Weed Technology 2016 30:958–964

Influence of Planting Depth and Application Timing on *S*-metolachlor Injury in Sesame (*Sesamum indicum* L.)

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Two experiments were conducted in 2015 at multiple locations in Florida to evaluate the effects of planting depth and application timing on *S*-metolachlor injury in sesame. In both studies, sesame responded negatively to increases in *S*-metolachlor rate. Altering sesame planting depth did not provide increased safety to PRE *S*-metolachlor applications. Sesame establishment declined with increased planting depth, likely because of the physical inability of the small seed to emerge from the 3.8-cm depth. Delaying applications of *S*-metolachlor by 3 or 6 d after planting (DAP) consistently improved sesame establishment. Applications 3 and 6 DAP resulted in 89 to 92% seedling emergence at 2 wk after planting (WAP), relative to 55 to 63% emergence when *S*-metolachlor was applied the day of planting (0 DAP) or 3 days before (−3 DAP), respectively. Applications 3 DAP resulted in 21 and 2% plant stunting when evaluated 3 and 6 WAP, respectively, whereas all other timings caused 25 to 51% stunting. Yield was reduced 22 and 33% by the −3 DAP and 0 DAP application timings, respectively, whereas no reduction in yield was observed by the delayed application timings. Therefore, delaying applications of *S*-metolachlor by 3 to 6 days will likely result in improved sesame seedling establishment and total seed yield.

Nomenclature: *S*-metolachlor; sesame, *Sesamum indicum* L. 'S38'.
Key words: Application timing, crop injury, planting depth.

En 2015, se realizaron dos experimentos en varias localidades en Florida para evaluar los efectos de la profundidad de siembra y el momento de aplicación de *S*-metolachlor sobre el daño causado al ajonjolí. En ambos estudios, el ajonjolí respondió negativamente a incrementos en la dosis de *S*-metolachlor. El alterar la profundidad de siembra del ajonjolí no aumentó la seguridad con respecto a las aplicaciones PRE de *S*-metolachlor. El establecimiento del ajonjolí disminuyó al aumentar la profundidad, probablemente debido a la inhabilidad física de la semilla pequeña de emerger desde 3.8 cm de profundidad. El retrasar las aplicaciones de *S*-metolachlor 3 ó 6 d después de la siembra (DAP) consistentemente mejoró el establecimiento del ajonjolí. Aplicaciones 3 ó 6 DAP resultaron en 89 a 92% de emergencia de plántulas a 2 semanas después de la siembra (WAP), en comparación con 63 y 55% de emergencia cuando *S*-metolachlor fue aplicado el día de la siembra (0 DAP) o 3 días antes (−3 DAP), respectivamente. Las aplicaciones 3 DAP resultaron en 21 y 2% de reducción en altura de plantas cuando se evaluó 3 y 6 WAP, respectivamente. Mientras que todos los otros momentos de aplicación causaron 25 a 51% de reducción en altura de planta. El rendimiento se redujo 22 y 33% con aplicaciones realizadas −3 DAP y 0 DAP, respectivamente. Sin embargo, no se observaron reducciones en el rendimiento con los momentos de aplicación realizados después de la siembra. De esta manera, el retrasar las aplicaciones de *S*-metolachlor de 3 a 6 días resultará en un mejor establecimiento de plántulas y rendimiento total de semilla de ajonjolí.

Sesame is an ancient crop with seed that are used for confectionary purposes or crushed for high-quality edible oil. Sesame production has traditionally occurred in India and China using dehiscent varieties that are prone to seedpod shattering during harvest, thus making hand-harvesting nearly compulsory for minimizing seed loss. However, nondehiscent varieties were developed in the United States during the 1950s to allow mechanized harvest (Langham et al. 2002). This advancement has permitted hectarage to expand in the United States. However, being a relatively new crop there, little research has been conducted, which makes production recommendations difficult.

One of the major obstacles facing sesame producers is adequate weed control. Successful early season weed control in sesame is important because both number of seed capsules per plant and number of seeds per capsule decrease when the crop is faced

DOI: 10.1614/WT-D-16-00081.1

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with full season weed competition (Ijlal et al. 2011). Additionally, weeds present a problem in non-dehiscent varieties by trapping moisture in the field during grain dry-down. Sesame seed must be dried down to 6% moisture in the field before harvest to ensure efficient seed release and to minimize mechanical damage. The presence of weeds at the time of seed maturity can prolong the dry-down period and delay harvest, as well as complicate combine operation. Weed seeds present in harvested seed can also increase the overall moisture content of the grain bin and cause spoilage during storage or damage during transportation and handling (Langham et al. 2002).

The use of herbicides is essential for economically viable sesame production in the United States. However, few herbicides are currently registered for use in this crop. Moreover, sesame sensitivity to many commonly used herbicides is highly variable, and can result in crop injury and reduced stand establishment (Grichar et al. 2009). In a Texas study comparing rates and methods of incorporation of PRE herbicides, ethalfluralin resulted in 5 to 48% stand reduction when application rates ranged from 0.42 to 1.68 kg ha^{-1}. Similar responses, ranging from very low to extreme stand losses, were observed when various rates of pendimethalin and trifluralin were applied (Grichar and Dotray 2007). Another example is linuron, which ranged from 0 to 51% stand loss, depending on location (Grichar et al. 2012). The reason for this variability is unknown. What is known is that sesame is a small-seed dicot that can be slow to emerge and establish. In soybeans, small seed size is directly related to reduced seedling vegetative growth and vigor compared with large seeds (TeKrony et al. 1987). It is unknown whether herbicide sensitivity is increased under conditions that slow sesame establishment.

Regardless of the efficacy of the PRE herbicides that have been tested, *S*-metolachlor is currently the only herbicide registered for PRE use. Trials have shown inconsistencies across multiple years and locations when applying *S*-metolachlor PRE on sesame. In Texas, sesame treated with *S*-metolachlor showed 9 to 29% stand reduction 28 d after treatment in one location, whereas in another location, plots showed 0 to 8% stand reduction 28 d after treatment (Grichar et al. 2012). Conversely, *S*-metolachlor has been observed to provide 99% weed control and 0% injury at other locations (Grichar et al. 2009). Regardless of early season injury, sesame yield after *S*-metolachlor application was often highest of all herbicides tested (Grichar et al. 2009). Aside from these studies conducted in Texas, published research that shows the effects of *S*-metolachlor on sesame stands in other regions is limited. Producers still use *S*-metolachlor in sesame production despite the unpredictable injury potential.

Altering planting depth is a simple adjustment for growers that may improve sesame tolerance to *S*-metolachlor. Planting corn (*Zea mays* L.) at a 5-cm depth has been shown to alleviate injury from isoxaflutole at 53 g ha^{-1} compared with a 2.5-cm depth in soils with low organic matter (Wicks et al. 2007). Similarly, increasing cotton planting depth has been shown to eliminate reductions in stand and yield from diuron (Hamilton et al. 1966). Soybean (*Glycine max* L. Merr.) tolerance to high rates of metribuzin has also been improved by increasing planting depth (Coble and Schrader 1973). However, being a small-seeded crop, sesame is often planted at just over 1 cm deep to facilitate emergence. It is unknown if planting at greater depths will affect sesame establishment negatively.

Another factor that may increase sesame tolerance to *S*-metolachlor is application timing. Cotton (*Gossypium hirsutum* L.) can also be sensitive to *S*-metolachlor when applied PRE. Trials have shown up to 47% injury to cotton from PRE-applied *S*-metolachlor in sandy soils, whereas applications after emergence did not affect cotton stand numbers (Keeling and Abernathy 1989). Additionally, Kendig et al. (2007) found that POST applications of *S*-metolachlor to cotton at the four-leaf stage caused less reduction in cotton biomass than when applied at the cotyledon stage. Therefore, it is questioned whether delayed *S*-metolachlor applications can result in greater sesame safety. Unfortunately, current label restrictions prohibit POST application of *S*-metolachlor to sesame. The objectives of this research were to examine how application timing or planting depth will influence sesame response to *S*-metolachlor.

Materials and Methods

Field studies were conducted in 2015 at two locations in Citra, FL, and one location in Jay, FL. Citra soil types were Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) with < 1% organic matter (OM) and Candler sand (hyperthermic, uncoated Quartzipsamments) with < 1% OM. The soil type in Jay, FL, was a Tifton sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 2.3% OM. All experiments were conducted under conventional tillage while keeping plots weed-free throughout the duration of the experiment. Plots were four rows wide using 76-cm row spacing and 7.62 m long. Variety 'S38′ (Sesaco Corporation, Austin, TX), a branching cultivar, was planted at a rate of 20 seeds m^{-1}. The two Citra, FL, locations were planted on April 30 and June 1, and the Jay, FL, location was planted on June 19. Rainfall for 10 d after planting (DAP) averaged < 1, 3, and 7.4 cm at the two Citra locations and Jay location, respectively. Fertilizer, irrigation, and fungicides were applied as needed based on local production practices. *S*-metolachlor (Dual Magnum herbicide, 915 g ai L^{-1}, Syngenta Crop Protection, Greensboro, NC) was applied using a CO_2-powered backpack sprayer calibrated to deliver 187 L ha^{-1} with 11003 flat fan nozzles. Plots were maintained weed free by manually removing weeds escaping *S*-metolachlor control and periodically hoeing and hand-weeding the nontreated check plots. In both experiments, stand counts were conducted on 1 m of row at 1, 2, and 3 weeks after planting (WAP) to measure sesame emergence. Likewise, heights of 10 plants per plot were measured 3 and 6 WAP by measuring to the shoot apex. When 90% of sesame plants had mature seed at the top of the plant, glyphosate (Roundup PowerMax, Monsanto Company, St. Louis, MO) was applied at 0.45 kg ae ha^{-1} to terminate plant growth and initiate dry-down (Langham et al. 2008). When seeds reached 6% moisture, the middle two rows of each plot were machine harvested, and seed weight was recorded.

Planting Depth. Experiments were conducted as a strip-split-plot design with four replications and a factorial treatment arrangement. The whole-plot factor was planting depth (0.64, 1.27, 2.54, and 3.81 cm) and the subplot factor was *S*-metolachlor rate (0, 0.69, 1.42, and 2.78 kg ai ha^{-1}). *S*-metolachlor was applied immediately after planting and incorporated with 1.27 cm of irrigation.

Application Timing. In a separate experiment, application timing was examined using a randomized complete block design with four replications and a factorial arrangement of treatments. The two factors were *S*-metolachlor rate (0, 0.69, 1.42, and 2.78 kg ai ha^{-1}) and application timing: 3 days before planting (–3 DAP), day of planting (0 DAP), 3 DAP, and 6 DAP. Sesame was planted 1.27 cm deep, and *S*-metolachlor was incorporated with 1.27 cm of irrigation after the 0 DAP application and again after the 6 DAP application to prevent photolysis.

Data were subjected to ANOVA to test for main effects and interactions using the agricolae package in R (version 0.98.1091, RStudio Inc., Boston, MA). Where significant effects were observed, means were separated using Fisher's protected LSD test ($\alpha = 0.05$).

Results and Discussion

Planting Depth. There were no significant interactions between the main effects and trial location ($P = 0.37$). Therefore, data were pooled across all locations. Additionally, interactions between main effects were not detected ($P > 0.05$), but the main effect of planting depth and *S*-metolachlor rate were significant and will be discussed separately.

The effect of planting depth on sesame emergence was significant at 1 and 3 WAP, but not at 2 WAP (Table 1). We anticipated that deeper planting depth would result in improved crop safety, but this trend was not observed. The deepest planting depth resulted in the lowest emergence 1 and 3 WAP, whereas no differences among other depths were found except 0.64 cm at 3 WAP. The reduction in emergence from deep planting is likely because sesame is relatively small seeded and not physically capable of emerging from these increased depths. Comparably, Nangju et al. (1976) observed the same response in rice (*Oryza sativa* L.) emergence to deep planting when trying to increase selectivity to herbicides. Increased planting depths have been shown to be associated with decreased emergence in other small-seeded dicots such as yellow sweetclover [*Melilotus officinalis* (L.) Lam.] (Haskins and Gorz 1975). Plant height did not respond to planting depth but yield did. Reductions in yield because of planting depth ranged from 31 to 44%, with no difference between depths except at 2.54 cm planting depth, which resulted in the highest yield with only a 16% reduction observed (Table 2). Despite reductions in emergence of up to 54%

Table 1. Effect of *S*-metolachlor rate and sesame planting depth on sesame emergence expressed as percentage of nontreated controls.[a]

	Emergence		
	1 WAP	2 WAP	3 WAP
	——% of nontreated——		
S-metolachlor rate (kg ai ha^{-1})			
0.694	86 a[b]	83 a	75 a
1.42	66 b	60 b	49 b
2.78	55 b	38 c	25 c
Planting depth (cm)			
0.64	74 a	62 a	46 b
1.27	80 a	62 a	56 a
2.54	71 a	65 a	59 a
3.81	52 b	51 a	38 b

[a] Abbreviation: WAP, weeks after planting

[b] Means within columns for each main effect followed by the same letter are not significantly different according to Fisher's protected LSD at P = 0.05. All data presented were significantly different from the nontreated control.

Table 2. Effect of *S*-metolachlor rate and sesame planting depth on sesame plant height and yield expressed as percentage of nontreated controls.[a]

	Plant height		
	3 WAP	6 WAP	Yield
	——% of nontreated——		
S-metolachlor rate (kg ai ha^{-1})			
0.694	75 a[b]	90 a*	90 a*
1.42	59 b	70 b	77 b
2.78	35 c	48 c	35 c
Planting depth (cm)			
0.64	52 a	68 a	60 b
1.27	56 a	64 a	69 b
2.54	62 a	72 a	84 a
3.81	56 a	73 a	56 b

[a] Abbreviation: WAP, weeks after planting.

[b] Means within columns for each main effect followed by the same letter are not significantly different according to Fisher's protected LSD at P = 0.05. Asterisk signifies mean is similar to the nontreated.

because of planting depth, reductions in yield were not as severe, likely because of the ability of this variety of sesame to compensate for lower population densities by branching. This compensation phenomena has been noted in other indeterminate crops such as soybean, which has been shown to suffer only a 33% reduction in yield when stands were reduced by 75% early in the season (Conley et al. 2008). Regardless, the lack of identifiable trends in these data indicate that planting depth likely has little to do with sesame safety to *S*-metolachlor.

Conversely, *S*-metolachlor rate affected sesame emergence, height, and yield at all times. As expected, greater reductions in emergence were observed at higher rates. At 2 and 3 WAP, sesame emergence continued to decline at higher *S*-metolachlor rates, because many sesame seedlings emerged but then died by the 3 WAP evaluation date (Table 1). The same response to *S*-metolachlor rate was observed in plant height and yield data as well. Plants were stunted ranging from 25 to 65% at 3 WAP, with higher rates causing higher reductions. Although yield was only reduced 10% by the 0.694 kg ha^{-1} rate, reductions of 23 and 65% occurred at the 1.42 and 2.78 kg ha^{-1} rates, respectively (Table 2).

Application Timing. Interactions between main effects and trial location were not significant (P = 0.26). Therefore, data were pooled across all locations. The main effects of rate and timing were significant, but no interactions were detected for plant height, yield, or emergence at 1 and 2 WAP. Therefore, only the main effects are presented for these factors. However, emergence at 3 WAP was found to have a significant interaction between main effects, rate, and timing, and the interaction is presented (Figure 1).

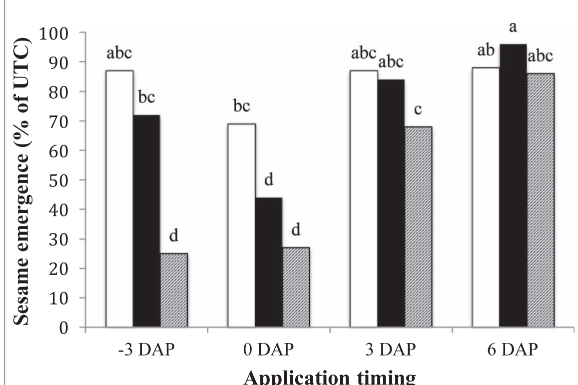

Figure 1. Sesame emergence 3 wk after planting (WAP) as influenced by *S*-metolachlor applied 3 d before planting (–3 DAP) to 6 d after planting (6 DAP). Legend for rates: open bars = 0.694 kg ai ha^{-1}, closed bars = 1.42 kg ai ha^{-1}, hashed bars = 2.78 kg ai ha^{-1}. Columns labeled with the same letter are not significantly different according to Fisher's protected LSD at P = 0.05.

https://doi.org/10.1614/WT-D-16-00081.1 Published online by Cambridge University Press

Table 3. Effect of *S*-metolachlor rate and application timing on sesame emergence, plant height, and yield expressed as percentage of nontreated controls.[a]

	Seedling emergence		Plant height		
	1 WAP	2 WAP	3 WAP	6 WAP	Yield
	% of nontreated				
S-metolachlor rate (kg ai ha^{-1})					
0.694	85 a[b]	87 a*	72 a	93 a*	100 a*
1.42	86 a	84 a	58 b	79 b	92 a*
2.78	82 a	56 b	43 c	58 c	69 b
Application timing					
−3 DAP	62 c	55 b	50 b	63 b	78 bc
0 DAP	81 b	63 b	52 b	68 b	67 c
3 DAP	93 ab*	89 a*	79 a	98 a*	101 a*
6 DAP	103 a*	92 a*	49 b	75 b	100 ab*

[a] Abbreviations: DAP, days after planting; WAP, weeks after planting.

[b] Means within columns for each main effect followed by the same letter are not significantly different according to Fisher's protected LSD at P = 0.05. Asterisk signifies mean is similar to the nontreated.

The same response to *S*-metolachlor rate that was observed in the planting depth study was also present here in the application timing study, although the reductions caused by *S*-metolachlor rate in the previously discussed study (planting depth) were slightly more severe. For example, emergence 2 WAP in the planting depth study was reduced 40 and 62% by the 1.42 and 2.78 kg ha^{-1} rates, respectively (Table 1). In the application timing study, emergence 2 WAP was reduced only 16 and 44% at the respective rates (Table 3). In the planting depth study, the 1.42 and 2.78 kg ha^{-1} rates reduced yield 23 and 65%, respectively (Table 2). In the application timing study, the same rates reduced yield only 8 and 31% (Table 3), most likely because all of the applications in the planting depth study occurred the day of planting. In this study, the response to rate was averaged across all application timings and the yield reduction was less than those observed in the planting depth study, inferring that there is an advantage to applications at other times.

Sesame emergence, plant height, and yield were affected by application timing at all times (Table 3). The delayed application timings (3 and 6 DAP) caused no reduction in emergence 1 and 2 WAP compared with the nontreated. Conversely, −3 DAP and 0 DAP application timings caused 45 and 37% reductions in emergence 2 WAP, respectively.

Emergence data 3 WAP showed an interaction of main effects (Figure 1). At the −3 and 0 DAP application timings, a trend to rate was present showing reduced emergence under increased rates. The 2.78 kg ha^{-1} rate caused reductions of 75 and 62% at the −3 and 0 DAP application timings, respectively. As shown in Figure 1, this response to higher rates is not present in the 3 and 6 DAP application timings, because *S*-metolachlor rates within those timings are not different. This response is likely due to the time the developing sesame seedlings were exposed to *S*-metolachlor. Sesame typically emerges between 4 and 8 DAP, depending on soil temperature and moisture. In this scenario with delayed applications, the hypocotyl has an opportunity to develop in the absence of *S*-metolachlor. This slight temporal difference between planting and application timing appears to be sufficient to avoid the injury symptoms associated with applying *S*-metolachlor at planting. This same response to application timing has been observed in peanut (*Arachis hypogaea* L.), when *S*-metolachlor applied preplant and PRE caused more injury than applications at emergence and POST (Grichar et al. 1996). Likewise, *S*-metolachlor applied early POST in cotton resulted in < 3% injury (Clewis et al. 2006), whereas PRE applications resulted in 27 to 47% injury (Keeling and Abernathy 1989).

Plant heights 3 and 6 WAP were least stunted by the 3 DAP application timing, with no difference among the other application timings (Table 3). This is a slightly different trend than that of the response to application timing in emergence. The 6 DAP application timing caused little to no reductions in emergence; however, it caused 51 and 25% reductions in plant heights 3 and 6 WAP, respectively (Table 3). The cause of this stunting is likely because, at two of the locations, sesame plants had emerged at the time of the 6 DAP application. These two locations had later planting dates in June, when soil temperature and moisture was higher and plants emerged faster. Although *S*-metolachlor is commonly applied POST in some crops without stunting, such as cotton (Clewis et al. 2006), foliar contact on sweetpotato [*Ipomoea batatas* (L.) Lam.] has been shown to result in stunting (Meyers et al. 2012). Applications made at –3 DAP and 0 DAP resulted in reductions in both emergence and plant height. These early applications appear to have affected plant vigor throughout the season and eventually translated into yield reductions of 22 and 33%, respectively. Applications of *S*-metolachlor 3 and 6 DAP, regardless of the rates tested, were successful in alleviating yield loss and were not statistically different from the nontreated.

Although *S*-metolachlor applied –3 and 0 DAP are likely to reduce sesame yield, the resulting yield loss from uncontrolled weeds will likely be worse. Islam et al. (2014) found that full-season weed competition reduced sesame yield as much as 48%. Additionally, foreign material in harvested sesame from these weeds would probably lead to additional price dockage because of lower grain quality. Therefore, *S*-metolachlor appears to be essential for sesame production, even if the applications can only be made at times or situations when injury is expected.

Although planting depth served little to no benefit in increasing sesame tolerance to *S*-metolachlor, application timing played a major role. These data consistently showed that the current practice of applying *S*-metolachlor the day of planting is not optimal for preventing injury, and delayed application timing should be considered. However, the 6 DAP application timing tested in this study should be considered with caution. Although this treatment resulted in excellent sesame yields, the level of crop stunting is a concern. Additionally, the current *S*-metolachlor label does not permit applications to emerged plants. Regardless, delaying the *S*-metolachlor application by just 3 d contributes greatly to sesame tolerance and is an easy adjustment for growers.

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Received May 16, 2016, and approved August 15, 2016.

Associate Editor for this paper: Lawrence Steckel, University of Tennessee.