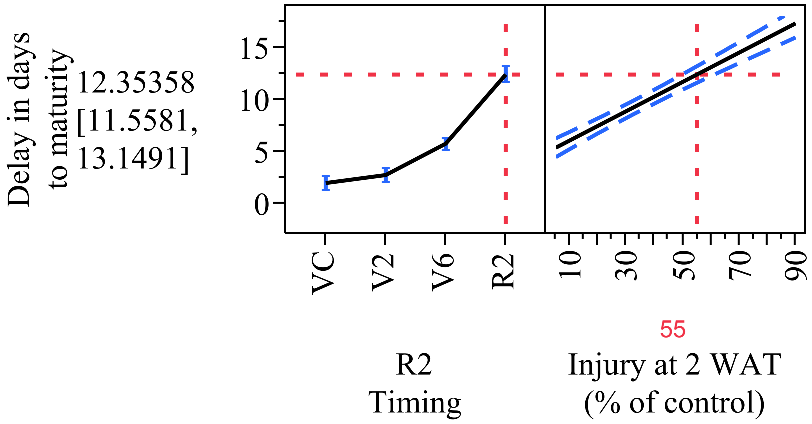
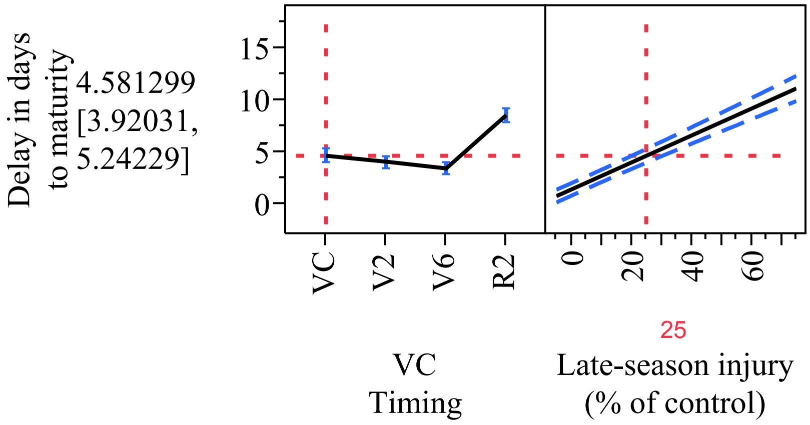
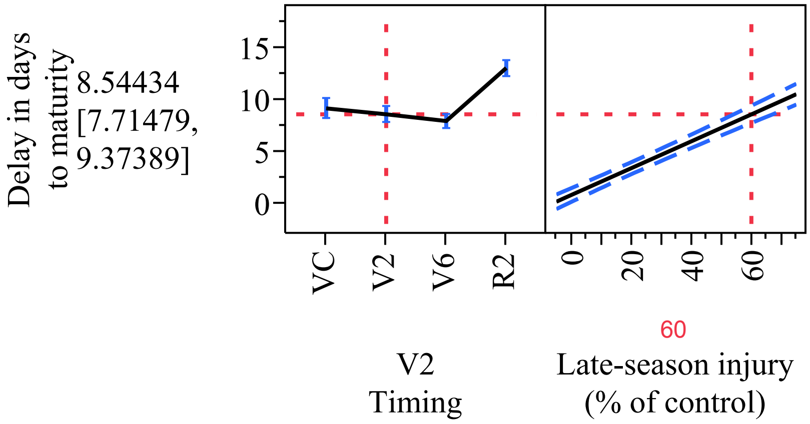


Figure 8. Predicted delay in days to soybean maturity [lower, upper confidence interval] in response to the highest levels of injury at 2 WAT observed at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.
*Dashed horizontal and vertical lines intersect each other to represent delay in days to maturity occurring at different soybean growth stages (x-axis of the left-side box) from injury at 2 WAT (x-axis of the right-side box in)
*I symbol in the left-side box represents standard error of delay in days to maturity.
*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of delay in days to maturity.
*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.



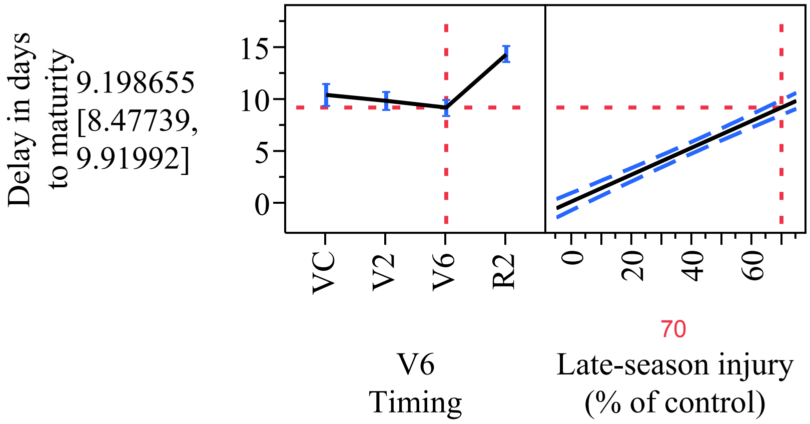
Delay in days to maturity
4.581299
[3.92031,
5.24229]
15
10
5
0
VC
V2
V6
R2
0
20
40
60
25
VC
Timing
Late-season injury
(% of control)

a)



Delay in days to maturity
8.54434
[7.71479,
9.37389]
15
10
5
0
VC
V2
V6
R2
0
20
40
60
60
V2
Timing
Late-season injury
(% of control)

b)



Delay in days to maturity
9.198655
[8.47739,
9.91992]
15
10
5
0
VC
V2
V6
R2
0
20
40
60
70
V6
Timing
Late-season injury
(% of control)

c)

d)

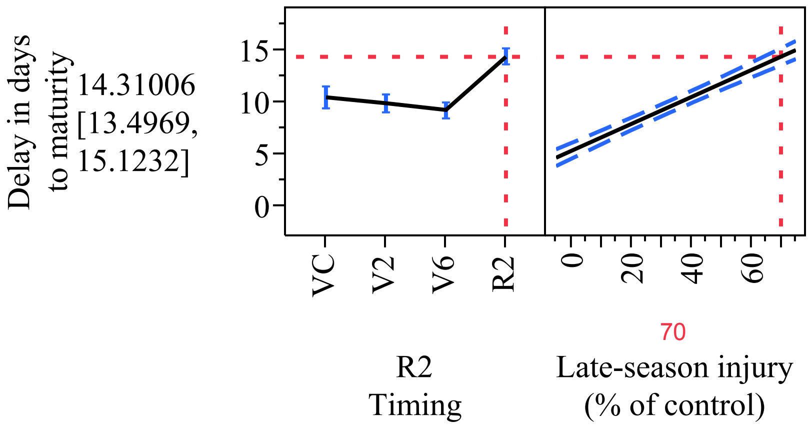


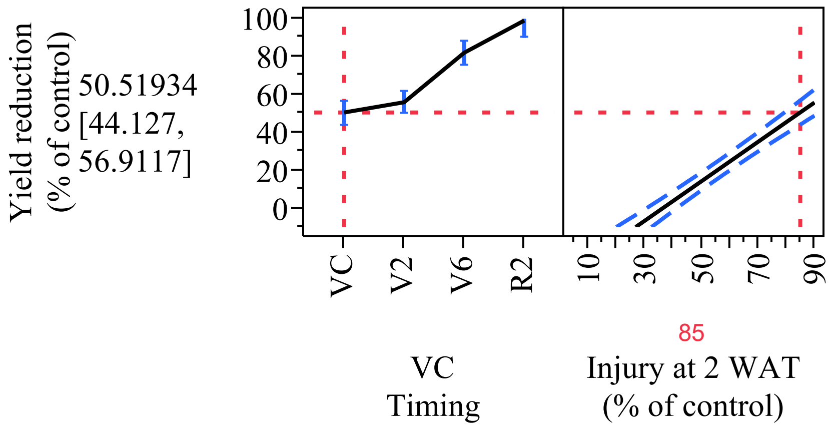
Figure 9. Predicted delay in days to soybean maturity [lower, upper confidence interval] in response to the highest levels of late-season injury observed at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.

*Dashed horizontal and vertical lines intersect each other to represent delay in days to maturity occurring at different soybean growth stages (x-axis of the left-side box) from late-season injury (x-axis of the right-side box in)

*I symbol in the left-side box represents standard error of delay in days to maturity.

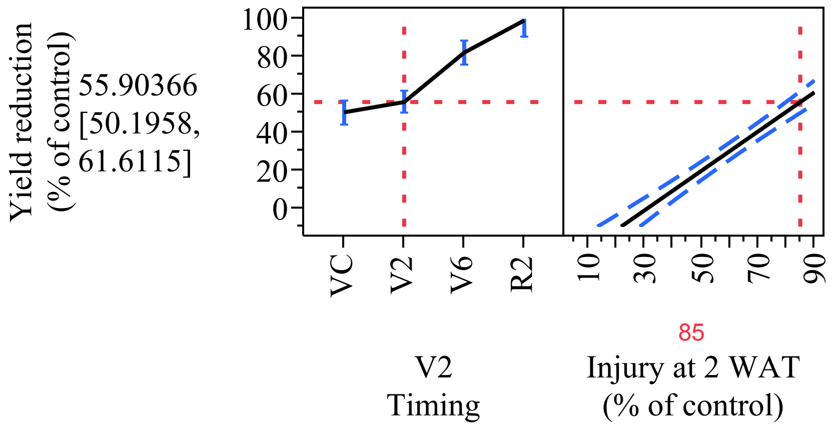
*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of delay in days to maturity.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.



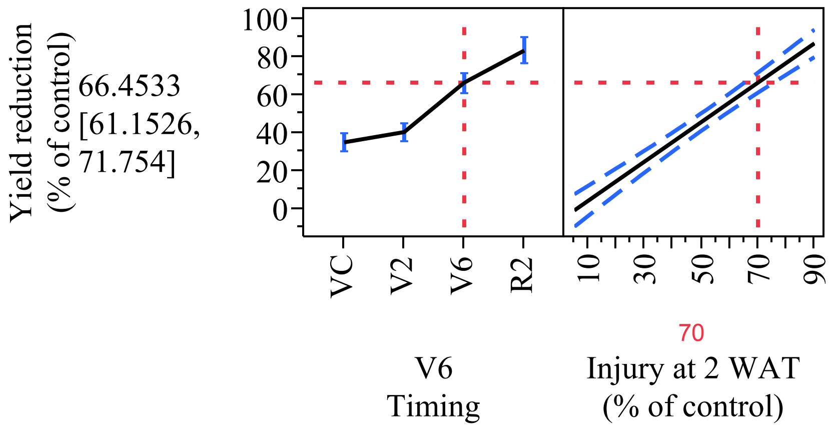
Yield reduction
(% of control)
50.51934
[44.127,
56.9117]
100
80
60
40
20
0
VC
V2
V6
R2
10
30
50
70
90
85
VC
Timing
Injury at 2 WAT
(% of control)

a)



Yield reduction
(% of control)
55.90366
[50.1958,
61.6115]
100
80
60
40
20
0
VC
V2
V6
R2
10
30
50
70
90
85
V2
Timing
Injury at 2 WAT
(% of control)

b)



Yield reduction
(% of control)
66.4533
[61.1526,
71.754]
100
80
60
40
20
0
VC
V2
V6
R2
10
30
50
70
90
70
V6
Timing
Injury at 2 WAT
(% of control)

c)

d)

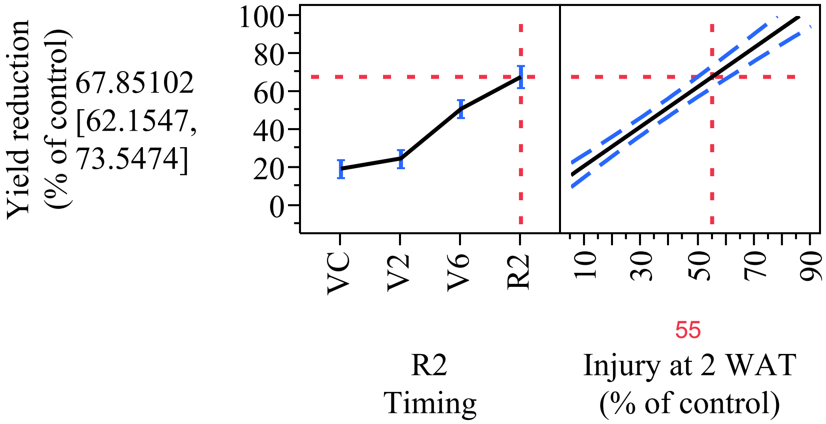


Figure 10. Predicted soybean yield reduction [lower, upper confidence interval] in response to the highest levels of injury at 2 WAT observed at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.

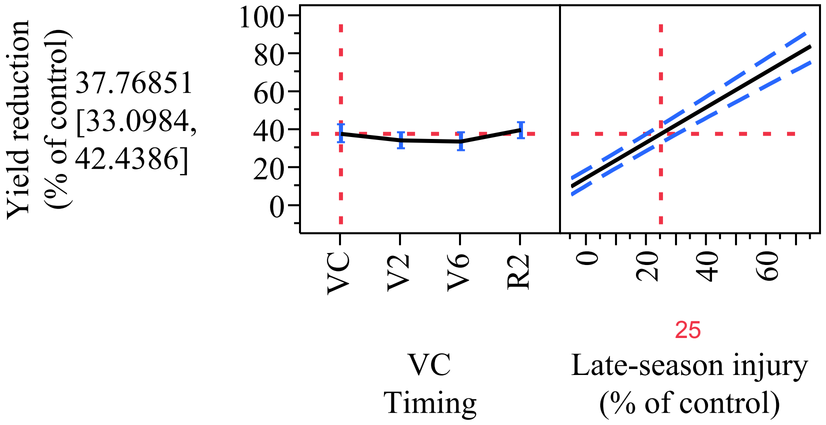
*Dashed horizontal and vertical lines intersect each other to represent yield reduction occurring at different soybean growth stages (x-axis of the left-side box) from injury at 2 WAT (x-axis of the right-side box in)

*I symbol in the left-side box represents standard error of yield reduction.

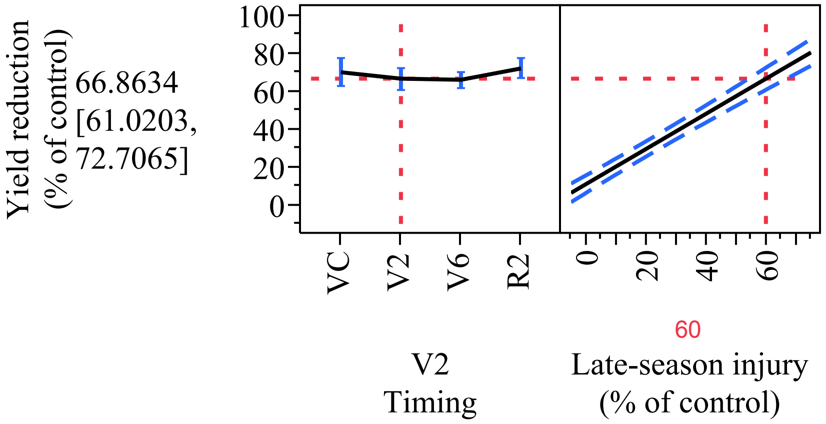
*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of yield reduction.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

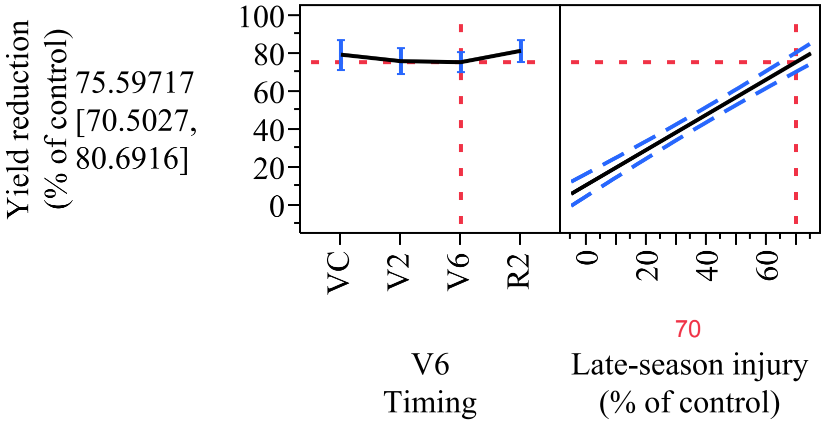
a)


Yield reduction
(% of control)
37.76851
[33.0984,
42.4386]
100
80
60
40
20
0
VC
V2
V6
R2
0
20
40
60
25
VC
Timing
Late-season injury
(% of control)

b)


Yield reduction
(% of control)
66.8634
[61.0203,
72.7065]
100
80
60
40
20
0
VC
V2
V6
R2
0
20
40
60
60
V2
Timing
Late-season injury
(% of control)

c)


Yield reduction
(% of control)
75.59717
[70.5027,
80.6916]
100
80
60
40
20
0
VC
V2
V6
R2
0
20
40
60
70
V6
Timing
Late-season injury
(% of control)

d)

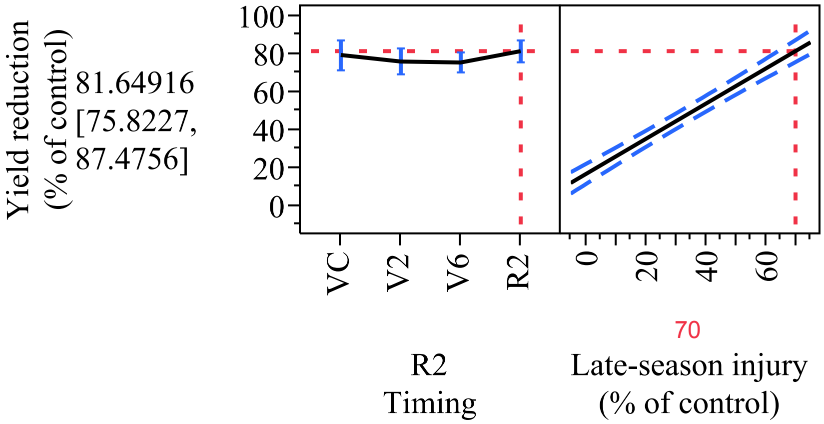
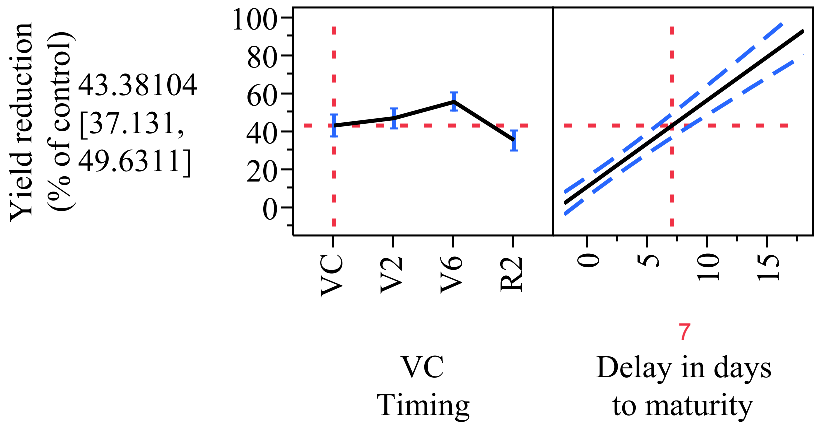
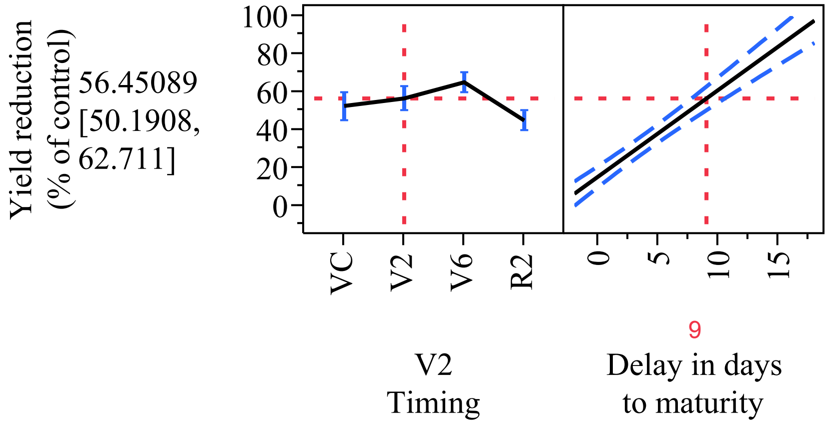


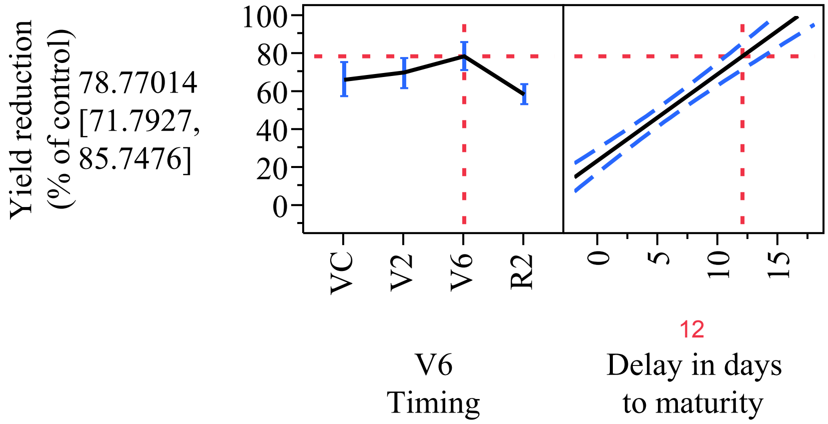
Figure 11. Predicted soybean yield reduction [lower, upper confidence interval] in response to the highest levels of late-season injury observed at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.
*Dashed horizontal and vertical lines intersect each other to represent yield reduction occurring at different soybean growth stages (x-axis of the left-side box) from late-season injury (x-axis of the right-side box in)
*I symbol in the left-side box represents standard error of yield reduction.
*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of yield reduction.
*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.


Yield reduction
(% of control)
43.38104
[37.131,
49.6311]
100
80
60
40
20
0
VC
V2
V6
R2
0
5
10
15
7
VC
Timing
Delay in days
to maturity

a)


Yield reduction
(% of control)
56.45089
[50.1908,
62.711]
100
80
60
40
20
0
VC
V2
V6
R2
0
5
10
15
9
V2
Timing
Delay in days
to maturity

b)


Yield reduction
(% of control)
78.77014
[71.7927,
85.7476]
100
80
60
40
20
0
VC
V2
V6
R2
0
5
10
15
12
V6
Timing
Delay in days
to maturity

c)

d)

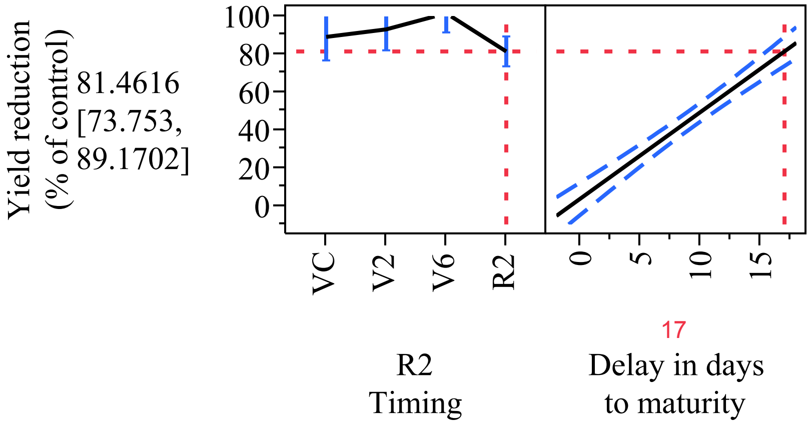
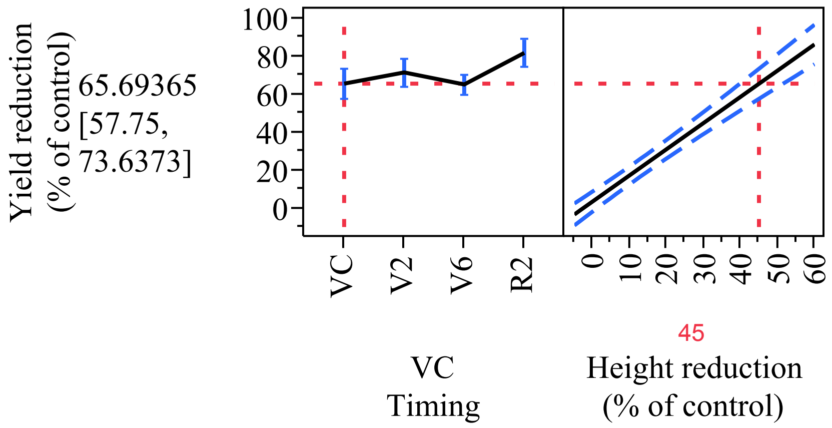
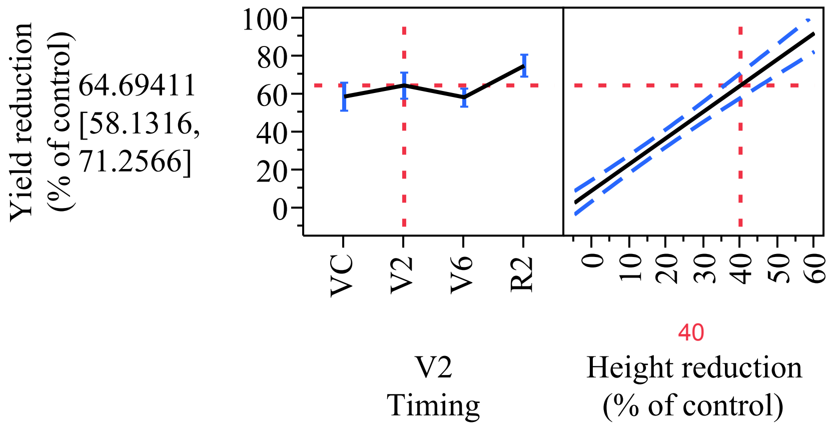


Figure 12. Predicted soybean yield reduction in response to the highest levels of delay in days to maturity [lower, upper confidence interval] measured at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.
*Dashed horizontal and vertical lines intersect each other to represent yield reduction occurring at different soybean growth stages (x-axis of the left-side box) from delay in days to maturity (x-axis of the right-side box in)
*I symbol in the left-side box represents standard error of yield reduction.
*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of yield reduction.
*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

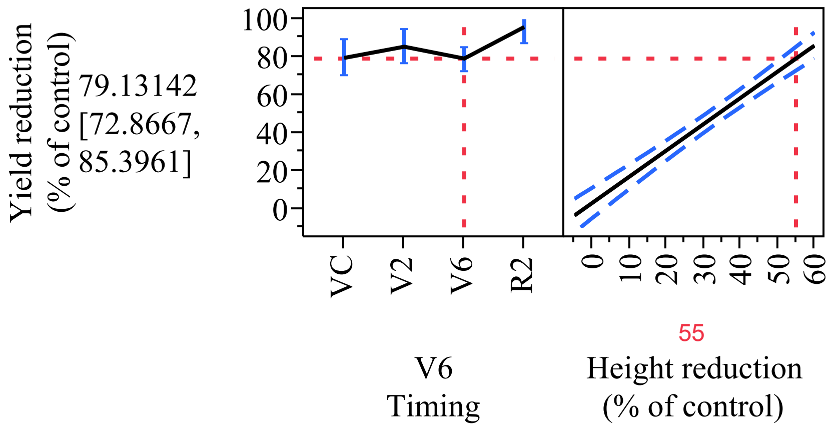
a)


Yield reduction
(% of control)
65.69365
[57.75,
73.6373]
100
80
60
40
20
0
VC
V2
V6
R2
0
10
20
30
40
50
60
45
VC
Timing
Height reduction
(% of control)

b)


Yield reduction
(% of control)
64.69411
[58.1316,
71.2566]
100
80
60
40
20
0
VC
V2
V6
R2
0
10
20
30
40
50
60
40
V2
Timing
Height reduction
(% of control)

c)


Yield reduction
(% of control)
79.13142
[72.8667,
85.3961]
100
80
60
40
20
0
VC
V2
V6
R2
0
10
20
30
40
50
60
55
V6
Timing
Height reduction
(% of control)

d)

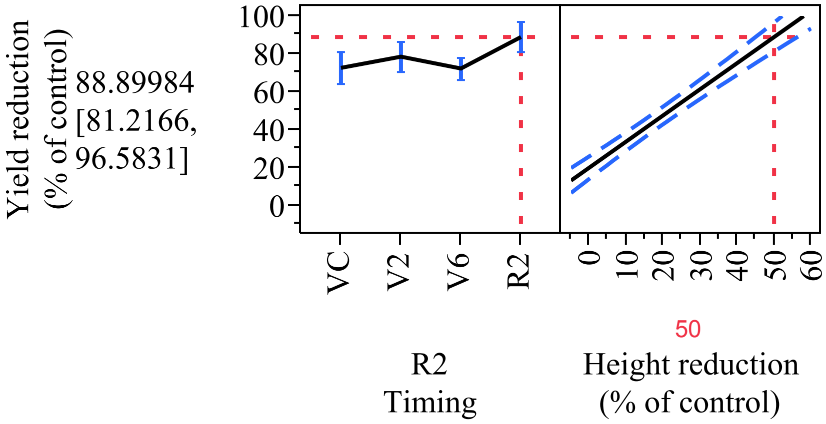


Figure 13. Predicted soybean yield reduction [lower, upper confidence interval] in response to the highest levels of height reduction measured at the: (a) VC, (b) V2, (c) V6, and (d) R2 growth stages.

*Dashed horizontal and vertical lines intersect each other to represent yield reduction occurring at different soybean growth stages (x-axis of the left-side box) from height reduction (x-axis of the right-side box in)

*I symbol in the left-side box represents standard error of yield reduction.

*Dashed diagonal lines in the right-side box represent upper and lower confidence interval of yield reduction.

*Abbreviations: VC, vegetative cotyledonary; V2, vegetative 2nd trifoliate; V6, vegetative 6th trifoliate; R2, reproductive full bloom.

CHAPTER II

CARRYOVER POTENTIAL OF IMAZOSULFURON TO SOYBEAN (*Glycine max*)

ABSTRACT

In the southern United States, soybean is often grown in rotation with rice; therefore, herbicides used in rice have the potential to injure soybean *via* carryover. Halosulfuron is the current standard of sulfonylurea herbicides used in rice at a field use rate of 52 g ai ha^{-1}. Imazosulfuron is a sulfonylurea herbicide that was recently labeled for use in Arkansas rice at a maximum use rate of 336 g ai ha^{-1}. Field trials were conducted under a weed-free environment to evaluate the response of soybean to imazosulfuron and halosulfuron applied preemergence (PRE) (tolerance study) and to determine the potential for imazosulfuron applied to rice to injure soybean grown in rotation the following year (rotation study). The tolerance study was conducted at Fayetteville (pH=5.9) and Marianna (pH=7.9), AR, and the rotation study was conducted at Pine Tree (pH=8.3) and Keiser (pH=7.1), AR. Imazosulfuron and halosulfuron were applied PRE at 1/256, 1/128, 1/64, 1/32, 1/16, 1/8, and 1/4 times (X) their respective labeled rates for the tolerance study. For the rotation study, imazosulfuron rates were 112, 224, 336, 448, and 672 g ha^{-1}. In the tolerance study, soybean was not injured by PRE-applied imazosulfuron or halosulfuron regardless of herbicide rate, and yield was comparable with that of the non-treated control. In the rotation study, soybean injury increased with increasing imazosulfuron rates applied to rice the previous year. Soybean injury at Keiser was ≤3%; whereas at Pine Tree, soybean injury was ≤13%. Soybean recovered from the initial injury over time. In both experiments and at both locations, soybean density (plants m^{-2}) at 5 wk after planting (WAP), plant height at 5 WAP and at the end of growing season, and yield were comparable with the non-treated control. Results of both tolerance and rotation studies indicate that imazosulfuron can injure soybean *via* carryover; however, soybean can recover from the injury over time to yield comparable with non-treated control.

Nomenclature: Halosulfuron; imazosulfuron; soybean, *Glycine max* (L.) Merr.; rice, *Oryza sativa* L.

Key words: Carryover, PRE-applied herbicide, sulfonylurea herbicides.

INTRODUCTION

Crop rotation is an important component of modern agriculture as alternating crops not only improves the physical and chemical properties of the soil, but also provides effective weed, insect, and disease control, is necessary to resistance management of pests, and improves yield in most crops (Delorit et al. 1974; Zhang et al. 2002). In Arkansas, rice is usually grown in rotation with soybean, another important crop in Arkansas. The close proximity of soybean to rice and the contribution of both the crops to the state's agricultural economy make it imperative to study the response of soybean to carryover from rice herbicides. Herbicides used in rice can persist in soil, and the residues have the potential to injure soybean the following year.

Halosulfuron (Permit^{TM}, Gowan Company LLC, 370 Main Street, Yuma, AZ 85364) is the current standard of sulfonylurea herbicides used in rice, with approximately 6,800 kg applied to rice fields in the U.S. each year, 60% of which is applied in Arkansas rice only (NASS 2006). Imazosulfuron (League^{TM}, Valent U.S.A. Corporation, Walnut Creek, CA 94596) is a newer sulfonylurea herbicide that was recently labeled for use in drill- and water-seeded rice. Imazosulfuron is an acetolactate synthase (ALS)-inhibiting herbicide that controls several broadleaf weeds and sedges (Godara et al. 2012; Riar and Norsworthy 2011; Sondhia 2008; Still et al. 2010). Imazosulfuron inhibits the activity of ALS, thereby blocking biosynthesis of the branched-chain amino acids valine, leucine, and isoleucine (Brown 1990). The lack of amino acids results in cessation of plant cell division and growth (Tanaka and Yoshikawa 1994).

Sensitivity of a crop and relative persistence of the chemical determines the carryover potential of a herbicide to affect the rotational crop (Johnson et al. 1993). Persistence of herbicides is partially dependent on environmental factors such as temperature and soil water content (Loux and Reese 1992; Loux and Reese 1993; Loux et al. 1989; Majika and Lavy 1977;

Mills and Witt 1989; Roeth et al. 1968; Shea 1985). The most important pathways of degradation of sulfonylurea herbicides in soil are chemical hydrolysis and microbial breakdown, whereas volatilization and photolysis are minor processes (Molinari et al. 1999). Both environmental conditions and soil properties influence all these processes (Molinari et al. 1999). As the conditions of high temperature and pH are detrimental for the growth of microbial organisms, herbicides that are degraded by microbial activity will have more persistence under such conditions (Paul and Clark 1989). For the same reason, imazosulfuron degradation is slow in acidic sandy loam soil because of high soil adsorption coefficient, which protects imazosulfuron from microbial attack (Morrica et al. 2001a). The factors influencing the retention of imazosulfuron in soil include soil organic carbon, clay content, pH, and temperature (Morrica et al. 2001b).

Half-life of imazosulfuron increases with an increase in pH and ranges from 3 to 6 d at pH <4 compared with 578 d at pH 5.9 (Morrica et al. 2001a). Under aerobic conditions, the main pathway of imazosulfuron degradation is the chemical cleavage of the sulfonylurea bond to give ADPM (2-amino-4, 6-dimethoxypyrimidine) and IPSN (2-chloroimidazo [1, 2-α] pyridin-3-sulfonamide). Imazosulfuron then degrades with a half-life of approximately 70 d under aerobic conditions. However, under anaerobic conditions, imazosulfuron is degraded by micro-organisms (via demethylation) to produce HMS {1-(2-chloroimidazo [1, 2-*a*] pyridin-3-ylsulfonyl)-3-(4-hydroxy-6-methoxypyrimidin-2-yl) urea} and degrades in soil with a half-life of approximately 4 d (Morrica et al. 2001a).

Adsorption and desorption in soil also play an important role in the degradation of imazosulfuron in soil (Morrica et al. 2000). Depending upon adsorption and availability, some sulfonylurea herbicides, such as chlorsulfuron and chlorimuron, are more persistent in soils with high pH; whereas other sulfonylurea herbicides, such as imazquin, are more persistent at lower pH (Loux and Reese 1992; Loux and Reese 1993; Loux et al. 1989; Renner et al. 1988a, 1988b; Stougaard 1990; Thirunarayanan et al. 1985; Weise et al. 1988). Increase in pH results in the consequent decrease in the soil adsorption rates, which in turn influence the degradation of imazosulfuron in soil (Beyer et al. 1988). The extent of adsorption depends not only on the soil properties, but also on the physiochemical properties of imazosulfuron (Morrica et al. 2000). The various soil properties that affect the adsorption of imazosulfuron in soil are ion exchange capacity, organic matter content, type and amount of clay, and pH (Morrica et al. 2000). Water solubility and octanol-water partition coefficient are the physiochemical properties of imazosulfuron that determine its extent of adsorption (Barriuso et al. 1992; Singh et al 1990).

When applied PRE at 30 and 40 g ha^{-1}, soil and transplanted rice had no imazosulfuron residues (Sondhia 2008). However, there was significant residual contamination at higher imazosulfuron rates of 50 and 60 g ha^{-1}. Neither imazosulfuron nor its degradation products were present below a 50-cm soil depth, which lead to the conclusion that only slight translocation of imazosulfuron and its degradation products occur in the groundwater (Mikata et al. 2003).

Carryover studies indicate that soybean yield is not significantly affected when grown in rotation with crops treated with sulfonylurea herbicides (Johnson et al. 1993; Jordan et al. 1993; Nandula et al. 2009; Ritter et al. 1988). General injury symptoms of sulfonylurea herbicides on soybean are stunting, death of terminal growing points, yellowing of leaves, vein reddening or purpling, leaf crinkling, epinastic effects, delayed maturity, and drooping of petioles (Brown 1990). Soybean plants respond differently to various sulfonylurea herbicides and rates of the same herbicide (Al-Khatib and Peterson 1999). Depending upon the sulfonylurea herbicide used, height reduction, leaf necrosis, chlorosis, and cupping are all good indicators of yield reduction following herbicide drift (Bailey and Kapusta 1993; Gunsolas and Curran 1999). Although sulfonylurea herbicides cause severe initial injury symptoms to soybean, yield is reduced only when the injury persists throughout the growing season (Al-Khatib and Peterson 1999). In addition, soybean can tolerate foliar injury without reduction in yield because foliar injury occurs at much lower rates, which are not high enough to cause yield reductions (Hamilton and Arle 1979; Weidenhammer et al. 1989).

Successful weed control in rice along with less carryover potential of imazosulfuron to soybean will help U.S. farmers achieve better sulfonylurea-based weed management programs and greater crop yield. However, limited information is available on the carryover potential of imazosulfuron from rice to soybean. Since imazosulfuron has same chemistry as that of halosulfuron, we hypothesized that imazosulfuron, like halosulfuron, will not injure soybean via carryover from rice fields. To test our hypothesis, field research was conducted with the goal of determining the sensitivity of soybean to low soil-applied doses of imazosulfuron and the potential for imazosulfuron to carryover from rice to soybean.

MATERIALS AND METHODS

Tolerance Study. Field trials were conducted at the University of Arkansas Agricultural Research and Extension Center, Fayetteville, and at the Lon Mann Cotton Research Station, Marianna, AR, in summer 2011 to determine the response of soybean to PRE-applied imazosulfuron and halosulfuron. The soil type at Fayetteville was 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 5.9; whereas at Marianna, soil type was a Zachary silt loam (Fine-silty, mixed, active, thermic Typic Albaqualfs), composed of 21% sand, 69% silt, 10% clay, with 1.3% organic matter and a pH of 7.9.

The experiment was arranged as a three-factor factorial arrangement of treatments in a randomized complete block (RCB) design, replicated four times. Factor A was two herbicides (imazosulfuron and halosulfuron), factor B was herbicide rate, and factor C was two soybean cultivars, AG 4703 [non-sulfonylurea-tolerant (non-STS), glyphosate-resistant (RR), indeterminate] and AG 4903 [sulfonylurea-tolerant (STS), RR, indeterminate]. Herbicide treatments included imazosulfuron and halosulfuron applied at 1/256, 1/128, 1/64, 1/32, 1/16, 1/8, and 1/4 times (X) their labeled rates, 336 and 52 g ai ha^{-1}, respectively. Treatments also included a non-treated control. 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.

Soybean was planted May 17, 2011, and emerged May 28, 2011, at both locations. Soybean at both locations was planted in plots 8 by 2 m, with a row spacing of 96 cm, at a depth of 2.5 cm, and a seeding rate of 60 seed m^{-2}. Soybean was irrigated twice a week with an overhead lateral-move irrigator at Fayetteville and once a week with poly-irrigation tube (Delta Plastics, 10801 Executive Center Drive, Ste 201, Little Rock, AR 72211) at Marianna. Each plot had two rows, one with STS soybean and one with non-STS soybean. There were two non-treated soybean rows between each plot. The test area was kept weed-free with timely broadcast applications of glyphosate (Roundup PowerMax^{TM}, Monsanto Co., 800 N. Lindbergh Blvd. St. Louis, MO 63167) at 870 g ae ha^{-1}.

Weekly visible estimates of injury caused by imazosulfuron and halosulfuron to soybean were rated. Injury was based on a scale of 0 to 100%, where 0% indicates no injury and 100%

indicates plant death. Injury ratings were based on chlorosis, purple veins, and stunting. Soybean density (plants per m of row) was determined at 2 and 6 weeks after treatment (WAT). The height of 10 plants was measured by random selection from each plot. Height was measured from the soil surface (top of the bed) to the top of fully expanded leaf, and finally, the heights of 10 plants were averaged to get the plant height data at 2 and 6 WAT and at the end of the growing season. Yields were determined by mechanically harvesting one row each of STS and non-STS soybean; yields were adjusted to 13% moisture content.

Rotation Study. Field studies were initiated at the Pine Tree Research Station and at the Northeast Research and Extension Center at Keiser, Arkansas, in summer 2010. The soil type at Pine Tree was a Calhoun silt loam (Fine-silty, mixed, active, thermic Typic Glossaqualfs), composed of 12% sand, 70% silt, 18% clay, with 1.0% organic matter and a pH of 8.3. At Keiser, soil type was characterized as Sharkey silty clay (Very-fine, smectitic, thermic Chromic Epiaquerts), composed of 2% sand, 48% silt, 50% clay, with 2.3% organic matter and a pH of 7.1.

The experiment was arranged in an RCB design with four replications, where the four replications acted as blocks. During PRE application of herbicides to drill-seeded crops there are chances of either skipping or overlapping passes. Therefore, herbicide treatments in the experiment included imazosulfuron applied at 112, 224, 336 (1X), 448, and 672 g ha^{-1} and a non-treated control. All herbicide treatments were made with a CO_2-pressurized backpack sprayer equipped with 11001 XR flat-fan spray nozzles calibrated to deliver 93 L ha^{-1} spray solution. At both locations, “Wells” cultivar of rice was drill-seeded at a seeding rate of 435 seeds m^{-2} on June 7, 2010. Rice was flooded 6 WAP and flood was dropped 2 wk before harvesting on

October 11, 2010. After harvesting, rice residue was left in the field over winter to make sure that imazosulfuron taken up by rice is also taken into account.

At both locations, AG 4703 (non-STS) soybean was planted in the rice field to which imazosulfuron was applied the previous season. Soybean at both locations was irrigated once a week with poly-irrigation tubes. At Pine Tree, soybean was drill-seeded May 10, 2011, and emerged May 19, 2011. Soybean at Keiser was row-planted May 20, 2011, and emerged May 30, 2011. At Keiser, planting was done in plots of size 4 by 8 m with a four-row planter set at a row spacing of 96 cm, depth of 2.5 cm, and seeding rate of 60 seed m^{-2}. At Pine Tree, soybean was drill-seeded in plots of 5 by 14 m, at row spacing of 18 cm, and a seeding rate of 55 seeds m^{-2} row. Trials were kept weed-free by timely broadcast applications of glyphosate at 870 g ha^{-1}.

Injury to soybean from imazosulfuron was rated every week similar to that in the tolerance studies. For soybean density data at Pine Tree at 5 weeks after planting (WAP), number of plants was counted per 1 m^{-2} in each plot; whereas at Keiser, number of plants was counted per 1 m row and were then converted into plants per m^{-2}. For plant height, 10 plants were selected at random from each plot, height was measured from the soil surface (top of the bed) to the top of fully expanded leaf, and finally, the heights of 10 plants were averaged to get the plant height data at 5 WAP and at the end of the growing season. At Keiser, yields were determined by mechanically harvesting the center two rows of a four-row plot using a small-plot combine; whereas at Pine Tree, a small-plot combine was used to harvest the center 1.5 m of each plot. Grain yield per plot was then used to calculate soybean yields converted to 13% moisture content.

Statistical Analyses. For both studies, data were subjected to a normality test for compliance with the assumptions of statistical analysis. Data were normal and needed no transformation.

Data were then subjected to ANOVA using PROC GLM procedure in SAS (Version 9.2. SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513-2414; SAS 2008). Type III statistics were used to test for significant differences ($P \leq 0.05$) among herbicides, herbicide rate, location, and their interactions for injury, stand count, plant height, and yield variables for the tolerance study; and among herbicide rates, locations, and their interactions for injury, stand count, plant height and yield variables for the rotation study. For the tolerance study, data were pooled across locations because ANOVA indicated no significant difference between locations or location-by-treatment interactions. Moreover, the growing conditions at both locations were similar. However for the rotation study, locations were treated as a fixed factor, and there was a location by treatment interaction only for crop injury. Therefore, data were analyzed separately by location. Data were also subjected to a paired t-test to compare the means among different treatment combinations using Fisher's protected LSD at the 5% level of significance.

RESULTS AND DISCUSSION

Tolerance Study. STS soybean was not injured; therefore, only results for non-STS soybean will be discussed further. Norsworthy et al. (2010) reported STS-soybean to be tolerant to imazosulfuron applied POST at 1/64 to 1/2X the labeled rate.

The highest (1/4X) rate of imazosulfuron and halosulfuron applied PRE resulted in 4% or less injury to non-STS soybean at 2 WAT (data not shown). The observed injury was in agreement with research conducted by Porterfield (2001) where less than 5% injury to non-STS soybean and no injury to STS-soybean was observed for trifloxysulfuron applied preplant at 3.75 and 7.5 g ai ha^{-1}. Soltani et al. (2009) also reported minimal (<3%) injury and no plant height and yield reduction to dry bean (*Phaseolus vulgaris* L.) treated with halosulfuron PRE at 35 g ha^{-1}.

Non-STS soybean recovered from the injury by the end of the growing season, and yield was comparable with the non-treated control (data not shown). Soybean in non-treated check produced yield of 3200 kg ha^{-1}. Likewise yield, plant density at 2 and 6 WAT, and plant height at 2 WAT, 6 WAT, and the end of the growing season (20 WAP) were not significantly different from the non-treated control for either cultivar (data not shown). At both 2 and 6 WAP, soybean that received no imazosulfuron treatment maintained a plant density of 44 seeds per m^{-2}. Non-treated soybean were 11, 34, and 84 cm tall when height was measured from top of the bed to the top of fully expanded leaf at 2 and 6 WAP and at the end of growing season, respectively. Injury was in the form of chlorosis, purple veins, and stunting that is characteristic of sulfonylurea herbicide (ALS-inhibiting herbicide) injury to soybean (Brown 1990). Injury was transient and was not visibly apparent 5 WAT onward. On the basis of results of this study, there is an adequate margin of crop safety in soybean to imazosulfuron and halosulfuron applied PRE at ≤1/4X their labeled rates.

Rotation Study. Imazosulfuron injury to non-STS soybean from the two highest rates (448 and 672 g ha^{-1}) applied the previous year was higher than the non-treated control for both locations; however, non-STS soybean was injured more at Pine Tree than at Keiser (Table 1). The presence of injury to soybean from imazosulfuron in rotation study against no injury in tolerance study was because of differences in tillage management. For the rotation study, the practice of no-tillage and presence of rice stubbles resulted in higher organic matter content, lower temperature, and reduced microbial attack on the herbicide; consequently, increasing the persistence of imazosulfuron in soil (Alleto et al. 2010). At 5 WAP, imazosulfuron at 672 g ha^{-1} resulted in ≤ 13% injury at Pine Tree and ≤ 3% at Keiser to non-STS soybean planted the year following rice (Table 1). The difference in crop injury between locations could be because of differences in soil properties including soil texture, amount of clay, organic matter content, and soil pH, which would impact persistence and herbicide availability, in turn influencing the potential for imazosulfuron to injure soybean via carryover. The silty-clay soil with higher organic matter content, higher clay content, and lower pH at Keiser would be expected to have greater adsorption of imazasulfuron than the silt loam soil at Pine Tree, making the herbicide less available to soybean at Keiser than at Pine Tree. Other studies have reported sulfonylurea herbicides to adsorb strongly at low pH and high organic matter content; and to degrade slowly in alkaline (high pH) and low organic matter soils (Beyer et al. 1988; Maheshwari and Ramesh 2007; Moyer and Hamman 2001). The average monthly temperatures at Keiser and Pine Tree did not vary significantly (Table 2). However, soybean at Keiser received more rainfall than at Pine Tree resulting in less injury to soybean at Keiser, probably because of loss imazosulfuron via leaching and runoff. Mesotrione has been reported to degrade faster in the years of with heavy rainfall (Maeghe et al. 2002). However, non-STS soybean at both locations recovered from imazosulfuron injury by the end of the growing season and yield was comparable with that of the non-treated control (data not shown). Other studies have reported that even though there is a direct relationship between soil pH and halosulfuron adsorption/desorption (Carpenter 1999; Grey 2007a,b), along with soybean being sensitive to halosulfuron (sulfonylurea herbicide) (Nandula et al. 2009), carryover to soybean does not appear to be overly risky (Johnson III et al. 2010). Averaged over locations, non-STS soybean in the non-treated check yielded 3,480 kg ha^{-1}, indicating soybean was grown in a high yielding environment at both locations. In addition, stand counts at 5 WAP and plant height at 5 WAP and at the end of growing season were not different from the non-treated control; further proof that that there was minimal or no impact of imazosulfuron carryover to soybean (data not shown). Non-treated soybean had a plant density of 49 plants per m^{-2}, again comparable to all imazosulfuron-treated plots (data not shown). At 5 WAP and at the end of growing season, soybean that received no imazosulfuron treatment was 16 and 93 cm tall, respectively (data not shown). Another sulfonylurea herbicide, trifloxysulfuron, applied at 3.75, 7.5, and 15 g ha^{-1} resulted in no injury to non-STS soybean the subsequent year and resulted in no yield reduction (Porterfield 2001).

Since soybean was irrigated at each of these locations, soil moisture limitations were not considered when assessing soybean injury from imazosulfuron carryover. The results of these studies suggest that early-season injury to soybean the year following rice treated with imazosulfuron may occur on silt loam soils having low organic matter and a high soil pH. Under conditions that may favor carryover, the planting of STS soybean would most likely result in less risk of imazosulfuron causing injury to soybean.

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Table 1. Imazosulfuron injury to non-STS soybean *via* carryover from rice[a].

Treatment[b]	Rate	Soybean injury[c]	
		Keiser	Pine Tree
	g ai ha^{-1}	------- % --------	
Imazosulfuron	112	0c	2b
Imazosulfuron	224	0b	4b
Imazosulfuron	336	0c	6b
Imazosulfuron	448	1b	7ab
Imazosulfuron	672	3a	13a

[a] Means in each column followed by the same letter are not different at $\alpha = 0.05$.

[b] Imazosulfuron was applied PRE (at above-mentioned rates) to rice in 2010.

[c] Soybean was rated for injury as percent of non-treated control.

Table 2. Total monthly rainfall and average monthly temperature at Keiser and Pine Tree, AR, 2011.

	Rainfall (cm)		Temperature (^oC)	
Month	Keiser	Pine Tree	Keiser	Pine Tree
January	5.33	2.92	2	2
February	8.97	6.73	5	7
March	12.85	11.25	11	11
April	28.80	12.29	18	18
May	29.54	24.18	20	20
June	9.02	6.53	29	28
July	9.22	0.89	30	29
August	3.15	9.07	28	27
September	5.49	4.62	22	21
October	5.74	4.50	17	16

CONCLUSION

In the southern U.S., the common practice of growing rice (*Oryza sativa*) and soybean (*Glycine max*) in close proximity makes soybean prone to injury from herbicides used in rice either via off-target movement or carryover. Imazosulfuron is a newer sulfonylurea herbicide that provides excellent control of broadleaf weeds and sedges in both drill- and water-seeded rice. Soybean sensitivity to imazosulfuron was evaluated in the current study. This study demonstrated that STS soybean was not injured with imazosulfuron. At 2 WAT, non-STS soybean was injured from drift rates of imazosulfuron (1/256 to 1/4X) and at all the application timings (VC, V2, V6, and R2). However, soybean treated with lower imazosulfuron rates at early growth stages recovered better from imazosulfuron injury and resulted in less yield loss compared with higher imazosulfuron rates at later growth stages. Conversely, at 2 WAT, different rates of imazosulfuron caused only little to no injury to non-STS soybean when applied preplant and resulted in no yield loss. Both delayed maturity and yield reductions were correlated more with late-season injury compared to injury at 2 WAT, and correlation for individual application timing was higher than the overall correlation across application timings. In addition, imazosulfuron carryover from rice injured non-STS soybean more on a silt-loam soil with lower organic matter content, lower clay content, and higher soil pH. However, non-STS soybean recovered completely from the early-season injury caused by imazosulfuron carryover with no yield loss. Results of the carryover study suggest that imazosulfuron injury to soybean is more likely on silt loam soils having low organic matter and a high soil pH. Under conditions conducive for imazosulfuron carryover, the planting of STS soybean is recommended to avoid possible risks of soybean injury.