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# Adoption of Best Management Practices for Herbicide-Resistant Weeds in Midsouthern United States Cotton, Rice, and Soybean

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In fall 2011, cotton and soybean consultants from Arkansas, Louisiana, Mississippi, and Tennessee were surveyed through direct mail and on-farm visits, and rice consultants from Arkansas and Mississippi were surveyed through direct mail to assess the importance and level of implementation of herbicide resistance best management practices (HR-BMPs) for herbicide-resistant weeds. Proper herbicide timing, clean start with no weeds at planting, application of multiple effective herbicide modes of action, use of full labeled herbicide rates, and prevention of crop weed seed production with importance rating of $\geq$ 4.6 out of 5.0 were perceived as the most important HR-BMPs in all crops. Purchase of certified rice seed was on 90% of scouted hectares. In contrast, least important HR-BMPs as perceived by consultants with importance ratings of $\leq$ 4.0 in cotton, $\leq$ 3.7 in rice, and $\leq$ 3.8 in soybean were cultural practices such as manual removal of weeds; tillage including disking, cultivation, or deep tillage; narrow ($\leq$ 50 cm)-row crops, cover crops, and altered planting dates. Narrow crop rows and cover crops in cotton; altered planting dates in cotton and soybean; and cleaning of farm equipment and manual weeding in rice and soybean is currently employed on $\leq$ 20% of scouted hectares. Extra costs, time constraints, adverse weather conditions, lack of labor and equipment, profitability, herbicide-related concerns, and complacency were perceived as key obstacles for adoption of most HR-BMPs. With limited adoption of most cultural practices that reduce risks of herbicide-resistant weeds, there are opportunities to educate growers concerning the proactive need and long-term benefits of adopting HR-BMPs to ensure sustainable weed management and profitable crop production.

**Nomenclature**: Cotton, *Gossypium hirsutum* L.; rice, *Oryza sativa* L.; soybean, *Glycine max* (L.) Merr.
**Key words**: Glyphosate-resistant cotton, glyphosate-resistant soybean, glyphosate-resistant Palmer amaranth, herbicide-resistant weeds, weed management survey.

En el otoño de 2011, se encuestó a asesores para la producción de algodón y soya de Arkansas, Louisiana, Mississippi, y Tennessee mediante correo directo o visitas en finca, y a asesores de producción de arroz de Arkansas y Mississippi mediante correo directo, para evaluar la importancia y el nivel de implementación de las mejores prácticas de manejo de resistencia a herbicidas (HR-BMPs) para el manejo de malezas resistentes a herbicidas. El momento apropiado de aplicación del herbicida, la siembra en condiciones libres de malezas, la aplicación de múltiples herbicidas efectivos con diferentes modos de acción, el uso de la dosis alta del herbicida, y la prevención de producción de semilla de malezas dentro del cultivo fueron percibidas como las HR-BMPs más importantes en todos los cultivos con niveles de importancia $\geq$4.6 de 5.0. La compra de semilla certificada de arroz estuvo presente en 90% de las hectáreas evaluadas. En cambio, las HR-BMPs menos importantes según la percepción de los asesores con niveles de importancia $\leq$4.0 en algodón, $\leq$3.7 en arroz, y $\leq$3.8 en soya fueron prácticas culturales tales como la deshierba manual, la labranza con discos, el cultivo, o la labranza profunda, el uso de distancias de siembra reducidas entre hileras ($\leq$50 cm), uso de coberturas vivas, y modificación de fechas de siembra. El uso de distancias reducidas entre hileras y de coberturas vivas en algodón, la modificación de fechas de siembra en algodón y soya, y la limpieza de equipo agrícola y la deshierba manual en arroz y soya son utilizados actualmente en $\leq$20% de las hectáreas evaluadas. Costos extra, limitaciones en disponibilidad de tiempo, condiciones climáticas adversas, falta de mano de obra y equipo, rentabilidad, preocupaciones relacionadas a los herbicidas, y la complacencia fueron percibidos como los principales obstáculos para la adopción de la mayoría de las HR-BMPs. La limitada adopción de la mayoría de las prácticas culturales para reducir los riesgos de las malezas resistentes a herbicidas, indican que existen oportunidades para educar a los productores sobre la necesidad y los beneficios en el largo plazo de adoptar HR-BMPs para asegurar el manejo sostenible de malezas y la rentabilidad de la producción.

Overuse of glyphosate alone in glyphosate-resistant cotton and soybean production systems in the United States has led to shifts to more tolerant weed species and increasing occurrence of glyphosate-resistant weed species (Kruger et al. 2009; Reddy and Norsworthy 2010). Even after wide-spread glyphosate resistance in the midsouthern United States, some producers still continue to grow glyphosate-resistant cotton and soybean without rotation of crops or herbicide-resistant crop traits. In this region, glyphosate and glufosinate alone are still applied to 9 and 13% of reported glyphosate- and glufosinate-resistant cotton hectares, respectively (Riar et al. 2013c), and 17 and 35% of

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reported glyphosate- and glufosinate-resistant soybean hectares, respectively (Riar et al. 2013d). However, the prevalence of and concern with glyphosate-resistant Palmer amaranth *Amaranthus palmeri* (S.) Wats. has most notably led to increased use of soil-applied residual herbicides and tillage in the southern United States. (Nichols et al. 2009; Prince et al. 2012).

The glyphosate-resistant technology in rice, another important midsouthern crop, was available for one year in research programs, but was never brought to commercial production (Baldwin 2009). However, after the evolution of resistance to propanil and quinclorac in barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], which is the most important weed in rice, adoption of imidazolinone-resistant (IR; Clearfield®) rice increased tremendously (Norsworthy et al. 2007a). Cultivation of IR rice and increased use of imazethapyr and other labeled acetolactate synthase (ALS; EC 2.2.1.6)-inhibiting herbicides made control of barnyardgrass and red rice (*Oryza sativa* L.) easier, but at the cost of selection for ALS-resistant barnyardgrass (Riar et al. 2012a, 2013b), red rice (Rajguru et al. 2005); and rice flatsedge (*Cyperus iria* L.) (Riar et al. 2012b).

Adoption of best management practices for mitigating the risk of herbicide-resistant weeds (HR-BMPs) evolving along with control of resistant weeds that have already evolved is imperative for the sustainability of cropping systems (Green 2007). Acknowledging the importance, Norsworthy et al. (2012) recommended BMPs that can mitigate the risk of evolution of herbicide-resistant weeds. In a survey of 22 states in 2010, U.S. growers considered labeled herbicide rates and timings, scouting of fields before and after herbicide application, and crop rotation as their most effective practices for controlling glyphosate-resistant weeds (Prince et al. 2012). The survey also reported that over a period of five years (2005 to 2010), the growers' perceived effectiveness of applying correct label rates, rotating crops, and rotating herbicide chemistries remained similar, but perceived effectiveness increased for BMPs that recommend use of multiple chemistries including POST and residual herbicides and tillage. Increase in the utilization of residual herbicides and tillage corresponding to evolution of herbicide resistance was also reported by other surveys (Frisvold et al. 2009; Givens et al. 2011). Additionally, the survey of 22 U.S. states reported that southern growers were more concerned about glyphosate-resistant weeds, especially Palmer amaranth, compared to eastern and western U.S. growers (Prince et al. 2012); therefore, the importance ranking and adoption of various HR-BMPs are likely different in the South compared to the rest of the United States.

Consultants routinely scout fields and have first-hand information regarding crop production and weed management practices, and surveys of crop consultants can provide valuable information regarding grower adoption of HR-BMPs (Norsworthy et al. 2007b). Surveys were conducted with objectives to determine consultants' perspectives on the importance and adoption of various HR-BMPs in midsouthern U.S. cotton, soybean, and rice.

## Materials and Methods

In fall 2011, names and addresses of registered crop consultants were obtained from the Agricultural Consultants' Associations of Arkansas, Louisiana, Mississippi, and Tennessee. The survey questionnaire was hand-delivered to the randomly selected cotton and soybean consultants from Louisiana (61) and Tennessee (54), and was directly mailed to all of the registered crop consultants from Arkansas (255) and Mississippi (66). The survey in Arkansas and Mississippi was sent to all consultants because consultants were not specified by crops in the list provided by the Agricultural Consultants Associations of these states. Some of the consultants in each state scouted both cotton and soybean and were asked to complete a questionnaire separately for cotton and soybean. The rice survey was conducted only in Arkansas and Mississippi.

The soybean and cotton survey questionnaire contained four sections entitled (1) Weed Control Focus, (2) General Weed Management Questions, (3) Herbicide Resistance, (4) glyphosate-resistant Palmer amaranth (Riar et al. 2013d, 2013c). The rice survey contained only the first three sections (Norsworthy et al. 2013). The first, second, and fourth section of the cotton and soybean surveys and first and second sections of the rice survey are covered in other manuscripts focused on assessment of weed management practices and problem weeds of midsouthern U.S. cotton (Riar et al. 2013c), rice (Norsworthy et al. 2013), and soybean (Riar et al. 2013d).

The current paper focuses on the third section. Consultants were asked about the presence of herbicide-resistant weeds in their scouted cotton, rice, and soybean fields and were provided with a list of HR-BMPs: (1) start clean; (2) proper herbicide timing; (3) apply multiple effective herbicide modes of action (MOAs) targeting the most problematic weeds; (4) use of full labeled herbicide rates; (5) prevent in crop weed seed production; (6) crop rotation; (7) rotate herbicide-resistant traits; (8) prevent post-harvest weed seed production; (9) prevent seed production in ditchbanks; (10) clean tillage and harvest equipment (sanitation); (11) hand-weeding; (12) tillage (disk, cultivation, or deep tillage); (13) narrow crop rows ($\leq$ 50 cm); (14) altered planting date; and (15) cover crops or double crop [wheat (*Triticum aestivum* L.)/soybean]. Only herbicide-resistant trait available in rice is IR rice, and there are chances of rice seed contamination with red rice seed in noncertified seed; therefore, in the rice survey, the "rotate herbicide-resistant traits" HR-BMP was replaced with "purchase certified seeds". Additionally in the rice survey, HR-BMPs such as cover crops, in-crop tillage, and hand-weeding were excluded because these practices are not feasible, and narrow-row spacing was excluded because all rice in these two states is either drill- or broadcast-seeded. For all crops, consultants were asked to provide the percent of their scouted area under each HR-BMP and to rate the importance of each HR-BMP on a scale of 1 to 5, with 1 = not important, 2 = rarely important, 3 = occasionally important, 4 = important, and 5 = very important. Additionally, consultants were asked to describe the perceived obstacles to adoption of each of the listed HR-BMPs.

Importance ranking of all listed HR-BMPs was calculated for cotton, rice, and soybean based on the point values assigned by consultants (Webster and MacDonald 2001). In the case of similar importance rating points, the HR-BMP

Table 1. Perceived importance rating of herbicide resistance best management practices (HR-BMPs) by the consultants of midsouthern United States cotton, rice, and soybean.

| HR-BMPs | Cotton (n = 60) | | Rice (n = 43) | | Soybean (n = 100) | |
|---|---|---|---|---|---|---|
| | Importance rating[a] (SEM) | Importance rank[b] | Importance rating (SEM) | Importance rank | Importance rating (SEM) | Importance rank |
| Proper herbicide timing | 4.95 (< 0.1) | 1 | 4.97 (< 0.1) | 1 | 4.94 (< 0.1) | 1 |
| Start clean (no weeds at planting) | 4.93 (< 0.1) | 2 | 4.84 (0.1) | 2 | 4.86 (0.1) | 2 |
| Apply multiple effective herbicide modes of action targeting most problematic weeds | 4.79 (0.1) | 4 | 4.68 (0.1) | 3 | 4.75 (0.1) | 3 |
| Use of full labeled herbicide rates | 4.71 (0.1) | 5 | 4.68 (0.1) | 4 | 4.71 (0.1) | 5 |
| Prevent in crop weed seed production | 4.82 (0.1) | 3 | 4.61 (0.1) | 6 | 4.72 (0.1) | 4 |
| Crop rotation | 4.33 (0.1) | 7 | 4.68 (0.1) | 5 | 4.47 (0.1) | 6 |
| Rotate herbicide-resistant traits | 4.28 (0.1) | 8 | —[c] | — | 4.32 (0.1) | 8 |
| Purchase certified seed | — | — | 4.42 (0.2) | 7 | — | — |
| Prevent post-harvest weed seed production | 4.56 (0.1) | 6 | 4.16 (0.2) | 8 | 4.35 (0.1) | 7 |
| Prevent seed production in ditchbanks | 4.03 (0.1) | 10 | 3.84 (0.2) | 9 | 4.00 (0.1) | 9 |
| Clean tillage and harvest equipment (sanitation) | 4.05 (0.2) | 9 | 3.74 (0.2) | 10 | 3.89 (0.1) | 10 |
| Hand-weeding | 4.02 (0.1) | 11 | — | — | 3.77 (0.1) | 11 |
| Tillage (disk, cultivation, or deep tillage) | 3.55 (0.1) | 12 | — | — | 3.59 (0.1) | 12 |
| Narrow crop rows (< 50 cm) | 3.23 (0.2) | 13 | — | — | 3.32 (0.1) | 13 |
| Cover crops | 2.88 (0.1) | 14 | — | — | 2.65 (0.1) | 14 |
| Altered planting date | 2.59 (0.2) | 15 | 3.24 (0.2) | 11 | 2.61 (0.1) | 15 |

[a] Importance rating was calculated based on the point value assigned to each HR-BMP by consultants. The rating scale was 1 = not important, 2 = rarely important, 3 = occasionally important, 4 = important, and 5 = very important. Standard error of mean (SEM) for each weed species is provided in parentheses.

[b] Importance ranking was based on the number of importance points. HR-BMPs with similar importance points were ranked in the order of area adopted under those HR-BMPs (Table 2).

[c] "—-" represents HR-BMP not rated by consultants of particular crop.

with greater adopted area was assigned the higher importance ranking. Standard error of mean for importance rating of each HR-BMP was calculated to determine variation in the responses of consultants.

## Results and Discussion

**Area Scouted.** In 2011, 60 cotton consultants representing 28% (241,660 ha) of total planted cotton (849,900 ha) and 100 soybean consultants representing 12% (373,600 ha) of total planted soybean (3,019,000 ha) across Arkansas, Louisiana, Mississippi, and Tennessee; and 43 rice consultants representing 38% (179,500 ha) of total planted rice (467,000 ha) across Arkansas and Mississippi returned valid surveys (for more details refer to Norsworthy et al. 2013; Riar et al. 2013d, 2013c).

**Importance and Adoption of HR-BMPs.** *Proper Herbicide Timing*. As documented in a previous survey (Prince et al. 2012), appropriate timing of herbicide application was the most important HR-BMP in each of the surveyed mid-southern crops, with an importance rating of $\geq$ 4.94 (Table 1). It is well known that herbicide effectiveness decreases with increasing weed size (Tharp et al. 1999), making timely scouting of fields and subsequent herbicide applications important for the management of herbicide-resistant weeds. Proper spray coverage, however, is needed even if herbicide applications are properly timed. Glyphosate and glufosinate are systemic and contact herbicides, respectively; therefore, gyphosate- and glufosinate-resistant technologies need different spray coverage for effective weed control (Riar et al. 2013d). Both soybean and cotton consultants in a 2011 survey expressed need for more training and awareness about differences in management practices and especially, spray coverage for existing herbicide-resistant technologies (Riar et al. 2013d, 2013c). Of the reported scouted area, proper herbicide timing was implemented on 58% of cotton, 86% of rice, and 59% of soybean hectares (Table 2). Greater adoption of proper herbicide timing in rice compared to soybean and cotton can be because almost all rice fields are treated with herbicides immediately prior to flooding; fewer herbicide options in rice including only one herbicide-resistant trait (IR rice); the existence of multiple herbicide resistance in barnyardgrass leaving few alternatives for control of escapes; and no possibility of in-crop tillage unlike cotton and soybean.

*Start Clean by Planting into Weed-Free Fields*. Recognizing the importance of planting into weed-free fields to avoid early-season competition and to avoid a high density of large weeds during the first POST application, cotton, rice, and soybean consultants ranked "starting clean" as the second most important HR-BMP with an importance rating of 4.84 to 4.93 across crops (Table 1). Starting clean has been a widely recommended HR-BMP (Norsworthy et al. 2012; Sammons et al. 2007) and was ranked among the top five out of 13 weed management practices by U.S. cotton, soybean, and corn (*Zea mays* L.) growers averaged across 22 states (Prince et al. 2012). Planting into weed-free fields has been adopted on 73 to 78% of scouted midsouthern cotton, rice, and soybean hectares (Table 2).

*Apply Multiple Effective Herbicide MOAs Targeting Most Problematic Weeds*. The use of multiple MOAs to control problematic weeds was ranked fourth in cotton and third in rice and soybean (Table 1). Residual herbicides in contrast to glyphosate and glufosinate can control emerging weeds up to

Table 2. Perceived adoption of herbicide resistance best management practices (HR-BMPs) by the consultants of Midsouth United States cotton, rice, and soybean.

| HR-BMPs | Area adopted | | |
|---|---|---|---|
| | Cotton (n = 60) | Rice (n = 43) | Soybean (n = 100) |
| | % of total scouted | | |
| Proper herbicide timing | 58 | 86 | 59 |
| Start clean (no weeds at planting) | 78 | 75 | 73 |
| Apply multiple effective herbicide modes of action targeting most problematic weeds | 68 | 85 | 67 |
| Use of full labeled herbicide rates | 81 | 75 | 77 |
| Prevent in crop weed seed production | 55 | 81 | 49 |
| Crop rotation | 33 | 69 | 51 |
| Rotate herbicide-resistant traits | 25 | —[a] | 28 |
| Purchase certified seed | — | 90 | — |
| Prevent post-harvest weed seed production | 30 | 51 | 29 |
| Prevent seed production in ditchbanks[b] | 22 | 27 | 18 |
| Clean tillage and harvest equipment (sanitation) | 22 | 20 | 15 |
| Hand-weeding | 36 | — | 14 |
| Tillage (disk, cultivation, or deep tillage) | 30 | — | 39 |
| Narrow crop rows (< 50 cm) | 2 | — | 47 |
| Cover crops | 14 | — | 22 |
| Altered planting date | 7 | 25 | 15 |

[a] "—" represents HR-BMP not rated by consultants of particular crop.

[b] "Prevent seed production in ditchbanks" represents percentage of reported farms for which ditchbanks were managed to prevent weed seed production.

two to three weeks after application. Overlay of residual herbicides of multiple MOAs every two to three weeks until crop canopy formation is highly recommended to delay the evolution and reduce selection for glyphosate- and glufosinate-resistant weed species in glyphosate- and glufosinate-resistant cropping systems, respectively, (Riar et al. 2011, 2013c) and ALS-resistant weeds in IR rice (Norsworthy et al. 2012). Nationwide, grower perception of effectiveness for the use of multiple chemistries and residual herbicides has increased in recent years (Prince et al. 2012).

Application of multiple effective herbicide MOAs was adopted on 68% of scouted cotton, 85% of scouted rice, and 67% of scouted soybean fields (Table 2). Greater adoption of multiple MOAs in rice is because of evolution of resistance in barnyardgrass, the most important weed of midsouthern U.S. rice, to commonly used herbicide MOAs: photosystem II (PS II)-inhibitors (propanil) (Baltazar and Smith Jr. 1994), synthetic auxins (quinclorac) (Lovelace 2003), carotenoid biosynthesis-inhibitors (clomazone) (Norsworthy et al. 2009), and ALS–inhibitors (bispyribac-sodium, imazamox, imazethapyr, and penoxsulam) (Riar et al. 2012a, 2013b).

*Use of Full Labeled Herbicide Rates.* The use of full labeled herbicide rates was ranked fourth with an importance rating of 4.68 by rice consultants, and fifth with an importance rating of 4.71 by both cotton and soybean consultants (Table 1). Of the reported scouted area, use of full labeled herbicide rates has been adopted on 81% of cotton, 75% of rice, and 77% of soybean hectares (Table 2). The use of reduced herbicide rates to decrease cost of production was widely practiced in the midsouthern United States before wide-spread evolution of glyphosate-resistant weeds, especially glyphosate-resistant Palmer amaranth (Johnson et al. 1998; Popp et al. 2000; Steckel et al. 1990). Pros and cons of using reduced herbicide rates are reviewed in Blackshaw et al. (2006) and risks and reliability of using reduced herbicide rates were studied by Zhang et al. (2000). However, in light of recent reports regarding evolution of polygenic non-target-site-based resistance (NTSR) that occurs because of NTSR gene accumulation in weeds under lower-than-labeled rate herbicide applications (Busi et al. 2013), emphasis has been placed on increased adoption of full labeled rates of herbicides, which reflects in the ranking of this HR-BMP among the top five. Even when a lower-than-recommended field rate of herbicide is not knowingly applied, target weed species can inadvertently receive a lower-than-lethal dose because of reasons such as difference in activation and decay kinetics of residual herbicides pertaining to environmental variability across field, less herbicide absorption by the large weeds with thick layer of epicuticular wax compared to small weeds, and less per unit area distribution of herbicide across large weeds compared to small weeds (Vila-Aiub et al. 2003; Wauchope et al. 1997; Zhang et al. 2000).

*Prevent In-Crop Weed Seed Production.* This HR-BMP has been adopted on 55% of cotton, 81% of rice, and 49% of soybean hectares scouted by midsouthern consultants (Table 2). Interestingly, importance ranking of in-crop weed seed production prevention in cotton (third) and soybean (fourth) was higher compared to rice (sixth) (Table 1). Greater importance rating of the prevention of in-crop weed seed production by cotton and soybean consultants compared to rice consultants is likely because of wide-spread prevalence of glyphosate-resistant Palmer amaranth in the midsouthern United States. Even a single escaped female glyphosate-resistant Palmer amaranth plant in a cotton field has potential to produce more than 500,000 seeds and spread throughout the field within 3 yr through farm machinery and irrigation (Griffith et al. 2010). A large percentage of the rice area (81%) is already under adoption of this HR-BMP because rice producers need to control weeds to minimize lodging of the crop, which is less of a problem in cotton and soybean.

*Crop Rotation.* Crop rotation as a HR-BMP was ranked fifth by rice consultants, with adoption on 69% of scouted hectares, sixth by soybean consultants with adoption on 51% of scouted hectares, and seventh by cotton consultants with adoption on 33% of scouted hectares (Tables 1 and 2). Shaw et al. (2009) also reported fewer growers rotating from cotton compared to soybean and corn. Crop rotation in comparison to monoculture crop production increases the diversification of weed communities and increases the opportunities for weed mortality events because of greater variability in the type and timing of weed management practices (Martin and Felton 1993). The risk of evolution of resistance in weeds is less in cropping systems with regular crop rotation, including rotation of herbicide-resistant traits compared to systems with no or limited rotation (Neve et al. 2011). Amidst the increased prevalence of herbicide-resistant weeds, perceived effectiveness of crop rotation among U.S. growers has increased from 2005 to 2010 (Prince et al. 2012). However,



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monoculture crop production is more common in southern compared to midwestern U.S. crops (Shaw et al. 2009), which has resulted in weed species shifts to glyphosate-resistant and –tolerant weed species (Kruger et al. 2009). Additionally among different fields, the difference in interval between rotations may bring considerable diversity in weed species.

*Rotate Herbicide-Resistant Traits.* Rotation of herbicide-resistant traits is one means of increasing the likelihood that different MOAs are used in subsequent crops, especially reducing the use of glyphosate, the most commonly applied herbicide in U.S. soybean and cotton. Rotation of herbicide-resistant traits was ranked eighth by cotton and soybean consultants (Table 1). Frequency of glyphosate-resistant Palmer amaranth was higher in plots with 4 yr of continuously grown glyphosate-resistant cotton (treated solely with glyphosate) compared to glyphosate-resistant cotton rotated annually with glufosinate-resistant cotton (Johnson et al. 2011). Crop rotation is important but rotation of crops with the same herbicide-resistant trait, for example glyphosate-resistant cotton, soybean, and corn, has minimal advantage because of similar levels of selection pressure on evolution of herbicide-resistant weeds unless multiple effective MOAs or residual herbicides are included in herbicide programs. In rice, there is currently only one herbicide-resistant (IR) trait. Current rotation restrictions following the use of imazethapyr in rice make it impossible to rotate to conventional rice.

Glyphosate resistance is the principal herbicide-resistant trait used by midsouthern U.S. cotton and soybean growers. Rotation of herbicide-resistant traits on only 25% of scouted cotton and 28% of scouted soybean hectares in the midsouthern United States is a reason for concern (Table 2). Adoption of herbicide-resistant technologies other than glyphosate resistance is expected to increase in near future with commercialization of technologies with stacked genes for auxinic (2,4-D and dicamba) or 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicide (isoxafluotole and mesotrione) resistance along with resistance to glyphosate and glufosinate (Riar et al. 2013c).

*Purchase Certified Seed (Specific to Rice).* Red rice, an important weed of rice has evolved resistance to imidazolinone herbicides and long-distance spread occurs when planting red rice-contaminated rice seed (Delouche et al. 2007). With 36% of the Arkansas and Mississippi rice planted to conventional (non-IR), inbred cultivars, growers have the option of retaining seed from these fields to plant subsequent rice crops (Norsworthy et al. 2013). However, 90% of the reported rice was planted with certified rice and, based on consultant ratings, purchase of certified seed was the seventh rated HR-BMP with an importance rating of 4.42 (Tables 1 and 2). Ninety percent of cotton and 94% of soybean in 2011 was planted with biotech varieties (USDA- NASS 2012); and thus, growers had to purchase new seed from seed companies, which have fewer chances of herbicide-resistant weed seed contamination. Accordingly, cotton and soybean consultants were not asked to rate "purchase certified seed" HR-BMP.

*Prevent Post-Harvest Weed Seed Production.* The prevention of post-harvest weed seed production was ranked sixth in cotton, seventh in soybean, and eighth in rice, respectively (Table 1). Previous studies have shown that weed escapes contribute significantly to the soil seedbank (Cavers 1983) and escape of prolific seed producers such as Palmer amaranth can overwhelm the soil seedbank of infested and surrounding areas within a few years of evolution of resistance (Culpepper and Sosnoskie 2011; Griffith et al. 2010). Post-harvest escapes of herbicide-resistant weeds will add resistant progeny to the soil seedbank; and thus, prevention of post-harvest weed seed production can mitigate the risk of evolution or spread of herbicide resistance (reviewed in Bagavathiannan and Norsworthy 2012). Economic optimum threshold proposed by Cousens (1987) and no seed threshold proposed by Norris (1999) that take into account long-term biological and economic consequences of late-season weed escapes including post-harvest weed escapes and seed setting in contrast to the commonly used economic threshold that considers only short-term savings are gaining attention in cropping systems prone to evolution of herbicide-resistant weeds. Of total scouted area, consultants reported prevention of post-harvest weed seed production by tillage or herbicide application on 30% of cotton, 51% of rice, and 29% of soybean planted area (Table 1).

*Prevent Seed Production in Ditchbanks.* Based on the importance rating given by consultants, prevention of seed production in ditchbanks appears to be less important to rice compared to cotton and soybean consultants (Table 1). Ditchbanks are a major source of problematic agricultural weed seed ingress to the adjacent crop fields and long-distance weed seed movement (Bagavathiannan and Norsworthy 2013). Tillage not being possible on ditchbanks, several herbicides are labeled for weed control on ditchbanks, but there is no effective option for the control of problematic weeds such as multiple-herbicide-resistant Palmer amaranth. Additionally, some grass groundcover is needed to avoid soil erosion in ditchbanks. A recent study reported that auxinic herbicides such as dicamba and triclopyr can effectively control ALS- and glyphosate-resistant Palmer amaranth along with keeping adequate grass groundcover (Hill et al. 2012). Ditchbanks around only 22% of reported cotton farms, 27% of reported rice farms, and 18% of reported soybean farms were prevented from seed set by weeds (Table 2).

*Clean Tillage and Harvest Equipment (Sanitation).* Cleaning of tillage and harvest equipment was ranked ninth by cotton consultants with importance rating of 4.05, and was ranked tenth by rice and soybean consultants with importance rating of 3.74 in rice and 3.89 in soybean (Table 1). Norsworthy et al. (2007b) stated that sanitation is one means of minimizing the likelihood of weed introductions and dispersal of existing weeds throughout a farm, especially herbicide-resistant weeds. Surprisingly, cleaning of tillage and harvest equipment has been practiced on only 22% of scouted cotton hectares, 20% of scouted rice hectares, and 15% of scouted soybean hectares (Table 2). Data from the current survey agrees closely with separate surveys of corn, cotton, and soybean growers, where only 28% of growers reported cleaning equipment before moving from one field to another (Frisvold et al. 2009; Prince et al. 2012).

*Hand-Weeding.* Manual removal of weeds from fields was ranked higher (eleventh) by cotton (importance rating of 4.02) and soybean (importance rating of 3.77) consultants than tillage, narrow crop rows, cover crops, and altered planting dates (Table 1). Similar to importance rating, area under manual removal of weeds is greater in cotton (36%) than soybean (14%) (Table 2). The greater area under hand-weeding in cotton compared to rice and soybean is attributed to the lack of effective over-the-top herbicide options for the control of glyphosate-resistant Palmer amaranth in cotton (Norsworthy et al. 2008). The morphology of problematic weeds of rice such as barnyardgrass and red rice is very similar to that of rice making it difficult to distinguish and remove them manually at vegetative stages (Barrett 1983).

*Tillage (Disking, Cultivation, or Deep Tillage).* This was one of the four HR-BMPs with $< 4.0$ importance rating in cotton (Table 1). The importance rating of tillage in cotton was 3.55 and soybean was 3.59 with 30% of reported cotton area and 39% of reported soybean area tilled to manage herbicide-resistant weeds (Tables 1 and 2). Although tillage has potential to suppress the evolution of herbicide-resistant weeds, growers often fail to acknowledge the importance of tillage, especially supplemental tillage, and rank it lower than most other HR-BMPs (Frisvold et al. 2009; Hurley et al. 2009). No-tillage and reduced tillage practices increased rapidly in the United States after commercialization of glyphosate-resistant cotton and soybean (Cerdeira and Duke 2006). As a result of glyphosate-resistant Palmer amaranth and other resistant weeds, the use of tillage has recently increased in U.S. agriculture as an additional weed management tool (Foresman and Glasgow 2008). Deep tillage using a moldboard plow is one tillage practice that has been proven effective for burying small-sized seeds of weeds such as Palmer amaranth deep in soil, preventing emergence (DeVore et al. 2012, 2013). Row cultivation is another tillage practice adopted by midsouthern cotton and soybean growers to control weeds that escape herbicide treatment (Riar et al. 2013d, 2013c).

*Narrow ($\leq$ 50 cm) Crop Rows.* Narrow crop rows was ranked 13$^{th}$ by both cotton (3.23 importance points) and soybean (3.32 importance points) consultants but adoption of this HR-BMP was at only 2% of reported cotton compared to 47% of reported soybean hectares (Tables 1 and 2). Narrow row spacings and high seeding rates have been shown to hasten crop canopy closure, and in turn, diminish weed competition because of suppression of late-season weed emergence and seed production in cotton and soybean (Jha and Norsworthy 2009). Consequently, narrowing of soybean row widths has been reported to decrease herbicide inputs (Mickelson and Renner 1997). Increase in soybean yield with narrow row cropping has been widely documented (Board et al. 1990); however, narrow row cotton studies have reported reduced (Boquet 2005), similar (Buehring and Dobbs 2000), or increased (Vories et al. 2001) lint and seed cotton yields with narrow-row compared to wide-row cotton. Stripper harvesting is suitable for narrow row cotton compared to spindle picking in wide-row cotton (Boquet 2005). Inferior lint quality with shorter staple length and greater trash has been documented in narrow row stripper harvested cotton compared to wide row spindle picked cotton (Vories et al. 2001).

*Cover Crops.* Along with reducing soil erosion and improving soil moisture retention, nitrogen content, and organic carbon content, a layer of cover crop residues on soil surface has been shown to suppress weeds by exhibiting allelopathic effects on sensitive weeds, creating unfavorable conditions for weed germination and establishment, imposing competition for soil nutrients and light, and delaying the need for early season herbicide application (reviewed in Hartwig and Ammon 2002). Overall, scouted area under cover crops was only 14% in cotton with importance rating of 2.88 and 22% in soybean with importance rating of 2.65 (Tables 1 and 2). Use of cover crops is not practiced on many acres in midsouthern soybean, and 22% adoption of this HR-BMP in soybean is a sole reflection of wheat being considered as a cover crop by some consultants.

*Altered Planting Date.* Consultants ranked altered planting date last among all the HR-BMPs in each crop (Table 1). Altered planting date was adopted on only 7% of scouted cotton, 25% of scouted rice, and 15% of scouted soybean hectares in 2011 (Table 2). Generally, advanced planting and establishment gives a competitive advantage to the crop compared to weed species, which are contending for the same limited resources (Steckel and Sprague 2004). However, environmental conditions and biology of the crop and weed species modifies the competitive balance among crop and weed species (Norsworthy and Oliveira 2004).

**Important Perceived Obstacles in Adoption of HR-BMPs.** Consultants listed weather, cost, time constraints, lack of labor or trained employees, availability of equipment, complacency, herbicide-related concerns, and profitability as their most important obstacles for the adoption of HR-BMPs (Table 3). Delays in tillage, planting, or herbicide application were major weather related obstacles restraining growers to keep their fields weed free with lesser weed seed addition to the soil seedbank before, during, and after the crop season.

According to consultants, out of the 16 listed HR-BMPs, 13 were not adopted by cotton, rice, and soybean growers because of the cost associated with herbicides, herbicide-resistant seed technology, equipment, and labor (Table 3). Several consultants reported that extra expense for soil weed seedbank reduction (in-crop and post-harvest) and weed seed production in ditchbanks and field borders is not shared by the land owner, which undermines the grower initiative to practice those HR-BMPs (data not shown). Past grower surveys also found that implementation of complex interrelated BMPs needs more human capital, and growers are unwilling to incorporate expensive HR-BMPs in their weed management programs unless they are facing the problem of herbicide-resistant weeds (Frisvold et al. 2009; Hurley et al. 2009; Llewellyn et al. 2002).

Time constraints corresponding to lack of labor or trained employees and large farm sizes are a critical obstacle for the adoption and timely implementation of several HR-BMPs (Table 3), indicating immense need of manpower or alternate strategies to manage herbicide-resistant weeds. Time con-



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Table 3. Perceived obstacles for the adoption of herbicide resistance best management practices (HR-BMPs) by the cotton, soybean, and rice consultants of the midsouthern United States.

| Obstacles | HR-BMPs | Consultants acknowledging obstacles | | |
|---|---|---|---|---|
| | | Cotton (n = 60) | Rice (n = 43) | Soybean (n = 100) |
| | | % of total | | |
| Weather | Proper herbicide timing | 53 | 74 | 53 |
| | Altered planting date | 36 | 56 | 40 |
| | Start clean | 30 | 54 | 28 |
| | Tillage | 11 | —[a] | 11 |
| | Cover crops | 8 | — | 7 |
| | Prevent in-crop weed seed production | 2 | 4 | 5 |
| | Prevent post-harvest weed seed production | 8 | 0 | 5 |
| Cost | Full herbicide rates | 62 | 63 | 56 |
| | Hand-weeding | 62 | 29 | 47 |
| | Multiple effective modes of action | 44 | 36 | 46 |
| | Start clean | 23 | 17 | 23 |
| | Prevent post-harvest weed seed production | 48 | 48 | 45 |
| | Seed production in ditchbanks/field borders | 45 | 41 | 36 |
| | Narrow rows | 47 | — | 55 |
| | Purchase certified seed | — | 50 | — |
| | Cover crops | 44 | — | 36 |
| | Prevent in-crop weed seed production | 27 | 39 | 25 |
| | Tillage | 33 | — | 33 |
| | Rotate herbicide-resistant traits | 16 | — | 15 |
| | Sanitation | 17 | 4 | 17 |
| | Rotate crops | 8 | 7 | 0 |
| Time constraints | Sanitation | 42 | 52 | 53 |
| | Prevent post-harvest weed seed production | 45 | 20 | 39 |
| | Tillage | 36 | — | 34 |
| | Altered planting date | 21 | 33 | 24 |
| | Seed production in ditchbanks/field borders | 28 | 19 | 25 |
| | Proper herbicide timing | 25 | 16 | 24 |
| | Hand-weeding | 7 | 26 | 9 |
| | Start clean | 11 | 23 | 18 |
| | Cover crops | 18 | — | 22 |
| | Prevent in-crop weed seed production | 12 | 15 | 20 |
| Lack of labor/trained employees | Hand-weeding | 48 | 39 | 44 |
| | Prevent in-crop weed seed production | 19 | 7 | 22 |
| | Seed production in ditchbanks/field borders | 14 | 13 | 11 |
| | Sanitation | 14 | 7 | 12 |
| | Proper herbicide timing | 13 | 6 | 10 |
| | Prevent post-harvest weed seed production | 13 | 0 | 9 |
| | Tillage | 7 | — | 6 |
| | Start clean | 4 | 0 | 2 |
| | Altered planting date | 3 | 0 | 2 |
| | Cover crops | 3 | — | 2 |
| Profitability | Rotate crops | 46 | 42 | 47 |
| | Rotate herbicide-resistant traits | 13 | — | 14 |
| | Cover crops | 10 | — | 13 |
| | Altered planting date | 10 | 7 | 10 |
| | Seed production in ditchbanks/field borders | 3 | 6 | 5 |
| | Narrow rows | 3 | — | 3 |
| | Tillage | 2 | — | 1 |
| Herbicide-related concerns | Multiple effective modes of action | 31 | 46 | 24 |
| | Prevent in-crop weed seed production | 19 | 30 | 23 |
| | Rotate herbicide-resistant traits | 22 | — | 25 |
| | Start clean | 11 | 9 | 8 |
| | Seed production in ditchbanks/field borders | 11 | 9 | 4 |
| | Prevent post-harvest weed seed production | 6 | 0 | 4 |
| Complacency | Sanitation | 12 | 33 | 12 |
| | Seed production in ditchbanks/field borders | 15 | 29 | 20 |
| | Prevent in-crop weed seed production | 4 | 29 | 3 |
| | Rotate herbicide-resistant traits | 6 | — | 18 |
| | Hand-weeding | 9 | 16 | 7 |
| | Prevent post-harvest weed seed production | 11 | 13 | 9 |
| | Start clean | 11 | 10 | 9 |
| | Proper herbicide timing | 6 | 3 | 7 |
| | Rotate crops | 3 | 3 | 6 |
| | Multiple effective modes of action | 2 | 0 | 4 |
| | Tillage | 2 | — | 2 |

Table 3. Continued.

| Obstacles | HR-BMPs | Consultants acknowledging obstacles | | |
|---|---|---|---|---|
| | | Cotton (n = 60) | Rice (n = 43) | Soybean (n = 100) |
| Availability of equipments | Proper herbicide timing | 22 | 10 | 17 |
| | Rotate crops | 19 | 0 | 18 |
| | Tillage | 13 | — | 11 |
| | Start clean | 7 | 0 | 2 |
| | Sanitation | 6 | 0 | 2 |
| | Prevent postharvest weed seed production | 5 | 0 | 2 |
| | Altered planting date | 3 | 0 | 2 |
| | Seed production in ditchbanks/field borders | 3 | 0 | 2 |

[a] "—-" represents HR-BMP not rated by consultants of particular crop.

straints were perceived as the most frequently mentioned obstacle for adoption of farm equipment sanitation that can restrict spread of herbicide-resistant weeds across fields, states, and even countries. Availability of labor is useless if additional equipment for timely tillage and herbicide applications are not available. Moreover, most of the growers are setup to grow only a specific crop, and they do not have equipment and storage facilities for rotational crops. Availability of additional equipment or sprayers was an obstacle for the adoption of only one HR-BMP (proper herbicide timing) in rice compared to eight HR-BMPs in cotton and soybean. Similarly, lack of labor or trained employees was an obstacle for the adoption of only five HR-BMPs in rice compared to ten in cotton and soybean.

Although lack of labor or nonavailability of equipment placed time constraints on growers of large farms, complacency is a key factor for growers to not adopt HR-BMPs (Table 3). Grower complacencies include procrastination and perceived inconvenience in adoption of a HR-BMP; doubts over importance of that particular HR-BMP; delays to reduce number of trips across field; and loss of focus by end of the season (data not shown).

According to consultants, herbicide-related concerns were limiting cotton, rice, and soybean growers from adoption of HR-BMPs that prevent evolution of herbicide resistance and buildup of the soil seedbank in and around field borders or ditchbanks (Table 3). Major concerns reported by consultants were: off-target herbicide movement; time needed for sprayer cleanout; fear of misapplication; plant-back restrictions of some herbicides; reduced control of large weeds; tank-mix problems; limited number of effective herbicides to control herbicide-resistant and –tolerant weed species; no rainfall for activation of soil-applied residual herbicides; reapplication because of incomplete weed control; weed seed produced before herbicide application; complexity in the application of multiple effective MOAs; and lack of knowledge about herbicide or herbicide-resistant crop technologies (data not shown).

Profitability dictated by commodity price is a major driving force for growers to include a crop in their cropping system. Cotton, rice, and soybean consultants (42 to 47% of respondents) perceived that growers are reluctant to include crops with lower market prices. Commodity prices in 2012 resulted in the planted area to corn being its highest in the United States since 1937 and the area planted to soybean was the third highest on record at the expense of other crops (USDA-NASS 2012). Growers adopt only those HR-BMPs that are associated with immediate management of problematic weeds and are high yielding (Frisvold et al. 2009). Probable yield drag, questionable benefits, and terms dictated by absentee landowners are other profitability related obstacles for less adoption of cultural weed management practices such as rotation of crops and herbicide-resistant traits, cover crops, altered planting date, prevention of seed production in ditchbanks and field borders, narrow rows, and tillage.

**A Path Forward.** Of all the obstacles listed by consultants, some were real and some appeared perceived. Planting dates, herbicide application and activation, and tillage can be affected by unfavorable weather conditions and there can be delays or failure in implementation of some HR-BMPs. In contrast, short-term profitability and volatility of commodity prices result in reluctance by many growers to spend extra time, financially as well as physically, and incur added costs associated with equipment needed to ensure weeds are managed in a timely manner. Mueller et al. (2005) conducted an economic analysis to compare reactive versus proactive management of glyphosate-resistant or -tolerant weeds and concluded that proactive management strategies that favor integrated use of several HR-BMPs are more cost effective in long-term management programs compared to reactive management strategies that are prone to evolution of herbicide-resistant weeds.

Private and public sector groups have launched stewardship programs individually and in collaboration to provide pertinent information to growers to mitigate evolution of herbicide-resistant weeds. Stewardship programs that incentivize growers are more successful in convincing growers to adopt HR-BMPs than ones with no incentives. For example, few growers are following stewardship guidelines to not plant Clearfield rice in the same field in consecutive years (Norsworthy et al. 2013). In the public sector, USDA Natural Resources Conservation Service is providing technical and financial assistance (incentives) to growers that adopt Herbicide Resistance Conservation Activity Plans designed to manage herbicide-resistant weeds. Similarly in the private sector, Monsanto's Roundup Ready PLUS™ programs offer cash-back incentives to soybean and cotton growers using residual herbicides in glyphosate based programs. These incentives are believed to have played a major role in the wide-scale adoption of residual herbicides and alternate modes of action in cotton and soybean throughout the midsouthern United States.

Evolution of herbicide-resistant weeds predates resistance to glyphosate by more than 50 years, but recent wide-spread evolution of glyphosate-resistant weeds has posed challenges for the sustainable use of glyphosate-resistant crops. Even so, some growers appear to be reluctant to put into practice HR-BMPs that can reduce or delay the evolution of herbicide-resistant weeds. Apparently, evolution of herbicide resistance appears to be more of a behavioral problem than a lack of knowledge concerning the factors contributing herbicide resistance. Therefore, there is a tremendous need to understand the current socio-economic psychology of growers and absentee landowners that has contributed to the evolution of herbicide-resistant weeds. Weed scientists can develop stewardship programs, but collaborative efforts of economists and sociologists will be very important in the future to persuade growers to adopt HR-BMPs that mitigate the risk of herbicide resistance evolution.

In summary, concern about herbicide-resistant weeds, especially glyphosate-resistant Palmer amaranth in cotton and soybean and ALS-resistant red rice and multiple-herbicide-resistant barnyardgrass in rice, has increased awareness among growers to adopt several HR-BMPs, with some more than others. Additionally, HR-BMPs inclined toward practices such as proper herbicide timing, a clean start with no weeds at planting, application of multiple effective herbicide modes of action targeting the most problematic weeds, use of full labeled herbicide rates, and prevention of in-crop weed seed production were deemed the important HR-BMPs by midsouthern consultants. In contrast, HR-BMPs inclined toward use of cultural practices for management of weeds were least important among consultants. Area under adoption of specific HR-BMPs varied according to the crop planted, but area under cultural practices such as rotation of herbicide-resistant traits, sanitation of farm equipment, prevention of seed production in dichbanks, manual weeding, tillage, narrow-row cropping (except in soybean), cover crops, and altered planting date was $< 40\%$. Although cost, time constraints, and weather were perceived by consultants as the main challenges for implementation of most HR-BMPs, the primary constraint appears to be psychological, resulting in the failure of growers to invest time and money in adopting a proactive strategy. A bigger challenge in future is the need to identify and educate farm-level decision makers regarding the long-term benefits of adopting HR-BMPs.

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