Interactions of Chlorpyrifos and Herbicides Applied to Peanut (*Arachis hypogaea* L.)

David L. Jordan*, Rick L. Brandenburg, P. Dewayne Johnson, Brian M. Royals, and Brenda Watson[1]

ABSTRACT

Experiments were conducted from 2004 through 2006 in North Carolina to determine peanut injury, pod scarring, pod yield, and percentages of extra large kernels (%ELK), fancy pods (%FP), and total sound mature kernels (%TSMK) following chlorpyrifos applied as a granular at pegging or as emulsifiable concentrate applied preplant incorporated (PPI) in mixture with pendimethalin. In one experiment, preemergence (PRE) herbicides consisted of *S*-metalochlor, *S*-metalochlor plus diclosulam, and *S*-metalochlor plus flumioxazin following chlorpyrifos. In a separate experiment, the postemergence (POST) herbicides acifluorfen, acifluorfen plus bentazon, imazapic, and paraquat plus bentazon were applied when peanut diameter was 10 to 15 cm. Chlorpyrifos did not interact with diclosulam or flumioxazin applied PRE or with the POST herbicides acifluorfen, acifluorfen plus bentazon, imazapic, or paraquat plus bentazon with respect to visual injury and pod yield. Applying chlorpyrifos at pegging was more effective than PPI applications in reducing pod scarification caused by southern corn rootworm (*Diabrotica undecimpunctata* Howardi) feeding. Although PRE and POST herbicides injured peanut in a manner consistent with standard application of these herbicides, pod yield, %ELK and %TSMK were not affected by early season injury. However, pod yield was lower in the experiment with POST herbicides when chlorpyrifos was applied PPI compared with granular application at pegging. No differences in pod yield, %ELK, %FP, and %TSMK were noted when comparing PPI and pegging applications of chlorpyrifos in the PRE herbicide experiment.

Key Words: Integrated pest management, peanut pegging, pesticide interaction, southern corn rootworm.

Effective weed control is essential to optimize pod yield and economic return of peanut (Wilcut *et al*., 1995). A range of herbicides can be applied PPI, PRE, and POST to control grasses, broadleaf weeds, and sedges (Wilcut *et al*., 1995). Diclosulam and flumioxazin are applied PRE on significant peanut hectares to control broadleaf weeds. Acifluorfen and paraquat are applied POST alone or with bentazon to control emerged weeds, and imazapic is applied POST to control broadleaf weeds, sedges, and escaped grasses. Imazapic also provides residual weed control.

Southern corn rootworm is one of the most important insect pests in peanut (Brandenburg, 2007). Clorpyrifos is often applied as a granular treatment over the peanut row at pegging to control this pest (Brandenburg, 2007). Although chlorpyrifos is effective in controlling southern corn rootworm, under relatively dry conditions chlorpyrifos applied in this manner can elevate populations of two-spotted spider mites (*Tetranycychus urticae* Koch) (Barbour and Brandenburg, 1995). A risk advisory was developed to assist practitioners in selecting fields that are at risk of damage from southern corn rootworm (Herbert *et al*., 1997; 2004). This approach can minimize two-spotted spider mite outbreaks by defining the likelihood of damage from southern corn rootworm so that practitioners do not apply chlorpyrifos in fields that are not conducive for southern corn rootworm development and are prone to two-spotted spider mites outbreaks. A more convenient application method would be preferable if efficacy is not reduced compared with application at pegging.

Herbert and Malone (2005) reported that chlorpyrifos incorporated prior to planting controls southern corn rootworm as effectively as application at pegging. Most growers apply pendimethalin prior to planting in conventional tillage systems, and applying chlorpyrifos with pendimethalin would be more convenient than making pegging applications of chlorpyrifos. Although not substantiated, it is plausible that application of chlorpyrifos prior to planting may minimize late-season outbreaks of two-spotted spider mites that are often attributed to pegging applications of chlorpyrifos (Barbour and Brandenburg, 1995).

Peanut response and weed control with herbicides can be affected by a variety of environmental

[1]Professor, Department of Crop Science, North Carolina State University, Box 7620, Raleigh, NC 27695; William Neal Reynolds Distinguished Professor, Department of Entomology, North Carolina Sate University, Box 7613, Raleigh, NC 27695; Research Technician, Department of Crop Science, North Carolina State University, Box 7620, Raleigh, NC 27695; Research Technician and Technician Assistant, Department of Entomology, North Carolina State University, Box 7613, Raleigh, NC 27695, respectively.

*Corresponding author's e-mail: david_jordan@ncsu.edu.

and edaphic factors (Wilcut *et al.*, 1995). Interactions of herbicides with other agrichemicals can affect crop response and efficacy of herbicides (Lancaster *et al.*, 2005). Defining these interactions is important in optimizing pesticide performance. Corn (*Zea mays* L.) injury from nicosulfuron increased when chlorpyrifos was applied in the seed furrow at planting in some but not all experiments (Bailey and Kapusta, 1994; Kapusta, 1994; Morton *et al.*, 1994; Rahman and James, 1993). Corn injury by nicosulfuron was exacerbated more by terbufos than chlorpyrifos (Bailey and Kapusta, 1994; Morton *et al.*, 1994). While diclosulam, imazapic, and nicosulfuron are from different herbicide families, these herbicides affect acetolactate synthase in susceptible plants. Allen and Snipes (1995) reported that cotton (*Gossypium hirsutum* L.) injury was greater when pyrithiobac, an herbicide that inhibits acetolactate synthase in sensitive plants, was co-applied with chlorpyrifos.

Determining if chlorpyrifos increases herbicide injury potential is important in determining if this application method is an effective alternative to current recommendations of application of chlorpyrifos at pegging. Therefore, the objectives of this research were to 1) determine if visual peanut injury, pod yield, and market grade characteristics from PRE and POST herbicides is affected by chlorpyrifos application with pendimethalin prior to planting and 2) determine if PPI application of chlorpyrifos is as effective in controlling southern corn rootworm as application at pegging.

Materials and Methods

General Procedures.

Two separate experiments were conducted in North Carolina during 2004, 2005, and 2006 at the Upper Coastal Plain Research Station located near Rocky Mount on a Goldsboro loamy sand soil (fine-loamy, siliceous, thermic, Typic Paleudults) under non-irrigated conditions. Organic matter ranged from 1.2 to 1.9% and soil pH ranged from 5.9 to 6.1. Experiments were conducted in conventionally prepared, raised seedbeds. Plot size was four rows spaced 91 cm apart by 12 m. Seeds of the cultivar VA 98R were placed 5 to 8 cm deep depending on soil moisture, and granular aldicarb (Temik, Bayer Crop Science, Research Triangle Park, NC) at 1.1 kg ai/ha was applied in the seed furrow prior to seed drop. The in-row plant population was 13 plants/m. Planting dates were 15 May 2004, 25 May 2005, and 12 May 2006.

With the exception of herbicide treatments and application of chlorpyrifos for southern corn rootworm control, production and pest management practices were held constant over the entire experiment and were based on Cooperative Extension recommendations for the region (Brandenburg, 2007; Jordan, 2007a, 2007b; Shew, 2007). Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L/ha using regular flat fan nozzles (8002 regular flat fan nozzles, Spraying Systems Company, Wheaton, IL).

Pendimethalin at 1.1 kg ai/ha was applied over the entire test area after the field was disked twice and then incorporated with two passes of a field cultivar traveling in opposite directions to a depth of 5 to 8 cm. The field was then bedded with an in-row subsoiler and approximately 8 cm of the top of the bed was leveled to allow planting. Escaped broadleaf weeds were removed by hand. Clethodim (Select herbicide, Valent USA Corp., Walnut Creek, CA) at 140 g ai/ha and crop oil concentrate (Agri-Dex crop oil concentrate, Helena Chemical Company, Memphis, TN) at 1.0% (v/v) were applied POST in late July of all years to control escaped grasses.

Visual estimates of percent peanut injury were recorded 3 weeks after planting (WAP) (PRE herbicide experiment) or 2 weeks after POST herbicide application (WAT) (POST herbicide experiment) using a scale of 0 to 100% where 0 = no injury and 100 = plant death. Foliar chlorosis, necrosis, and plant stunting were considered when making the visual ratings. Peanut pods were dug and vines inverted based on pod mesocarp color from a composite sample of four plants collected from the no-PRE herbicide or no-POST herbicide control treated with chlorpyrifos PPI (Sholar *et al.*, 1995; Williams and Drexler, 1981). Peanut was harvested 4 to 7 days after digging and dried to final moisture of 8%. One hundred pods from each plot were removed at harvest to determine scarification caused by southern corn rootworm feeding. Percentages of ELK, FP, and TSMK were determined using Federal-State Inspection Service criteria (USDA, 1998).

Preemergence Herbicides.

Treatments included a factorial arrangement of two levels of chlorpyrifos application method (PPI or pegging) and three levels of PRE herbicide (*S*-metalochlor, *S*-metalochlor plus diclosulam, *S*-metalochlor plus flumioxazin). Chlorpyrifos (Lorsban 4EC insecticide, Dow ArgroSciences, Indianapolis, IN) was applied at 2.2 kg ai/ha mixed with pendimethalin prior to planting as described previously or applied at pegging at 2.2 kg/ha on a 29 cm band over the row (Lorsban 15G insecticide, Dow AgroSciences, Indianapolis, IN). Diclosulam

Table 1. Analysis of variance for peanut injury 3 weeks after planting, pod yield, the percentage of pods with scarring caused by southern corn rootworm feeding, and percentages of extra large kernels (%ELK), fancy pods (%FP), and total sound mature kernels (%TSMK) following application of chlorpyrifos and selected preemergence (PRE) herbicides.

Treatment factor	df	Injury	Pod yield	Pod scarring	%ELK	%FP	%TSMK
		F statistic[a]					
Year	2	8.5**	5.9**	0.9	24.6**	43.9**	43.5**
Chorpyrifos Method	1	1.8	1.7	10.7**	0.1	0.3	0.1
PRE Herbicide	2	29.3**	0.1	0.1	0.4	1.0	1.2
Year × Chlorpyrifos Method	2	0.3	1.5	1.2	2.0	0.4	0.1
Year × PRE Herbicide	4	12.6**	0.7	1.6	1.6	2.5	2.1
Chlorpyrifos Method × PRE Herbicide	2	0.5	0.4	2.2	2.0	1.2	2.1
Year × Chlorpyrifos Method × PRE Herbicide	4	0.3	1.9	0.4	1.0	0.4	0.1
Coefficient of variation (%)	-	82.7	14.9	80.2	8.6	5.9	4.2

[a]* and ** indicate significance at $p = 0.05$ and $p = 0.01$, respectively.

(Strongarm herbicide, Dow AgroSciences, Indianapolis, IN), flumioxazin (Valor SX herbicide, Valent USA Corp., Walnut Creek, CA), and *S*-metalochlor (Dual Magnum herbicide, Syngenta Crop Protection, Greensboro, NC) were applied at 24, 70, and 1100 g ai/ha, respectively. A no-chlorpyrifos and a no-PRE herbicide control was included.

Postemergence Herbicides.

Treatments included a factorial arrangement of two levels of chlorpyrifos application method (PPI or pegging) and four levels of POST herbicide (acifluorfen, acifluorfen plus bentazon, imazapic, paraquat plus bentazon). Chlorpyrifos was applied PPI or at pegging as described previously. Acifluorfen (Ultra Blazer herbicide, BASF Corp., Research Triangle Park, NC), acifluorfen plus bentazon (Storm herbicide, BASF Corp., Research Triangle Park, NC), imazapic, (Cadre herbicide, BASF Corp., Research Park, NC), and paraquat (Gramoxone MAX herbicide, Syngenta Crop Protection, Greensboro, NC) plus bentazon (Basagran herbicide, BASF Corp., Research Triangle Park, NC) were applied at 560, 320 plus 1100, 70, and 140 plus 560 g ai/ha, respectively. A nonionic surfactant (Induce nonionic surfactant, Helena Chemical Company, Memphis, TN) was applied at 0.25% (v/v) with acifluorfen, acifluorfen plus bentazon, and imazapic or at 0.125% (v/v) with paraquat plus bentazon. A no-chlorpyrifos and a no-POST herbicide control was included.

Experimental design and Statistical Analyses.

The design for both PRE and POST herbicide experiments was a randomized complete block with four replications. Data for visual estimates of peanut injury, pod yield, the percentage of pods with scarring caused by southern corn rootworm feeding, %ELK, %TSMK, and %FP were subjected to analyses of variance for each experiment using appropriate error terms for fixed and random effects (Tables 1 and 2, Carmer *et al*., 1989). Means of significant main effects and interactions were separated using Fisher's Protected LSD test at $p \leq 0.05$.

Results and Discussion

The main affect of PRE herbicide and the interaction of year by PRE herbicide were signif-

Table 2. Analysis of variance for peanut injury 2 weeks after application, pod yield, and the percentage of pods with scarring caused by southern corn rootworm feeding, and percentages of extra large kernels (%ELK), fancy pods (%FP), and total sound mature kernels (%TSMK) following application of chlorpyrifos and selected postemergence (POST) herbicides.

Treatment factor	df	Injury	Pod yield	Pod scarring	%ELK	%FP	%TSMK
		F statistic[a]					
Year	2	31.9**	9.5**	7.3**	14.3**	123.7**	3.6
Chlorpyrifos Method	1	0.7	7.5**	7.3**	0.5	0.1	0.1
POST Herbicide	3	85.9**	0.3	0.6	1.2	3.0*	0.5
Year × Chlorpyrifos Method	2	1.1	0.4	0.6	0.2	1.4	0.8
Year × POST Herbicide	6	15.8**	0.7	1.5	1.2	1.0	0.3
Chlorpyrifos Method × POST Herbicide	3	0.7	1.4	1.2	0.2	1.0	0.2
Year × Chorpyrifos Method × POST Herbicide	6	0.4	0.8	0.7	1.1	2.0	0.6
Coefficient of variation (%)	-	24.9	16.5	0.5	10.6	4.9	4.7

[a]* and ** indicate significance at $p = 0.05$ and $p = 0.01$, respectively.

Table 3. Interaction of year and preemergence or postemergence herbicide for peanut injury three weeks after application.[a,b]

	Peanut herbicide injury		
	2004	2005	2006
	%		
Preemergence herbicide			
S-metalochlor	0 b	0 b	0 b
S-metalochlor plus diclosulam	5 a	6 a	3 b
S-metalochlor plus flumioxazin	7 a	6 a	26 a
Postemergence herbicide			
Acifluorfen	3 c	16 b	17 b
Acifluorfen plus bentazon	5 c	8 c	7 c
Imazapic	11 b	17 b	28 a
Paraquat plus bentazon	22 a	24 a	19 b

[a]Means within a year for preemergence or postemergence herbicides followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data were combined over methods of chlorpyrifos application.

[b]Preemergence and postemergence herbicides were evaluated in separate experiments.

icant for peanut injury 3 WAP (Table 1). Similarly, the main effect of POST herbicide and the interaction of POST herbicide with year were also significant for peanut injury 2 WAT (Table 2). In both experiments, chlorpyrifos application method did not affect peanut injury and there was no significant interaction between chlorpyrifos application method and PRE or POST herbicide treatment (Tables 1 and 2). The pegging application of chlorpyrifos was not applied until after PRE and POST herbicides were applied and visual estimates of peanut injury were recorded, and therefore serves as a no-chorpyrifos control for visual injury for each herbicide when compared with chlorpyrifos applied before planting.

When pooled over chlorpyrifos method of application, PRE application of diclosulam and flumioxazin injured peanut similarly during 2004 and 2005 (Table 3). In contrast, peanut was injured 26% when flumioxazin was applied compared to only 3% when diclosulam was applied during 2006. Flumioxazin can be more injurious to peanut than diclosulam (Jordan, 2007b). Excessive injury from flumiozaxin in 2006 could not be explained by environmental conditions or application variables. Although excessive rainfall and below-normal temperatures at the time of peanut emergence have been suspected but not documented as causes of increased peanut injury from flumioxazin, these conditions were not present in 2006. Johnson *et al.* (2006) and Robinson *et al.* (2006) reported variation in peanut injury from flumioxazin applied according to the manufacturer's recommendations for use in peanut.

Peanut herbicide injury following application of acifluorfen was the same as injury observed for acifluorfen plus bentazon during 2004 but higher than acifluorfen plus bentazon during 2005 and 2006 (Table 3). Injury by imazapic exceeded that of acifluorfen during 2004 and 2006; injury by these herbicides was similar in 2005. Paraquat plus bentazon was more injurious than all treatments during 2004 and 2005 but was lower than injury caused by imazapic during 2006. Injury symptoms were typical for herbicides representing these modes of action (Senseman, 2007). Paraquat plus bentazon is often more injurious than acifluorfen or imazapic (Wilcut *et al.*, 1995). However, in some instances imazapic can injure peanut significantly by stunting plants (Wilcut *et al.*, 1995). Variation in visual injury across years could not be easily explained. However, lack of a significant interaction between chlorpyrifos and POST herbicides under conditions where variation in peanut response to POST herbicides was noted suggests that chlorpyrifos and POST herbicides will not interact under a wide range of environmental and edaphic conditions that may occur in peanut production systems.

Pod yield was not affected by PRE or POST herbicides (Tables 1 and 2) even though herbicides injured peanut significantly early in the season (Table 3). The herbicides evaluated in these experiments are often applied to peanut and seldom adversely affect pod yield when applied based on the manufacturer's suggested use rate. Pod yield was affected by year in both PRE and POST herbicide experiments (Tables 1 and 2). However, year and chlorpyrifos method of application did not interact. When pooled over herbicide treatments and chlorpyrifos method of application, pod yield was the lowest during 2004, the highest during 2005, and intermediate during 2006 (Table 4). These experiments were conducted in the same field each year with the same cultivar, and therefore yield for the two experiments would have been expected to be similar. Surprisingly, method of application was not significant in the experiment evaluating PRE herbicides but was significant in the experiment evaluating POST herbicides (Tables 1 and 2). In the latter experiment, pod yield ranged from 3410 and 3240 kg/ha when chlorpyrifos was applied at pegging or PPI, respectively, with the no-chlorpyrifos control yielding 2740 kg/ha (Table 4). Pod yield was 3720 kg/ha when chlorpyrifos was applied at pegging compared with a lower yield of 3390 kg/ha when chlorpyrifos was applied before planting (Table 4). The no-chlorpyrifos control yielded only 3210 kg/ha in this experiment.

Percentages of ELK, FP, and TSMK were not affected by method of chlorpyrifos application,

Table 4. Influence of year and chlorpyrifos application method on peanut pod yield and percentage of pods scarred by southern corn rootworm feeding.[a,b]

Treatment factor	Pod yield — Experiment: PRE herbicides	Pod yield — Experiment: POST herbicides	Pod scarring — Experiment: PRE herbicides	Pod scarring — Experiment: POST herbicides
	kg/ha		%	
Year				
2004	2920 c	2930 c	5 a	6 c
2005	3650 a	4150 a	4 b	13 a
2006	3310 b	3520 b	4 b	9 b
Chlorpyrifos method of application				
Pegging	3410 a	3720 a	3 b	7 b
Preplant	3240 a	3390 b	6 a	11 a
Non-treated[c]	2740	3210	6 a	10 a

[a]Means followed by the same letter within the preemergence herbicide or postemergence herbicide experiment for the main effect of year or chlorpyrifos application method followed by the same letter are not significantly different according to Fisher's Protected LSD test at $p \leq 0.05$. Data were combined over preemergence or postemergence herbicides within the respective experiment.

[b]Preemergence and postemergence herbicides were evaluated in separate experiments.

[c]No-chlorpyrifos control was not included in the factorial analysis.

PRE herbicide, or interactions of these treatment factors (Table 1). Additionally, %ELK and %TSMK were not affected by chlorpyrifos method of application, POST herbicide, or interactions of these treatment factors (Table 2). Although not affected by chlorpyrifos method of application, %FP was affected by POST herbicide (Table 2). When pooled over years and methods of chlorpyrifos application, %FP was similar when acifluorfen, acifluorfen plus bentazon, or paraquat plus bentazon were applied (74 to 75%, data not shown). The %FP was 72% when imazapic was applied which was lower than the %FP for other herbicide treatments. The no-POST herbicide control produced 73% FP (data not shown). Although a lower %FP suggests a possible delay in pod development when comparing %FP following application of imazapic to application with the other herbicides, %FP from imazapic-treated peanut did not differ from the no-POST herbicide control. Additionally, %ELK and %TSMK were not affected by POST herbicides, and these market grade characteristics influence gross economic value of peanut while %FP does not affect gross economic value (USDA, 1998).

Pod scarring varied by year in the experiment with POST herbicides but not in the PRE herbicide experiment (Table 4). The highest amount of scarring in the POST experiment was noted during 2005 (13%) and exceeded scarring during 2004 (6%) or 2006 (9%) (Table 4). Planting date may have contributed to the higher amount of pod scarring during 2005 (25 May) compared with 2004 (15 May) and 2006 (12 May) (Table 4). The current advisory index for southern corn rootworm management (Brandenburg, 2007) indicates that peanut pods are at greater risk of damage when peanut is planted after 15 May than earlier plantings. A later planting date can result in pods being less developed and more susceptible to scarring and puncturing from southern corn rootworm feeding.

Pod scarring was lower when chlorpyrifos was applied at pegging rather than PPI, and this response was consistent across years and in both PRE and POST herbicide experiments within the same year (Tables 1, 2, and 4). In fact, pod scarring was the same when chlorpyrifos was applied before planting compared with the no-chlorpyrifos control (6%) in the PRE herbicide experiment (Table 4). Similarly, in the experiments with POST herbicides, scarring following chlorpyrifos applied prior to planting and the non-treated control was 11 and 10%, respectively (Table 4).

These data indicate that southern corn rootworm control, which is reflected in pod scarring, most likely will be lower when chlorpyrifos is applied prior to planting and incorporated. These results are in contrast to those of Brandenburg and Herbert (1991) and Herbert and Malone (2005) who reported similar control of southern corn rootworm by chlorpyrifos applied PPI versus pegging application in experiments where southern corn rootworm damaged peanut and reduced yield when chlorpyrifos was not applied. In our experiments, chlorpyrifos was applied to the soil surface and incorporated twice in the opposite direction to a depth approximately 8 cm using a field cultivator. The field was then ripped and bedded, and the top of the bed leveled prior to planting. Although uniformity and dilution of pesticides is a concern when fields are bedded, the majority of farmers in the Virginia-Carolina region apply PPI herbicides in conventional tillage systems in this manner. Less control of southern corn rootworm and subsequently greater scarring may have been associated with non-uniform distribution and possibly less chlorpyrifos in the pegging zone where southern corn rootworm develop after hatching and begin feeding on pegs and pods later in the season. Brandenburg and Herbert (1991) applied chlorpyrifos directly to the row bed after planting and incorporated in the pegging zone. In contrast, Herbert and Malone reported similar southern corn rootworm control when chlorpyrifos was applied as a granular at pegging or incorporated prior to begging in a manner similar to the method used in our experiment. Additional research is needed to determine the most feasible method of incorporation of chlorpyrifos at planting to obtain control that is both effective and consistent.

Results from these experiments also indicate peanut response to commonly used herbicides most likely will not vary when chlorpyrifos is applied to the soil prior to planting. However, the quantity of chlorpyrifos absorbed by emerging peanut shoots and roots is not known with respect to PPI application. Less corn injury from POST application of nicosulfuron was reported when organophosphate insecticides were applied in a band after planting rather than in the seed furrow (Bailey and Kapusta, 1994). Chlorpyrifos controls southern corn rootworm through contact between larvae and insecticide (Brandenburg and Herbert, 1991; Brandenburg, 2007) and is considered very insoluble in water and immobile in soil (Brandenburg and Herbert, 1991; Racke, 1992; Wauchope *et al.*, 1992). Incorporation of chlorpyrifos at a more shallow depth after bed establishment or as a PRE application may result in more uniform distribution in the pegging zone where southern corn rootworm feeds on pods. Additional research is needed to define interactions of chlorpyrifos and herbicides when chlorpyrifos is applied in this manner.

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