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Changes in the Prevalence of Weed Species in the Major Agronomic Crops of the Southern United States: 1994/1995 to 2008/2009

Theodore M. Webster and Robert L. Nichols*

Changes in the weed flora of cropping systems reflect the impacts of factors that create safe sites for weed establishment and facilitate the influx and losses to and from the soil seedbank. This analysis of the annual surveys of the Southern Weed Science Society documents changes in the weed flora of the 14 contiguous southern states since the advent of transgenic, herbicide-resistant crops. In 1994 and 2009, the top five weeds in corn were morningglories, Texas millet, broadleaf signalgrass, johnsongrass, and sicklepod; in this same period Palmer amaranth, smartweeds, and goosegrass had the greatest increases in importance in corn. In cotton, morningglories and nutsedges were among the top five most troublesome weeds in 1995 and 2009. Palmer amaranth, pigweeds, and Florida pusley were also among the five most troublesome species in 2009; the weeds with the largest increases in importance in cotton were common ragweed and two species with tolerance to glyphosate, Benghal dayflower and Florida pusley. In soybean, morningglories, nutsedges, and sicklepod were among the top five weed species in 1995 and 2009. Two species with glyphosate resistance, Palmer amaranth and horseweed, were the second and fourth most troublesome weeds of soybean in 2009. In wheat, the top four weeds in 2008 were the same as those in 1994 and included Italian ryegrass, wild garlic, wild radish, and henbit. Crop production in the southern region is a mosaic of various crop rotations, soil types, and types of tillage. During the interval between the surveys, the predominant change in weed management practices in the region and the nation was the onset and rapid dominance of the use of glyphosate in herbicide-resistant cultivars of corn, cotton, and soybean. Because of the correspondence between the effects of glyphosate on the respective weed species and the observed changes in the weed flora of the crops, it is likely the very broad use of glyphosate was a key component shaping the changes in weed flora. Only eight of the top 15 most troublesome weeds of cotton and soybean, the crops with the greatest use of glyphosate, were the same in 1995 and 2009. In contrast, in corn and wheat where adoption of glyphosate-resistant cultivars lags or is absent, 12 of the 15 most troublesome weeds were the same in 1994 and 2008. These findings show on a regional scale that weeds adapt to recurrent selection from herbicides, currently the predominant weed management tool. Future research should seek methods to hinder the rapid spread of herbicide-tolerant and evolution of herbicide-resistant weed species. As new tools are developed, research should focus on ways to preserve the efficacy of those tools through improved stewardship.

Nomenclature: annual bluegrass, *Poa annua* L. POAAN; Benghal dayflower, *Commelina benghalensis* L. COMBE; broadleaf signalgrass, *Urochloa platyphylla* (Nash) R.D. Webster BRAPP; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; Florida pusley *Richardia scabra* L. RCHSC; goosegrass *Eleusine indica* (L.) Gaertn. ELEIN; groundcherries, *Physalis* spp.; henbit, *Lamium amplexicaule* L. LAMAM; horseweed, *Conyza canadensis* (L.) Cronq. ERICA; Italian ryegrass, *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot LOLMU; johnsongrass, *Sorghum halepense* (L.) Pers. SORHA; morningglories, *Ipomoea* spp.; nutsedges, *Cyperus* spp.; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; pigweed, *Amaranthus* spp.; sicklepod, *Senna obtusifolia* (L.) H.S. Irwin & Barneby CASOB; smartweeds, *Polygonum* spp.; Texas millet, *Urochloa texana* (Buckl.) R. Webster PANTE; wild garlic, *Allium vineale* L. ALLVI; wild radish, *Raphanus raphanistrum* L. RAPRA; corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; soybean *Glycine max.* (L.) Merr.; wheat, *Triticum aestivum* L.

Key words: Economically important weeds, troublesome weeds, survey, weed distributions, weed population shifts.

Cropping systems managed using tools and tactics that apply a consistent selection pressure will result in the weed species with high levels of adaptation for that system (Buhler 1996). A previous summary of the annual weed surveys of the Southern Weed Science Society evaluated changes in weed flora over a 20-yr period concluding in 1995 (Webster and Coble 1997). In 1996, the first herbicide-resistant crop cultivars of glyphosate-resistant soybean were commercially introduced, soon followed by the release of glyphosate-resistant cotton and corn cultivars (Young 2006). All three glyphosate-resistant crops were very popular and widely adopted because of the utility, reliability, and ease of application of the broad-spectrum herbicide, glyphosate (Duke and Powles 2008). One immediate effect was a great expansion in the overall use of glyphosate (Figure 1) and subsequent reduction in the use of herbicides with other mechanisms of action. A second consequence was the expansion of conservation tillage, as glyphosate's broad spectrum of efficacy in controlling weeds provided growers' the capacity and confidence to eliminate primary tillage and cultivation as weed management tools (Givens et al. 2009b). Such major changes in weed management would be expected to differentially affect weed species, and their subsequent reproduction would change the long-term composition of the weed flora of southern crops.

Surveys are a critical tool in determining the relative importance of various weeds and how these weed complexes are changed over time in response to management practices (Loux and Berry 1991; McWhorter 1993). Many of the most pernicious weeds have growth requirements and herbicide tolerances that are similar to the crop they infest. For instance, grass weeds accounted for 5 of the 10 most troublesome weed species in grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*] in a survey of the southern states (Webster 2008). Similar surveys of cotton and peanut averaged fewer than two grass weeds among the 10 most troublesome weeds (Webster 2005). Use of selective herbicides contributes to shifts in weed species composition. For instance, yellow nutsedge (*Cyperus esculentus* L.) is a shade-intolerant species that becomes

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* First author: Research Agronomist, Crop Protection and Management Research Unit, U.S. Department of Agriculture–Agricultural Research Service, Tifton, GA 31794; Second author: Senior Director, Cotton Incorporated, Cary, NC 27513. Corresponding author's E-mail: ted.webster@ars.usda.gov

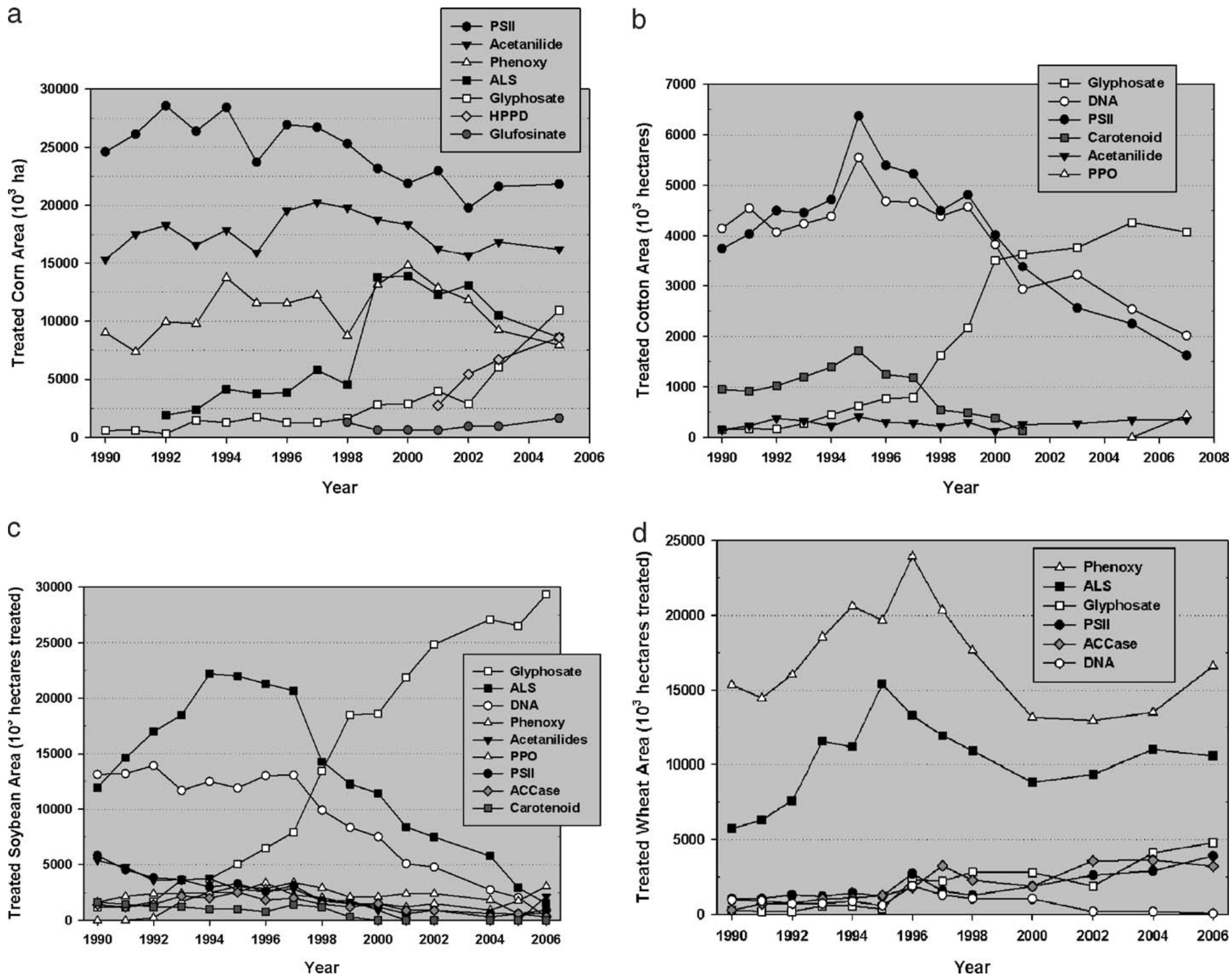

Figure 1. The number of crop hectares treated with herbicides, displayed by mechanism of herbicide action family for corn (a), cotton (b), soybean (c), and wheat (d).

troublesome after most other weeds have been controlled (Wills 1975). In the 1950s, < 10% of Mississippi cotton received herbicides, and nutsedges (*Cyperus* spp.) were not among the 10 most troublesome weeds (Wills 1977). In contrast, nutsedges were the second most troublesome weed in 1961, when 75% of the cotton land was treated with herbicides (Wills 1977). In North Carolina, yellow nutsedge densities increased in cotton fields where large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and crowfootgrass [*Dactyloctenium aegyptium* (L.) Willd.] were controlled with fluometuron or trifluralin (Weber et al. 1974). Between 1982 and 2000, the occurrence of common cocklebur (*Xanthium strumarium* L.) and johnsongrass [*S. halepense* (L.) Pers.] in Mississippi soybean was reduced seven- and fourfold, respectively, while yellow nutsedge became more common (Rankins et al. 2005). The use of selective herbicides (e.g., acetolactate synthase [ALS]-inhibitors, acetyl CoA carboxylase [ACCase]-inhibitors, protox-inhibitors, and glyphosate) likely reduced the occurrence of common cocklebur and johnsongrass (Rankins et al. 2005).

The Southern Weed Science Society has conducted an annual survey of the most common and troublesome weeds for over 40 yr. Changes in weed spectrum over time have been previously evaluated following the 1983 and 1995 surveys (Elmore 1983; Webster and Coble 1997). The objective of this article is to evaluate how weed flora has changed over a 14-yr period and document concurrent transformations in crop production technology that likely influenced the prevalence of the most troublesome weed species in corn, cotton, soybean, and wheat in the southern United States.

Materials and Methods

Reports of the most troublesome weeds have been complied annually in the Proceedings of the Southern Weed Science Society since 1971. The annual surveys were intended to identify the most troublesome species in each state for each of the primary crop groups. The surveys were sent to the university appointed extension weed specialists who assist growers and county agents with weed management issues. The representative of each state was requested to complete this voluntary survey and compile a single response from his or her state. Thus, this survey represents a consistent and comprehensive sampling of the region over time. Responses were based on expert opinion, or consensus among the weed

Table 1. Common and scientific names of weeds from the 1994, 1995, 2008, and 2009 surveys of the most troublesome weeds of corn, cotton, soybean, and wheat (Dowler 1994, 1995; Webster 2008, 2009).

Scientific name	Common name
Abutilon theophrasti Medik.	velvetleaf
Acalypha ostryifolia Riddell	hophornbeam copperleaf
Acanthospermum hispidum DC.	bristly starbur
Allium vineale L.	wild garlic
Alopecurus carolinianus Walt.	Carolina foxtail
Alternanthera philoxeroides (Mart.) Griseb.	alligatorweed
Amaranthus palmeri S. Wats.	Palmer amaranth
Amaranthus rudis Sauer or *Amaranthus tuberculatus* (Moq.) Sauer	waterhemps
Amaranthus spp.	pigweeds
Ambrosia artemisiifolia L.	common ragweed
Ambrosia trifida L.	giant ragweed
Anoda cristata (L.) Schlecht.	spurred anoda
Apocynum cannabinum L.	hemp dogbane
Arachis hypogaea L.	peanut
Bromus commutatus Schrad.	hairy chess
Bromus secalinus L.	cheat
Brunnichia ovata (Walt.) Shinners	redvine
Buglossoides arvensis (L.) I.M. Johnston	corn gromwell
Campsis radicans (L.) Seem. ex Bureau	trumpetcreeper
Capsella bursa-pastoris (L.) Medik.	Shepherd's-purse
Cardiospermum halicacabum L.	balloonvine
Carduus nutans L.	musk thistle
Cenchrus spp.	sandburs
Centaurea cyanus L.	cornflower
Chamaesyce spp.	spurges
Chenopodium album L.	common lambsquarters
Commelina benghalensis L.	Benghal dayflower
Commelina spp.	dayflowers
Convolvulus arvensis L.	field bindweed
Convolvulus spp.	bindweeds
Conyza canadensis (L.) Cronq.	horseweed
Coronopus spp.	swinecress
Croton glandulosus var. *septentrionalis* Muell.-Arg.	tropic croton
Cynanchum laeve (Michx.) Pers.	honeyvine swallowwort
Cynodon dactylon (L.) Pers.	bermudagrass
Cyperus spp.	nutsedges
Datura stramonium L.	jimsonweed
Desmodium tortuosum (Sw.) DC.	Florida beggarweed
Digitaria ischaemum (Schreb.) Schreb. ex Muhl.	smooth crabgrass
Digitaria spp.	crabgrasses
Echinochloa crus-galli (L.) Beauv.	barnyardgrass
Eclipta prostrata L.	eclipta
Eleusine indica (L.) Gaertn.	goosegrass
Euphorbia heterophylla L.	wild poinsettia
Gamochaeta spp.	cudweed
Geranium carolinianum L.	Carolina geranium
Gossypium hirsutum L.	glyphosate-resistant cotton
Hordeum pusillum Nutt.	little barley
Indigofera hirsuta Harvey	hairy indigo
Ipomoea spp.	morningglories
Jacquemontia tamnifolia (L.) Griseb.	smallflower morningglory
Lamium amplexicaule L.	henbit
Lamium purpureum L. var. incisum (Willd.) Pers.	purple deadnettle
Lepidium virginicum L.	Virginia pepperweed
Leptochloa panicea (Retz.) Ohwi	red sprangletop
Lolium perenne L. ssp. *multiflorum* (Lam.) Husnot	Italian ryegrass
Mollugo verticillata L.	carpetweed
Oenothera laciniata Hill	cutleaf evening-primrose
Ornithogalum umbellatum L.	star-of-Bethlehem
Oryza sativa L.	red rice
Panicum dichotomiflorum Michx.	fall panicum
Paspalum dilatatum Poir.	dallisgrass
Physalis spp.	groundcherries
Phytolacca americana L.	common pokeweed
Poa annua L.	bluegrass
Polygonum spp.	smartweeds
Proboscidea lutea (Lindl.) Stapf.	devil's claw
Raphanus raphanistrum L.	wild radish
Richardia scabra L.	Florida pusley
Rubus spp.	perennial vines
Rumex crispus L.	curly dock
Scleranthus annuus L.	knawel
Senna obtusifolia (L.) H.S. Irwin & Barneby	sicklepod
Senna occidentalis (L.) Link	coffee senna
Sesbania herbacea (P. Mill.) McVaugh	hemp sesbania
Setaria faberi Herrm.	giant foxtail
Sicyos angulatus L.	burcucumber
Sida spinosa L.	prickly sida
Sinapis arvensis L.	wild mustard
Solanum carolinense L.	horsenettle
Solanum elaeagnifolium Cav.	silverleaf nightshade
Solanum ptychanthum Dunal	eastern black nightshade
Solanum rostratum Dunal	buffalobur
Sorghum bicolor (L.) Moench ssp. *arundinaceum* (Desv.) deWet & Harlan	shattercane
Sorghum halepense (L.) Pers.	johnsongrass
Spergula arvensis L.	corn spurry
Stellaria media (L.) Vill.	common chickweed
Taraxacum officinale G.H. Weber ex Wiggers	dandelion
Thlaspi arvense L.	field pennycress
Urochloa platyphylla (Nash) R.D. Webster	broadleaf signalgrass
Urochloa texana (Buckl.) R. Webster	Texas millet
Veronica spp.	speedwells
Vicia sativa L.	common vetch
Vigna unguiculata (L.) Walpers	cowpea
Viola bicolor Pursh	field pansy
Xanthium strumarium L.	common cocklebur

scientists in the state, and derived from interactions with growers, consultants, and county extension agents. Each respondent was asked to rank the 10 most troublesome weeds for a particular crop in their state. A troublesome weed is a one that is not easily controlled with available technologies and, if left uncontrolled, will cause significant crop yield loss. The most troublesome weeds of grass crops were analyzed using the annual surveys of 1994 and 2008 (Dowler 1994; Webster 2008), while the broadleaf crop surveys from 1995 and 2009 were analyzed (Dowler 1995; Webster 2009). The crops are surveyed on a 4-yr rotating cycle that includes: (1) grass crops [corn; grain sorghum; hay, pastures, and rangelands; rice (*Oryza sativa* L.); small grains; sugarcane (*Saccharum* spp.); turf; and wheat]; (2) broadleaf crops [cotton, peanut, soybean, tobacco (*Nicotiana tabacum* L.), and forestry]; (3) vegetable, fruit, and nut crops {cucurbits, fruiting vegetables, cole crops and greens, other vegetables, peaches [*Prunus persica* (L.) Batsch], apples (*Malus domestica* Borkh., fruits and nuts, citrus crops}; and (4) aquatic, industrial, nursery, and container ornamentals, power lines, and rights-of-way.

Each weed that appeared in these surveys in 1994, 1995, 2008, or 2009 is listed in Table 1. To evaluate the relative importance of each weed species in these surveys, a weighted scoring system was utilized (Elmore 1983; Webster and Coble 1997); the troublesome weed index (TWI) is a weighted average used to account for the importance of a species in all of the surveyed states and the distribution of the species in the region. If a weed was listed in all of the states surveyed, then the average ranking and the TWI were equal. If a weed was not listed among the 10 most troublesome weeds in a particular state, then it was assigned a ranking as the 11th most troublesome species in that state (Webster and Coble 1997). Weeds were arranged in ascending rank order, with the lowest TWI being the most troublesome species. Troublesome

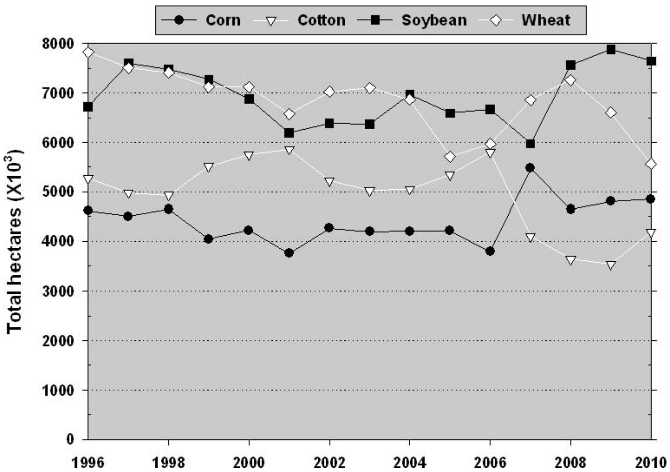

Figure 2. The annual distribution of crop production hectares summed over the southern region.

weed surveys of seven states (Alabama, Florida, Georgia, Kentucky, North Carolina, South Carolina, and Tennessee) were included in this summary for corn, nine states (Alabama, Arkansas, Florida, Georgia, Missouri, North Carolina, Oklahoma, South Carolina, and Virginia) for cotton, 10 states (Alabama, Arkansas, Florida, Georgia, Kentucky, Missouri, North Carolina, Oklahoma, South Carolina, and Virginia) for soybean, and seven states (Alabama, Florida, Georgia, Kentucky, North Carolina, South Carolina, and Tennessee) for wheat.

Instead of separating species into two lists based on distribution (i.e., important weeds vs. up-and-coming weeds) as was previously done (Webster and Coble 1997), all weeds were included on a single list in the current summary. A single list necessitates altering the order in which weeds were listed; the weeds were ordered by relative rank of the TWI. To assess which species became relatively less and more important over the 14-yr time interval, the change in relative rank among the surveys (1994 to 2008 for corn and wheat; 1995 to 2009 for cotton and soybean) was used.

National statistics for crop hectares are collected annually by the U.S. Department of Agriculture, National Agricultural Statistics Service (USDA-NASS) and reported for crops by state (USDA-NASS 2011). Data on the number of hectares receiving particular herbicides were collected annually in corn, cotton, soybean, and wheat, but only selected crops were reported each year (U.S. Department of Agriculture, Economic Research Service 2011). The reported data for herbicides were combined based on mechanism of action for each crop between 1990 and 2005 (corn), 1990 and 2006 (wheat and soybean), and 1990 and 2007 (cotton).

Results and Discussion

The ranking of troublesome weeds for each of the crops in the states of the Southern Weed Science Society provides measures of the most difficult to control weed species. While the rankings are not an absolute measure of the populations that emerge or escape management, they indicate those weed species that are most difficult to control and are most likely to reproduce and create future problems. The method of collection is consistent, and when analyzed over time, reflects the relative survival of weeds in crops in response to the environment and management. Aggregate changes in the weed flora of crops are a function of the environment, the crops grown, and crop production factors that create safe sites for weeds to emerge, grow, interfere with the crops, and reproduce. Thus, several factors may have altered weed species dynamics over this time interval, including weather patterns, changes in weed management practices, the timing of herbicide applications, and the increases in conservation tillage occasioned by the increased use of glyphosate (Price et al. 2011). The relevant effects of weather on crop production are the moisture available at planting, mean in-crop temperatures and diurnal fluctuations, and precipitation that occur during the growing season. Weather is dynamic across seasons, but the naturalized weeds within a location are adapted to grow in concert with the crops of the area. There is evidence that climate change can affect crop adaptation, weed distribution, and weed–crop interactions (McDonald et al. 2009; Patterson 1995). It is estimated that mean surface air temperature has increased < 0.9 C relative to preindustrial years (1880 to 1909) (Joshi et al. 2011). However, the period of contrast in this report is 14 yr; we suggest that the relatively small changes in climate that might have occurred over such a short a period are too small to significantly affect the composition of the flora across the sampled interval.

Weed management primarily includes tillage and herbicides. Thus, changes in tillage practices and in the types of herbicides used both affect the species and number of weed escapes that will propagate in future years. Conservation tillage has increased 49 and 85% for soybean and cotton, respectively, between 1994 and 2008, in large part, due to the adoption of glyphosate-resistant crops (Price et al. 2011). Such a fundamental change in crop management clearly affects the presence and character of safe sites for weed emergence in several ways. An increase in conservation tillage will alter water infiltration from precipitation and soil moisture retention (Triplett and Dick 2008). The presence of cover crops used in conservation tillage systems also alters soil water dynamics, soil temperature early in the cropping season, and the sites available for spring weed emergence (Hartwig and Ammon 2002). Previous studies have documented that reduced tillage alters the flora and fauna of the soil, increases weed species diversity, and concentrates weeds seeds near the soil surface, relative to moldboard plow systems (Cardina et al. 2002; Sosnoskie et al. 2009; Tillman et al. 2004; Yenish et al. 1992). Other changes attributed to reduced tillage include reduced herbicide loss through runoff and greater amounts of carbon accretion (Causarano et al. 2006; Potter et al. 2004). Levels of soil organic matter may have increased over the period of the surveys, especially in areas where conservation tillage has been most widely practiced (Triplett and Dick 2008). However, conservation tillage is not universally practiced, the accrual of soil organic matter is slow (especially in the Southeast Coastal Plain), and we lack information on the effects of changes in organic matter on weed flora in agricultural soils. Therefore, we make no speculations concerning the influence of potential changes in soil organic matter on the weed composition on a regional basis.

Crop production in the southern region is a mosaic of various crop rotations, soil types, and levels of conservation tillage. The alteration in weed management practices, primarily the use of glyphosate in herbicide-resistant crops, has been the most consistent change across the region, and we

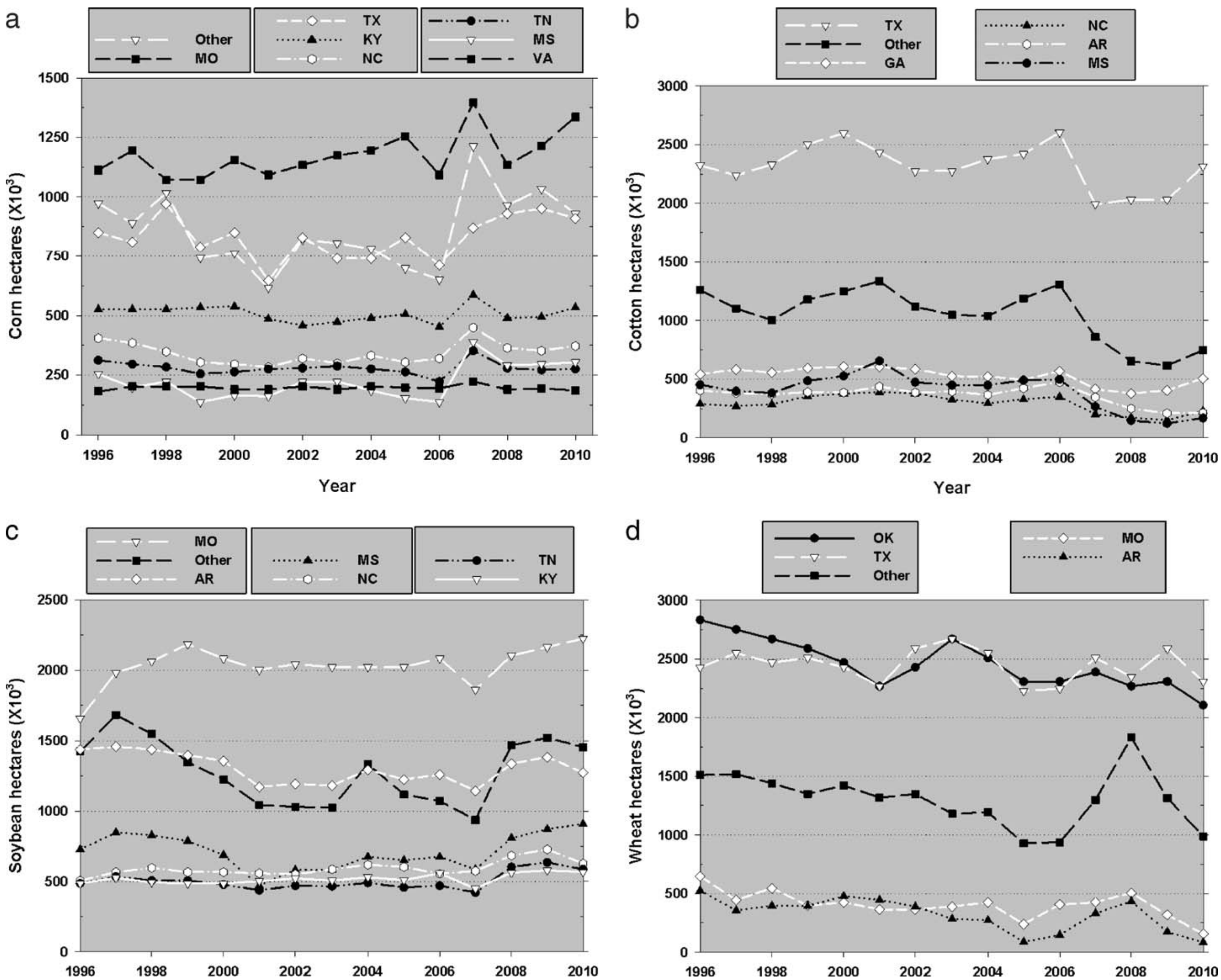

Figure 3. The annual distribution of crop production hectares by state for corn (a), cotton (b), soybean (c), and wheat (d).

suspect, one of the primary forces behind the shift in the spectrum of troublesome weeds.

Corn. *Production*. Overall, corn is the row crop with the greatest number of hectares in the United States, but in the South between 1996 and 2010, corn was planted on fewer hectares than were soybean and wheat, with cotton grown on more hectares than was corn until 2007 (Figure 2). In the southern region between 1996 and 2010, corn production ranged from 3.7 ($\pm$ 0.29) million ha to 5.4 ($\pm$ 0.36) million ha. Corn growth in the South comprises only about 10% of the total U.S. corn crop, with corn production concentrated in the region's northern states (i.e., Missouri, Kentucky, and North Carolina), which account for 47% of the total hectares (Figure 3a). Texas has the second highest percentage of the crop in the South (19%), but such a relative abundance of corn production is more of a reflection of Texas' size rather than the prominence of corn in Texas agriculture. Some corn is raised directly in support of the local dairy industries, but the majority is grown for grain. Corn is often a rotation crop for peanut, cotton, or soybean to suppress soil-borne diseases caused by nematodes or fungi.

Corn may also be used to manage weed problems in other crops; photosystem II (PSII) inhibiting herbicides (e.g., triazines) can be used in corn and are effective against many broadleaf weeds that are difficult to control in broadleaf rotation crops. Also, corn can grow to more than 2.5 m in height and is competitive with most weeds. Corn is an early harvested crop in the South, with little effort to deter weed growth following harvest; corn harvested in late July or early August, as it is often in Louisiana, southern Alabama, southern Georgia, and Florida, permits three or more months of summer weed growth and reproduction to occur following corn harvest.

Herbicides. Triazines were the most common herbicides used in corn production between 1990 and 2005, applied to 62 to 89% of corn land (Figure 1a). Typically used to target broadleaf weed species, the triazines have selected for certain weeds that are resistant to the PSII mechanism of action. In the region, resistance to PSII herbicides has been documented for: Palmer amaranth (Texas and Georgia), smooth pigweed (*Amaranthus hybridus* L.) (Virginia, North Carolina, and Kentucky), redroot pigweed (*A. retroflexus* L.) (Virginia),

Table 2. The relative rank of troublesome weeds of corn in the southern United States.

Relative rank 2008	Weed	TWI[a]	Average rank	No. of states	Average change	Relative rank 1994
1	morningglories	3.00	3.00	7	3.14	4
2	Texas millet	4.71	2.20	5	−0.20	2
3	broadleaf signalgrass	6.57	4.80	5	−1.60	3
4	johnsongrass	7.43	7.43	7	−4.86	1
5	sicklepod	7.71	7.17	6	−1.83	4
6	nutsedges	7.86	7.86	7	1.00	8
7	Palmer amaranth	8.00	4.00	3	7.00	25
8	pigweeds	8.14	6.00	4	2.50	13
9	crabgrasses	8.29	6.25	4	3.50	17
10	burcucumber	9.00	6.33	3	0.33	10
11	bermudagrass	9.14	7.75	4	0.00	10
12	fall panicum	9.29	8.60	5	−2.40	6
13	honeyvine swallwort	9.57	6.00	2	0.00	13
13	smartweeds	9.57	7.67	3	3.33	25
15	giant ragweed	10.00	7.50	2	−4.00	9
15	goosegrass	10.00	4.00	1	7.00	25
17	Florida pusley	10.14	5.00	1	6.00	25
17	wild radish	10.14	5.00	1	6.00	25
19	ryegrass	10.29	9.33	3	1.00	21
19	dandelion	10.29	6.00	1	5.00	25
19	prickly sida	10.29	6.00	1	5.00	25
22	hemp sesbania	10.43	7.00	1	4.00	25
22	common pokeweed	10.43	7.00	1	4.00	25
22	redvine	10.43	7.00	1	4.00	25
25	smooth crabgrass	10.57	8.00	1	2.00	23
25	cutleaf evening-primrose	10.57	8.00	1	3.00	25
27	Benghal dayflower	10.71	10.00	2	1.00	25
28	common cocklebur	10.86	10.75	4	−4.50	7
28	trumpetcreeper	10.86	10.50	2	−1.50	18
28	bristly starbur	10.86	10.00	1	−1.00	21
31	horsenettle	11.00	11.00	0	−6.00	12
31	Florida beggarweed	11.00	11.00	0	−5.00	13
31	shattercane	11.00	11.00	0	−7.00	16
31	bindweeds	11.00	11.00	0	−3.00	19
31	woody perennials	11.00	11.00	0	−3.00	19
31	dallisgrass	11.00	11.00	0	−1.00	23

[a] Abbreviation: TWI, troublesome weed index.

common lambsquarters (*Chenopodium album* L.) (North Carolina, Tennessee, and Virginia), tall waterhemp [*A. tuberculatus* (Moq.) Sauer] (Missouri), and annual bluegrass (*Poa annua* L.) (Mississippi, North Carolina, and Virginia) (Heap 2011).

The second most commonly used class of herbicides in corn was the acetanilides, with 49 to 63% of the corn treated between 1990 and 2005 (Figure 1a). Acetanilides are PRE herbicides that target grasses and small-seeded broadleaf species. Currently, there are no documented cases of weed species in the region with resistance to acetanilide herbicides. Phenoxy herbicides were the first class of herbicide developed (Timmons 1970) and were applied to 24 to 46% of corn between 1990 and 2005 to target broadleaf weeds.

Nicosulfuron was the first ALS-inhibiting herbicide released for use in corn in 1992, and since then, ALS herbicides have been applied on 6 to 44% of corn land (Figure 1a). Numerous weeds have developed resistance to ALS herbicides in the southern United States, including four species of *Amaranthus*, three *Lolium* species, two *Sorghum* species, common cocklebur, common sunflower (*Helianthus annuus* L.), kochia [*Kochia scoparia* (L.) Schrad.], and common chickweed [*Stellaria media* (L.) Vill.] (Heap 2011). Hydroxy-phenylpyruvate dioxygenase inhibiting herbicides were first applied to corn in the southern region in 2001 (9% of the area) and increased in each successive survey; in 2005, 26% of corn area received an application. Commercialization of glyphosate-resistant corn cultivars increased glyphosate use in corn, from less than 10% prior to 2001 to 33% in the most recent survey available in 2005. Glufosinate was applied to 2 to 5% of the corn area beginning in 1998.

Weeds. The five most troublesome weeds of corn in 2008 were the same as in 1994 but in a different order (Table 2). Morningglories were the most troublesome weed species of corn in 2008, ranked in seven states; morningglories were ranked as fourth most troublesome weeds in 1994. Morningglories are a complex of weed species of the genus *Ipomoea* and commonly refer to one or more of the following weed species: ivyleaf morningglory (*Ipomoea hederacea* Jacq.), pitted morningglory (*I. lacunosa* L.), tall morningglory [*I. purpurea* (L.) Roth.], red morningglory (*I. coccinea* L.), cotton morningglory [*I. corato-triloba* Dennst. Var. torreyana (Gray) D. Austin], sharppod morningglory (*I. coratotriloba* Dennst.), cypressvine morningglory (*I. quamoclit* L.), palmleaf morningglory (*I. wrightii* Gray), bigroot morningglory [*I. pandurata* (L.) G.F.W. Meyer], and purple moonflower (*I. turbinata* Lag.). Where it occurs, smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] is often separated from this group due to differences in the species' herbicide tolerance from that of the *Ipomoea* spp. Morningglories have historically been difficult to control in corn, due to their tolerance to many commonly used herbicides and their persistence in the soil seedbank. To date, herbicide resistance in morningglories has not been documented.

Three grasses (Texas millet, broadleaf signalgrass, and johnsongrass) were the next most troublesome weeds, reported in five, five, and seven states, respectively (Table 2). Grasses are among the most difficult weeds to control in corn, due to their similarity in herbicide tolerances, and they account for approximately one-third of the ranked weed species of corn. Between 1974 and 1994, both Texas millet and broadleaf signalgrass were two species identified as increasing in importance, while johnsongrass was the #1 most troublesome weed of corn in 1994. Sicklepod was the fifth most troublesome weed of corn in 2008 and tied for the fourth most troublesome in 1994.

Several of the most troublesome species are resistant to commonly used herbicides, including johnsongrass (#4), Palmer amaranth (#7), pigweed species (#8), giant ragweed (*Ambrosia trifida* L.) (#15), and ryegrass (#19) (Table 2). Certain populations of johnsongrass are resistant to one of four herbicide mechanisms of action, including inhibitors of: ACCase, ALS, and enolpyruvyl shikimate phosphate synthase (EPSPS), and mitosis (specifically the inhibition caused by dinitroaniline [DNA] herbicides). Glyphosate-resistant johnsongrass populations occur in Arkansas, Louisiana, and Mississippi and are very significant agronomic problems. Giant ragweed has evolved resistance to three herbicide mechanisms of action in other regions of the United States, while glyphosate-resistant giant ragweed occurs in Tennessee (Heap 2011). Recent introductions of glyphosate-resistant and glufosinate-resistant corn has increased the concern of stewardship of these herbicide-resistance traits due to potential lack of rotation of herbicide mechanisms of action among cropping systems and seasons.

The weeds that increased in importance most between 1994 and 2008 were Palmer amaranth (three states) and goosegrass (one state), both with an average change of 7.0 (Table 2). Neither of these weeds specifically appeared in the 1974 or 1994 surveys, though the generic *pigweeds* did signify the presence of an *Amaranthus* species. The increase in Palmer amaranth is likely due its increased prevalence in the region in rotational crops where herbicide resistance has developed and complicated effective weed management.

Several species were considered less troublesome in 2009 relative to 1994, including horsenettle (*Solanum carolinense* L.) (average change −6.0), Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.] (average change −5.0), and shattercane [*S. bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) deWet & Harlan] (average change −7.0) (Table 2). Common cocklebur was the species with the greatest reduction in relative ranking; the seventh most troublesome weed in 1994, common cocklebur was the 28th most important weed in 2009.

Cotton. *Production*. The southern United States is the primary cotton growing region in the United States, with production between 1996 and 2010 ranging from 3.5 (± 0.52) million ha to 5.9 (± 0.65) million ha (Figure 2). The southern United States comprises approximately 90% of the U.S. cotton production, with Texas accounting for about 47% of the planted hectares (Figure 3b). The other top five cotton producing states included Georgia, Mississippi, Arkansas, and North Carolina and together totaled 32% of the U.S. hectares. Cotton is a slow-growing seedling that requires effective early-season weed control to avert yield loss (Bryson 1990; Rogers et al. 1996; Snipes et al. 1987; Webster et al. 2009). Multiple herbicide applications within a season (e.g., PRE, POST, and POST-directed) are typically required due to the lack of robust growth and rapid canopy closure. In addition, cotton has tolerance to relatively few herbicides, compared to other agronomic crops, with several of the herbicides available only as POST-directed applications that minimize contact with cotton foliage and require large cotton plants and small weeds.

Herbicides. Herbicides representing six mechanisms of action classes were applied to cotton (Figure 1b). Between 1990 and 1999, the two dominant classes of herbicides (71 to 93% of the hectares) were PSII-inhibitors (e.g., cyanazine, diuron, and fluometuron) and DNAs (e.g., pendimethalin and trifluralin). Both of these classes were surpassed by POST applications of glyphosate in 2001; glyphosate continued to increase until 2007 (most recent data available) when it was applied to 93% of the hectares. Glyphosate was applied frequently, and often exclusively, for weed control in these cotton systems (Culpepper et al. 2004). Of the remaining three herbicide mechanisms of action, only acetanilides (e.g., *s*-metolachlor) were consistently applied to cotton during the period analyzed, with ≤ 8% of the hectares treated with this class of herbicides. However, acetanilides represent a potential means for managing glyphosate-resistant Palmer amaranth (Culpepper et al. 2011). Similarly, protoporphyrinogen oxidase inhibiting (PPO) herbicides (e.g., carfentrazone and fomesafen), which first appeared in the database for cotton in 2007, are currently a prominent component of glyphosate-resistant Palmer amaranth control programs. The final mechanism of action used in cotton was the carotenoid biosynthesis inhibitors (e.g., clomazone and norfluazon), which was consistently applied to 16 to 25% of the hectares between 1990 and 1997. However, use of carotenoid biosynthesis inhibitors gradually declined, with no use reported since 2001.

Weeds. In cotton, 8 of the top 10 weeds of 1995 are listed among the top 10 weeds of 2009 (Table 3). Palmer amaranth is now the most troublesome weed of cotton, up from the 10th position in 1995 and is ranked as troublesome in nine states. In 1995, Palmer amaranth was listed as an up-and-coming weed because it was ranked as troublesome in only two states (Webster and Coble 1997). However, in those two states (North and South Carolina) it was the most troublesome weed. Palmer amaranth has evolved resistance to several mechanisms of action, including inhibitors of: EPSPS, PSII, mitosis, and ALS (Culpepper et al. 2006; Gossett et al. 1992; Heap 2011; Horak and Peterson 1995; Vencill et al. 2008; Wise et al. 2009). Glyphosate-resistant Palmer amaranth was initially detected on a single Georgia farm in 2004 (Culpepper et al. 2006). However, following the 2008 growing season, glyphosate-resistant Palmer amaranth was found in 26 counties in Georgia, 11 counties each in North and South Carolina, and one county in Alabama; totaling an estimated 250,000 ha of agronomic land with glyphosate-resistant Palmer amaranth in the southeast United States (Culpepper et al. 2010). A survey of 20 Georgia counties in 2008 revealed that ≥ 35% of growers were using hand-weeding in order to control glyphosate-resistant Palmer amaranth in their cotton (Culpepper et al. 2010). Glyphosate-resistant Palmer amaranth was confirmed from populations collected and assayed in 2009 to be in most cotton-growing

Table 3. The relative rank of troublesome weeds of cotton in the southern United States.

Relative rank 2009	Weed	TWI[a]	Average rank	No. of states	Average change	Relative rank 1995
1	Palmer amaranth	2.00	2.00	9	5.56	10
2	morningglories	3.33	3.33	9	−0.22	1
3	nutsedge	5.78	5.13	8	−0.75	2
4	pigweeds	8.00	6.50	6	1.17	10
5	Florida pusley	8.44	6.40	5	4.00	27
6	bermudagrass	8.56	8.25	8	−1.63	4
7	Benghal dayflower	9.00	2.00	2	9.00	34
8	sicklepod	9.33	8.50	6	−3.50	3
8	Texas millet	9.33	8.00	5	0.80	13
10	common cocklebur	9.56	8.83	6	−2.83	5
10	velvetleaf	9.56	8.40	5	−1.80	8
12	common ragweed	9.67	5.00	2	6.00	34
13	horseweed	9.78	5.50	2	5.50	34
13	dayflowers	9.78	5.50	2	5.50	34
15	goosegrass	9.89	9.00	5	0.80	24
16	spurges	10.00	9.20	5	−2.80	7
16	silverleaf nightshade	10.00	2.00	1	−1.00	10
18	peanut	10.11	3.00	1	8.00	34
19	prickly sida	10.22	9.25	4	−5.50	6
19	red sprangletop	10.22	4.00	1	7.00	34
19	johnsongrass	10.22	8.67	3	−2.00	17
22	tropic croton	10.33	9.00	3	−3.00	14
23	barnyardgrass	10.44	6.00	1	5.00	34
23	alligatorweed	10.44	6.00	1	5.00	34
25	fall panicum	10.56	7.00	1	4.00	34
25	smallflower morningglory	10.56	9.00	2	2.00	34
25	devil's claw	10.56	7.00	1	−1.00	22
25	smartweeds	10.56	9.00	2	−3.00	18
29	broadleaf signalgrass	10.67	9.50	2	1.50	34
29	field bindweed	10.67	8.00	1	1.00	26
29	crabgrasses	10.67	9.50	2	1.00	32
29	perennial vines	10.67	8.00	1	−1.00	14
29	spurred anoda	10.67	10.00	3	−2.00	20
34	wild mustard	10.78	9.00	1	2.00	34
35	coffee senna	10.89	10.75	4	−5.00	9
35	eastern black nightshade	10.89	10.00	1	1.00	34
35	hophornbeam copperleaf	10.89	10.00	1	1.00	34
38	jimsonweed	11.00	11.00	0	−1.00	27
38	buffalobur	11.00	11.00	0	−1.00	32
38	trumpetcreeper	11.00	11.00	0	−2.00	22
38	bristly starbur	11.00	11.00	0	−2.00	30
38	eclipta	11.00	11.00	0	−2.00	30
38	redvine	11.00	11.00	0	−3.00	18
38	wild poinsettia	11.00	11.00	0	−3.00	27
38	cowpea	11.00	11.00	0	−4.50	9
38	sandburs	11.00	11.00	0	−5.00	24
38	hemp sesbania	11.00	11.00	0	−5.00	16
38	Florida beggarweed	11.00	11.00	0	−6.00	34

[a] Abbreviation: TWI, troublesome weed index.

counties in Georgia, South Carolina, North Carolina, Arkansas, and is widespread in western Tennessee (Nichols et al. 2009).

The five most troublesome weeds in 1995 (in order) were morningglory (#2 in 2009), nutsedges (#3 in 2009), sicklepod (#8 in 2009), bermudagrass [*Cynodon dactylon* (L.) Pers.] (#6 in 2009), and common cocklebur (#10 in 2009) (Table 3). Historically, these species have been persistent weeds in the region and among the most troublesome in 1974 and 1983 (Buchanan 1974; Elmore 1983). The reduction in the importance of sicklepod is likely attributed to the effectiveness of control from glyphosate. In Mississippi, weed surveys indicated a sevenfold decline in the occurrence of common cocklebur between 1982 (62% of fields) and 2000 (9% of fields) (Rankins et al. 2005). The sharp decline in common cocklebur was attributed to the introduction and use of ALS-inhibiting herbicides in Mississippi row crops (Rankins et al. 2005).

Prior to the introduction of glyphosate-resistant cultivars, pigweeds were ranked among the top six weed species of cotton in the southern region in 1974 and 1995 (Webster and Coble 1997) and currently are ranked as fourth most troublesome species (Table 3). In 2005, 8 of the 10 surveyed southern states listed pigweeds among the five most troublesome weeds of cotton, while pigweeds held this rank in only 4 of 12 states in 1995 and 1 of 10 states in 1983 (Dowler 1995; Elmore 1983; Webster 2005).

There are several species that are new in the 2009 survey. Of the 35 weed species listed in cotton as troublesome in the southern states, 14 of them did not appear in the 1995 survey, which is indicated by a relative rank of 34 in the 1995 survey (Table 3). The high ranking recent additions to the 2009 list include Benghal dayflower, common ragweed, horseweed, dayflowers (*Commelina* spp.), and peanut (*Arachis hypogaea* L.). With the exception of peanut, each of these weeds was ranked in two states. Even with a limited distribution, the

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high ranking of Benghal dayflower in Georgia and Florida (both #2) resulted in a #7 ranking overall and the largest average change (+9.0). Benghal dayflower is troublesome because of its tolerance to many commonly used herbicides in cotton, including glyphosate (Culpepper et al. 2004; Webster et al. 2006). Populations of horseweed and common ragweed have developed resistance to glyphosate, which may have contributed to their increased importance in the region (Brewer and Oliver 2009; Koger et al. 2004; Powles 2008).

There are several species of previously important weeds that have become relatively less important, including prickly sida (*Sida spinosa* L.) (#19, average change of −5.5) and coffee senna [*Senna occidentalis* (L.) Link](#35, average change of −5.0) (Table 3); both are readily controlled with glyphosate (Culpepper and York 1999; Reddy et al. 2008). Prickly sida was the most troublesome weed of cotton in 1974 and third most troublesome in 1995 (Webster and Coble 1997). Johnsongrass is distributed throughout the United States (Bryson and DeFelice 2009) and was ranked as the most troublesome weed of cotton in 1983 and second most troublesome weed in 1974 (Webster and Coble 1997) but is only ranked as #19 in the current evaluation. This is in large part due to the effective johnsongrass control with ACCase-inhibiting herbicides and glyphosate. However, johnsongrass has recently developed resistance to these herbicide mechanisms of action (Heap 2011) and will likely again become a significant weed problem.

Soybean. *Production*. Between 1996 and 2010, soybean production in the southern region ranged from 5.9 (± 0.51) million to 7.9 (± 0.59) million ha (Figure 2). Missouri had the greatest number of hectares (averaged 2.0 million ha; approximately 29% of the production in the region), followed by Arkansas (averaged 1.3 million ha; approximately 19%), Mississippi (averaged 714,000 ha; approximately 10%), Kentucky (averaged 517,000 ha; approximately 7%), and Texas (averaged 500,000 ha; approximately 7%) (Figure 3c). Each state in the region produced soybean, with the remaining states accounted for approximately 18% of the soybean area, ranging from 9,000 ha in Florida to 389,000 ha in Louisiana.

Herbicides. Herbicides representing nine different mechanisms of action were used in soybean, providing the greatest variability in mechanism of action options among the four agronomic crops that were evaluated (Figure 1c). In 1990, DNA herbicides (e.g., trifluralin and pendimethalin) were the most commonly applied (56% of ha) herbicides but have steadily decreased between 1997 (46% of ha) and 2006 (1% of ha). Small-seeded broadleaf and grass weeds are targeted by DNA herbicides, but more recent herbicide mechanisms of action exhibited less crop injury. In addition, with the development of effective POST herbicides, growers were introduced to the threshold concept of weed management, which emphasized remedial control of emerged weeds in place of preventive weed control with PRE herbicides (Coble and Mortensen 1992; Wilkerson et al. 1991). In the middle-1990s, the U.S. Department of Agriculture and Environmental Protection Agency launched a presidential initiative to increase Integrated Pest Management adoption from 50 to 75% of U.S. cropland by 2000 (Coble and Ortman 2009). As herbicides accounted for 70% of pesticides used on U.S. cropland (Coble 1994), the use of weed thresholds was targeted as a potential means of accomplishing this goal.

ALS inhibiting herbicides (e.g., chlorimuron, imazaquin, and imazethapyr) were more commonly used than were DNA herbicides after 1991 and quickly became the dominant herbicides in soybean throughout most of the 1990s (Figure 1c). By 1994, 87% of the soybean area was treated with ALS herbicides. However, ALS use rapidly declined between 1997 (73%) and 2006 (5%), due to the development of resistance to the ALS mechanism of action in numerous weeds and the release and rapid adoption of glyphosate-resistant soybean cultivars.

Glyphosate was applied to ≤ 20% of the soybean area between 1990 and 1995 (Figure 1c). Glyphosate-resistant soybean cultivars were released in 1996, and by 1998 glyphosate was applied to 46% of the soybean ha, which increased annually to 96% in 2006. Use of glyphosate-only programs was most common (85%) in continuous glyphosate-resistant soybean production relative to corn and cotton (Givens et al. 2009a). To put the dominance of glyphosate in perspective, in 2006, all other herbicide mechanisms of action were applied to a total of 29% of the soybean ha, with phenoxy herbicides the most common at 10%. Use of phenoxy herbicides in soybean peaked in 1996 at 13% of soybean ha receiving an application, with maximum use of 10% in other years. Only PSII inhibiting herbicides (e.g., linuron and metribuzin) and the very long chain fatty acid (VLCFA)-inhibiting acetanilide herbicides (e.g., alachlor and metolachlor) exceeded application to as much as 20% of the soybean ha; peak usage occurred in 1990 for both of these mechanisms of action. Since 1998, both of these groups of herbicides have been applied to ≤ 7% of soybean ha. The three remaining herbicide classes—PPO (e.g., acifluorfen and sulfentrazone), ACCase inhibiting herbicides (e.g., fluazifop), and the carotenoid biosynthesis inhibitors (e.g., clomazone)—were applied to a maximum of 12, 10, and 7% of soybean ha, respectively, but as of 2006 each was applied to ≤ 2% of ha.

Weeds. Only morningglories and sicklepod were among the top five weed species in both 1995 and 2009, with 2009 rankings of #1 and #5, respectively (Table 4). Both of these large-seeded broadleaf weeds have been persistent issues in soybean, with previous surveys ranking morningglories and sicklepod among the top five most troublesome soybean weeds in the region in 1974, 1983, and 1995 (Elmore 1983; Webster and Coble 1997). Surveys of Georgia extension agents and South Carolina soybean growers demonstrated that sicklepod and morningglories were among the top three most troublesome species in these states (Norsworthy 2003; Webster and MacDonald 2001). Morningglories can be difficult to control with glyphosate due to their natural tolerance to the herbicide (Jordan et al. 1997) and discontinuous emergence pattern. The near region-wide distribution of sicklepod (eight states) reflects the importance of this weed, though it is readily controlled with glyphosate.

In 2009, Palmer amaranth, horseweed, and Florida pusley were the second, fourth, and fifth (tie with sicklepod) most troublesome weeds of soybean, respectively. Each of these species can be difficult to manage in glyphosate-dominated systems, either due to glyphosate-resistance in Palmer amaranth and horseweed or glyphosate-tolerance in Florida

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Table 4. The relative rank of troublesome weeds of soybean in the southern United States.

Relative rank 2009	Weed	TWI[a]	Average rank	No. of states	Average change	Relative rank 1995
1	morningglories	3.00	3.00	10	−0.40	1
2	Palmer amaranth	6.10	2.83	6	5.00	23
3	nutsedges	8.10	7.38	8	0.25	6
4	horseweed	8.30	5.60	5	5.00	38
5	sicklepod	8.70	8.13	8	−5.38	2
5	Florida pusley	8.70	6.40	5	4.40	39
7	common cocklebur	9.20	8.75	8	−3.88	4
8	Texas millet	9.40	7.00	4	2.25	21
9	eastern black nightshade	9.50	7.25	4	−2.00	7
9	common ragweed	9.50	6.00	3	2.33	20
9	giant ragweed	9.50	6.00	3	3.00	30
9	Benghal dayflower	9.50	3.50	2	7.50	40
9	groundcherries	9.50	3.50	2	7.50	40
14	pigweeds	9.60	8.67	6	−3.17	5
14	common lambsquarters	9.60	4.00	2	0.00	10
14	prickly sida	9.60	7.50	4	0.25	13
17	tropic croton	9.70	6.67	3	1.33	17
18	johnsongrass	9.80	9.50	8	−4.88	3
19	trumpetcreeper	9.90	5.50	2	4.00	33
20	Florida beggarweed	10.00	7.67	3	−1.67	9
20	waterhemps	10.00	1.00	1	3.00	16
20	hemp sesbania	10.00	7.67	3	2.00	28
23	bermudagrass	10.10	8.00	3	−1.67	10
23	honeyvine swallowwort	10.10	2.00	1	4.00	22
23	cowpea	10.10	6.50	2	2.00	29
23	dayflowers	10.10	6.50	2	4.50	40
27	cutleaf evening- primrose	10.20	3.00	1	8.00	40
27	hairy indigo	10.20	3.00	1	8.00	40
29	velvetleaf	10.30	7.50	2	−4.50	8
29	common pokeweed	10.30	4.00	1	7.00	40
31	spurges	10.40	8.00	2	−1.50	14
31	burcucumber	10.40	5.00	1	2.00	24
31	horsenettle	10.40	8.00	2	1.00	30
34	balloonvine	10.70	11.00	1	−3.00	27
34	barnyardgrass	10.70	8.00	1	3.00	40
34	goosegrass	10.70	8.00	1	3.00	40
37	bristly starbur	10.80	10.00	2	−5.00	12
37	red rice	10.80	9.00	1	−7.00	14
37	coffee senna	10.80	10.33	3	−2.33	17
37	broadleaf signalgrass	10.80	10.50	4	−0.50	30
37	dandelion	10.80	9.00	1	2.00	40
42	carpetweed	10.90	10.00	1	1.00	40
42	glyphosate-resistant cotton	10.90	10.00	1	1.00	40
44	shattercane	11.00	11.00	1	−6.00	17
44	crabgrasses	11.00	11.00	1	−4.00	24
44	hemp dogbane	11.00	11.00	1	−4.00	24
44	fall panicum	11.00	11.00	1	−1.00	34
44	giant foxtail	11.00	11.00	1	−1.00	34
44	jimsonweed	11.00	11.00	1	−1.00	34
44	smartweeds	11.00	11.00	1	−1.00	34

[a] Abbreviation: TWI, troublesome weed index.

pusley (Culpepper et al. 2006; Norsworthy 2005; VanGessel 2001). Palmer amaranth was listed by South Carolina growers as the second most troublesome weed in 2000 (Norsworthy 2003). In addition, the weeds with the largest increases in importance (change in relative rank between 1995 and 2009) were Benghal dayflower, groundcherries, and giant ragweed, with only giant ragweed previously appearing in the 1995 survey. Other weeds new to the 2009 survey that did not appear in 1995 include dayflowers, cutleaf evening-primrose (*Oenothera laciniata* Hill), hairy indigo (*Indigofera hirsuta* Harvey), common pokeweed (*Phytolacca americana* L.), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], goosegrass, dandelion [*Taraxacum officinale* G.H. Weber ex Wiggers], carpetweed (*Mollugo verticillata* L.), and glyphosate- resistant cotton; of these species, only dayflowers were listed in multiple states.

Several species have decreased in importance between 1995 and 2009 but most were listed in two or fewer states (Table 4). Johnsongrass, the #3 most troublesome species in 1995 and ranked in eight states as troublesome, was reduced to the #18 most troublesome weed of soybean in 2009. This change is likely due to the use and efficacy of glyphosate in controlling johnsongrass. In Mississippi, there was a fourfold reduction in the occurrence of johnsongrass in soybean fields between 1982 and 2000 (Rankins et al. 2005). However, glyphosate-resistant johnsongrass populations occur within the region and could make it one of the more important and troublesome weeds in southern soybean.

Wheat. *Production*. In the southern region between 1996 and 2010, wheat production ranged from 5.5 (± 0.77) million to 7.8 (± 0.90) million ha (Figure 2). Oklahoma had the

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Table 5. The relative rank of troublesome weeds of wheat in the southern United States.

Relative rank 2008	Weed	TWI[a]	Average rank	No. of states	Average change	Relative rank 1994
1	Italian ryegrass	1.57	1.57	7	1.00	1
2	wild garlic	4.43	4.43	7	−1.71	2
3	wild radish	5.00	2.60	5	0.20	3
4	henbit	5.43	5.43	7	0.43	4
5	annual bluegrass	7.43	4.75	4	6.00	25
6	chickweeds	7.86	6.60	5	0.20	7
7	cutleaf evening-primrose	8.00	7.50	6	1.00	8
8	wild mustard	8.43	6.50	4	1.25	11
9	curly dock	9.43	9.43	7	−2.71	5
10	hairy chess	9.71	2.00	1	9.00	28
11	cheat	9.86	8.33	3	−4.67	6
12	little barley	9.86	9.00	4	−0.20	13
13	purple deadnettle	9.86	3.00	1	2.00	16
14	common vetch	10.14	9.80	5	−1.80	9
15	cornflower	10.14	9.00	3	−1.33	12
16	speedwells	10.14	9.00	3	1.00	19
17	Carolina geranium	10.14	5.00	1	6.00	29
18	field pansy	10.14	5.00	1	6.00	30
19	star-of-Bethlehem	10.14	5.00	1	6.00	31
20	swinecress	10.43	7.00	1	3.00	26
21	pennycress	10.43	7.00	1	4.00	32
22	musk thistle	10.57	9.50	2	−2.00	14
23	horseweed	10.57	9.50	2	1.00	27
24	Virginia pepperweed	10.71	10.00	2	−2.50	15
25	cudweeds	10.71	10.00	2	0.00	22
26	Carolina foxtail	10.86	10.00	1	1.00	33
27	knawel	11.00	11.00	2	−7.00	10
28	corn spurry	11.00	11.00	1	−6.00	17
29	shepherd's-purse	11.00	11.00	1	−5.00	18
30	common lambsquarters	11.00	11.00	1	−3.00	20
31	Florida pusley	11.00	11.00	1	−3.00	21
32	carpetweed	11.00	11.00	1	−2.00	23
33	corn gromwell	11.00	11.00	1	−2.00	24

[a] Abbreviation: TWI, troublesome weed index.

greatest number of ha (average 2.5 million ha, approximately 36%), followed by Texas (average 2.4 million ha, approximately 36%), Missouri (average 400,000 ha, approximately 6%), and Arkansas (average 320,000 ha, approximately 5%) (Figure 3d). The remaining states accounted for 18% of the wheat ha, ranging from 6,000 ha in Florida to 262,000 ha in North Carolina.

Herbicides. Six herbicide mechanisms of action are used in wheat (Figure 1d). Phenoxy and benzoic acid herbicides (e.g., 2, 4-D, dicamba, and MCPA) have been the dominant herbicide class between 1990 and 2006, with 49 to 79% of wheat receiving an application. ALS (e.g., thifensulfuron, tribenuron-methyl, and metsulfuron-methyl) was the next most commonly used class, ranging from 18% of wheat in 1990 to 55% in 1995. As of 2006, the next most commonly used herbicide was glyphosate; used in less than 2% of the wheat before 1996, glyphosate applications increased to 21% of the wheat ha in 2006. PSII (e.g., bromoxynil) use in wheat increased from a low of 3% in 1990 up to 17% in 2006. ACCase herbicides (e.g., fenoxaprop-ethyl and clodianafop-propargil) were used on ≤ 6% of wheat between 1990 and 1996, with a maximum of 15% receiving an application in 2004. The final class of herbicides, the DNAs, was used on 2 to 6% of wheat between 1990 and 2000 but dropped to ≤ 1% between 2002 and 2006.

Weeds. An autumn planted crop, wheat has a very different spectrum of weeds compared to the summer annual crops in this survey. Composed primarily of winter annual weeds, only ryegrass (corn), evening-primrose (corn and soybean), horseweed (cotton and soybean), and wild radish (corn and cotton) are considered troublesome in the other crops.

Italian ryegrass was the most troublesome weed of wheat in 1994 and 2008 (Table 5). Italian ryegrass in the southern region has developed resistance to three herbicide mechanisms of action, including ACCase-inhibitors (Arkansas, Georgia, North Carolina, Tennessee, and Virginia), ALS-inhibitors (Arkansas), glyphosate (Arkansas and Mississippi), and multiple resistance to both ALS- and ACCase-inhibitors (Arkansas and Georgia) (Heap 2011). The next three most troublesome weeds of wheat occurred in the same order in both 1994 and 2008: wild garlic, wild radish, and henbit. These species were among the top five most troublesome species of wheat in a survey of Georgia extension agents (Webster and MacDonald 2001). Annual bluegrass was the fifth most troublesome species in 2008, up from #25 in 1994, which made it the species that increased most in importance over this interval. Weeds six through nine [chickweeds, evening-primrose, mustard (*Sinapis arvensis* L.), and curly dock (*Rumex crispus* L.)] had relatively similar ranking in both 1994 and 2008. Hairy chess (*Bromus commutatus* Schrad.) was ranked in one state as the second most troublesome species, but even with the limited distribution in this survey, it moved from #28 in 1994 to #10 in 2008.

Conclusions

The Southern Weed Science Society's surveys provide a benchmark of weed prevalence each year. This analysis documents the changes in the weed flora of southern crops

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over time. Weeds have responded to consistent selection pressure when applied to an agro-ecosystem, whether as the presence or absence of tillage (Cardina et al. 1991; Egley and Williams 1990) or reliance of on a limited number of herbicide mechanisms of action (Owen 2008; Webster and Sosnoskie 2010; Young 2006). While we cannot ignore that many factors contributed to the relative prevalence of species in the weed flora, weeds persist and propagate when they avoid or overcome the practices engaged against them.

Herbicides are the predominant factors employed in weed management and have most likely been the driving force behind the observed changes in the relative prevalence of troublesome weeds in the region. In 1995, the technology of weed management changed dramatically with the advent of transgenic, glyphosate-resistant cultivars (Dill et al. 2008). Glyphosate was an herbicide of truly exceptional broad-spectrum efficacy and reliability, and the ability to apply glyphosate topically to resistant crops fundamentally changed weed management in the United States and other countries where herbicides are routinely applied (Duke and Powles 2008). As documented here, glyphosate use increased dramatically in soybean, cotton, and corn, clearly because of the wide use of glyphosate-resistant cultivars. Accordingly, the high efficacy of glyphosate displaced the use of most other herbicide mechanisms of action, beginning in soybean and cotton, and continuing more recently in corn. As a consequence, the exposure of weed populations to the EPSPS mechanism of action was greater than that previously observed for any other herbicide mechanism of action. As glyphosate became the principal, or often sole, means of weed management, growers abandoned tillage/cultivation for weed control and adopted soil conservation practices that increased stewardship of soil resources. The net effect was a major change in the field conditions affecting weed emergence, survival, and propagation. The changes in weed flora in the southern United States can be viewed, in part, by the advancement in weed management technology and dominance of glyphosate in cotton and soybean. Where adoption of glyphosate-resistance technology lagged behind cotton and soybean (i.e., corn), or is nonexistent (i.e., wheat), changes in the weed species composition were not as dramatic. In corn and wheat, 12 of the top 15 most troublesome weeds in 1994 were also ranked in the top 15 in 2008. In contrast, only 8 of the top 15 most troublesome weeds of cotton and soybean were common in 1995 and 2009, likely related to the glyphosate susceptibility of the species that decreased in importance (e.g., coffee senna, johnsongrass, Florida beggarweed, and spurges).

Research efforts focused on further evaluating the effect of the several factors that alter safe sites would enhance our knowledge of weed establishment, fecundity in weed management systems, and persistence. Also, it is clear from these findings that weeds possess the ability to adapt to a recurrent selection pressure. As herbicides are currently the predominant weed management tool, future research should seek methods to hinder the rapid development of herbicide-tolerant and herbicide-resistant weed species. As new tools are developed, research should focus on ways to preserve the efficacy of those tools through improved stewardship.

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