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Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) Increases Herbicide Use, Tillage, and Hand-Weeding in Georgia Cotton

Lynn M. Sosnoskie and A. Stanley Culpepper*

In 2005, the existence of glyphosate-resistance in Palmer amaranth was confirmed at a single 250 ha field site in Macon County, Georgia. Currently, all cotton producing counties in Georgia are infested, to some degree, with glyphosate-resistant Palmer amaranth. In 2010 and 2011, surveys were administered to Georgia growers and extension agents to determine how the development of glyphosate-resistance has affected weed management in cotton. According to respondents, the numbers of cotton acres that were treated with paraquat, glufosinate and residual herbicides effective against Palmer amaranth more than doubled between 2000 to 2005 and 2006 to 2010. Glyphosate use declined between 2000 to 2005 and 2006 to 2010 although, on average, the active ingredient was still applied to a majority of cotton acres. Although grower herbicide input costs have more than doubled following the evolution and spread of glyphosate resistance, chemically-based control of Palmer amaranth is still not adequate. As a consequence, Georgia cotton growers hand weeded 52% of the crop at an average cost of $57 per hand-weeded ha; this represents a cost increase of at least 475% as compared to the years prior to resistance. In addition to increased herbicide use and hand weeding, growers in Georgia are also using mechanical, in-crop cultivation (44% of acres), tillage for the incorporation of preplant herbicides (20% of the acres), and post-harvest deep-turning (19% of the acres every three years) for weed control. Current weed management systems are more diverse, complex and expensive than those employed only a decade ago, but are effective at controlling glyphosate-resistant Palmer amaranth in glyphosate-resistant cotton. The success of these programs may be related to producers improved knowledge about herbicide resistance, and the biological attributes that make Palmer amaranth so challenging, as well as their ability to implement their management programs in a timely manner.

Nomenclature: 2,4-D; diuron; fomesafen; flumioxazin; fluometuron; glyphosate; glufosinate; MSMA; paraquat; pendimethalin; pyrithiobac; *S*-metolachlor; trifluralin; Palmer amaranth, *Amaranthus palmeri* (S. Wats); cotton, *Gossypium hirsutum* L.

Key words: Extension, glyphosate-resistance, resistance management, survey.

Many recent crop improvement initiatives have focused on the generation and advancement of transgenic cultivars that are resistant to nonselective herbicides, the most important, to date, being glyphosate (Duke 2005; Duke et al. 2002; Green 2012; Kuiper at al. 2000; Marshall 1998; Riches and Valverde 2002). Since their introduction, GR crops have been planted on an increasing number of acres (Bonny 2008; Gianessi 2005; Green 2012; James 2012). In 2011, herbicide resistance (primarily glyphosate resistance) traits in canola (*Brassica napus* L.), corn (*Zea mays* L.), cotton, soybean [*Glycine max* (L.) Merr.] and sugarbeet (*Beta vulgaris* L.) occupied 59% of the 160 million ha, worldwide, that were planted to biotech crops (Brookes and Barfoot 2010; James 2012). With respect to the United States, Martino-Catt et al. (2012) reported that 80, 88 and 94% of the total corn, cotton and soybean acreage, respectively, in 2009 was planted to cultivars that were resistant to glyphosate.

The benefits derived from GR crops are numerous, although simplified production practices and increased grower revenues are regularly advertised as being two of the most significant advantages (Brookes and Barfoot 2010; Dill 2005; Dill et al. 2008; Duke 2005; Duke et al. 2002; Green 2012; Kuiper at al. 2000; Marshall 1998; Radosevich et al. 1992; Riches and Valverde 2002; Young 2006). Analysis of economic data suggests that the use of herbicide-resistant cotton has improved overall producer profitability (Brookes and Barfoot 2010). According to Brookes and Barfoot (2010), cumulative net farm income benefits for cotton in the US increased by $799 million between 1997, when GR cultivars were first released, and 2008. The adoption of GR cotton has also resulted in decreased herbicide use. Since 1997, the US, Australia, Argentina, and South Africa have reduced the amounts of

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herbicide active ingredients applied to cotton by a total of 6.3 million kg (Brookes and Barfoot 2010). Concurrently, the associated environmental impact quotient (EIQ), an indicator that estimates the comprehensive environmental impact of a pesticide or pesticide program, fell by 5.5% (Brookes and Barfoot 2010). The cumulative (1997 to 2008) value of nonpecuniary benefits derived from GR cotton, such as the adoption of conservation tillage and reduced herbicide use, was an estimated $461 million for US growers (Brookes and Barfoot 2010).

Because of its slow emergence and growth, cotton is susceptible to early season weed competition. Consequently, conventional weed management programs relied heavily on preplant tillage and the use a diverse suite of preplant, PRE, POST and post-directed herbicides to suppress weed emergence and development. The use of GR crop technology greatly simplified cotton weed management by allowing growers to safely apply glyphosate over the top of the crop in order to control a broad spectrum of competitive species. This, in turn, facilitated the transition of many growers to conservation tillage systems and postemergence-dominated weed management programs (Givens et al. 2009a; Givens et al. 2009b; Shaner 2000; Young 2006). According to a survey conducted by Givens et al. (2009a), 46% of continuous GR cotton growers shifted from conventional- to reduced- or no-tillage. With respect to herbicide use, Shaner (2000) and Young (2006) reported that the application of arsenates, photosystem II (PS II)-inhibitors and dinitroanilines in cotton decreased in the years directly following the release of GR cultivars, whereas glyphosate use more than doubled. Givens et al. (2009b) reported that 56% of growers engaged in continuous GR cotton production applied glyphosate to their crops up to two times per year, while 42% applied glyphosate three or more times per year. The unprecedented use of glyphosate in cotton over space and time, and the limited use of other control strategies, subsequently led to the development of GR Palmer amaranth (Culpepper et al. 2006), which currently infests millions of hectares across 13 states (Heap 2013).

The widespread adoption of GR cultivars has directly impacted chemical and cultural weed management practices in cotton and other crops (Brookes and Barfoot 2010; Givens et al. 2009a; Givens et al. 2009b; Shaner 2000; Young 2006); it is logical to assume that the evolution of GR Palmer amaranth would prompt additional, compensatory shifts in weed control strategies in Georgia cotton production. The objective of this study was to determine how GR Palmer amaranth has influenced producer use of herbicides, tillage and hand weeding in Georgia cotton.

Materials and Methods

Grower Survey. A survey instrument was designed by the authors to identify changes in cotton growers' weed management practices, at the farm level, in response to GR Palmer amaranth. To reduce the potential for bias, a sociologist was consulted regarding the phrasing of the questions. An expert committee, which consisted of six university research personnel, three state cooperative extension agents and two members of the agrochemical industry, reviewed the document for composition and content prior to distribution. The finalized survey included 18 questions, the majority of which focused on cotton production practices before and after the discovery of GR Palmer amaranth. In order to simplify the survey and facilitate its completion, the 'before resistance' and 'after resistance' categories were designated as including the years 2000 to 2005 and 2006 to 2010, respectively. The existence of GR Palmer amaranth in Georgia was confirmed in 2005 (Culpepper et al. 2006); since 2006, state- and county-level cotton extension programs have been heavily focused on preventing and managing the spread of the GR biotype. Ultimately, the questionnaire was arranged into five sections, each with a distinct focus including: (1) farm size (including rented acreage) and crop composition, (2) herbicide usage, (3) adoption of tillage, (4) adoption of hand-weeding and (5) the most troublesome weeds of cotton production.

Farm Crop Composition. The first portion of the survey asked growers to state whether or not they currently produced row and forage crops, poultry and eggs, livestock, forestry products, vegetables, or ornamental landscape plants and turf on their farms. In a follow-up question, which was specifically concerned with the production of traditional agronomic crops, growers were asked whether or not they had planted peanuts, winter wheat, rye and conventional or genetically-modified (GM) herbicide-resistant (HR) cotton, soybean and corn on their farmed acres both before and after the confirmation of GR Palmer amaranth in Georgia.

Herbicide Usage. Participants were presented with a list of herbicides available for weed control in cotton

(Culpepper and Sosnoskie 2011) and then asked whether the product had been applied on their farms in 2000 to 2005 and 2006 to 2010. Herbicides were grouped into three categories that corresponded to their application timing in cotton including: (1) preplant burndown and/or PRE, (2) POST, and (3) POST-directed at layby; herbicides that could be applied at multiple stages of cotton development were listed in each appropriate category. If a grower indicated that they had used a given herbicide for cotton weed control, they were then asked to estimate, on average, how many acres were treated per year over the given time periods. In order to understand how changes in herbicide use practices may have affected the individual farm economy, growers were also asked to estimate the cost, on a per acre basis, of their cotton herbicide programs before and after resistance.

Adoption of Tillage. Growers were asked to describe what production practices (strip-tillage into winter weed residue, strip-tillage into fall-planted cover crops or conventional tillage) they employed before and after discovery of GR Palmer amaranth. Respondents were also questioned about the importance of in-season cultivation in their operations in 2000 to 2005 and 2006 to 2010. Growers indicating that they had used mechanical cultivation for weed control were directed to estimate, on average, the number of acres that were cultivated, yearly, for the 2000 to 2005 and 2006 to 2010 time periods.

Adoption of Hand-Weeding. Growers were asked to describe how many of their cotton production acres, on average, were hand-weeded from 2000 to 2005 and 2006 to 2010 and what their estimated average cost per acre was for the practice during each time period.

Most Troublesome Weeds. Growers were asked to rank the most commonly occurring weeds in cotton production in Georgia (Webster 2001, 2005, 2009) with respect to how problematic each species was on their farm both before and after confirmation of GR Palmer amaranth. Growers were also allowed to 'write-in' and rank weed species that they felt were erroneously excluded from the list. To ensure consistency among responses, growers were directed to consider an individual species' pervasiveness and relative insensitivity to control measures when assigning ranks.

Extension agents from 16 cotton producing counties in Georgia each invited between two and eight representative growers to participate in the survey (Table 1). Producers were disqualified from the study if either they, or an immediate family member, worked for an organization that produced, distributed, or sold farm chemicals or seed. Potential participants were also excluded from the survey if they were not the primary individual responsible for making decisions regarding crop trait selection and pest management for their farming operation. Ultimately, written surveys were administered to 65 growers between October of 2010 and March of 2011. These respondents accounted for a total of 53,500 ha of cotton, or 10% of the 2010 crop in Georgia (Wolfe and Luke-Morgan 2011). Differences in estimated grower use (reported as mean percent of acres treated) of individual herbicides and mechanical weed control practices before and after the discovery of GR Palmer amaranth were evaluated using paired *t*-tests ($\alpha = 0.05$).

Cooperative Extension Agent Survey. Two different written surveys were administered to University of Georgia Cooperative Extension agents. Ten agents from counties (representing 18% of the cotton acreage in Georgia for 2010) returned a survey that was similar in structure and format to the one provided to the grower-cooperators that was designed to capture information regarding changes in county-wide cotton production practices (Table 1). Because of the limited sample size, this set of survey data was not statistically analyzed. In the second survey, 52 agents (representing 76% of the cotton acreage during 2010) were asked in person (1) the number of acres receiving mechanical incorporation of herbicides just before cotton planting and (2) the number of acres being deep turned, both in an effort to manage GR Palmer amaranth.

Results and Discussion

Grower Crop Composition. A total of 65 growers from 16 cotton producing counties participated in the survey. With respect to farm gate value, these counties accounted for almost \$200 million, which is more than 35% of the total crop value for the state of Georgia in 2010 (Wolfe and Luke-Morgan 2011) (Table 1). According to survey respondents, mean individual farm size was approximately 800 ha and the average producer had been farming for 25 years. Georgia agriculture is diverse (Wolfe and Luke-Morgan 2011) and this diversity was well represented in the survey; all of the participating growers produced agronomic crops, approximately

Table 1. Cotton production and economic data for counties represented by survey participants.

County[a]	Number of growers participating	Cotton hectares (thousands)	Farm gate value (millions)
Berrien*	5	8.8	$14.3
Candler*	2	3.6	$6.5
Grady*	5	9.1	$17.0
Irwin	3	11.4	$20.5
Macon	2	4.0	$6.4
Miller*	2	11.5	$21.6
Randolph	2	2.9	$6.0
Screven	4	5.2	$12.1
Seminole*	3	9.9	$14.1
Sumter	8	7.2	$11.5
Taylor*	4	< 1	$0.2
Terrell*	5	6.3	$9.5
Tift	5	7.6	$12.2
Thomas	4	10.5	$17.3
Turner*	8	8.4	$15.1
Worth*	3	19.9	$37.8

[a] An asterisk (*) indicates that the University of Georgia Cooperative Extension county agent also returned a survey. Although no growers from Colquitt County, Georgia, (21.9 thousand hectares of cotton produced worth $42.1 million) participated in the survey, the extension agent did complete and return a questionnaire.

36% engaged in livestock or forestry operations, 19% produced vegetables and 3% managed poultry houses or sod farms.

With respect to agronomic crops, herbicide-resistant cotton cultivars were grown by almost all of the respondents (> 97%) in 2000 to 2005 and 2006 to 2010 (Figure 1). Conventional cotton varieties were planted by 11% of growers in 2006 to 2010, as compared to 49% of growers in 2000 to 2005. Fifty-four percent to 64% of the growers planted HR soybean and corn cultivars in 2006 to 2010, as compared to 33% to 41% during 2000 to 2005; conventional corn and soybean production decreased by 27% and 71%, respectively, over the same time periods. Although GR Palmer amaranth is widespread across the Southeast and Mid-South (Culpepper et al. 2010; Heap 2013), continued adoption of GR crops suggests there is value in GR technology even in fields infested with GR weeds. This is likely the result of high yielding germplasm and the effectiveness of glyphosate on numerous other weed species (Anonymous 2013b; Collins and Whitaker 2012; USDA 2012; Webster 2009). Herbicide resistance, particularly glyphosate resistance, is an important feature in most breeding programs; as a consequence, the most advanced genetics will likely be combined with the glyphosate

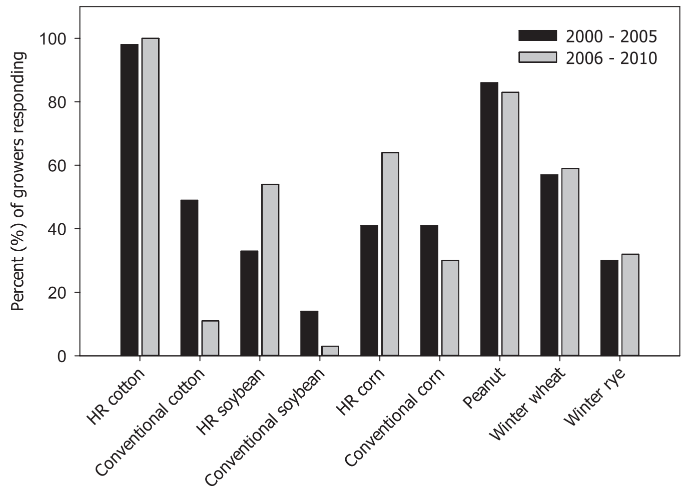

Figure 1. Agronomic crop composition of grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth.

resistance trait. The proportion of growers planting peanut, winter wheat and winter rye remained relatively unchanged between 2000 to 2005 and 2006 to 2010 (Figure 1).

Herbicide Use. Growers reported ($P < 0.05$) changes in the use of glyphosate, glufosinate and paraquat for preplant burndown following the discovery of GR Palmer amaranth (Figure 2). Growers estimated that, on average, 86% of their cotton acres were treated with glyphosate in 2000 to 2005; in 2006 to 2010 this value decreased to 74%. In contrast to glyphosate, use of glufosinate and paraquat ($P < 0.05$) increased between 2000 to 2005 and 2006 to 2010. Prior to the discovery of GR Palmer amaranth, glufosinate and paraquat were applied to < 1% and 15% of Georgia's cotton acres, respectively; in 2006 to 2010, 25% to 29% of cotton acres received these herbicides as burndown applications. Similar trends in glyphosate, glufosinate and paraquat use were also reported by county extension agents (Figure 2). The increased adoption of paraquat and glufosinate, and the subsequent reduction in glyphosate use at burndown may have been influenced by extension efforts stipulating that fields must be free of Palmer amaranth at planting in order to reduce competitive interference and maximize crop yields. Both glufosinate and paraquat can be used, effectively, to control small emerged Palmer amaranth plants prior to planting (Anonymous 2013a; Coetzer et al. 2002; Culpepper et al. 2010). Agents and growers disagreed about the application of 2,4-D. According to growers, the use of 2,4-D at burndown has not changed over time, while agents suggested a sharp three-fold rise in use

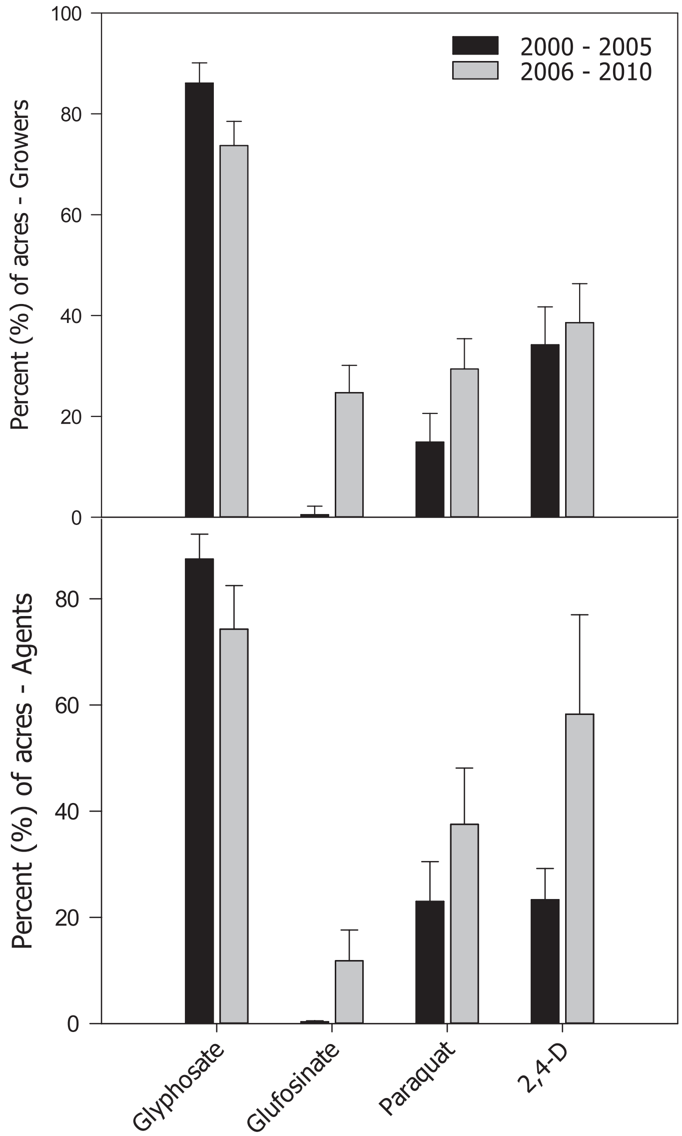

Figure 2. Changes in preplant burndown or PRE herbicide use on grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth.

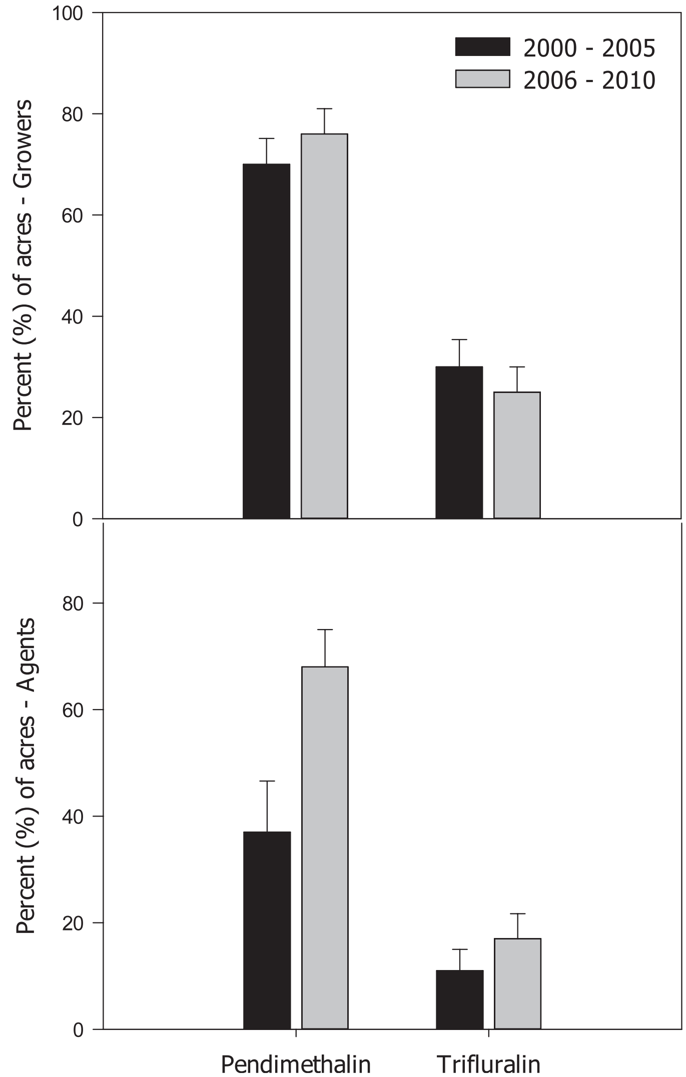

Figure 3. Changes in preplant and PRE pendimethalin and trifluralin use on grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth.

(Figure 2). Synthetic auxins can be used to effectively control problematic broadleaves such as common cocklebur (*Xanthium strumarium* L.), sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], Palmer amaranth, and morningglory spp. (*Ipomoea* spp.) (Ferrell and Witt 2002; Lancaster et al. 2005; Norsworthy et al. 2008); agents may have reported higher uses of 2,4-D across their counties because they are actively recommending the product as an additional burndown tool.

Grower use of pendimethalin and trifluralin at-plant remained constant over time (Figure 3). Growers indicated that they applied pendimethalin to 70% of their cotton acres in 2000 to 2005 and 76% of acres in 2006 to 2010. Trifluralin was used on 25% to 30% of their cotton acres both before and after the development of resistance. Agents' estimates regarding trifluralin use was similar to those of the growers (Figure 3). Use of the dinitroaniline herbicides likely remained consistent across time on many farms because of the widespread occurrence Florida pusley (*Richardia scabra* L.). Control of Florida pusley by glyphosate is often sporadic, whereas the dinitroaniline herbicides are effective at managing this species (Johnson and Mullinex 2002; Webster 2009; York 2012). Extension agents' estimations regarding pendimethalin use differed substantially from growers' assessments, with extension personnel indicating that the mean percent of acres treated with pendimethalin nearly doubled following the discovery of GR Palmer amaranth. Both sets of respondents indicated that pendimethalin was applied to a greater proportion of cotton acres than was trifluralin; pendimethalin is less volatile than trifluralin and may be a better option for when incorporation efforts might be delayed (Weber 1990).

Grower use of two protoporphyrinogen oxidase-inhibitors (PPO-inhibitors), flumioxazin and fomesafen, increased ($P \leq 0.05$) after the discovery of GR Palmer amaranth (Figure 4). Before resistance, growers applied flumioxazin for burndown and fomesafen PRE to 3% and 8% of their cotton acres, respectively. After resistance, the percentages of acres treated had increased ten-fold for both products. Data provided by cooperative extension agents regarding flumioxazin and fomesafen use agreed with growers' estimates (Figure 4). Flumioxazin and fomesafen are the two most effective residual herbicides available for controlling Palmer amaranth biotypes that are resistant to both glyphosate and acetolactate synthase-inhibiting (ALS-inhibiting) herbicides in cotton (Whitaker et al. 2011). The potential for overuse of these two herbicides is a serious concern for cotton production in Georgia and the rest of the Southeast. Resistance to the PPO-inhibitors has developed in six weed species, worldwide, including a dioecious amaranth (common waterhemp [*Amaranthus rudis* Sauer]) that is common to Midwestern agricultural systems (Heap 2013). Consequently, current extension efforts are focused on promoting the judicious and responsible application of this herbicide mechanism of action in a system that uses over six herbicide modes of action in conjunction with tillage, cover crops, and/or hand weeding (Culpepper et al. 2010).

According to growers, diuron use increased slightly, although not significantly ($P > 0.05$), between 2000 to 2005 and 2006 to 2010; diuron was applied preplant or PRE to 38% of cotton acres before resistance and to 46% of acres after resistance (data not shown). Agents also reported an increase in diuron use, although the change in magnitude was more pronounced; according to extension personnel, diuron was applied to 3% of cotton acres in 2000 to 2005 and to 26% of cotton acres in 2006 to 2010. Diuron plus paraquat offers the most effective control of emerged Palmer amaranth prior to planting cotton in Georgia (Culpepper and Sosnoskie 2011), which likely contributed to the increased use of both products. Growers reported a decline in fluometuron PRE use, from 25% of acres in 2000 to 2005 to 15% of acres in 2006 to 2010 (data not shown). Fluometuron is less effective than diuron or fomesafen applied at-planting for the control of GR Palmer amaranth; thus, fluometuron was simply displaced by more effective options (Whitaker et al. 2011). According to both growers and agents, pyrithiobac used as a PRE remained statistically unchanged over time; growers and agents indicated that pyrithiobac was applied to no more than 25% and 12% of the cotton acres, respectively, for both 2000 to 2005 and 2006 to 2010 (data not shown).

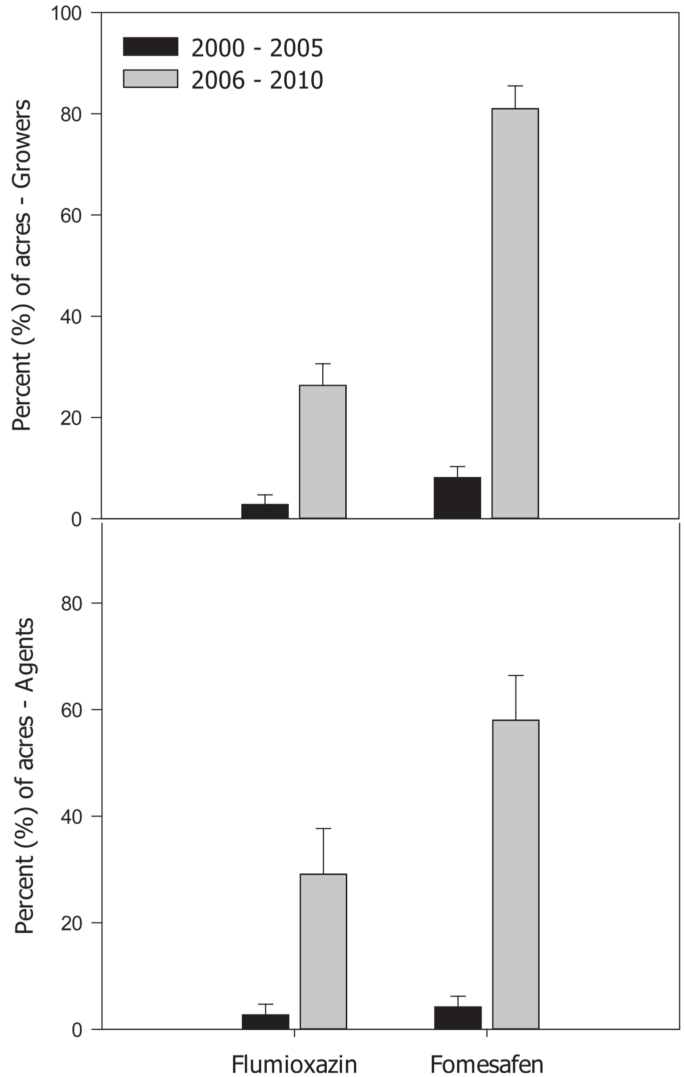

Figure 4. Changes in flumioxazin preplant burndown or fomesafen PRE use on grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth.

Although less glyphosate was applied POST over-the-top of cotton in 2006 to 2010, as compared to 2000 to 2005 (Figure 5), the active ingredient was still used on over 75% of the acres. Glyphosate remains a desirable chemical as it effectively controls numerous other weeds commonly infesting Georgia cotton fields (Anonymous 2013b; Webster 2009). In contrast to glyphosate, an increase ($P < 0.05$) in the use of glufosinate POST was reported by both growers and agents (Figure 5). Less than 1% of the respondents' cotton acres were treated with glufosinate before the discovery of GR Palmer amaranth; use increased to at least 30% of the acres after

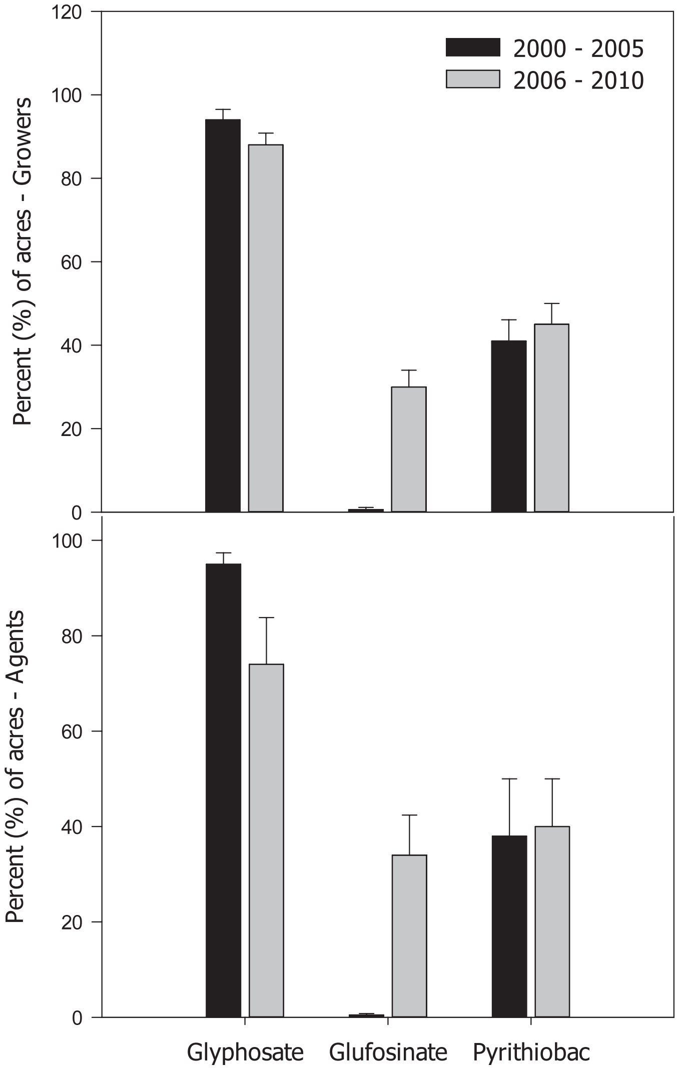

Figure 5. Changes in POST applied herbicide use on grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth.

resistance. Increased glufosinate use is associated with the increased adoption cotton cultivars tolerant to topical applications of glufosinate. Cotton acreage in Georgia planted to glufosinate-tolerant cultivars increased from < 1% in 2004 to 49% in 2012 (USDA 2004; USDA 2012). According to both growers and agents, the use of pyrithiobac POST has remained unchanged over time with use ranging from 38% to 41% of the acres (Figure 5). Although pyrithiobac can effectively control Palmer amaranth (Burke and Wilcut 2004), populations with acetolactate synthase-resistance are spread through the state and may have been a limiting factor on the potential for additional adoption (Vencill et al. 2002; Wise et al. 2009). Growers and agents indicated that the use of *S*-metolachlor POST increased from 20% before resistance to 42 to 54% after confirmation of GR Palmer amaranth (data not shown). Although *S*-metolachlor does not control emerged Palmer amaranth, growers include it in with POST applications as they adopt the concept of overlapping residual herbicides throughout the season (York 2012).

According to growers, glyphosate was directed at layby to fewer cotton acres in 2006 to 2010 (46% of acres), as compared to 2000 to 2005 (62% of acres) (Figure 6); agents also noted similar trends in glyphosate use between 2000 to 2005 and 2006 to 2010 (Figure 6). Glyphosate use post-directed likely declined because other, more effective alternatives are available for the control of GR Palmer amaranth at cotton layby (Culpepper and Sosnoskie 2011; York 2012). Agents indicated that the use of both diuron and MSMA increased at least 30% following the discovery of GR Palmer amaranth (Figure 6); a combination of diuron plus MSMA is the most effective option at layby to control emerged GR Palmer amaranth. According to both groups, the use of flumioxazin and *S*-metolachlor at layby also increased over time. Growers indicated that flumioxazin and *S*-metolachlor were applied, on average, to < 1% and 10% of Georgia's cotton acres, respectively, in 2000 to 2005; in 2006 to 2010, use increased to 23% to 26% (Figure 6). Agents reported that flumioxazin was applied to 4% of cotton acres before the discovery of GR Palmer amaranth and 9% of cotton acres afterwards; *S*-metolachlor was applied to 5% of cotton acres in 2000 to 2005 and 30% of cotton acres in 2006 to 2010 (Figure 6). Flumioxazin and *S*-metolachlor are often mixed with other layby herbicides to prevent late emerging weeds (Whitaker et al. 2011; York 2012).

Glyphosate use, on a per acre basis, declined during burndown, POST, and PD timings after the discovery of GR Palmer amaranth; however, growers still estimated that they made 2.4 applications of glyphosate per season in cotton. These values are consistent with Young (2006), suggesting that glyphosate remains an important chemical tool for weed control in cotton, despite the incidence of GR Palmer amaranth. However, glyphosate is being displaced on some acres by a more effective POST herbicide option for the control of Palmer amaranth. Applications of glufosinate increased from less than one application per season before resistance up to two applications per season afterwards.

Tillage. Although tillage is an effective means for managing Palmer amaranth (Culpepper et al. 2010; York 2012), neither growers nor agents reported any significant changes in preplant tillage practices

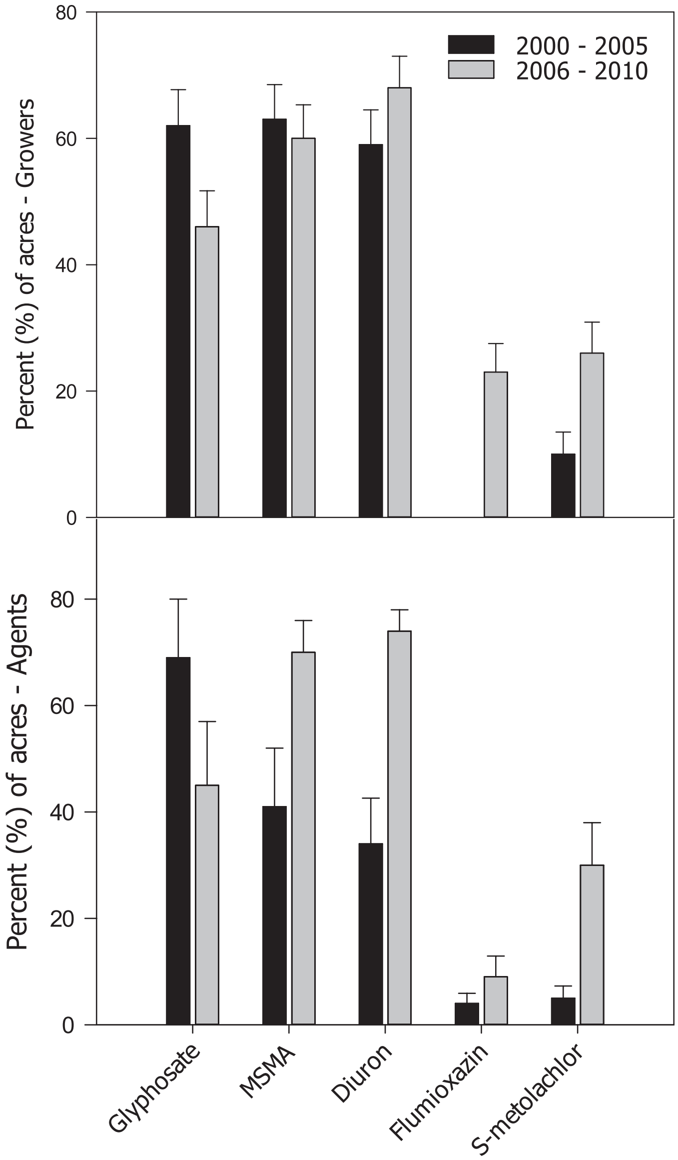

Figure 6. Changes in post-directed herbicide use on grower farms before (2000 to 2005) and after (2006 to 2010) the discovery of GR Palmer amaranth. Data represent responses provided by cooperative extension agents, only.

following the development of GR Palmer amaranth. Growers and agents reported that the acres devoted to strip-tillage into winter weeds, strip-tillage into cover crops and conventional tillage ranged from 21% to 35%, 24% to 36%, and 36% to 43%, respectively, for both 2000 to 2005 and 2006 to 2010 (data not shown). With respect to mechanical weed control in-crop, growers estimated that 34% of cotton acres were cultivated in 2000 to 2005; in 2006 to 2010, this value increased ($P \leq 0.05$) to 44%. Agents reported that 32% of the cotton acreage was cultivated in 2006 to 2010 as compared to 13% in 2000 to 2005. Although cultivation only controls weeds in-between the cotton row, it can be used to effectively reduce Palmer amaranth plants escaping earlier weed management approaches in the row middle. According to the survey of Georgia county agents that was conducted in 2010, cotton farmers were using tillage to mechanically incorporate herbicides on 106,990 ha of land each year and deep turned 103,674 ha of land every three years in an effort to reduce the impact of Palmer amaranth on cotton production. Research has shown that physical incorporation of herbicides prior to planting not only improves the level of control, but also improves the consistency of control especially in dry land production (Kichler et al. 2010, Kichler et al. 2011). Additionally, deep turning the soil can place Palmer amaranth at a depth in the soil profile in which Palmer amaranth does not emerge thereby improving control (Keeley et al. 1987).

Hand-Weeding. The proportion of cotton acres being hand-weeded increased between 2000 to 2005 and 2006 to 2010. Growers and agents estimated that 3% to 5% of the cotton acres were hand-weeded before resistance; after resistance, hand-weeding acreage increased to 52% (according to growers) and 66% (according to agents) (data not shown). Hand-weeding operations that occurred prior to development of glyphosate resistance were typically conducted by growers that followed a cotton crop with vegetables, where herbicidal weed management tools are limited. After the development of resistance, hand-weeding was conducted in an effort to remove Palmer amaranth from fields prior to seed production and cotton harvesting. According to growers and agents, average hand-weeding costs before the discovery of GR Palmer amaranth amounted to less than $2 per ha; by 2006 to 2010, the mean cost of hand-weeding had increased to $27 per ha, when averaged across all farm acreage.

Most Troublesome Weeds. Grower and agent survey results suggest that weed shifts have occurred in Georgia cotton between 2000 to 2005 and 2006 to 2010 (data not shown). Thirty-six percent of the growers and 60% of the extension personnel surveyed indicated that the morningglory complex (*Ipomea* spp.) was the most significant weed problem facing Georgia growers in 2000 to 2005; 20% of both groups listed sicklepod as the second-most significant plant pest. No more than 13% of the surveyed growers or agents selected Palmer amaranth as being the most important weed species of cotton production in 2000 to 2005. Conversely, in 2006 to 2010, 92% of growers and 100% of the agents ranked Palmer amaranth as the most troublesome weed species infesting Georgia's cotton acreage. At the time the surveys were conducted, growers indicated that approximately 78% of their agricultural acreage was infested with GR Palmer amaranth.

Cotton weed management programs in Georgia have undergone, and are continuing to undergo, significant changes. With the adoption of GR cotton, growers moved away from residual herbicides and tillage towards reduced-tillage systems that were heavily dependent on multiple applications of glyphosate. Currently recommended programs are complex and expensive (mean herbicide costs have more than doubled following the development of glyphosate-resistance) but are proving successful in controlling GR Palmer amaranth in glyphosate and/or glufosinate-resistant cotton cultivars. Despite the increased cost and effort associated with current weed control recommendations, cotton, with a farm gate value of more than $1 billion, is still the most important row crop commodity in Georgia (Wolfe and Luke-Morgan 2011). In order to manage GR Palmer amaranth and prevent the development of new resistances, growers are rotating herbicide chemistries and limiting their reliance on a single mechanism of action, are applying residual herbicides throughout the cropping season, and are integrating herbicide programs with physical and cultural practices.

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