Effect of tillage intensity and herbicide programs on changes in weed species density and composition in the southeastern coastal plains of the United States

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Abstract

An experiment was conducted from spring 2001 to 2005 at Blackville, SC, to determine the impact of no-till and glyphosate-resistant crops on changes in the weed community. *Glycine max* (L.) Merr. (soybean) was grown in 2001 and 2003, and *Zea mays* L. (corn) was grown in 2002 and 2004. Tillage each year included no-tillage and conventional tillage (disking and field cultivation prior to crop sowing). Glyphosate-only and nonglyphosate programs were evaluated within each tillage system. Soil cores were collected at 0–5 and 5–10 cm depths prior to spring to estimate the seedbank. Weed biomass by species was determined in mid-summer each year, except in 2003. Twenty-seven species were found in soil collected from the test site throughout the study. *Digitaria sanguinalis* (L.) Scop. (large crabgrass), *Amaranthus palmeri* S. Wats. (Palmer amaranth), and *Mollugo verticillata* L. (carpetweed) were the dominant weeds in soil at initiation of the experiment. Summer annual grasses comprised more than 20% of total weed biomass in 2001, but less than 1% of total biomass in 2002 and 2004. *D. sanguinalis* seed density in soil was reduced rapidly in all management systems and was replaced by *Dactyloctenium aegyptium* (L.) Willd (crowfootgrass) as the dominant summer annual grass. There was an 80–99% reduction in the *A. palmeri* seed density (0–5 cm depth) during the first year of the study and *M. verticillata* became the dominant summer annual broad-leaved weed. Perennial weeds comprised <10% of the total weed biomass in 2001, but by 2004, >99% of the total weed biomass was made up of perennial weeds in nonglyphosate systems regardless of tillage treatment. These perennial weeds consisted of *Cynodon dactylon* (L.) Pers. (bermudagrass), *Cyperus rotundus* L. (purple nutseedge), and *Solanum carolinense* L. (Carolina horsenettle). The seed density in soil of most species declined over the four cropping seasons.

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Keywords: Crop management practices; Perennial weeds; Population dynamics; Weed shifts

1. Introduction

Glyphosate is a broad-spectrum herbicide registered for postemergence applications in glyphosate-resistant *Glycine max*, *Zea mays*, and other crops. The effectiveness of glyphosate on a wide array of weeds, lack of rotational restrictions, crop safety, and application flexibility have contributed to rapid adoption of this technology (Baylis, 2000; Culpepper, 2006). Glyphosate-resistant *G. max* was released in 1996, and by 2005, 88% of the United States *G. max* hectares were treated with glyphosate (NASS, 2006). Adoption of glyphosate-resistant *Z. mays* has been much slower, but is increasing as evidenced by 31% of the *Z. mays* hectares being treated with glyphosate in 2005 compared to 19% in 2003 (NASS, 2006). In South Carolina, 68% of *G. max* growers were using glyphosate-resistant *G. max* by 2000, with *Z. mays* being the most common rotation with *G. max* (Norsworthy, 2003). In addition to glyphosate use in *Z. mays* and *G. max*, glyphosate was applied to 95% of the 2005 *Gossypium hirsutum* L. (cotton) hectares (NASS, 2006).

Over-reliance on glyphosate in three of the major crops of the southern United States is a concern for development
of glyphosate-resistant weeds as well as changes in weed species composition. No cases of resistance were reported before 1996, but by 2006, 12 species have been confirmed glyphosate resistant (Heap, 2006).

Continued use of a single herbicide often results in weed composition shifts from highly susceptible species to those having greater tolerance to the herbicide. For instance, extensive use of atrazine was associated with changes in weed composition to a predominance of *Panicum dichotomiflorum* Michx. (fall panicum) (Coffman and Frank, 1992; Johnson and Coble, 1986). In Virginia, increases in *Eleusine indica* (L). Gaertn. (goosegrass) and *Eleusine indica* (Hilgenfeld et al., 2004a; Jordan et al., 1997; Norsworthy and Oliver, 2002a), *Ipomoea* spp. (morningglories) (Jordan et al., 1997; Norsworthy et al., 2001; Norsworthy and Oliver, 2002a), *Ipomoea* spp. (morningglories) (Hilgenfeld et al., 2004a; Jordan et al., 1997; Norsworthy et al., 2001; Norsworthy and Oliver, 2002b), *Richardia brasiliensis* (Moq.) (Gomez) (Brazil pusley), and *Commelina benghalensis* L. (Benghal dayflower) (Webster et al., 2005) are just a few of the weeds that are difficult to control with glyphosate.

Many weed scientists believe that glyphosate-induced weed shifts have already reached economic concern (Culpepper, 2006). In 2000, Shaner stated, “shifts in the weed species ‘composition from highly susceptible toward more tolerant species will happen more rapidly than selection of resistance’”. Changes in weed species composition have occurred in fields planted to glyphosate-resistant *G. hirsutum* in Georgia where *C. benghalensis* was not among the most common or troublesome weeds in 1998 (Dowler, 1998), but is now the most troublesome weed, partially because of continual reliance on glyphosate (Webster, 2005; Webster et al., 2005). In Kansas, *Ipomoea heederacea* Jacq. (ivyleaf morningglory) increased over time in a glyphosate-only system (Marshall et al., 2000). The cause of the shift was likely twofold: one contributor being the tolerance of *I. heederacea* to glyphosate (Hilgenfeld et al., 2004a), and the other, its avoidance of glyphosate through late-season emergence (Hilgenfeld et al., 2004b). In research plots in Pennsylvania, *Polygonum convolvulus* L. (wild buckwheat) became an increasing problem in a glyphosate-only system, particularly in *Z. mays* (Curran et al., 2002). In contrast, weed species shifts in Mississippi were not apparent in glyphosate-resistant *G. hirsutum* and *G. max*, but weed population densities were reduced over time (Flint et al., 2000). Similarly, in a 3-year study in *G. hirsutum* in Mississippi, Reddy (2004) did not observe a change in weed composition in a glyphosate-only system, but did in bromoxynil-resistant *G. hirsutum*.

Herbicide avoidance from certain weed species in a glyphosate-only system can lead to changes in relative abundance in the soil seedbank, resulting in a shift in the weed community. Hillgenfeld et al. (2004a, b) demonstrated that *Sorghum bicolor* (L.) Moench (shatterpod), a late-emerging weed, could avoid sequential glyphosate applications in *G. max*, increasing the size of its seedbank. Conversely, seedbank density was reduced for earlier emerging species that were effectively controlled. In the southern United States, duration of emergence may span 4–6 mo for many of the most common and troublesome weeds of row crops, such as *Sesamum indicum* L. (Sesame) and *Senna obtusifolia* (L.) H.S. Irwin & Barneby (sicklepod), *I. lacunosa* L. (pitted morningglory), *Xanthium strumarium* L. (common cocklebur), and *Amaranthus palmeri* (Jha et al., 2006; Oliveira and Norsworthy, 2004; Oliveira et al., 2006). This extended emergence period may increase the occurrence of these weeds in glyphosate-only fields.

Conservation tillage has gained widespread acceptance by producers in most regions and is used on about 41% of all United States cropland (Peterson, 2005). Conventional tillage practices in the southeastern Coastal Plains, however, still involve disking, field cultivating, and deep tillage to disrupt the E horizon (hardpan), with approximately 57% of the *G. max* producers in South Carolina using these practices in 2000 (Norsworthy, 2003). Use of deep tillage implements to shatter the E horizon are essential for optimum crop yields on the Coastal Plain (Frederick et al., 1998). Disturbance of the soil surface with deep tillage implements is minimal, resulting in greater debris on the surface and reduced loss of soil moisture compared to conventional tillage practices. Other benefits include reduction in organic matter oxidation, which affects soil water holding capacity, and fewer tillage passes, which reduces tillage costs.

Tillage practices vary by cropping system and region, with tillage intensity routinely influencing weed seedbank size and composition (Barberi and Cascio, 2000). For instance, grass weeds generally dominate under reduced tillage systems (Pleasant et al., 1990). Tillage experiments conducted over multiple years have shown seed density often to be greatest in a no-tillage system and decline with tillage intensity (Cardina et al., 1991, 2002; Feldman et al., 1997). Conversely, Clements et al. (1996) found seedbank populations to increase with tillage intensity. This difference among experiments may in part be a result of the initial seedbank composition, since seed size affects emergence success following burial (Benvenuti et al., 2001).

Tillage practices influence vertical distribution of weed seeds in soil in addition to the rate of seedbank decline (Ball, 1992; Barberi and Cascio, 2000; Buhler et al., 1996, 1997; Cardina et al., 1991). Increased seed density at
shallow depths led Barberi and Cascio (2000) to speculate that no-tillage might increase weed infestations as a result of increased recruitment. Tillage systems causing the least soil disturbance generally lead to a build-up of a larger and more diverse soil seedbank (Cardina et al., 1991, 2002; Feldman et al., 1997). Fortunately, tillage has minimal impact on weed shifts in systems where weed control from herbicides is adequate (Ball and Miller, 1990) because herbicides are generally a stronger constraint (filter) to community assembly than is tillage intensity (Booth and Swanton, 2002).

The objective of this research was to evaluate the impact of tillage practices and continued use of a glyphosate-only herbicide program on the weed community in a Z. mays–G. max rotation in the southeastern United States. Because a high frequency of glyphosate-resistant crops generally results in a less dense and variable weed community (Harker et al., 2005; Puricelli and Tuesca, 2005), it is expected that tillage will not have as strong of an impact on changes in weed composition in glyphosate-resistant crops when a high level of weed control is maintained.

2. Materials and methods

2.1. Experimental design

A dryland field experiment was conducted at the Edisto Research and Education Center at Blackville, SC, from spring 2001 to 2005. The soil type was a Dunbar sandy loam (fine, kaolinitic, thermic Aeric Paleaquults) with 0.6% organic matter. In 2000, the test area was sown to Z. mays, with weed management consisting of atrazine plus metolachlor at sowing. Severe drought in 2000 resulted in crop failure; thus, no grain was harvested and the test area was mowed in the fall after most weeds had produced seeds. A. palmeri and D. sanguinalis were the dominant weed species in 2000.

The experimental design was a split plot with tillage systems (conventional tillage and no-tillage) as the main plot factor and herbicide programs (glyphosate-only and nonglyphosate) as the subplot factor. Plots were 23 m by 45 m, and treatments were replicated four times. Plots were cultivated, and drill seeded with a conventional drill. After deep tillage, no-tillage plots were seeded with a no-till drill. ‘NK S73-ZSRR’ G. max (glyphosate resistant) was seeded in 19-cm width rows at 500,000 seeds/ha on May 30, 2001, and June 26, 2003. Glyphosate-only plots received glyphosate at 840 g/ha at the V3 and V6–V7 G. max growth stages in both years. Nonglyphosate plots in 2001 received pendimethalin at 554 g a.i./ha applied preemergence followed by clethodim at 105 g a.i./ha, chlorimuron at 8.8 g a.i./ha, and crop oil concentration at 1% v/v at the V6–V7 G. max growth stages. In 2003, nonglyphosate plots received flumetsulam at 56 g a.i./ha plus pendimethalin at 554 g/ha applied preemergence followed by clethodim at 140 g/ha, thifensulfuron-methyl at 4.4 g a.i./ha, and crop oil concentration at 1% v/v at the V6–V7 G. max growth stages. Plots were harvested for G. max grain following crop maturity.

2.2. G. max

All plots, including no-tillage, were broadcast deep tilled to a 36-cm depth each year using a four-shankled ParaTill equipped with a serrated cutting coulter mounted in front of each shank. This implement was designed to fragment the natural hardpan (E horizon) while causing minimal disturbance of the soil surface. Conventional tillage plots were then disked to an approximate depth of 10 cm, field cultivated, and drill seeded with a conventional drill. After deep tillage, no-tillage plots were seeded with a no-till drill. ‘NK S73-ZSRR’ G. max (glyphosate resistant) was seeded in 19-cm width rows at 500,000 seeds/ha on May 30, 2001, and June 26, 2003. Glyphosate-only plots received glyphosate at 840 g/ha at the V3 and V6–V7 G. max growth stages in both years. Nonglyphosate plots in 2001 received pendimethalin at 554 g a.i./ha applied preemergence followed by clethodim at 105 g a.i./ha, chlorimuron at 8.8 g a.i./ha, and crop oil concentration at 1% v/v at the V6–V7 G. max growth stages. In 2003, nonglyphosate plots received flumetsulam at 56 g a.i./ha plus pendimethalin at 554 g/ha applied preemergence followed by clethodim at 140 g/ha, thifensulfuron-methyl at 4.4 g a.i./ha, and crop oil concentration at 1% v/v at the V6–V7 G. max growth stages. Plots were harvested for G. max grain following crop maturity.

2.3. Z. mays

Tillage systems for Z. mays were similar to those for G. max. Z. mays was seeded with a conventional planter with 48 cm between planting units. Prior to sowing Z. mays, the experimental test area was fertilized with nitrogen, phosphorus, and potassium at 173 kg/ha of each. ‘Asgrow RX897RR’ Z. mays (glyphosate resistant) was planted on March 29, 2002, and ‘DeKalb C66-80RR2’ Z. mays (glyphosate resistant) was planted on April 8, 2004, at 74,000 seeds/ha. Glyphosate-only plots received glyphosate at 840 g/ha at 31- and 76-cm height Z. mays in both years. Nonglyphosate treatments in 2002 received atrazine at 1680 g a.i./ha plus S-metolachlor at 874 g a.i./ha at sowing followed by atrazine at 1120 g/ha plus 1% v/v crop oil concentrate at 31-cm height Z. mays. In 2004, nonglyphosate treatments received atrazine at 2240 g/ha plus nicosulfuron at 35 g a.i./ha plus 1% v/v crop oil concentrate at 31-cm height Z. mays. At maturity, Z. mays was harvested.

1Brigham Brothers, Inc., P.O. Box 3338, 705 East Slanton Rd., Lubbock, TX, USA 79452.
2.4. Data analysis

Separate ANOVAs (PROC GLM, SAS) were performed each year to determine tillage and herbicide program effects on weed variables. The seedbank data from 2002 to 2005 were expressed relative to the initial seedbank in 2001. Hence, a positive or negative change in the seedbank was measurable using a least-square means test to determine if the treatment mean each year differed from the initial density.

Weed biomass data were grouped as summer annual broad-leaved, summer annual grass, and perennial weeds, and log-transformed prior to ANOVA. Fisher’s protected LSD at a 5% level of significance was used to separate transformed tillage and herbicide program means, with data presentation of nontransformed means.

3. Results and discussion

Twenty-seven species were found in soil samples collected from the test site from spring 2001 to 2005 (Table 1). D. sanguinalis, A. palmeri, and Mollugo verticillata were the dominant weeds in soil at initiation of the experiment.

3.1. Summer annual grass weeds

D. sanguinalis was the dominant summer annual grass at initiation of the experiment, averaging 1332 and 1012 germinating seeds/m² in spring 2001 at 0–5 and 5–10 cm, respectively (data not shown). Other summer annual grasses in 2001 included E. indica and Dactyloctenium aegyptium, but density of these collectively was only 13 germinating seeds/m² (data not shown).

D. sanguinalis density in soil was significantly reduced in all management systems after the first cropping season (Fig. 1). The herbicide programs evaluated in G. max were found previously to provide season-long effective D. sanguinalis control (Norsworthy 2004). As a result of the effectiveness of both herbicide programs, there were no differences in seedbank density among management systems in any year that the soil seedbank was sampled.

No D. sanguinalis plants were found in sampled quadrats in 2001 or beyond and no more than 190 germinating D. sanguinalis seeds/m² was found in soil from any experimental plot after 2001.

D. sanguinalis does not appear to form a persistent seedbank, and when effectively controlled, the seedbank can be rapidly reduced. These findings are similar to those of the closely related Digitaria ciliaris (Retz.) Koel. (southern crabgrass) in that seeds rarely persist more than 1 year in conventional tillage and no-tillage systems (Kobayashi and Oyanagi, 2005).

D. aegyptium existed in soil at an average density of five germinating seeds/m² in spring 2001, but rapidly increased in density over the first two cropping seasons (Fig. 2). By spring 2002, D. aegyptium seed density in soil at 0–5 cm had increased to 177 germinating seeds/m² in conventional tillage/nonglyphosate plots. By 2003, the no-tillage/nonglyphosate treatment had also significantly increased in seed density in the upper soil sample. Conversely, D. aegyptium density at 0–5 cm in conventional tillage/glyphosate plots did not increase during the study (Fig. 2). D. aegyptium densities in soil at both depths for all management programs by spring 2005 were not different from the initial density.

Unlike D. sanguinalis, D. aegyptium emerged later in the summer, which may have resulted in its avoidance of herbicides, including residual herbicides applied at sowing. Hilgenfeld et al. (2004a) have shown that herbicide avoidance by late-emerging weeds can result in significant increases in the soil seedbank. This was evident in 2001 when late-summer rainfall was more frequent than in other years, allowing summer annual grasses, particularly

<table>
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<tr>
<th>Morphotype</th>
<th>Life cycle</th>
<th>Scientific name</th>
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<tr>
<td>Monocotyledous</td>
<td>Summer</td>
<td>Digitaria sanguinalis (L.) Scop.</td>
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<td>Winter</td>
<td>Echinochloa crus-galli (L.) Beauv.</td>
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<td></td>
<td>perennial</td>
<td>Dactyloctenium aegyptium (L.) Wild.</td>
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<td>annual</td>
<td>Urochloa platyphylla (Nash)</td>
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<td>Zea mays L.</td>
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<td>Cyperus compressus L.</td>
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<td>Dicotyledous</td>
<td>Summer</td>
<td>Eleusine indica (L.) Gaertn.</td>
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<td>Cydonon dactylon (L.) Pers.</td>
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<td>Cyperus rotundus L.</td>
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<td>Senna obtusifolia (L.) H.S.</td>
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<td>Mollugo verticillata L.</td>
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<td>Capsella bursa-pastoris (L.)</td>
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<td>Lamium amplexicaule L.</td>
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<td>Pseudognaphaliium luteoalbum (L.) Hilliard &amp; Burtt</td>
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<td>Oxalis stricta L.</td>
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<td>Oenothera laciniata Hill</td>
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<td>Stellaria media (L.) Vill.</td>
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<td>Conyza canadensis (L.) Cronq.</td>
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<td>Solina decumbens (Ell.) Torr. &amp; Gray</td>
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<td>Zymochara salicola (Lam.) Cabrera</td>
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Table 1
Weed species in soil samples in spring of each year or plots at end of the cropping season each year between spring 2001 and 2005 at Blackville, SC
D. aegyptium, to thrive late in the year (Table 2). D. aegyptium comprised 86% of the total annual grass density in late summer in 2001 (data not shown). Summer annual grass biomass was minimal at the time of sampling in 2002. The low biomass production is likely a result of sampling too early in the year (July 23). Evidently D. aegyptium did emerge and produce seeds in 2002 after the biomass sampling based on increases in the soil seedbank in spring 2003 (Fig. 2).

All management systems resulted in a net reduction in the seed density of summer annual grasses in spring 2002 at both soil depths, with no difference among management systems (Fig. 3). Loss of D. sanguinalis from the soil seedbank was for the most part greater than the increase in D. aegyptium in spring 2002 and 2003 (Figs. 1 and 2). In spring 2003, the effect of herbicide program at 0–5 cm was significant (P = 0.0295), with the glyphosate program providing superior reduction in the seedbank. The increase in summer annual grasses in the no-tillage/nonglyphosate program in 2003 at 0–5 cm resulted in the seedbank density being similar to that at initiation of the study. All management systems were similar with regards to seedbank numbers of summer annual grasses within each year at 0–5 cm, and all management programs resulted in a reduction of the initial seedbank by spring 2005.

Another annual grass that occurred at low densities during years that G. max was grown was glyphosate-resistant Z. mays. In nonglyphosate plots, clethodim was generally effective in controlling volunteer Z. mays, whereas in the glyphosate-only system, volunteer Z. mays plants persisted through harvest. This problem has been noted by others (Curran et al., 2002), requiring a herbicide other than glyphosate for removal of the off-type crop (Deen et al., 2006; Soltani et al., 2006; York et al., 2005).

Biomass of summer annual grasses differed between herbicide programs in 2001, but not between tillage systems (Table 2). Averaged over tillage systems, summer annual grass biomass on August 29, 2001, was more than threefold greater in nonglyphosate than in glyphosate programs (Table 2). Summer annual grass biomass production was not affected by tillage intensity and herbicide program in 2002 and 2004. In 2001, summer annual grasses comprised more than 20% of the total weed biomass, whereas in 2002 and 2004, less than 1% of the total biomass was.
contributed by summer annual grasses, indicating a shift to other species (Table 2).

### 3.2. Summer annual broad-leaved weeds

*A. palmeri* was one of the two dominant summer annual broad-leaved weeds at initiation of the experiment, averaging 240 and 153 germinating seeds/m² at depths of 0–5 and 5–10 cm, respectively (data not shown). *A. palmeri* seeds at 0–5 cm decreased from its initial density in all management programs during the first cropping season (Fig. 4). *A. palmeri* seeds were diminished in the conventional tillage/glyphosate program at 0–5 cm by spring 2002, and the seedbank remained low throughout the remainder of the study, unlike the seedbank in other programs that fluctuated yearly. There was an 80–99% reduction in the *A. palmeri* seedbank at 0–5 cm during the first year of the study. This is in agreement with other research that has shown loss of seed viability on the soil surface is more rapid than that of buried seeds (Miller and Nalewaja, 1990). Furthermore, seeds on the soil surface are more prone to predation (Jacob et al., 2006). It is likely that *A. palmeri* does not form a persistent seedbank based on seed viability of *Amaranthus retroflexus* L. (redroot pigweed) being only 2% after burial for 3.5 years (Egley and Chandler, 1983).

In spring 2003, there was a tillage by herbicide interaction ($P = 0.0237$) for *A. palmeri* seed density at a 0–5 cm. At this depth, *A. palmeri* seeds had increased in the conventional tillage/nonglyphosate and no-tillage/glyphosate programs to a level comparable to the initial seedbank (Fig. 4). Both seedbanks that increased in 2002 (sampled...
spring 2003) had declined by spring 2004, and remained lower than the initial seedbank density throughout the remainder of the study. With exception of spring 2003, no differences in *A. palmeri* seedbank density occurred among management programs at 0–5 cm.

For *A. palmeri* seed density at a 5- to 10-cm soil depth, there was an interaction between tillage and herbicide program \((P = 0.0499)\) in 2003. By spring 2003, *A. palmeri* density at 5–10 cm had increased in the conventional tillage/glyphosate-only \((\Delta)\); no-tillage/nonglyphosate \((\Box)\); and no-tillage/glyphosate-only \((\bigcirc)\). Standard error bars are presented.

*Fig. 4.* Change in *A. palmeri* seed density in soil from initiation of study in spring 2001 at 0–5 and 5–10 cm in the spring during the 5-year period at Blackville, SC. *A. palmeri* density averaged 240 and 153 germinating seeds/m² in spring 2001 at 0–5 cm and 5–10 cm, respectively. Management systems included conventional tillage/nonglyphosate \((\bigtriangleup)\); conventional tillage/glyphosate-only \((\bigtriangledown)\); no-tillage/nonglyphosate \((\bigcirc)\); and no-tillage/glyphosate-only \((\bigotimes)\). Standard error bars are presented.

### 2001 2002 2003 2004 2005

### 0 to 5 cm

### 5 to 10 cm

### Change in *A. palmeri* seed bank (No. m⁻²)

-200
-100
0
100
200

### 2001 2002 2003 2004 2005

### 0 to 5 cm

### 5 to 10 cm

### Change in *M. verticillata* seed bank (No. m⁻²)

0
500
1000
1500
2000
2500

*Fig. 5.* Change in *M. verticillata* seed density in soil from initiation of study in spring 2001 at 0–5 and 5–10 cm in the spring during the 5-year period at Blackville, SC. *M. verticillata* density averaged 230 and 159 germinating seeds/m² in spring 2001 at 0–5 and 5–10 cm, respectively. Management systems included conventional tillage/nonglyphosate \((\bigtriangleup)\); conventional tillage/glyphosate-only \((\bigtriangledown)\); no-tillage/nonglyphosate \((\bigcirc)\); and no-tillage/glyphosate-only \((\bigotimes)\). Standard error bars are presented.

*M. verticillata* was the second dominant broad-leaved weed in soil in spring 2001 at average densities of 230 and 159 germinating seeds/m² at depths of 0–5 and 5–10 cm, respectively (data not shown). In spring 2002, *M. verticillata* density in all management programs within soil depths were similar and all were comparable to the initial density (Fig. 5). In spring 2003, the effect of herbicide program on *M. verticillata* seed density at 0–5 cm was significant \((P = 0.0322)\). The *M. verticillata* seedbank in spring 2003 at 0–5 cm increased ninefold over the initial density, averaged over glyphosate-only programs. There are three probable reasons for the increase in *M. verticillata* density. First, the 2002 growing season was extremely dry as evidenced by the *Z. mays* yields being no more than 800 kg/ha (data not shown). The dry conditions resulted in shorter stature *Z. mays* and greater opportunity for establishment of late-emerging weeds, such as *M. verticillata*. Second, *M. verticillata* density in glyphosate plots averaged 4 plants/m² on July 23, 2002, compared to 1 plant/m² in nonglyphosate plots. The lack of residual weed control in the glyphosate plots contributed to the increased density and likely increased seed production. Lastly, *Z. mays* was harvested in mid-September in 2002, which allowed *M. verticillata* that had emerged prior to harvest to thrive in absence of shading from *Z. mays*. Similarly in other research, late-emerging annual broad-leaved
Weeds were found to increase in density in a no-tillage system where glyphosate was the only herbicide used for weed control (Puricelli and Tiesca, 2005).

### 3.3. Perennial Weeds

The test area contained few perennial weeds at the beginning of the study, probably because of the field’s history of yearly tillage. For 4 years prior to initiating the experiment, glyphosate was applied prior to sowing the test site each year in *G. max* or *Z. mays*, and a nonglyphosate weed management program was used in both crops. *Solanum carolinense*, *Cyperus rotundus*, and *Cynodon dactylon* were the three weeds found scattered throughout the test site prior to initiating the study. Unlike for summer annuals that propagate sexually, sampling the soil seedbank did not provide a realistic estimate of these weeds. *S. carolinense* seeds were found in some soil samples at the beginning of the study, but seed production is only one of two means by which this weed reproduces. Hence, differences in perennial weed biomass among weed management programs and changes in the contribution of perennial weed biomass to total weed biomass over time was used as a means of assessment.

Perennial weed biomass was similar between tillage programs and herbicide programs on August 29, 2001 (Table 2). By 2002, both tillage and herbicide programs had begun to impact perennial weeds. Among management programs in 2002, perennial weed biomass was greatest in the no-tillage/nonglyphosate program. Perennial weed biomass in no-tillage plots was ninefold greater than in conventional tillage plots, averaged over herbicide programs, which is similar to findings in other research where reduced or no-tillage systems were often associated with perennial species (Thomas et al., 2004). Perennial biomass in 2002 in nonglyphosate plots was 74-fold greater than in glyphosate-treated plots, averaged over tillage systems. Perennial weeds comprised 69% of the total biomass in conventional tillage/nonglyphosate plots and 99% of total biomass in no-tillage/nonglyphosate plots in 2002, further evidence of the shift to perennial weeds in these systems. Perennial weeds often increase in reduced tillage systems because of lack of disturbance of vegetative propagules (Cardina et al., 1991; Thomas et al., 2004).

Perennial biomass differed between herbicide programs in 2004, averaging 0.2 g/m² in glyphosate plots compared to 75.3 g/m² in nonglyphosate plots (Table 2). Perennials comprised >99% of the total weed biomass in conventional tillage/nonglyphosate and no-tillage/nonglyphosate plots in 2004. The perennial weeds *S. carolinense*, *C. rotundus*, and *C. dactylon* were not observed in 2001, 2002, or 2004 in conventional tillage/glyphosate plots, a testament to the combined effectiveness of tillage and glyphosate on prevention of perennial weed establishment. These results agree well with those published previously where *C. rotundus* was effectively controlled in glyphosate-resistant *G. max* with glyphosate (Edenfield et al., 2005). Furthermore, sequential glyphosate applications in glyphosate-resistant *G. max* have been found to reduce *C. rotundus* viability and tuber density (Akin and Shaw, 2001), explaining the lack of *C. rotundus* build-up in glyphosate-only systems over the 4 years. For *C. dactylon*, Abdullahi (2001) reported tillage in combination with glyphosate was an effective and affordable means of control comparable to the results here.

The lack of a consistent and prolonged weed shift in glyphosate-only systems is similar to findings in Mississippi in glyphosate-resistant *G. max* and *G. hirsutum* (Flint et al., 2000; Reddy, 2004). Additionally, recent research investigating differences in weed composition between glyphosate and nonglyphosate programs found that sequential glyphosate applications in *G. max* along a north–south transect in the United States encompassing five states generally resulted in a similar level of diversity to that of standard herbicide programs that excluded glyphosate (Scursoni et al., 2006). This does not mean that weed shifts in glyphosate-only fields are not occurring. As noted earlier, extension weed scientists throughout most of the United States perceive that shifts are occurring or have occurred already (Culpepper, 2006). Considering the widespread adoption of glyphosate-resistant crops and increasing adoption of conservation tillage practices, it is not likely that there will be a change by producers away from this technology in the near future, even with occurrence of weed shifts or glyphosate resistance. Rather, it is more likely that additional herbicide chemistries will begin to be used with glyphosate when its effectiveness begins to diminish (Shaner, 2000).

In summary, a rapid shift in weed composition occurred in both nonglyphosate and glyphosate programs, and tillage subsequently influenced species shifts, especially perennial weeds. *D. sanguinalis* did not persist in soil and was replaced by end of the second cropping season with *D. aegyptium* becoming the dominant annual grass weed at the test site, regardless of management system. *A. palmeri*, one of two dominant broad-leaved weeds, was short-lived in the seedbank and was reduced in density over time whereas *M. verticillata* generally increased through the second cropping season. By the end of the fourth and final cropping season, broad-leaved and grass weeds were of minimal importance, but a build-up of perennial weeds in nonglyphosate plots, regardless of tillage, had occurred, indicating the effectiveness of in-crop multiple glyphosate applications on all weeds at the test site. Although the seedbank of summer annual broad-leaved and annual grass weeds was reduced by end of the fourth cropping season, increases in seed densities to levels as high or higher than the initial state can occur if herbicide use is discontinued (Burnside et al., 1986; Schweizer and Zimdahl, 1984).

### References

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