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Research Article

Influence of Simulated Imazapic and Imazethapyr Herbicide Carryover on Cotton (*Gossypium hirsutum* L.)

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Field studies were conducted during the 2001 and 2002 growing seasons in the Texas peanut growing regions to simulate residual concentrations of imazapic and imazethapyr in the soil and subsequent effects on cotton (*Gossypium hirsutum* L.). Simulated imazapic or imazethapyr rates included 0, 1/64X (1.09 g ai/ha), 1/32X (2.19 g ai/ha), 1/16X (4.38 g ai/ha), 1/8X (8.75 g ai/ha), 1/4X (17.5 g ai/ha), and 1/2X (35 g ai/ha) of the full labeled rate for peanut (*Arachis hypogaea* L.) and incorporated prior to cotton planting. Cotton stunting with imazapic or imazethapyr was more severe at Denver City than other locations. All rates of imazapic and imazethapyr resulted in cotton stunting at Denver City while at Munday and Yoakum the 1/8X, 1/4X, and 1/2X rates of imazapic resulted in reduced cotton growth when compared with the untreated check. At all locations imazapic caused more stunted cotton than imazethapyr. Cotton lint yield was reduced by imazapic or imazethapyr at 1/4 X and 1/2 X rates at all locations when compared with the untreated check.

1. Introduction

Imazethapyr and imazapic are imidazolinone herbicides registered for use in peanut (*Arachis hypogaea* L.) and are used extensively in the various peanut growing regions of Texas. Imazethapyr may be applied preplant incorporated (PPI), preemergence (PRE), ground cracking (GC), or postemergence (POST) for effective weed control [1]. Imazethapyr applied PPI or PRE controls many troublesome weeds such as coffee senna (*Cassia occidentalis* L.), common lambsquarter (*Chenopodium album* L.), morningglory species (*Ipomoea* spp.), pigweed species (*Amaranthus* spp.) including Palmer amaranth (*Amaranthus palmeri* S. Wats), prickly sida (*Sida spinosa* L.), purple and yellow nutsedge (*Cyperus rotundus* L. and *C. esculentus* L., resp.), spurred anoda [*Anoda cristata* (L.) Schlecht.], and wild poinsettia (*Euphorbia heterophylla* L.) [2–6].

Imazethapyr applied POST provides broad spectrum and most consistent control when applied within 10 d of weed emergence [3, 7–9]. Imazethapyr and imazapic are the only POST herbicides to effectively control both yellow and purple nutsedge [5, 10]. Control is most effective when imazethapyr is applied to the soil or to yellow nutsedge that is no more than 13 cm tall [1, 10, 11].

Imazapic is similar to imazethapyr and controls all the weeds controlled by imazethapyr [1, 9, 12–14]. In addition, imazapic provides control or suppression of Florida beggarweed [*Desmodium tortuosum* (S.W.) D.C.] and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby], which are not adequately controlled by imazethapyr [15]. Imazethapyr provides consistent control of many broadleaf and sedge species if applied within 10 d after emergence, but imazapic has a longer effectiveness period when applied POST [1, 10, 14, 16]. Imazapic also is effective for control of rhizome and seedling johnsongrass [*Sorghum halepense* (L.) Pers.], Texas millet [*Urochloa texana* (Buckl.) R. Webster], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.], and broadleaf signalgrass [*Brachiaria platyphylla* (Griseb.) Nash] [14].

In crop rotations, the imidazolinone herbicides must be used with caution. Monks and Banks [17] observed slight corn (*Zea mays* L.) injury and severe cotton injury from

imazaquin (another imidazolinone herbicide) applied to soybean [*Glycine max* (L.) Merr.] the previous year. Renner et al. [18] observed significant corn injury from imazaquin applied the previous year in one of two years. In Arkansas, cotton yield was reduced 7 to 42% as the soil concentration of imazaquin increased from 7.5 to 26 g ai/ha [19]. Imazethapyr has been observed to moderately injure corn [20]. Johnson et al. [21] reported slight but significant injury to rice (*Oryza sativa* L.) from imazethapyr applied to soybean the previous year. Rotational crops such as sugarbeet (*Beta vulgaris* L.), canola (*Brassica napus* L.), cauliflower (*Brassica oleracea* L.), broccoli (*Brassica oleracea* L.), and lettuce (*Lactuca sativa* L.) may also be damaged when planted following imazethapyr [22, 23].

Previous research on imazapic carryover has shown varying results. In North Carolina, imazapic applied PPI at 35 g ai/ha reduced cotton yield 43% the following year while imazapic at the same rate applied at emergence caused 20% cotton injury but no yield reduction the following season [24]. In Georgia, imazapic at 35 g ai/ha reduced cotton yield an average of 34% the year following application regardless of application method [24].

A Mississippi study indicated no reduction in shoot weight when corn, grain sorghum [*Sorghum bicolor* (L.) Moench], cotton, rice, wheat (*Triticum aestivum* L.), soybean, and Italian ryegrass (*Lolium multiflorum* L.) were planted directly into soil treated and incorporated with imazapic at rates up to 35 g ai/ha [25]. In that study, all crops were more sensitive in the greenhouse with rates of 11.6 g ai/ha reducing corn and grain sorghum shoot weights. However, cotton, rice, and wheat tolerated rates of 19 to 38 g ai/ha. Grymes et al. [26] reported that imazapic at 69 g ai/ha or imazapic plus imazethapyr each at 35 g ai/ha reduced rice yield the year following application. Grymes et al. [26] felt that imazapic injury to rice grown in rotation with soybean may be reduced by implementing a later rice planting date. They hypothesized that the later date allowed time for more herbicide degradation in the soil. Also, herbicide metabolism by the rice plant may be greater at the later planting date due to warmer temperatures [26].

The persistence of the imidazolinones in soil is influenced by the degree of adsorption to soil, soil moisture content, temperature, and amount of exposure to sunlight [27–29]. The degree of soil adsorption increases as organic matter content increases and pH decreases [30, 31].

The primary mode of herbicidal decomposition is by microbial degradation, and degradation is most rapid in soils with temperatures and moisture contents that favor microbial activity [32, 33]. Photodecomposition accounts for a small amount of imidazolinone degradation when the herbicide is on the soil surface but rainfall or incorporation removes the herbicide from exposure to light [32, 34].

Above soil pH 4.0, the carboxyl groups on imazethapyr dissociate, and soil adsorption of the resulting herbicide anion is negligible [29]. However, in the presence of clay at pH 5.0, fluorescence emission spectra indicate that imazethapyr is adsorbed in the neutral form [30]. At pH 8.0, only the ionized form was observed even in the presence of clay. Increased adsorption and persistence were observed as the pH decreased from 6.5 to 4.5 [33]. Injury to crops seeded following imidazolinone herbicide application also increased as soil pH decreased from 7.7 to 6.0 [35]. This indicated that increased adsorption did not protect crops from imidazolinone herbicide residue at pH 6.0.

Most peanut soils in south and central Texas have a pH of 6.5 to 7.5 and organic matter content $\leq 1\%$. Therefore, in these soils, imidazolinone herbicides are readily available for microbial degradation. However, in the Texas High Plains, the pH may range from 7.0 to 8.5 resulting in reduced microbial degradation. With soils low in organic matter and near neutral pH, little imidazolinone herbicide should be adsorbed onto soil particles. Crops with low tolerance to the imidazolinone herbicides such as cotton are grown in rotation with peanut in many areas of Texas where imazethapyr or imazapic may be used. Evaluating imazethapyr or imazapic in the different regions will provide a more relevant understanding of the persistence issue. Therefore, the objective of this research was to evaluate cotton tolerance to imazethapyr and imazapic concentrations when planted at several locations in the peanut growing areas of Texas.

2. Materials and Methods

Field studies were conducted in Knox County (Munday), Lavaca County (Yoakum), and Yoakum County (Denver City), Texas during the 2001 and 2002 growing seasons to evaluate cotton response to sublabeled imazapic and imazethapyr rates to simulate carryover. Soil characteristics are presented in Table 1. The soils selected are representative of the soils found in different areas of Texas where a peanut-cotton rotation may be found.

The experimental design was a randomized complete block with a factorial arrangement of two herbicide treatments and seven rates with four replications. One factor was herbicide which included imazapic (Cadre, BASF Corporation, P.O. Box 13528, Research Triangle Park, NC 27709) and imazethapyr (Pursuit, BASF Corporation). The other factor was herbicide rate applied at 0, 1.09 g ai/ha (1/64X), 2.19 g ai/ha (1/32X), 4.38 g ai/ha (1/16X), 8.75 g ai/ha (1/8X), 17.5 g ai/ha (1/4X), and 35 g ai/ha (1/2X). These rates were chosen as a representation of the dissipation of imazapic and imazethapyr over time with respect to estimated dissipation time. The normal use rate of imazapic and imazethapyr in peanut is 69 g ai/ha with a half-life of 120 d [36].

Herbicides at the Yoakum location were applied with a CO_2 pressurized backpack sprayer equipped with Teejet 11002 DG flat fan spray tips (Spraying Systems Company, P.O. Box 7900, North Avenue, Wheaton, IL 60188) which delivered a spray volume of 190 L/ha at 180 kPa. At the Denver City location, herbicides were applied with a CO_2 pressurized backpack sprayer using Teejet 110015 TT flat fan spray tips calibrated to deliver a spray volume of 94 L/ha at 207 kPa. At the Munday location, herbicides were applied with a CO_2 pressurized backpack sprayer equipped with Teejet 110015 AI flat fan spray tips which delivered 94 L/ha at 180 kPa. After application, herbicides at Yoakum were incorporated approximately 5 to 6 cm deep with a tractor-driven power tiller while at the Denver City location,

Table 1: Cotton varieties, planting dates, and soil characteristics of each site.

	2001			2002	
Variables	Denver City	Munday	Yoakum	Denver City	Yoakum
Herbicides applied	April 26	May 8	April 27	April 18	April 23
Planting date	May 18	May 8	April 27	June 3	April 23
Soil texture	LFS	FSL	SL	LFS	SL
Soil name	Brownfield	Miles	Hallettsville	Brownfield	Hallettsville
pH	7.6	8.1	6.8	7.6	7.2
OM (%)	<1.0	0.1	1.2	<1.0	1.0
Sand (%)	80	75	65	80	65
Silt (%)	3	16	18	3	17
Clay (%)	17	9	17	17	18
Cotton variety	PM1218RR	PM1218RR	ST 4793RR	PM 2280RR	SG 215RR

[a] Abbreviations: FSL: fine sandy loam; LFS: loamy fine sand; SL: sandy loam; OM: organic matter.

herbicides were incorporated into the soil using a tandem disk set to incorporate 10 to 15 cm deep. At the Munday location, herbicides were applied and incorporated twice 2.5 to 5 cm deep with a rolling cultivator. Cotton was planted at Yoakum and Munday within 24 h of herbicide incorporation while at Denver City herbicides were applied approximately 6 wk prior to cotton planting. At Yoakum, each plot contained two rows, 91 cm apart and 7.9 m long while at Denver City and Munday each plot contained four rows spaced 102 cm apart and 9.5 m long. All plots were maintained weed-free using standard herbicides recommended by the Texas AgriLife Extension Service.

Visual estimates of crop stunting were determined 7 to 9 wk after cotton planting using a scale of 0 to 100, where 0 equals no crop stunting and 100 equals complete crop death. Cotton was either hand-picked or mechanically harvested using commercial harvesting equipment modified for plot harvest. Data were analyzed using the general linear models and means separated using Fisher's protected LSD at $P < 0.05$.

3. Results and Discussion

3.1. Cotton Emergence. No stand reduction was noted with any rate of imazethapyr or imazapic at any location (data not shown). In previous work in Texas, Matocha et al. [37] reported that cotton stand was not affected by imazapic applied at rates up to 144 g ai/ha the previous season. Wixson and Shaw [25] reported that imazapic did not reduce the emergence of cotton with rates up to 35 g ai/ha on a silty clay soil with pH of 7.2 and 3.2% organic matter while Walsh et al. [38] found that imazethapyr at 48 to 96 g ai/ha did not cause a loss of cotton stand. Wiatrak et al. [39] noted that imazapic at the 1X rate (70 g ai/ha) reduced cotton stand in one of two years in Florida while Grey et al. [40] reported no stand reduction at Tifton, GA on a loamy sand with pH of 6.0 and 1.3% organic matter. However, at Plains, GA on a sandy loam with pH of 5.8 to 6.0 and 1.0% organic matter, cotton plants emerged at all imazethapyr and imazapic rates, but by 14 days after treatment (DAT), cotton began to die with sporadic plants exhibiting distended growth. Similar effects were seen in cotton with imazaquin carryover at 70 g ai/ha in Arkansas [41]. None of these effects were observed at any of the Texas locations.

3.2. Cotton Injury and Stunting. Cotton injury observed at all locations included malformation and chlorosis of leaf tissue and plant stunting, typical of imidazolinone herbicides [19, 42, 43]. There was a herbicide, rate, and location interaction; therefore, data are presented individually by herbicide rate and location.

2001. Stunting with imazapic and/or imazethapyr was more severe at Denver City than the other locations (Table 2). At Denver City, imazapic at 1/16 to 1/2X resulted in 81 to 100% cotton stunting while imazethapyr at 1/16 to 1/2X resulted in 60 to 100% cotton stunting. At all rates, with the exception of the 1/64 and 1/2X rates, imazethapyr was less injurious to cotton than imazapic.

At Munday, the high rate of imazapic and imazethapyr caused 48 and 16% cotton stunting, respectively. No significant stunting was observed at Munday with imazapic rates 1/16X or lower or imazethapyr rates 1/4X or lower. The 1/4X rate of imazapic resulted in over 20% cotton stunting.

At Yoakum, cotton stunting was at least 45% when the rate of either imazapic or imazethapyr was 1/4X or greater (Table 2). Although imazapic at 1/8X rate caused 15% stunting, only 4% cotton stunting was noted with the same rate of imazethapyr. None of the other rates of imazapic or imazethapyr resulted in cotton stunting that was different from the untreated check.

2002. At Denver City, all rates of imazapic or imazethapyr resulted in at least 32% cotton stunting (Table 2). No difference in cotton stunting was noted between imazapic and imazethapyr. The highest applied rate of 35 g ai/ha (1/2X) of imazapic or imazethapyr resulted in at least 85% cotton stunting.

At Yoakum, imazapic caused no greater than 18% cotton stunting while imazethapyr resulted in 8% or less cotton stunting at all rates (Table 2). The 1/4 and 1/2X rates of imazapic were the only treatments that resulted in cotton stunting that was different from the untreated check. Rainfalls for May, June, July, August, and September were 33,

Table 2: Cotton stunting as affected by simulated rates of imazapic and imazethapyr.[a]

Herbicide	Rate[b]	2001 Denver City	2001 Munday	2001 Yoakum	2002 Denver City	2002 Yoakum
				%		
Untreated	—	0	0	0	0	0
Imazapic	1/64X	14	0	3	37	6
	1/32X	48	3	0	43	3
	1/16X	81	4	8	54	10
	1/8X	84	8	15	54	13
	1/4X	98	23	62	73	18
	1/2X	100	48	75	85	15
Imazethapyr	1/64X	8	0	3	32	8
	1/32X	17	3	0	33	8
	1/16X	60	1	0	53	5
	1/8X	70	1	4	64	4
	1/4X	89	6	45	77	3
	1/2X	100	16	53	89	4
LSD (0.05)		9	7	14	15	13

[a]Stunting ratings taken 7 weeks after herbicide application at Yoakum in 2001; 8 weeks after herbicide application at Denver City in 2001, Munday, and Yoakum in 2002; 9 weeks after herbicide application at Denver City in 2002.
[b]Herbicide rate: 1.09 g ai/ha (1/64X), 2.19 g ai/ha (1/32X), 4.38 g ai/ha (1/16X), 8.75 g ai/ha (1/8X), 17.5 g ai/ha (1/4X), and 35 g ai/ha (1/2X).

Table 3: Cotton lint yield as affected by simulated rates of imazapic and imazethapyr.

Herbicide	Rate[a]	2001 Denver City	2001 Munday	2001 Yoakum	2002 Denver City	2002 Yoakum
				Kg/ha		
Untreated	—	1080	1800	925	830	1455
Imazapic	1/64X	1205	1905	995	860	1565
	1/32X	1050	1630	1210	910	1690
	1/16X	800	1920	700	975	1425
	1/8X	785	1845	845	1020	1350
	1/4X	195	1615	275	805	1040
	1/2X	0	1645	100	400	1385
Imazethapyr	1/64X	1195	1890	935	955	1635
	1/32X	1160	1660	1180	885	1310
	1/16X	1073	1720	1220	1100	1690
	1/8X	830	1685	895	975	1675
	1/4X	485	1600	435	780	1645
	1/2X	100	1685	375	700	1740
LSD (0.05)		280	NS	370	310	535

[a]Herbicide rate: 1.09 g ai/ha (1/64X), 2.19 g ai/ha (1/32X), 4.38 g ai/ha (1/16X), 8.75 g ai/ha (1/8X), 17.5 g ai/ha (1/4X), and 35 g ai/ha (1/2X).

114, 136, 106, and 114 mm, respectively. Normal rainfalls for these months are 112, 109, 66, 79, and 102 mm, respectively. The above normal rainfall for July and August may have accounted for the lack of cotton response to imazapic and imazethapyr. Microbial degradation is the primary degradation mechanism of imidazolinones and is accentuated by warm, moist soil conditions [44]. In contrast, dry conditions can prolong carryover effects of these herbicides [44]. Wixson and Shaw [25] reported that in soils with a pH 7.2 and 3.2% organic matter, corn and cotton tolerated imazapic up to 35 g ai/ha. Crop injury was observed with imazethapyr in both crops at rates from 5.5 to 17 g ai/ha. The authors indicated that the injury noted with low rates of imazethapyr could be related to the increase of adsorption of the imidazoline herbicides with increasing organic matter content. Wiatrek et al. [39] reported that cotton height was reduced with the high rates of imazapic in one year but not another. Grey et al. [40] reported a negative exponential trend where

cotton height decreased as imazapic rate increased. Matocha et al. [37] reported a reduction in cotton height with imazapic applied at 140 and 210 g ai/ha the previous year.

3.3. Cotton lint Yield. There was a herbicide (imazapic and imazethapyr), rate, and location interaction; therefore, data are presented separately by herbicide, rate, and location.

2001. Lint yields at Denver City were reduced following the 1/8X, 1/4X, and 1/2X rates of imazethapyr or imazapic (Table 3). No cotton was produced from plots treated with imazapic at the 1/2X rate while imazethapyr at the 1/2X rate produced cotton yield that was 8% of the untreated check.

At Munday, none of the herbicide treatments reduced cotton yield when compared with the untreated check. An explanation for the lack of yield differences may be due to soil characteristics. The other locations all had a clay content of at least 17% while this site had a clay content of less than 10%. The pH at the Munday site was 8.1 which was greater than the pH values of 7.6 or less at the other locations (Table 1). Imazapic is weakly adsorbed in high pH soils and adsorption increases as the pH decreases and with increasing clay and organic matter content [19, 37, 40, 42, 45]. At Yoakum, cotton lint yields were reduced by the 1/4X and 1/2X rates of imazapic and imazethapyr (Table 3). Imazapic at the 1/16X rate resulted in lower yields than imazethapyr at the 1/16 or imazapic and imazethapyr at the 1/32X rates.

2002. At Denver City, only the 1/2X rate of imazapic resulted in lower cotton yields than the untreated check (Table 3). No negative response was noted with any of the imazethapyr treatments.

At Yoakum, no reduction in cotton yield was noted when the untreated check was compared with any imazapic or imazethapyr treatments (Table 3). However, plots which received imazethapyr, with the exception of the 1/32X rate, produced higher yields than those that received 1/4X rate of imazapic. The above average rainfall amounts for July and August may help explain a lack of yield reduction observed with the higher rates of imazapic and imazethapyr. The imidazolinones are soluble in water and are not degraded hydrolytically in aqueous solution [34]. However, in water, these herbicides are rapidly photodegraded by sunlight with a half-life of one to two days [29, 34].

Previous research on imazapic carryover has shown varying results. In North Carolina, imazapic applied PPI to peanut at 36 g ai/ha reduced cotton yield 43% the following year while the same rate of imazapic applied at peanut ground cracking resulted in 20% injury but no yield reduction [24]. In Georgia, imazapic at 36 g ai/ha reduced cotton yield an average of 34% the following year regardless of application timing [24]. Grey et al. [40] also reported that there were no detectable differences in cotton variety response to the imidazolinone herbicides.

4. Conclusion

Although different cotton cultivars were used in this study over locations and years, no previous work could be found that reported differential response of cotton cultivars to any of the imidazolinone herbicides. Cotton stunting did not always result in reduced yield, and this may be the result of soil characteristics. However, when stunting was greater than 50% there was almost always a decrease in cotton yield when compared with the untreated check. This study reveals that several factors are involved in the persistence of imazethapyr and imazapic in the soil and helps to explain the various results observed under varying conditions. By possibly knowing the level of imazapic or imazethapyr residual in the soil, producers could have some flexibility in crop rotations if sensitive crops such as cotton are to be planted following imidazolinone use on peanut.

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