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Chapter 2

Cotton (*Gossypium hirsutum* L.) Response to Pendimethalin Formulation, Timing, and Method of Application

Timothy Grey and Theodore Webster

Additional information is available at the end of the chapter

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1. Introduction

The introduction of glyphosate-resistant cotton for production in the southeast United States changed herbicide application strategies and increased the profitability of no-tillage and strip-tillage techniques. Glyphosate (*N*-[phosphonomethyl]-glycine) is a highly effective herbicide that controls a broad spectrum of annual and perennial grass and broadleaf weeds in cotton [3, 37]. When glyphosate-resistant cotton varieties were first introduced, glyphosate was applied two to four times on most fields and may have been the only herbicide used [4, 5]. In Georgia, 93% of the cotton acres received at least one glyphosate application in 2005 [3]. The technology allowed growers to reduce or eliminate soil-applied herbicides, allowing them to abandon cultivation and make the transition to conservation tillage, which promotes soil conservation and compliance with USDA Federal regulations. Greater than 50% of Georgia cotton was produced using no-tillage or strip-tillage techniques in 2007, a strategy that has been affected by glyphosate weed control [1, 11].

2. Importance

With the elimination of cultivation as a control tactic in conservation tillage systems, herbicides were the primary and often only method used for weed control [24]. However, the incidence of herbicide-tolerant or resistant weeds emerging in the southeast United States [33, 34] has increased the need for multiple herbicide modes of action in both conservation tillage and conventional tillage weed management systems [3, 5, 16]. In Georgia, there are populations of Palmer amaranth (*Amaranthus palmeri* S. Wats.) (Figure 1) with resistance to glyphosate, ALS,

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triazines, dinitroanilines, with some populations demonstrating resistance to multiple mechanisms of action [5, 26, 31, 38]. While glyphosate- and ALS-resistant Palmer amaranth is widespread in Georgia, the frequency and distribution of triazine- and dinitroaniline-resistant has not been characterized in Georgia. With the potential mobility of herbicide resistance traits, through movement of pollen [27, 28] or seed [18] and/or potentially high levels of naturally occurring mutations conferring resistance, cotton production in the region is threatened by herbicide resistant weeds.



Figure 1. Glyphosate resistant Palmer amaranth in conventional upland cotton in Georgia.

The increased occurrence of herbicide-resistant weeds necessitates the search for alternative control tactics. For instance, metolachlor had not been traditionally used in cotton because of excessive crop injury when applied preemergence after planting. However, changing its use pattern to be applied after cotton emergence avoided crop injury, while controlling an exotic weed that had become troublesome [4]. This technology and new mechanism of action has been instrumental in current management of glyphosate-resistant Palmer amaranth. Research on a new use pattern for pendimethalin may provide an additional tool for weed management at different times in the growing season.

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3. Background information on soil applied herbicides

Herbicides with soil persistence and weed control activity were extensively used for pre-emergence weed control in cotton until the commercial release of herbicide-resistant cotton in 1997. Cotton herbicides with soil residual properties included cyanazine (2-((4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile), diuron (*N*'-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea), flumeturon (*N*,*N*-dimethyl-*N'*(3-(trifluoromethyl)phenyl]urea), pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine), trifluralin (2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl(benzenamine), and others. Pendimethalin was registered for cotton in 1975 [22]. These herbicides were applied pre-plant soil incorporated (PPI), pre-emergence (before cotton and weed emergence) and/or post-directed (where applications are directed to the soil and bottom portion of the stems of mature cotton plants). Cotton in the southeastern U.S. has a growing season that can extend to over 150 days ranging from late March to early November. Growers can PRE apply pendimethalin but have to PPI trifluralin. This allows conservation tillage cotton growers an option to use a dinitroaniline herbicide for grass and small seeded broadleaf weed control. A weakness in weed efficacy of these residual herbicides was the lack of extended weed control due to dissipation of the herbicide in the soil. With the introduction and high rate of adoption of glyphosate-resistant cotton varieties and almost exclusive use of glyphosate for weed control, the herbicides with soil residual activity was reduced in favor of total post-emergence weed control programs. The cotton registration for cyanazine was eventually canceled in 2002 in the United States. However, even with increased herbicide-resistant weeds in growers' fields in the first decade of the 2000's, diruon, flumeturon, and pendimethalin use did not increase, even though residual herbicides could improve weed control (Figure 2). Diuron and flumeturon are widely applied to cotton as post-directed sprays in this region. However, growers using conservation tillage practices in cotton often rely on pendimethalin for early season residual weed control with preemergence applications either sprayed or impregnated on fertilizers.

3.1. Pendimethalin

Pendimethalin is a member of the dinitroanaline family of herbicides. Pendimethalin prevents plant cell growth by inhibiting spindle formation during cell division [6]. Pendimethalin is applied PRE to the soil surface, with or without incorporation into the soil, to approximately 37% of Georgia cotton [17] for control of grasses and small-seeded broadleaf weed species [2]. Pendimethalin inhibits mitotic cell division in susceptible plants [30], while tolerant crops grow through, or are planted below, the treated zone [13, 14]. Among the dinitroanaline herbicides, pendimethalin has greater water solubility of 0.275 ug mL^{-1} and less volatility at 9.4 x 10^{-6} mm Hg at 25 C [22], allowing it to be applied to the soil surface rather than needing mechanical incorporation [35, 36]. However, pendimethalin still requires moisture in the form of rainfall or irrigation in order to move it into the active zone of weed germination. Cotton selectivity of pendimethalin pre-emergence is due to differences in metabolism and sequestration of pendimethalin in the lysigenous glands [25]. Pendimethalin is registered for PRE application up to 2 days after cotton planting. However, delayed application in combination with excessive moisture (rainfall or irrigation) can result in injury to seedling cotton. Pendimethalin injury to

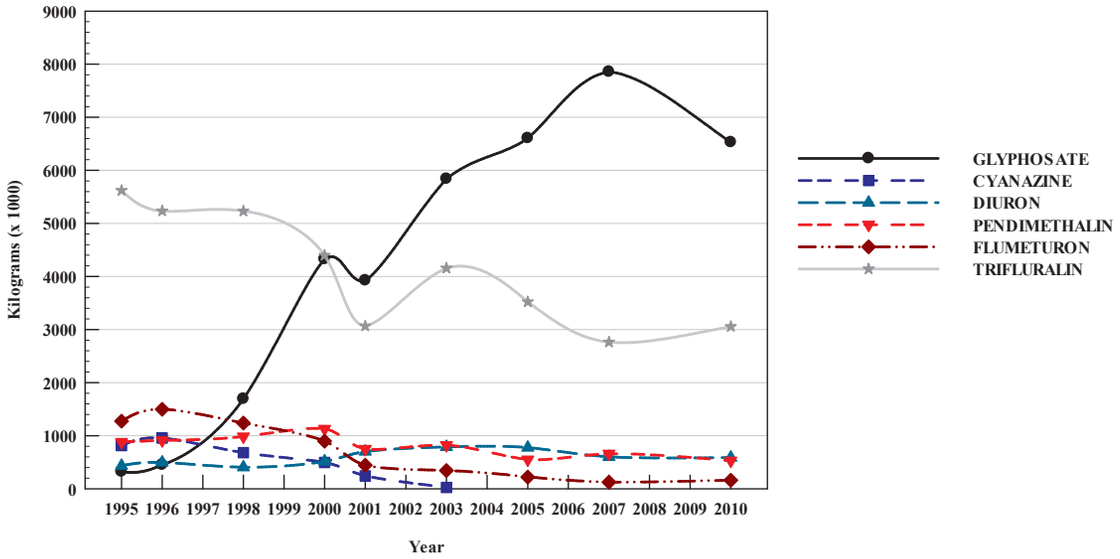


Figure 2. Residual cotton herbicides use as compared to glyphosate in United States cotton production since the advent of glyphosate resistant cotton [17].

cotton seedlings results in delayed hypocotyl development and can also cause abnormal root growth. This injury is commonly associated with enlarged lower stems and 'bottle brush' root development. Microbial decomposition is the main method of pendimethalin dissipation [19, 32]. While pendimethalin has a reported soil half-life of 74 to 114 days [30], surface applied half-lives of 4 to 6 days can occur due to volatilization, photo-chemical, and other degradation processes [21]. Additionally, increased degradation can occur with no-tillage application [9].

3.2. Pendimethalin weed control

Pendimethalin is often used in cotton to supplement control of grass weeds and small-seeded broadleaf weed species. According to the University of Georgia Extension recommendations, pendimethalin provides excellent (90%) control of crabgrass (*Digitaria sanguinalis* (L.) Scop.), crowfootgrass (*Dactyloctenium aegyptium* (L.) Willd.), foxtails (*Setaria* species), goosegrass (*Eleusine indica* (L.) Gaertn.), seedling johnsongrass (*Sorghum halepense* (L.) Pers.), and sandbur (*Cenchrus echinatus* L.); good control (80-90%) of fall panicum (*Panicum dichotomiflorum* Michx.) and Texas millet (*Urochloa texana* (Buckl.) R. Webster). Pendimethalin also provides excellent (90%) to good (80-90%) control of the broadleaf species Florida pusley (*Richardia scabra* L.), pigweeds (*Amaranthus* species), lambsquarters (*Chenopodium album* L.), and pink purslane (*Portulaca pilosa* L.); and fair to good (60-90%) control of Palmer amaranth.

3.3. Pendimethalin formulation

There are two liquid formulations of pendimethalin registered for cotton in the United States. One contains 37.4% pendimethalin (0.41 kg ai/L) formulated with aromatic naphtha as an emulsifiable concentrate (EC), and the other contains 38.7% pendimethalin (0.47 kg ai/L)

formulated as a microencapsulated (ME) aqueous capsule suspension [12] (Figure 3). One potential method of obtaining extended weed control to apply pendimethalin as an in-season application, i.e. from emergence to when the cotton crop has up to six leaves, or just prior to canopy formation. However, injury to cotton from the EC formulation has prevented topical applications in the past.



(Photo courtesy Sidney Cromer, University of Georgia).

Figure 3. Pendimethalin microencapsulated aqueous capsule suspension (left) and pendimethalin emulsifiable concentrate (right)

3.4. Research

Cotton response to pendimethalin ME applied at different growth stages is less injurious to cotton because of its formulation. An alternative method of application is to impregnate pendimethalin onto fertilizer for in-season application to extend residual weed control, reducing the number of herbicide applications [15, 20], and minimizing potential crop injury. Crop injury has been noted with pendimethalin EC and ME when applied topically to cotton at the 4th leaf growth stage [7] and its effects on cotton nutrient uptake [10]. Weed control for comparing pendimethalin EC to ME in cotton have been made using spray applications [11]. Florida pusley and Texas millet control were similar and consistent for PRE applied EC and ME formulations (Table 1). While weed control has been evaluated, cotton crop response to

applications made PRE up to the 6th leaf growth stage comparing season- long factors is also needed. Therefore, this chapter will emphasize pendimethalin use, formulation (EC and ME), and cotton response. Additionally, this chapter will focus on pendimethalin formulations when applied as an aqueous solution in water or impregnated on fertilizers [15].

Formulation	Application method	Timing	Texas millet	Florida pusley
			——————%——————	
Pendimethalin EC	Spray	PRE	75	66
Pendimethalin ME	Spray	PRE	75	68

[a]Abbreviations: EC, emulsifiable concentrate; ME, microencapsulated; PRE, prior to plant emergence.

Table 1. Weed control in Georgia cotton with pendimethalin EC[a] and ME[a] formulations applied at planting.

4. Studies

4.1. Field studies

Field trials were conducted in 2005, 2006, and 2007 at the University of Georgia Ponder Research Station near Ty Ty, Georgia. Soil was Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiadults) with 83% sand, 12% silt, 5% clay, organic matter content of 1 to 1.8%, and pH of 5.6 to 6.1. Conventional tillage was used during all three years of the study to obtain optimal herbicide/soil contact, since pendimethalin has been observed to adsorb to cover crop residue [9]. Delta and Pineland 555 BG/RR was planted in 2005 and Delta and Pineland Flex 445 BG/RR in 2006 and 2007 using a Monosem precision vacuum planter set to deliver 14 seeds per linear meter of row with 0.9 m between row centers. The experimental design was a two factor randomized complete block with treatments replicated four times. Plots were 1.8 m (two rows) wide by 8 m long. Four different methods of pendimethalin application were made at four different timings during the growing season. All herbicide treatments consisted of 1.1 kg active ingredient/ha of pendimethalin EC or ME. Only the method or time of application varied. Treatments were pendimethalin EC or ME applied as either an aqueous solution in water, or impregnated on fertilizer (10-10-10) that was applied at 280 kg ha^{-1} with a Gandy fertilizer applicator (Figure 4). All herbicide spray treatments were made with a CO_2-pressurized backpack sprayer using Teejet 11002 flat fan nozzles, which delivered 140 L/ha of water at 130 kPa. For the fertilizer treatment, pendimethalin EC or ME at 1.1 kg active ingredient ha^{-1} was impregnated on fertilizer using a CO_2–pressurized sprayer with a Teejet 8002 flat fan nozzle at 130 kPa. Fertilizer was rotated at a constant speed of 12 meter $minute^{-1}$ using a rotating steel drum. The drum freely rotated on a twin roller rod system set at a 30º angle, powered by an electric motor, with speed adjusted by a rheostat (Figure 5).

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Figure 4. Pendimethalin impregnated fertilizer treatment on soil surface (left) and application (right).



Figure 5. Fertilizer prior to (left) and after (right) treatment with pendimethalin formulation Prowl 3.3EC.

All plots received the same fertilizer rates to ensure no variability for fertility. Plots were then irrigated the day after treatments were applied. Treatments were made at four different application timings, at planting prior to plant emergence (PRE), at seedling emergence (AE), to 3rd leaf, or to 6th leaf cotton. A non-treated control was included for comparison for a total of 17 treatments. All plots were maintained weed free by hand pulling weed escapes and treatments with glyphosate. Other cultural and pest management practices were based upon recommendations by the Georgia Cooperative Extension Service. Supplemental overhead sprinkler irrigation was applied as needed. Cotton injury ratings were evaluated after applications using a scale of 0 (no injury) to 100 % (plant death) [8]. Cotton height measures were made up to five times in 2005, 2006 and 2007. Both rows of each plot were harvested with a spindle picker, and seed cotton yield was quantified. Data were subjected to mixed model ANOVA using Proc Mixed in SAS 9.1, with random effects of years and replications. Mean separation was determined using the PDMIX800 macro. Regression analysis was performed using Sigmaplot 12 nonlinear regression. The intent was to determine if the response could be described by using the exponential growth, Stirling Model.

$$y = y0 + \frac{a\left(e^{bx}\right) - 1]}{b} \quad (1)$$

Where y is the response variable of treatment, $y0$ is the value of the response variable (y) when X is equal to zero, a is the rate of growth, and X is time in days. Data for growth were analyzed by ANOVA under the general linear models procedure and used mean separation of 95% asymptotic confidence intervals for comparison of parameter estimates.

4.2. Laboratory studies

Fertilizer samples were taken prior to and after treatment with EC and ME pendimethalin. Samples were viewed at ×125 and ×200 magnification with a light microscope. Images were captured with a digital camera with image analysis software. Figure 6 notes the smooth surface for the EC formulations verses the course texture of the ME formulation alone and when impregnated on fertilizer.

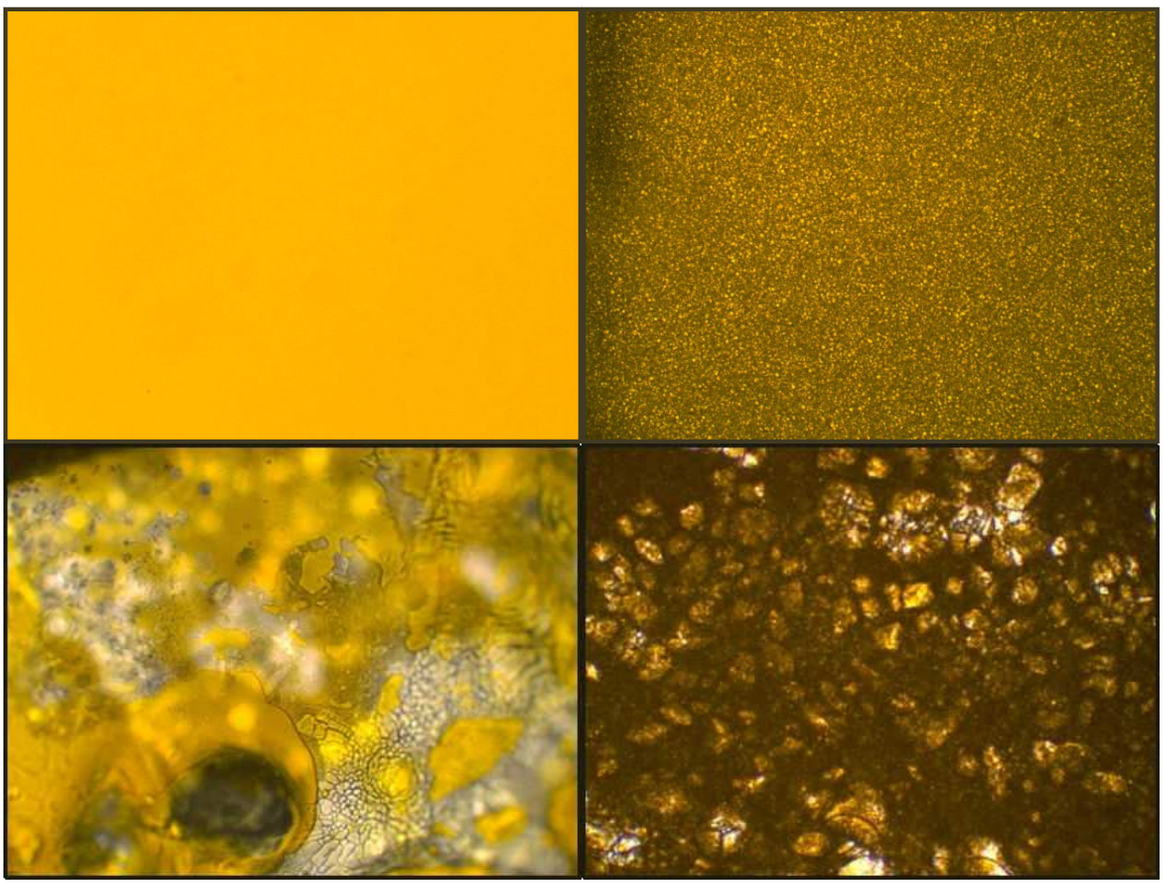


Figure 6. Pendimethalin EC (top left) and ME (top right) formulations alone (x125 light microscope magnification), and EC (bottom left) and ME (bottom right) impregnated on fertilizers (x200).

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5. Cotton response

There were significant formulation by application method, application method by timing, and formulation by timing interactions for cotton plant injury and cotton yield. Since the non-treated control had no associated timing effects and did not differ significantly in cotton yield or injury from the PRE applications (Table 2), comparisons of injury and yield included only the treated plots to simplify the model.

5.1. Cotton injury

Spray applications of pendimethalin EC resulted in greater crop injury (27%) than when pendimethalin EC was applied with fertilizer (12%) or both application methods of pendimethalin ME (≤12%) (Table 2). Pendimethalin on fertilizer applied at the 3rd leaf stage and both application methods applied PRE or the 6th leaf stage of cotton had lower levels (≤7%) of cotton injury than all other treatments. For PRE applications, pendimethalin injury in the form of stunting, leaf curl, leathery cotyledons, swollen hypocotyl, and intense green color were observed, but this did not affect plant establishment, confirming previous results [14]. There was similar and significant injury when pendimethalin (Figure 7) was applied as cotton emerged (AE) with both the fertilizer (27%) and spray (42%) application and when sprayed at the 3rd leaf stage (27%). Previous reports of cotton injury resulting from a topical application of pendimethalin ME at the 4th leaf growth stage (≤20%) was lower than that from pendimentalin EC (≤33%) [7]. When averaged over application method, there was minimal cotton injury when either pendimethalin formulation was applied PRE or at the 6th leaf stage. Greatest injury occurred when pendimethalin EC was applied AE (47%). At both the AE and 3rd leaf stage timings, pendimethalin ME caused less cotton injury than pendimethalin EC.



Figure 7. Cotton injury from pendimethalin EC (110) as compared to pendimethalin ME (112). Both rates were 1.1 kg active ingredient/ha at cotton emergence (AE) applied.

			Injury			LSD[a]
Formulation	**Application**	**Timing**	**%**			
Pendimethalin EC[bc]	Spray		27	a[d]	(4)[d]	7
	Fertilizer[f]		12	b	(4)	
Pendimethalin ME	Spray		12	b	(4)	
	Fertilizer		8	b	(4)	
	Spray	PRE	7	c	(5)	10
	Fertilizer	PRE	6	c	(5)	
	Spray	AE	42	a	(5)	
	Fertilizer	AE	27	b	(5)	
	Spray	3LF	27	b	(5)	
	Fertilizer	3LF	5	c	(5)	
	Spray	6LF	1	c	(5)	
	Fertilizer	6LF	3	c	(5)	
Pendimethalin EC		PRE	7	c	(5)	10
Pendimethalin ME		PRE	6	c	(5)	
Pendimethalin EC		AE	47	a	(5)	
Pendimethalin ME		AE	21	b	(5)	
Pendimethalin EC		3LF	24	b	(5)	
Pendimethalin ME		3LF	8	c	(5)	
Pendimethalin EC		6LF	3	c	(5)	
Pendimethalin ME		6LF	7	c	(5)	

[a]Because *proc Mixed* measures pair-wise differences, multiple LSDs may be obtained. In these cases, the LSD (α=0.05] included is the mean LSD for all treatments.

[b]Pendimethalin rates were 1.1 kg ai/ha for the EC and ME formulations.

[c] Abbreviations: EC, emulsifiable concentrate (0.41 kg ai/L); ME, microencapsulated (0.47 kg ai/L); PRE, prior to plant emergence; AE, at seedling emergence; 3LF, to 3rd leaf cotton; 6LF, 6th leaf cotton

[d]Means within a variable followed by the same letter are not significantly different using Fisher's protected $LSD_{(P=0.05)}$. Standard error of the mean for that treatment enclosed in ().

[f]Fertilizer [10 -10-10] rate was 280 kg/ha, with all plots equally treated. Pendimethalin EC and ME were spray impregnated.

Table 2. Interaction effects between pendimethalin formulation, application method, and application timing for injury in conventional tillage cotton.

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5.2. Cotton height

There were no significant effects on cotton height during the year regardless of the pendimethalin formulation or application type (Figures 8 to 10). The pendimethalin EC formulation (Figure 8) and spray application (Figure 9) did reduce height at 45 days after planting, but this was not significant and was not observed by 75 days after planting for either scenario. Cotton height was reflected in the injury for the timing of application (Figure 10). No differences were noted in height for the 6th leaf treatment timings. While there was cotton injury and height reduction when pendimethalin EC was spray applied at the AE or 3rd leaf timings, cotton recovered and height measures were equivalent by the end of the season. Utilizing exponential growth Stirling model, all curves converged with the analysis at no greater than 14 iterations (data not presented) with no differences for parameter estimates (Tables 3, 4 and 5). The long growing season in tandem with cotton's physiological ability to compensate for early season injury essentially explains why growth models can be effectively used to predict the lack of net negative effects from early season injury from pendimethalin applications.

	Rate of cotton growth[b]					
Herbicide	***a*[c]**		**95% CL**	**b**		**95% CL**
Pendimethalin EC	0.0537	a	±0.0179	0.0513	a	±0.00555
Pendimethalin ME	0.0516	a	±0.0173	0.0514	a	±0.0056
Nontreated	0.0669	a	±0.0558	0.0471	a	±0.0140

[a]Each herbicide for first-order rate constants for each column followed by the same letter are not significantly different according to Fisher's protected LSD test (P≤0.05). General linear models procedures were used for mean separation with 95% asymptotic confidence intervals.

[b]Rates of cotton growth were calculated by nonlinear regression of the herbicide treatments with respect to time in days after planting.

[c]Abbreviations: *a*, rate of cotton growth; CL, confidence limit.

Table 3. Rate of cotton growth (*a*) as a response to pendimethalin formulation.[a]

	Rate of cotton growth[b]					
Application method	***a*[c]**		**95% CL**	**b**		**95% CL**
Fertilizer	0.0653	a	±0.0208	0.0485	a	±0.0053
Spray	0.0418	a	±0.0144	0.0545	a	±0.0057
Nontreated	0.0689	a	±0.0594	0.0463	a	±0.0145

[a]Each application method for first-order rate constants for each column followed by the same letter are not significantly different according to Fisher's protected LSD test (P≤0.05). General linear models procedures were used for mean separation with 95% asymptotic confidence intervals.

[b]Rates of cotton growth were calculated by nonlinear regression of the herbicide treatments with respect to time in days after planting.

[c]Abbreviations: *a*, rate of cotton growth; CL, confidence limit.

Table 4. Rate of cotton growth (*a*) as a response to method of pendimethalin application.[a]

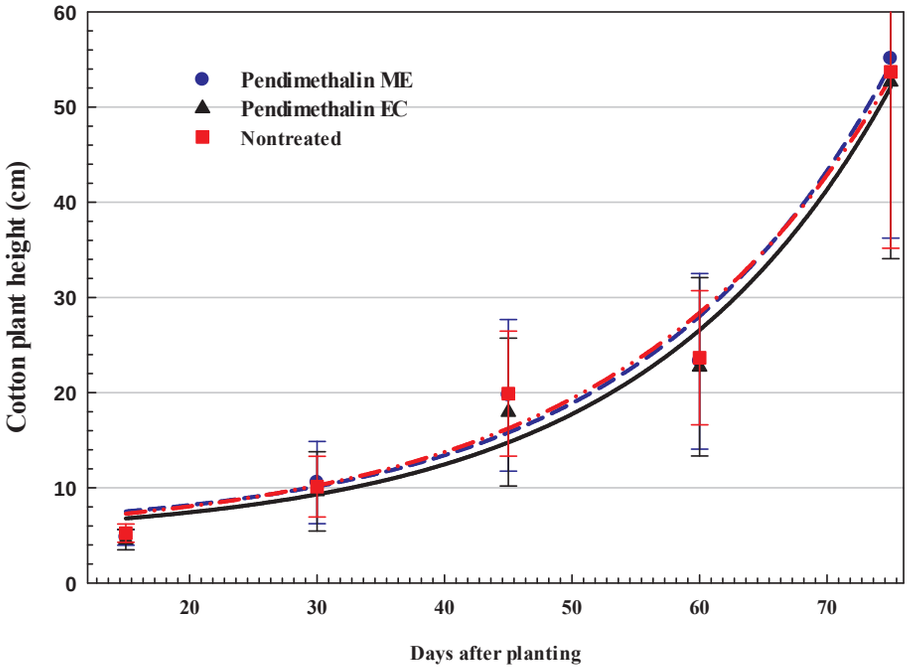


Figure 8. Cotton growth response as affected by pendimethalin formulation. The line represents the first-order regression equation. Data points are the means of replications with bars indicating the standard error of the mean:

$$\text{Fertilizer applied } y = 6.31 + \frac{0.0537\left[\left(e^{0.05137x}\right) - 1\right]}{0.05137} \quad P < 0.0001$$

$$\text{Spray applied } y = 5.62 + \frac{0.0516\left[\left(e^{0.0514x}\right) - 1\right]}{0.0514} \quad P < 0.0001$$

$$\text{Nontreated } y = 5.83 + \frac{0.0669\left[\left(e^{0.0471x}\right) - 1\right]}{0.0471} \quad P < 0.0001$$

	Rate of cotton growth[b]					
Application timing	***a*[c]**		**95% CL**	**b**		**95% CL**
Preemergence	0.1104	a	±0.0621	0.0395	a	±0.0067
At cotton emergence	0.0649	a	±0.0384	0.0488	a	±0.0099
3rd leaf cotton	0.0550	a	±0.0372	0.0512	a	±0.0112
6th leaf cotton	0.0415	a	±0.0319	0.0559	a	±0.0126
Nontreated	0.0689	a	±0.0594	0.0463	a	±0.0145

[a]Each application timing for first-order rate constants for each column followed by the same letter are not significantly different according to Fisher's protected LSD test (P≤0.05). General linear models procedures were used for mean separation with 95% asymptotic confidence intervals.

[b]Rates of cotton growth were calculated by nonlinear regression of the herbicide treatments with respect to time in days after planting.

[c]Abbreviations: *a*, rate of cotton growth; CL, confidence limit.

Table 5. Rate of cotton growth (*a*) as a response to timing of pendimethalin application.[a]

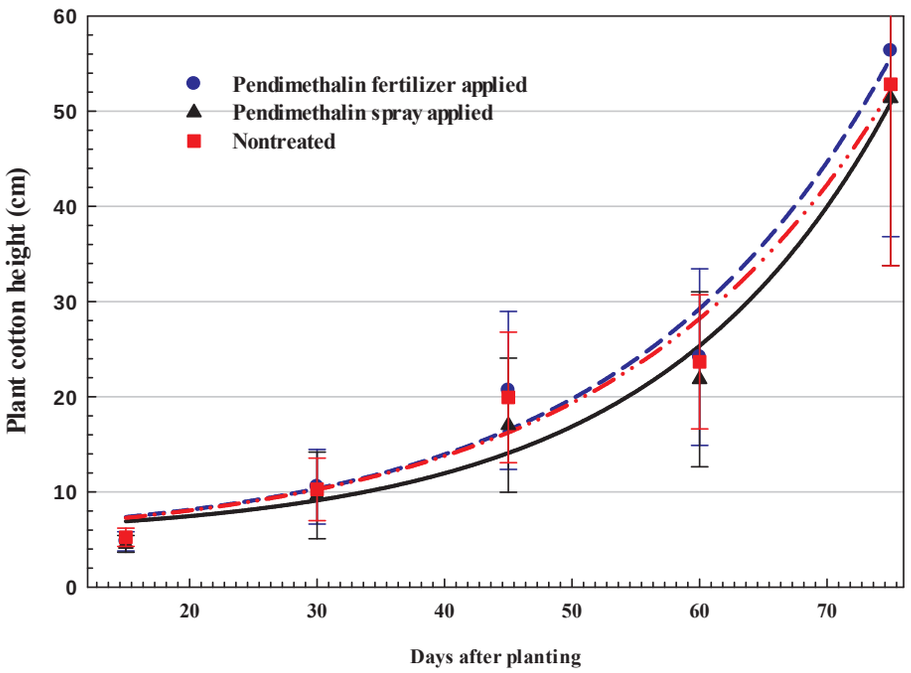


Figure 9. Cotton growth response as affected by application method. The line represents the first-order regression equation. Data points are the means of replications with bars indicating the standard error of the mean:

$$\text{Pendimethalin ME } y = 5.93 + \frac{0.0653\left[\left(e^{0.0485x}\right) - 1\right]}{0.0485} \quad P < 0.0001$$

$$\text{Pendimethalin EC } y = 5.95 + \frac{0.0418\left[\left(e^{0.0545x}\right) - 1\right]}{0.0545} \quad P < 0.0001$$

$$\text{Nontreated } y = 5.78 + \frac{0.0689\left[\left(e^{0.0463x}\right) - 1\right]}{0.0463} \quad P < 0.0001$$

5.3. Cotton yield

Cotton yields reflected the trends initially revealed with cotton injury. Pendimethalin EC spray applied (3,610 kg ha^{-1}) had lower cotton yield than pendimethalin EC applied on fertilizer (4,010 kg ha^{-1}) and both pendimethalin ME treatments (≥4,000 kg ha^{-1}) (Table 6). The treatments that caused the greatest cotton injury for application method by timing interaction had the lowest yields, included both spray AE and 3rd leaf stage of cotton applications. Application timing of pendimethalin on fertilizer did not affect cotton yield. When averaged over application method, cotton yield for the pendimethalin ME treatments had equivalent cotton yields

across all application timings. Only pendimethalin EC applied AE or 3rd leaf stage cotton lower yields compared to the typical PRE use-pattern.

None of the PRE or 6th leaf application treatments displayed crop injury, significant decreased growth, or significant yield loss. The AE and 3rd leaf application treatments resulted in significant cotton crop injury and decreased yield, with pendimethalin EC treatments having greater injury than the pendimethalin ME, with spray applications exhibiting more injury than the fertilizer-applied treatments. The fertilizer application of pendimethalin at 3rd leaf did not significantly enhance crop injury, but did enhance injury at the AE application timing. Based on injury, subsequent height, and final yield measurements, pendimethalin ME caused less injury than pendimethalin EC, and fertilizer application of both formulations was less injurious than spray application. The AE application timing was prone to greater injury by any formulation or application method and should be avoided. The 3rd leaf appears to be more prone to spray injury than fertilizer injury.

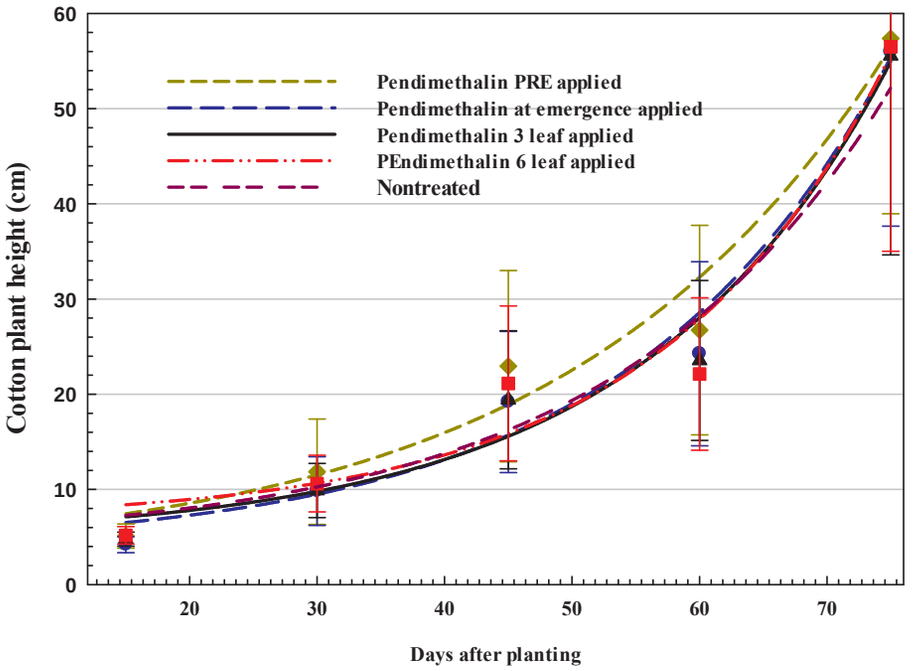


Figure 10. Cotton growth response as affected by application timing. The line represents the first-order regression equation. Data points are the means of replications with bars indicating the standard error of the mean:

$$\text{Pendimethalin PRE applied } y = 5.18 + \frac{0.1104\left[\left(e^{0.0395x}\right) - 1\right]}{0.0395} \quad P < 0.0001$$

$$\text{Pendimethalin AE applied } y = 5.08 + \frac{0.0649\left[\left(e^{0.0488x}\right) - 1\right]}{0.0545} \quad P < 0.0001$$

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Pendmethalin 3 leaf applied $y = 5.87 + \frac{0.0550\left[\left(e^{0.0512x}\right) - 1\right]}{0.0512}$ $P < 0.0001$

Pendimethalin 6 leaf applied $y = 7.42 + \frac{0.0450\left[\left(e^{0.00559x}\right) - 1\right]}{0.0559}$ $P < 0.0001$

Nontreated $y = 5.78 + \frac{0.0689\left[\left(e^{0.0463x}\right) - 1\right]}{0.0463}$ $P < 0.0001$

			Yield			LSD
Formulation	**Application**	**Timing**	**kg/ha**			
Pendimethalin EC	Spray		3610	b	(145)	252
	Fertilizer		4010	a	(149)	
Pendimethalin ME	Spray		4000	a	(149)	
	Fertilizer		4230	a	(154)	
	Spray	PRE	4130	a	(176)	370
	Fertilizer	PRE	4260	a	(180)	
	Spray	AE	3570	b	(172)	
	Fertilizer	AE	4050	a	(175)	
	Spray	3LF	3450	b	(170)	
	Fertilizer	3LF	4070	a	(176)	
	Spray	6LF	4080	a	(188)	
	Fertilizer	6LF	4110	a	(182)	
Pendimethalin EC		PRE	4140	a	(181)	369
Pendimethalin ME		PRE	4250	a	(178)	
Pendimethalin EC		AE	3630	bc	(169)	
Pendimethalin ME		AE	3980	ab	(175)	
Pendimethalin EC		3LF	3510	c	(169)	
Pendimethalin ME		3LF	4000	ab	(174)	
Pendimethalin EC		6LF	3960	ab	(185)	
Pendimethalin ME		6LF	4230	a	(185)	

[a]Because *proc Mixed* measures pair-wise differences, multiple LSDs may be obtained. In these cases, the LSD (α=0.05) included is the mean LSD for all treatments.

[b]Pendimethalin rates were 1.1 kg ai/ha for the EC and ME formulations.

[c] Abbreviations: EC, emulsifiable concentrate (0.41 kg ai/L); ME, microencapsulated (0.47 kg ai/L); PRE, prior to plant emergence; AE, at seedling emergence; 3LF, to 3-leaf cotton; 6LF, 6-leaf cotton

[d]Means within a variable followed by the same letter are not significantly different using Fisher's protected $LSD_{(P=0.05)}$. Standard error of the mean for that treatment enclosed in ().

[f]Fertilizer (10-10-10) rate was 280 kg/ha, with all plots equally treated. Pendimethalin EC and ME were spray impregnated.

Table 6. Interaction effects between pendimethalin formulation, application method, and application timing for yield in conventional tillage cotton.

6. Discussion

Comparing the EC to ME pendimethalin formulations, when either spray or fertilizer impregnated applied, indicated the ME formulation consistently reduced cotton injury. The reason for the reduced cotton injury from the ME as compared to the EC-pendimethalin formulation is due to the microencapsulation. This has been observed with another ME formulated herbicide, alachlor [29]. While pendimethalin has lower volatilization than other dinitroanaline herbicides such as trifluralin [21], the ME formulation decreases volatilization and provides extended activity. As previously noted, pendimethalin half-lives of 74 to 114 days in soil have been reported [30], surface applied half-lives of 4 to 6 days can occur due to volatilization, photo-chemical, and other degradation processes with EC formulation [21]. By utilizing the ME formulation, supplementing, or even delaying pendimethalin application to in-season timings impregnated on fertilizer, growers could extend residual weed control until cotton can canopy and suppress weed growth. Our recommendation would be to utilize pendimethalin as a PRE application followed by an in-season application impregnated on prilled fertilizers to extend weed control. Total seasonal pendimethalin applications in cotton are up to 2.24 kg ha^{-1}. Cotton fertility recommendations for the southeast include in-season nitrogen applications which could be pendimethalin impregnated. Given advanced global positioning systems (GPS) used for accurate fertilizer applications, even greater precision for pesticide applications can now be achieved in tandem with these advanced technologies. These data indicate that cotton growers can successfully incorporate in-season pendimethalin application into their cotton production programs with minimal potential for cotton injury, while supplementing weed control with a residual herbicide.

Author details

Timothy Grey[1*] and Theodore Webster[2]

*Address all correspondence to: tgrey@uga.edu

1 Crop and Soil Sciences Department, University of Georgia, Tifton Georgia, USA

2 Crop Protection and Management Research Unit, USDA-ARS, Tifton Georgia, USA

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