doi:10.2489/jswc.66.4.265

Glyphosate-resistant Palmer amaranth: A threat to conservation tillage

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Abstract: Conservation tillage reduces the physical movement of soil to the minimum required for crop establishment and production. When consistently practiced as a soil and crop management system, it greatly reduces soil erosion and is recognized for the potential to improve soil quality and water conservation and plant available water. Adoption of conservation tillage increased dramatically with the advent of transgenic, glyphosate-resistant crops that permitted in-season, over-the-top use of glyphosate (N-[phosphonomethyl] glycine), a broad-spectrum herbicide with very low mammalian toxicity and minimal potential for off-site movement in soil or water. Glyphosate-resistant crops are currently grown on approximately 70 million ha (173 million ac) worldwide. The United States has the most hectares (45 million ha [99 million ac]) of transgenic, glyphosate-resistant cultivars and the greatest number of hectares (46 million ha [114 million ac]) in conservation tillage. The practice of conservation tillage is now threatened by the emergence and rapid spread of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* [S.] Wats.), one of several amaranths commonly called pigweeds. First identified in Georgia, it now has been reported in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. Another closely related dioecious amaranth, or pigweed, common waterhemp (*Amaranthus rudis* Sauer), has also developed resistance to glyphosate in Illinois, Iowa, Minnesota, and Missouri. Hundreds of thousands of conservation tillage hectares, some currently under USDA Natural Resources Conservation Service conservation program contracts, are at risk of being converted to higher-intensity tillage systems due to the inability to control these glyphosate-resistant *Amaranthus* species in conservation tillage systems using traditional technologies. The decline of conservation tillage is inevitable without the development and rapid adoption of integrated, effective weed control strategies. Traditional and alternative weed control strategies, such as the utilization of crop and herbicide rotation and integration of high residue cereal cover crops, are necessary in order to sustain conservation tillage practices.

Key words: conservation tillage—herbicide resistance—resistant pigweed

The benefits of conservation tillage are under threat. Crop production has historically relied on tillage to prepare a smooth, weed-free seedbed and to incorporate fertilizer and lime (Gebhardt et al. 1985). Conservation tillage systems were originally developed to reduce soil erosion but have more recently been recognized for improving soil quality and water availability (Reeves 1994, 1997; Kaspar et al. 2001). Large-scale successful implementation of conservation tillage across the United States came only after the introduction of broad-spectrum herbicides for weed control and the development of planters capable of penetrating crop residues to place seed directly into the soil (Triplett and Dick 2008). Substitution of innovative technologies for more intensive tillage practices has resulted in fewer operations thus saving time, money, and energy.

Conservation tillage has numerous environmental benefits, including controlling soil erosion and reducing runoff, which can be attributed to the accumulation of crop residues and increased soil organic matter near the soil surface (Reeves 1994; Reeves 1997; Truman et al. 2003). Crop residues dissipate rain drop energy and slow runoff from the field (Baumhardt and Lascano 1996). Soil fauna and microorganisms convert crop residues into soil organic matter, and in the process, increase soil aggregate formation and aggregate stability (Bruce et al. 1992). Improving surface aggregate stability reduces the potential for crust formation and surface sealing, which improves water infiltration and storage in the soil profile (Kemper and Derpsch 1981; Bruce et al. 1992; Truman et al. 2003) and reduces soil erosion (Le Bissonnais 1990; Truman et al. 2005). Soil organic matter directly affects soil water holding capacity because it has nearly four times the water holding capacity of mineral soil (Hudson 1994).

More soil fauna are found in conservation tillage systems compared to tilled systems (Kemper and Derpsch 1981; Riley et al. 2005). These differences are usually greater in the top 0 to 5 cm (0 to 2 in) than for deeper depths (Brévault et al. 2007; Minoshima et al. 2007). Brévault et al. (2007) observed that the abundance and diversity of soil arthropods were greater in no-till (NT) with a cover crop than in conventional tillage or NT without cover crops. Larger soil organisms like earthworms are sensitive to tillage intensity, and populations are generally greater in conservation tillage systems (Kladivko 2001). Earthworms increase water infiltration, nutrient cycling, and root growth through their burrowing activity and are important for incorporating crop residues in no-tillage systems (Kladivko 2001). Crop residue management can also affect aboveground insect pest populations and their natural enemies (Hammond and Stinner 1999). Cover crops and crop residues have been shown to increase natural enemy populations in some conservation tillage systems (McCutcheon 2000; Tillman et al. 2004), while in others pest populations were either not affected (Ruberson et al. 1997) or were reduced (Ruberson et al. 1995).

Reducing soil disturbance and maintaining crop residues near the surface also increases biological diversity both above and below

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ground (Holland 2002). Accumulation of soil organic matter at the soil surface in conservation tillage systems encourages a broader and different range of organisms compared to systems in which crop residues are buried (Rasmussen and Collins 1991). Microbial biomass, diversity, and overall biological activity are generally considered to be greater in soils cultivated using conservation tillage techniques compared to those receiving deep cultivations (Heisler 1998; Lupwayi et al. 2001). Tillage causes soil disturbance, altering the vertical distribution of soil organic matter and plant nutrient supplies in the soil surface, and it may affect enzyme activity and microbial biomass, which are responsible for transformation and cycling of organic matter and plant nutrients.

Economic analyses indicate that conservation tillage systems are not riskier than are conventional tillage systems, even in the short term (Baker and Saxton 2007). Many studies show that conservation tillage systems reduce overall risk. Crop yields under conservation tillage systems in the United States are similar to those with conventional tillage systems (DeFelice et al. 2006). A comparison of corn (*Zea mays* L.) and soybean (*Glycine max* L.) yields in different regions of the United States and Canada found that no-till conservation tillage systems tended to have greater yields than conventional tillage in the south and west regions and similar yields in the central United States, while no-till systems typically produced lower yields than conventional tillage in the northern United States and Canada (DeFelice et al. 2006). A southern United States study compared cotton (*Gossypium hirsutum* L.) yield in multiple tillage systems, including no-till, strip-till, and conventional tillage, and found that yields for conservation tillage treatments were consistently greater or at least equal to conventional tillage (Schwab et al. 2002). Reduced energy and operator time requirements compared with conventional tillage systems result in generally greater economic returns and lower production cost of conservation tillage systems (Raper et al. 1994; Smart and Bradford 1999). Many studies indicate conservation tillage systems have lower costs in labor, fuel, and machinery inputs (Lithourgidis et al. 2006).

Although some aspects of conservation tillage have presented challenges to adoption in some situations, the numerous benefits achieved through conservation tillage are fundamental to ensuring agricultural sustainability. Recent developments in herbicide resistance threaten this sustainable practice, reducing conservation tillage and adoption, and serving as a reminder that vigilance is required in the fight against weeds.

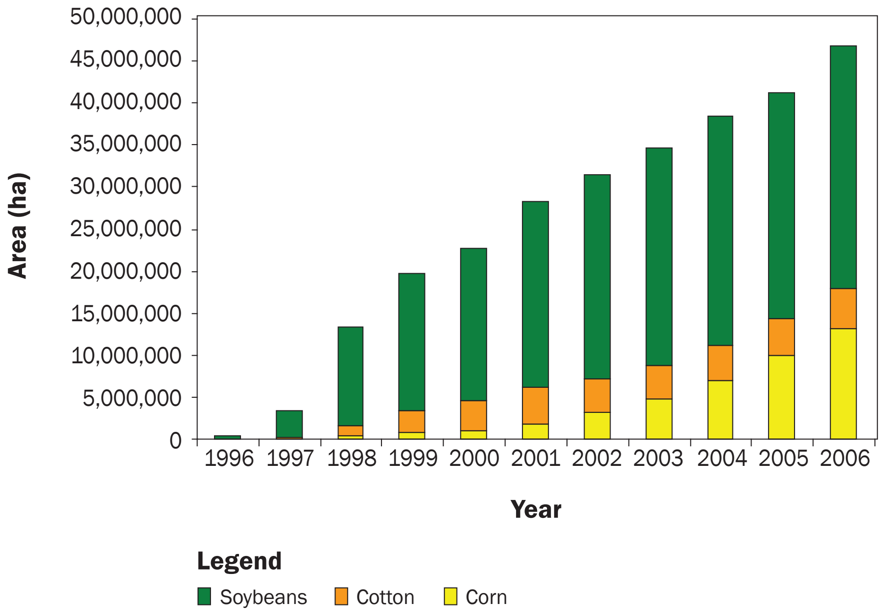
Weed Management and Conservation Tillage. Row crops have historically been planted into tilled areas for several reasons previously discussed and others including increased aeration of soil, increased penetration of precipitation, and increased disturbance of the soil surface crust (Cates and Cox 1912; Klingman and Ashton 1975). In addition, conventional tillage can provide a substantial amount of weed control. Tillage disrupts weed seed germination through seed burial and seedling growth by physical displacement of emerging seedlings (Shrestha et al. 2006; Steckel et al. 2007). With the rapid increase in herbicide use beginning in the 1960s (Timmons 2005), tillage, along with chemical applications, provided efficacious control of many problematic weed species. Combining herbicides with tillage provided control of weeds that were not easily destroyed by tillage alone. Historically, herbicide application strategies have included preplant-incorporated (PPI) or preemergence (PRE) herbicide treatment (or both) to prevent weed germination, followed by postemergence (POST) or postdirected (PDS) treatments to control weeds emerging after the crop. The selection of an herbicide is based on several factors, including the species of weeds within fields, a herbicide's efficacy with respect to weed species and size, and additionally, for soil-applied herbicides, soil characteristics and soil moisture conditions. Weed control practices in conventional systems require a considerable amount of knowledge about herbicides and weed identification. A substantial commitment of time for scouting and decision making is required to achieve high levels of weed control.

Weed control in conservation tillage can prove to be even more challenging than that in conventional tillage. As tillage is reduced, the reliance on herbicides increases. Herbicide use in conservation tillage systems poses unique problems to producers, in part because weed species composition frequently changes after a few years in conservation systems. Weed populations increase under reduced tillage, and weed species composition shifts to include more perennial species (Chhokar et al. 2007; Swanton et al. 2008). Such shifts in weed flora can require different weed management practices to control hardy perennial weeds and may necessitate a complete change in herbicide program to achieve control over species that were of minor concern in previously tilled fields. Additionally, crop residues, often present in conservation tillage systems, intercept and bind PRE herbicides, thus reducing their activity (Potter et al. 2008). Shifts in weed populations, the inability to incorporate residual at-plant herbicides, and limited possibilities for cultivation previously inhibited the adoption of conservation tillage (Buhler et al. 1994).

The Glyphosate Revolution. Since 1996, the United States and world agriculture have experienced an extraordinary change in weed management practices (Young 2006; James 2008). The changes in herbicide use resulted from development of transgenic crop cultivars. From the Neolithic until the late 20th century, plant breeding was limited to crossing plants within a species. More recently, science expanded our ability to make crosses among species within a genus by use of chemical mutagens and embryo culture techniques. Development of transgenic technology allowed geneticists to insert genes into a candidate line from outside the plant's genus. This change has popularly been called the transgenic revolution (Leidner 1995). Because transgenic technology remains proprietary, expensive, and the regulatory costs of releasing a transgenic cultivar are extremely high, the use of transgenic plant technologies remains the province of large, for-profit companies (James 2008).

The first commercial transgenic cultivars with resistance to the broad-spectrum herbicide, glyphosate, were soybeans. Genetically modified cultivars now affect virtually every aspect of agronomic crops (Nichols et al. 2003). The predominant soybean cultivars in production worldwide, and therefore in international commerce, are transgenic. Transgenic corn and cotton cultivars are commonly grown in the major production regions for these crops. Transgenic canola (*Brassica napus* L.) cultivars comprise the greater part of North American production. Transgenic rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) cultivars have also been developed but have not yet been commercialized. For US agriculture, the term "conventional cultivar," as now applied to soybeans, cotton, and increasingly corn, is now somewhat misleading considering that

Figure 1
Glyphosate-resistant crop hectares in the United States from 1996 to 2006. Data are from Monsanto (2009).



the majority of these crops are transgenic cultivars (figure 1).

The great majority of commercial transgenic cultivars express pest-managing traits, such as resistance to specific herbicide modes of action (James 2008). The first and most widely commercialized herbicide-resistant crops were developed to survive applications of the herbicide glyphosate. Before the release of glyphosate-resistant (Roundup Ready) soybeans in 1996, the nonselective herbicide glyphosate had been used for terminating cover crops and winter weeds as a "burn down" application that replaced primary tillage before planting in conservation systems. Since that time, glyphosate-resistant cultivars have become common, and glyphosate applications are made annually, on approximately 70 million ha (173 million ac) worldwide, with the US leading with 45 million ha (111 million ac) treated. Glyphosate, which offers a broad spectrum of weed control, works through the inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), the enzyme required for the production of aromatic amino acids (Schönbrunn et al. 2001). Glyphosate-resistant crops were developed by inserting the glyphosate-resistant transgene, CP4-EPSPS, into candidate lines. Inclusion of the EPSPS transgene allows the shikimate pathway to continue to function despite glyphosate application (Dill et al. 2005; Funke et al. 2006). The broad-spectrum weed control offered by this technology and the elimination of the need for other POST herbicides continues to induce producers to choose glyphosate-resistant cultivars over conventional crop cultivars (Givens et al. 2009; Shaw et al. 2009).

The adoption of conservation tillage was greatly accelerated by the introduction of herbicide-resistant crop cultivars (Fernandez-Cornejo and Caswell 2006). The introduction of glyphosate-resistant cultivars of corn, cotton, and soybeans provided producers with a highly effective POST herbicide that reduced reliance on PPI or PRE herbicides for successful weed control. Glyphosate was particularly helpful in conservation tillage systems, where effective herbicide options were previously limited (Askew and Wilcut 1999). The effectiveness of glyphosate-resistance technology, along with reduced production costs, facilitated an extensive adoption of conservation tillage practices, especially in cotton (figure 2). By 2000, more than 44 million ha (109 million ac) of US cropland had been converted to conservation tillage (Sandretto 2001). However, this dependence upon a single weed control strategy for production in conservation tillage would bring with it a critical fault that may now threaten the future sustainability of conservation tillage.

Changes in Herbicide Use. The number and diversity of herbicides available for use in US agriculture has seen tremendous growth since the introduction of 2,4-dichlorophenoxy acetic acid (2,4-D) in the 1940s (Appleby 2005; Timmons 2005). The rapid adoption of chemical weed control increased the herbicide-treated area in the US from 30 million ha (90 million ac) in 1962 to current levels of over 87 million ha (215 million ac) (Timmons 2005; Gianessi and Reigner 2007). During this time, herbicide choices and application strategies have changed in the major crops produced throughout the United States, with the most notable shift occurring in conjunction with the release of glyphosate-resistant cultivars.

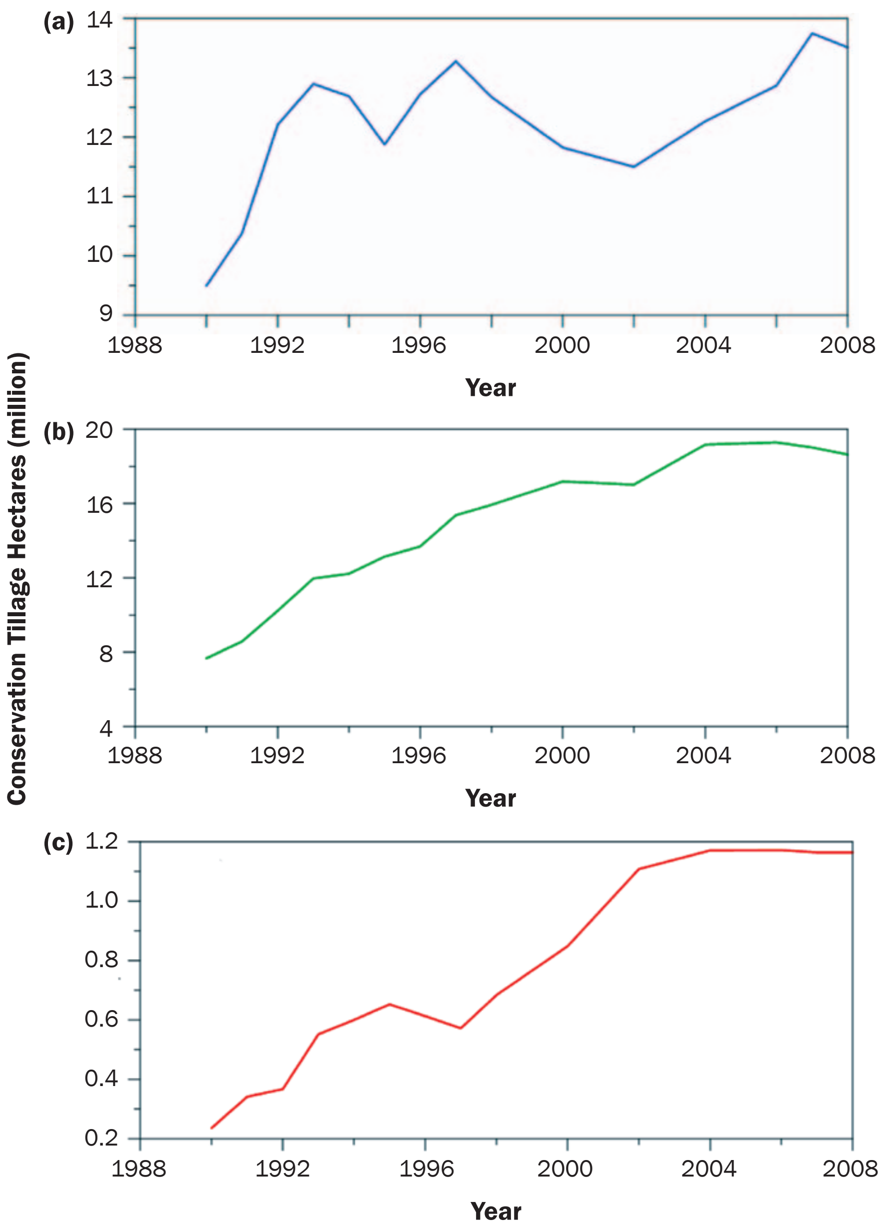
Many herbicides are registered for use in row crops; however, herbicides are grouped by chemists and weed scientists into a relatively small number of classifications based on their modes of action—that is, by reference to the biochemical pathways that they disrupt in susceptible plants (Ashton and Crafts 1981). Frequently, herbicides with the same modes of action control approximately the same botanical families. Thus whenever they are used in weed management programs, they tend to exert selection against the same groups of weed species.

Before the advent of glyphosate-resistant cultivars, soybean weed control was typically a two-pass system that utilized a PRE herbicide for grass and some broadleaf weed control (figure 3). Broadleaf weed control in a broadleaf crop was always problematic. Large seeded weeds, such as cocklebur (*Xanthium strumarium* L.), morning glory species (*Ipomea* spp.), and sicklepod (*Senna obtusifolia* L.), and weeds with very high rates of reproduction, such as pigweeds (*Amaranthus* spp.), were always difficult to manage. The ability to use glyphosate in conjunction with glyphosate-resistant cultivars enabled growers to use a single product, and sometimes a single POST application, as the complete weed control program.

In soybeans, the use of preplant incorporated dinitroaniline herbicides for grass and pigweed control and of acetolactate synthase–inhibiting POST herbicides for broadleaf weed control declined sharply following the introduction and the subsequent general availability of glyphosate-resistant soybean cultivars where glyphosate was heavily relied upon for weed control (Dalley et al. 2004; Gianessi 2005). Today, US soybean production utilizes glyphosate-resistant culti-

Figure 2

Conservation tillage hectares for (a) corn, (b) soybeans, and (c) cotton from 1988 to 2008. Data are from the Conservation Tillage Information Center (CTIC) National Crop Residue Management Survey (CTIC 2010).



vars for over 90% of all soybeans grown and has the greatest use of glyphosate of all the major crops within the United States.

Cotton weed control is intrinsically more difficult than soybean weed control because cotton is slow to emerge and seedlings are not competitive (McWhorter and Bryson 1992). Before glyphosate-resistant cultivars, cotton weed control in conventional tillage typically used five herbicides and two to three cultivations (Chandler 1984) (figure 4). As in soybeans, dinitroaniline herbicides were PPI for grass and some broadleaf weed control, particularly including pigweed control, but broadleaf weed control was very difficult due to limited availability of herbicides that were not injurious to the cotton plant (Kendig et al. 2007). Before glyphosate-resistant cultivars, broadleaf weed control in cotton was only just achieved through early and midseason PDS applications that frequently damaged the crop (McWhorter and Bryson 1992). Use of the triazine herbicide, cyanazine, was very common in cotton and very effective when applied as a lay-by PDS. With glyphosate-resistant cultivars, glyphosate replaced most of the other herbicides (Burke et al. 2005). As a result, use of glyphosate-resistant cotton cultivars grew to greater than 70% of total cotton produced in less than 10 years (Gianessi 2005).

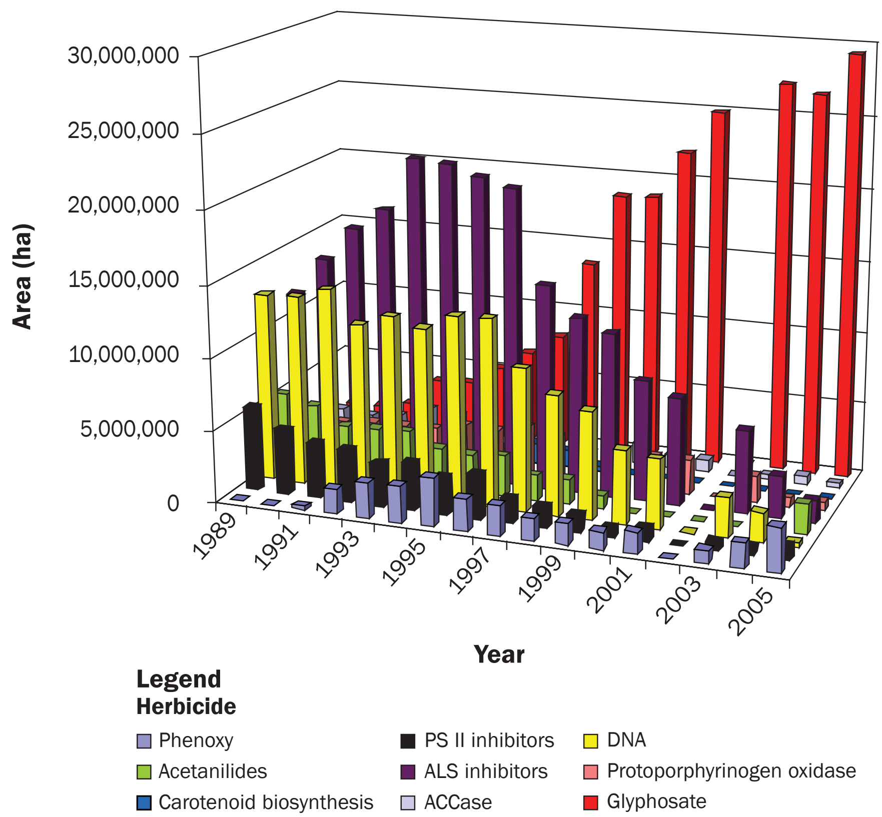
Glyphosate-resistant corn cultivars were first released in 1998; however, growth in sales was initially slow due to the availability of effective herbicides within corn production systems (figure 5). Relative to other crops, market penetration in corn was still modest in 2006 but has increased in recent years. Triazine, acetanilide, and phenoxy herbicides are well tolerated by corn; thus corn has the most efficacious suite of herbicides available of any of the major crops (Dalley et al. 2004). The use of certain acetolactate synthase-inhibiting herbicides for control of difficult to control grasses, such as fall panicum (*Panicum dichotomiflorum* Michx.) and proso millet (*Panicum millaceum* L.), and for grass escapes, when low rates of the triazines were used, caused a rise in use of acetolactate synthase-inhibitors in corn around the turn of the 21st century, but this trend has declined with the rise of glyphosate use. In 2006, the acres planted to glyphosate-resistant corn were substantial and constituted more than three times the whole cotton crop or about half of the national soybean crop (figure 1).

In most years, corn, soybeans, wheat (*Triticum aestivum* L.), and cotton comprise more than 70% of all US crop acres. The collective impact of glyphosate use in these major crops is evident with the increase in land area treated with this mode of action (figure 6). The four most commonly used herbicide modes of action used in the United States in corn, soybeans, and cotton are the triazines, acetanilides, dinitroanilides, and glyphosate. Triazine and acetanilide use remained stable over the period 1990 to 2006, largely because of their efficacy in corn production. Dinitroaniline use has declined in cotton and soybean and overall. Of these four top modes of action, however, glyphosate use has seen a marked increase to become the most widely used mode of action over the past decade (Powles 2008).

Changes in Weed Resistance. From the beginning of herbicide use on a large scale, concerns about the potential development of

Figure 3

Use of major herbicides and modes of herbicide action in US soybean. Data were compiled from USDA NASS (2010); no data were available for 2002.



Notes: PS II = photosystem II. DNA = dinitroaniline. ALS = acetolactate synthase. ACCase = acetyl-coenzyme A carboxylase.

herbicide-resistant biotypes among agricultural weed populations have been expressed (Appleby 2005). These fears were realized in 1968, when the first case of triazine resistance was confirmed (Ryan 1970; Ross and Lembi 1999). Since that time, 358 resistant weed biotypes have been reported within all major herbicide modes of action (Heap 2010a).

Since the primary contributing factor to resistance development is repeated exposure to a single mode of action, glyphosate became an ideal candidate to produce resistant weed biotypes. At one time, however, the argument was advanced that glyphosate resistance was highly improbable (Bradshaw et al. 1997). Nevertheless, a resistant biotype of rigid ryegrass (*Lolium rigidum* L.) was confirmed in Australia in 1996 (Heap 2010b). There are now 19 reported instances of weed species resistant to glyphosate found on all agriculturally productive continents (figure 7). In 2005, the confirmation of glyphosate resistance in Palmer amaranth threatened not only to reduce the effectiveness of glyphosate as a tool for weed control in several crops but also jeopardized the use of conservation tillage in many areas (Culpepper et al. 2006). In principle, glyphosate resistance could be managed by the same means that would serve to prolong the utility of other herbicides; that is, diversification of management tactics, with the consequent reduction in reliance on one mode of action. With the dramatic growth and dependence on the use of glyphosate-resistant crop varieties, the availability of nontransgenic crop varieties, particularly cotton, became problematic. Consequently, cotton production became nearly solely dependent on glyphosate-resistant varieties. In this system, alternative practices that are equally effective and economical as glyphosate have yet to be fully developed for conservation tillage (Green 2007; Sammons et al. 2007).

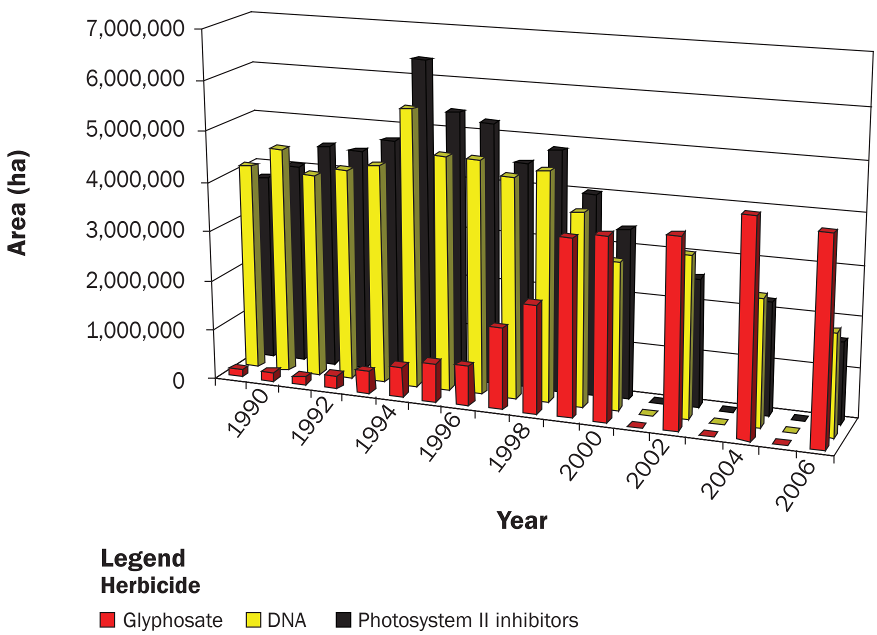
Palmer Amaranth and Glyphosate Resistance. The risks to conservation tillage from Palmer amaranth are due in part to this weed's competitive characteristics. Before the appearance of herbicide-resistant cultivars, Palmer amaranth was recognized as a troublesome weed in agriculture, particularly in cotton production (Smith et al. 2000). This rapidly growing weed species can reach heights of over 2 m (7 ft) and can produce over 600,000 seeds per plant (Fast et al. 2009). With the adoption of conservation tillage, the agricultural environment became even more suited to Palmer amaranth. Palmer amaranth germinates prolifically from shallow depths, and populations flourished when POST herbicides replaced PRE applications that had previously provided effective control (Grichar et al. 2004).

Repeated use of glyphosate in glyphosate-resistant soybeans, cotton, and more recently, glyphosate-resistant corn, even when crops were rotated, resulted in a herbicide monoculture on large numbers of hectares. Since the first confirmed case of glyphosate-resistant Palmer amaranth appeared in Georgia in 2005, resistant biotypes have been reported in Alabama, Arkansas, Florida, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee (Culpepper et al. 2006; Norsworthy et al. 2008; Steckel et al. 2008; Nichols et al. 2009). Additionally, another amaranth species, common waterhemp (*Amaranthus rudis* Sauer), has also been confirmed to have glyphosate-resistant populations (Legleiter and Bradley 2008).

There is an urgent need to find successful strategies to control Palmer amaranth, a weed that can out-compete crops, reduce yields, and hinder harvest operations. The continued spread of glyphosate-resistant Palmer amaranth, in the absence of proven management strategies, threatens to reduce conservation tillage throughout potentially affected areas of the United States. In some areas, emergency stop-gap recommendations have been made that producers should rely on greater tillage intensity for control, due to the ability to bury shallow germinating Palmer amaranth seeds and incorporate soil-applied herbicides. Moldboard plowing when inverting the soil 30 cm (12 in) in depth has been shown to reduce glyphosate-resistant Palmer amaranth emergence 46% to 60% because many of the weed seeds are placed at a depth where emergence cannot occur (Culpepper et al. 2009; 2010). Similarly, glyphosate-resistant Palmer amaranth control can be improved at least 10% by incorporating dinitroanaline

Figure 4

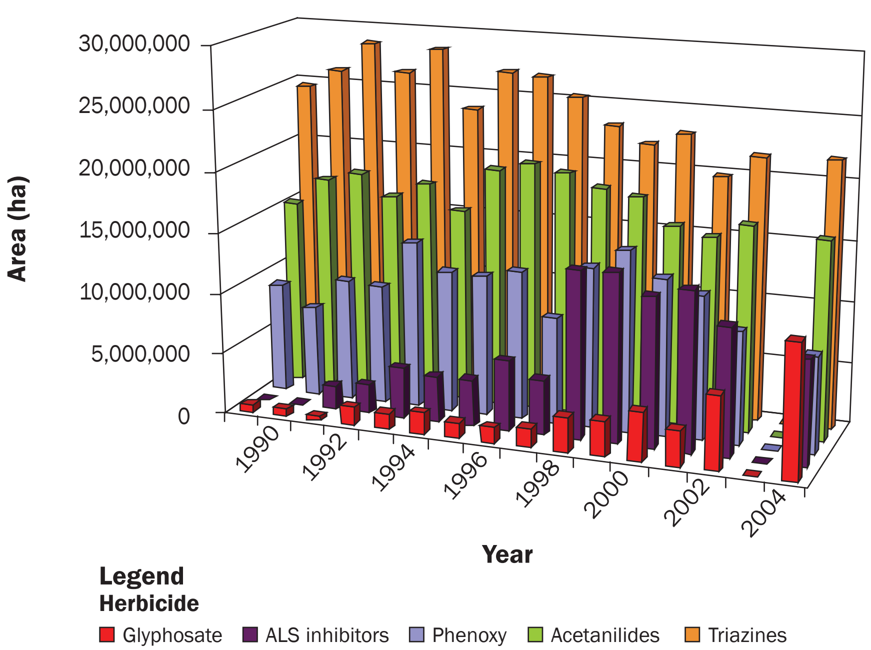
Use of major herbicides and modes of herbicide action in US cotton. Data were compiled from USDA NASS (2010); no data were available for 2001, 2003, 2005.



Note: DNA = dinitroaniline.

Figure 5

Use of major herbicides and modes of herbicide action in US corn. Data were compiled from the USDA NASS (2010); no data were available for 2003.



Note: ALS = acetolactate synthase.

herbicides into the soil as compared to applying these herbicides to the soil surface as well as with cultivation (Culpepper et al. 2009). Although tillage can be used to improve control of glyphosate-resistant Palmer amaranth, increased input costs and potential soil erosion are significant challenges for growers, and the need for alternative management programs with lower production costs and less environmental disruption are needed.

Control Strategies and Future Needs. New tactics are needed to control established populations of glyphosate-resistant Palmer amaranth as well as to prevent further spread of resistant biotypes. Where glyphosate-resistant Palmer amaranth is established or developing, aggressive management with multiple herbicide modes of action, cultivation, and hand weeding to remove escapes has been necessary. However, in some areas, for the present, some producers and technical providers think Palmer amaranth populations are higher than can be managed by any tactics growers are familiar with except deep tillage and the use of PPI dinitroaniline herbicides, which negates previous conservation practices and, in many cases, still proves ineffective in providing acceptable Palmer amaranth control.

In light of the critical need for potential solutions for controlling Palmer amaranth, a 2008 USDA Agricultural Research Service (ARS)/Cotton Incorporated sponsored stakeholder workshop involving scientists and experts from Auburn University, Bayer CropScience, Clemson University, Cotton Incorporated, Dow AgroSciences, Louisiana State University, Mississippi State University, Monsanto, National Cotton Council of America, North Carolina State University, The University of Georgia, The University of Tennessee, University of Arkansas, University of Florida, USDA ARS, and USDA Natural Resources Conservation Service was held at the USDA ARS Richard B. Russell Research Center in Athens, Georgia, to assess prospective management tactics that have been explored by those most affected by the development of glyphosate resistant Palmer amaranth. Many alternative cultural and chemical management tactics were discussed at the workshop (Price et al. 2009b).

The following is a list of suggested cultural approaches that could be implemented to aid in control of glyphosate-resistant Palmer amaranth:

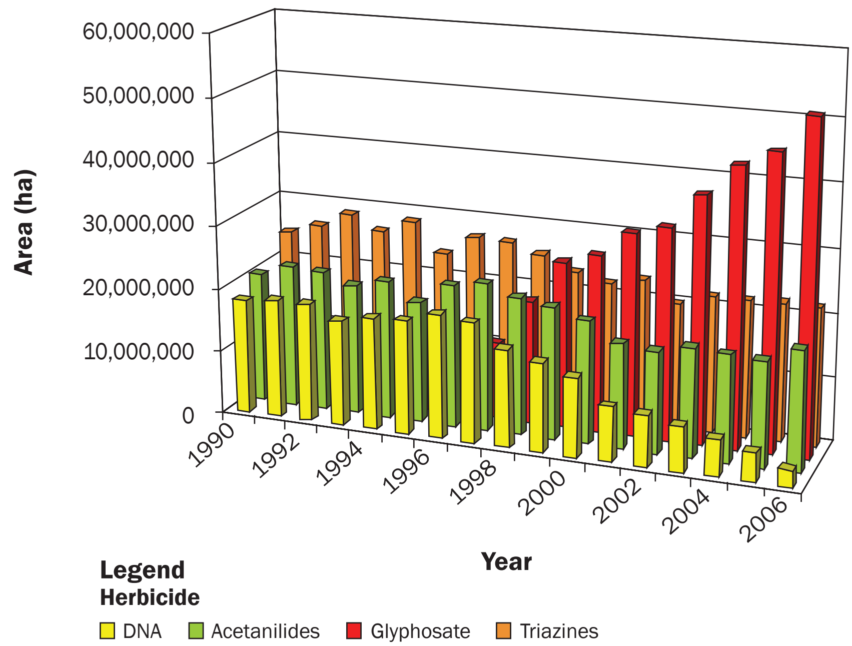
1. Intensify crop rotations (including pasture-based rotations)
2. Use of inversion tillage to bury seed bank followed by a continuous high residue conservation system
3. Integration of cultural solutions (high residue cover crops, delayed cotton planting, narrow-subsoiling to minimize soil/residue disturbance, etc.)
4. Use of high residue cultivators
5. Intensify weed management (scouting, timely herbicide applications, etc.)

Alternative chemical management strategies for improved glyphosate-resistant Palmer amaranth control include:

6. Use of alternative herbicide chemistries
7. Improve residual herbicide performance in dry-land conservation systems
8. Use of fall residuals on harvested fallow fields to reduce weed seedbank
9. Create new cotton herbicide paradigm that is site specific for Coastal Plain/Uplands/Delta regions

Figure 6

Herbicide mode of action use in corn, cotton, and soybeans in the United States from 1990 to 2006.



Note: DNA = dinitroaniline.

Cultural management practices are multifaceted and can be utilized in conjunction with other strategies to help control Palmer amaranth. Crop rotation tends to reduce weed populations if competitiveness, cultural practices, and canopy structure differ among crops–thus not favoring specific weed traits. The greatest effect (excluding tillage) is typically due to changes in weed management tactics, such as choice of herbicide system that allow for alternative and more diverse herbicide selection. Thus, when crops are all predominantly utilizing one herbicide system, e.g. glyphosate, the beneficial effect of crop rotation is compromised. Inversion tillage may be effective for burying and suppressing germination of small-seeded weeds such as pigweeds, but it is tillage that we wish to avoid. This approach was suggested as an extreme used to potentially rescue fields where glyphosate-resistant Palmer amaranth populations are otherwise unmanageable. Utilization of high residue cover crops mulches, including cereal rye (*Secale cereale* L.) or black oats (*Avena strigosa* Schreb.) are proven to suppress Palmer amaranth germination and growth. Integration with the above mentioned inversion tillage system followed immediately by a high-reside cover crop may offer the opportunity to intensify subsequent conservation-tillage practices in some instances. Delayed cotton planting would extend cover crop growth and increase soil temperatures at planting, facilitating increased cotton growth. In this context, the development of equipment that can provide in-season cultivation in high residues may prove useful compared to other more intensive soil disturbance methods or hand removal when herbicide systems fail. With the compromise of the efficacy of the broad-spectrum herbicide glyphosate, weed management will require more scouting, decision making, and timeliness of treatment, more similar to weed management prior to the advent of herbicide-resistant crops.

Development of new herbicides is beyond the expertise or financial capacity of the public sector. However, the public sector can assist the private sector in determining the optimum deployment of herbicides to provide for their current utility and future sustainability, which is incorporating resistance management as an integral feature of integrated weed management. The response of herbicide chemistries to soil moisture depends heavily on the chemical properties of the active herbicide and its formulation and has generally been an area of technology within the private sector. Broadening soil active herbicide activity in lower moisture conditions and penetration through crop residues utilizing new formulations or herbicide delivery systems would be beneficial, specifically in dryland production systems. Agronomic weed management in the humid region has generally avoided use of fall herbicides due to continual weed germination warranting sequential postemergence herbicide applications and persistence of soil active herbicides and cover crop/crop rotation restriction concerns. However, weed control in rotation crops must be summer long; Palmer amaranth can germinate and set seed in late summer after crop harvest and may force use of fall treatments in some crop rotations and environments. It is clear that the current weed management paradigm, which makes heavy reliance on glyphosate in conjunction with glyphosate-resistant cultivars is in serious difficulty, and a new paradigm will emerge. At present, the situation is dynamic, and the solution is unclear.

Among these possibilities, there is increased interest in utilization of the Brazilian style rolled high residue cover crop system adapted in the mid-1990s by USDA ARS researchers for use in the southeastern United States (figure 8) (Bauer et al. 1999; Ashford et al. 2003; Reeves 2003; Raper et al. 2004; Price et al. 2009a). High residue systems using a rye cover crop has shown in research results

Figure 7
Number of glyphosate-resistant species on all agriculturally productive continents. Data are from the International Survey of Herbicide Resistant Weeds (Heap 2010b).

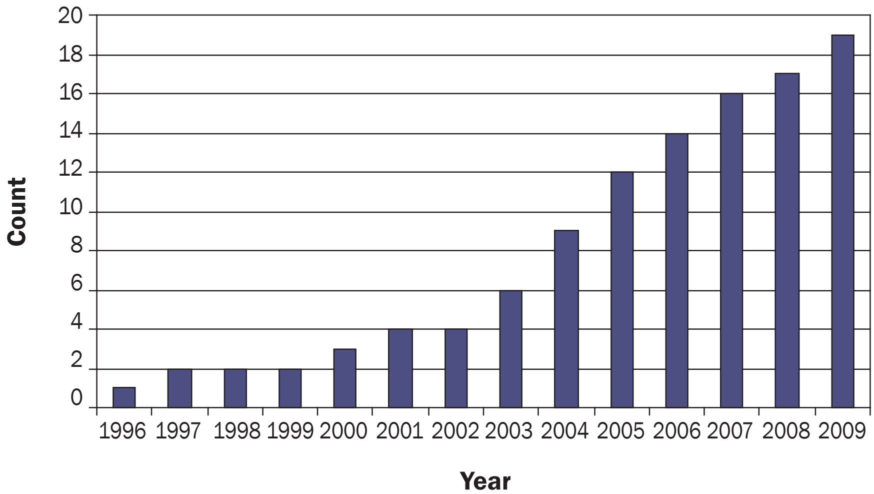


Figure 8
Cotton growing in rolled black oat (*Avena strigosa* Schreb.) residue.

to reduce weed germination and growth over winter fallow conservation systems due to mulching and allelopathic affects (Barnes and Putnam 1985; Teasdale 1991; Reeves et al. 2005; Price et al. 2006; 2007; 2008a; 2008c; Culpepper et al. 2009; 2010). Saini et al. (2006) reported early season weed biomass was eleven times higher (31 versus 345 kg ha^{-1} [28 versus 308 lb ac^{-1}]) following rye termination when rye biomass was lowest (2,649 kg ha^{-1} [2,363 lb ac^{-1}]) compared to when rye biomass was highest (8,878 kg ha^{-1} [7,919 lb ac^{-1}]). Previous research has also shown that weed suppression by residue is mainly influenced by biomass amount (Teasdale et al. 2000; Price et al. 2005). In a high-residue study in Alabama, nontransgenic cotton systems that did not include herbicides were not effective at controlling weeds (including Palmer amaranth) adequately season long and resulted in substantial yield losses (Reeves et al. 2005). However, when black oat or rye was managed for maximum biomass along with PRE herbicides, similar weed control compared to a system with higher inputs was attained. In a recent cotton study in Georgia, rye residue alone reduced glyphosate-resistant Palmer amaranth emergence by 94% in the row middle and 50% in the drill (Culpepper et al. 2010). In southern Brazil, black oat is utilized on millions of hectares of conservation-tilled soybean because, in part, of its weed-suppressive capabilities (Derpsch et al. 1991). Black oat was introduced in the southeastern United States through a joint release fostered by the USDA ARS between Auburn University and The Institute of Agronomy of Paraná, Brazil, and is currently marketed as "SoilSaver black oat" (Bauer and Reeves 1999). In a greenhouse study, allelopathic compounds released from black oat were shown to inhibit cotton root elongation by 16%, compared to rye, when residue was mixed with soil (Bauer and Reeves 1999). However, in a field study where residue remained on the soil surface, cotton stand establishment was not affected by black oat, rye, or wheat winter covers, and cotton lint yield was higher in plots containing black oat residue than in rye (Bauer and Reeves 1999). The use of cover crops managed for heavy residue employed in conjunction with chemical and cultural weed control tactics could offer effective Palmer amaranth control in established glyphosate-resistant populations as well as help prevent the development of resistance in current glyphosate-susceptible populations (Price et al. 2008b). The ongoing evaluation of weed management options suggests that control of glyphosate-resistant Palmer amaranth can be achieved without intensified tillage; however, it will require the use of diverse management tactics, dedication, and grower vigilance.

The return to full tillage, which has been seen as inevitable by some growers and technical specialists, would cause a substantial loss of several economic and environmental benefits that have been achieved through conservation tillage. However, reduction in tillage requires the availability of effective alternative strategies to replace it. We will continue to need new herbicides, better tactics of using older herbicides, including use of directed or hooded sprayers, as well as continued development of systems that combine chemical and cultural practices, such as high residue cultivators. We see opportunities to make better use of cover crops, but such systems depend on good conditions for fall establishment, development of better techniques for spring termination and management, and a timely and diversified in-season weed management program, all resulting in season-long management and planning instead of disjointed short-term within- and between-crop management. Most importantly, however, is producer, extension, and private sector advisor education about high residue cover crop systems to achieve proper implementation of these practices and ensure their continued use.

Adoption of conservation tillage increased when effective planters and management systems for its use was developed and when effective herbicides were available in the respective crops that gave growers the confidence to attempt tillage reduction. The reliable, flexible, broad-spectrum activity of glyphosate greatly accelerated adoption of conservation tillage. Since the efficacy of glyphosate is now significantly compromised, new systems are necessary that utilize integrated weed management practices that will be as effective as the techniques they aim to replace. Although glyphosate made conservation tillage a relatively easy system to adopt, there is no reason to expect that new conservation tillage systems cannot be developed that are easily adopted, less costly, and more environmentally friendly than increased tillage practices. New systems may include new genetically modified organisms—like 2,4-D resistant cotton and dicamba resistant cotton—but without proper resistance management, inevitably weed resistance will occur. Despite new seed trait technologies, producers will be faced with serious weed resistance problems in the future if the lessons learned from managing glyphosate-resistant weeds are not heeded. There is no "silver-bullet" to combat weed resistance but rather it is a "systems approach" that effectively merges new technologies, new chemistries, and sound cultural and management practices.

At this time, the threat posed by Palmer amaranth to conservation tillage may be under-appreciated by those external to it; however, we face a clear threat to conservation tillage in the southern portion of the United States—possibly in other areas as well. If those working on the problem succeed quickly, present difficulties will be little noticed by the public. If we fail and tillage increases, we will suffer a significant setback in the abatement of soil erosion, the protection of water quality, the expenditure of fuel in agriculture production, the potential to improve soil quality, and our ability to formulate strategies to increase carbon sequestration in agriculture soils.

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