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Herbicide-resistant Weeds Threaten Soil Conservation Gains: Finding a Balance for Soil and Farm Sustainability

The balance between conservation tillage and herbicide-resistant weed management is the central issue addressed in this paper. (Left photo from ARS; middle photo from Howard F. Schwartz, Colorado State University, Bugwood.org; right photo from Shutterstock.)

Abstract

Tillage has been an integral part of crop production since crops were first cultivated. Growers and scientists have long recognized both beneficial and detrimental aspects of tillage. There is no question that most tillage operations promote soil loss, adversely affect (lower) surface water quality, and negatively impact soil productivity. Weed management is a primary reason for tillage, and until the development of highly effective herbicides, conservation tillage was not feasible. Furthermore, with the development of herbicide-resistant (HR) crops, particularly glyphosate-resistant (GR) crops, herbicides such as glyphosate minimized the need for tillage as a weed control tactic; the resulting crop production systems have been primary enablers for the success of U.S. Department of Agriculture Natural Resource Soil Conservation programs.

Glyphosate-resistant crops are planted on the majority of canola, corn, cotton, soybean, and sugarbeet acres in the United States and many other nations as a result of efficacy and economics. When any single herbicide mechanism of action is used repeatedly without alternative management tactics, however, selection pressure becomes intense for plants that are tolerant or resistant to that herbicide. The unintended consequence of the predominance of GR crops on the agricultural landscape has been intense selection pressure for the development of GR weeds. Several weed species now exhibit resistance to glyphosate, and most are also resistant to other herbicide mechanisms of action. There is now a large and growing threat to soil conservation gains because of the dire need in some situations to manage these resistant weeds through any means necessary, including tillage. Importantly, there are situations where the farmer does not need to modify or abandon his current conservation tillage practices in order to manage a resistant weed population. Best management practices (BMPs) that have been established for both proactive and reactive management of HR populations include recommendations on how to manage HR populations without the need for farmers to abandon conservation tillage systems.

The Natural Resources Conservation Service (NRCS) currently has a number of herbicide resistance BMPs that qualify for programs such as the Environmental Quality Incentive Program. Often these practices, however, are not given priority status, and therefore they either are not listed as options at the local level or are not funded by soil conservation district boards. Additionally, educational programs are not adequately bringing these BMPs to growers, NRCS staff, and

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conservation district boards. These practices cannot be implemented without adequate and effective educational programs.

In some instances, tillage is one of the few effective options to manage particular HR weeds. For example, Palmer amaranth (*Amaranthus palmeri*) has become the dominant weed problem in southeastern U.S. cotton production because of evolved resistance to glyphosate. Inversion tillage was clearly demonstrated to be an effective tool in helping the management of this weed. Creative research programs have been developed that meet conservation compliance requirements and at the same time judiciously use tillage as an element for management of this species. Similar programs are needed to help manage other HR species in other regions and cropping systems. Further research is critically needed in instances when few or no other options are available to ensure the economic viability of farming operations while addressing long-term soil quality concerns.

Textbox 1. Tillage terminology.

Alternative tillage: A strategy whereby different methods of tillage are used to avoid repetition and subsequent ineffectiveness.

Conservation tillage: A form of minimum tillage where sufficient crop residue (≥30% minimum to meet Natural Resources Conservation Service standards) is left on the soil surface to significantly decrease soil erosion.

Conventional tillage: Full-width tillage that disturbs the entire soil surface and is performed before and/or during planting; less than 15% residue cover after planting; generally involves plowing or intensive (numerous) tillage trips (USEPA 2009).

Inter-row cultivation: Tillage that occurs between rows after crop planting and emergence at depths of 10 centimeters (4 inches) or less and controls small emerged weeds, provides soil aeration, and improves water infiltration.

Inversion tillage: Tillage that flips over a layer (often 6–12 inches) of soil burying surface residues in the process; the moldboard plow is the standard inversion tillage implement, although disc plows also perform inversion tillage.

Minimum tillage: See conservation tillage.

Moldboard plowing: Cultivation using a moldboard plow, which has a curved plate that turns over the soil.

Mulch till: Full-width tillage that disturbs all of the soil surface; done before and/or during planting.

No-till: The technique of planting crops directly into the previous crop's residue without tillage; also called direct seeding.

Noninversion tillage: A narrow shank tillage system that minimally disturbs the soil surface and is used to disrupt hardpans, which are compacted layers of soil that are impenetrable by roots; widely used in the Coastal Plain.

Primary tillage: Disturbance of the soil to depths of as much as 60 centimeters (24 inches) that results in substantial soil inversion.

Ridge till: Cultivation of the previous crop produces ridges or hills where the plants grow; these ridges are not tilled out after harvest.

Secondary tillage: Disturbance of the soil to depths of less than 15 centimeters (6 inches).

Tandem disking: A system of dual rolling circular blades with straight or fluted edges intended to cut residues, pulverize soil structure, and level the soil surface.

Introduction

Tillage has been an integral part of crop production since crops were first cultivated. Some historians have even evaluated the progress of agrarian societies by their developments in tillage. The premise for tillage was to subdue or destroy native vegetation so desired plants might develop free from competition. From the onset of agriculture, tillage was synonymous with plant or weed management. Forms of tillage evolved as methods of animal- and mechanical-powered equipment evolved, and in the mid-1700s the moldboard plow became the ultimate tillage tool. It was touted for its ability to break sod, turn under *crop residue,*[1] kill weeds, and bury weed seeds.

With improvements in mechanization, the magnitude of soil disturbance became variable, which led to more descriptive classifications of tillage such as primary, secondary, and inter-row cultivation. Disturbance of the soil to depths of as much as 60 centimeters (cm; 24 inches) results in substantial soil inversion and is referred to as primary tillage. Primary tillage can be followed by secondary tillage, which typically occurs at soil depths of less than 15 cm (6 inches). Secondary tillage requires less energy and is used to kill emerged weeds and prepare a seedbed for crop planting. After crop planting and emergence, inter-row cultivation represents tillage that occurs at depths of 10 cm (4 inches) or less and controls small emerged weeds, provides soil aeration, and improves water infiltration. This farming process is often termed conventional tillage.

For centuries the popular notion was that successful farming involved tillage that inverted, smoothed, pulverized, stirred, and leveled the soil before and after planting. The popularity of conventional tillage influenced equipment manufacturers, crop breeders, and the chemical industry in their quest for improvements in crop production. It was during the period from the 1940s to the 1980s that the agricultural chemical industry developed herbicides to be used in conjunction with conventional tillage for improved weed control. A number of herbicides have physicochemical properties that require their immediate placement in the soil to prevent volatilization or photodegradation. By combining secondary tillage with herbicide applications, these highly effective herbicides became widely used.

[1] Italicized terms (except genus/species names and published material titles) are defined in the Glossary.

There are advantages and disadvantages associated with tillage. Decreasing soil compaction with some types of tillage; improving aeration and water infiltration; managing residue, which leads to better planter performance and pest management; increasing soil temperature; and decreasing the need for herbicides are considered advantages of tillage. Disadvantages of tillage include more soil erosion; greater compaction with some types of tillage implements; the need for better managerial and cultural knowledge; loss of soil *tilth*, moisture, and structure; lower surface water quality; and higher expenses associated with equipment, operations, and energy.

Tillage in its simplest form kills weeds by some combination of severing shoots from roots, uprooting, or covering the plant. Because conventional tillage has been practiced continually for many years, selection pressure has resulted in weed species, or a selection of biotypes within a species, that have adaptations for survival in conjunction with tillage. Secondary tillage can move the seeds near the soil surface, where they are in a position to germinate with the crop (Roberts and Stokes 1965). Without repeated tillage operations in a rangeland ecosystem, kochia (*Kochia scoparia*) seed germinates in spring as soon as the soil temperature reaches about 4.5ºC (~40ºF); however, in fields where conventional tillage has been practiced the seed remains dormant until the soil temperature reaches 15ºC (~60ºF), thus avoiding the effects of early season preplant tillage (Sbatella and Wilson 2010).

Other weed species have adapted to tillage by evolving *photoreceptors* that allow the seed to germinate after exposure to light during tillage (Scopel, Ballare, and Radosevich 1994). If tillage does not occur or the seed remains buried, *dormancy* continues. Other weed species respond in various manners to changes in primary and secondary tillage: population densities of common sunflower (*Helianthus annuus*) increased with moldboard plowing, longspine sandbur (*Cenchrus longispinus*) and redroot pigweed (*Amaranthus retroflexus*) with tandem disking, and kochia with ridge till (Wilson 1993). This leads to selection of the species best adapted to the specific cropping and tillage system used.

The U.S. Soil Conservation Service was formed in 1935 in an attempt to manage soil resources by decreasing soil erosion and water runoff, aiding in flood control, and stabilizing agricultural production. Beginning in the 1950s, researchers and farmers took a serious look at the concept of minimum tillage. Minimum tillage became possible in large part because newly developed herbicides could be used to kill weeds and thus replace tillage. Minimum tillage was an evolving concept but in the simplest form meant decreasing tillage operations to those that were timely, were essential to producing the crop, and avoided damage to the soil. The term minimum tillage changed to conservation tillage and gained acceptance through the U.S. Farm Bills of 1985 and 1990. Compared to conventional tillage, conservation tillage systems decreased sediment losses from 28 to as much as 88%, depending on the type of system and region (Figure 1).

Schertz (1991) defined the term conservation tillage as a form of minimum tillage where sufficient crop residue is left on the soil surface to significantly decrease soil erosion. Where water erosion is the primary concern, at least 30% of the soil surface must be covered by plant residues, whereas when wind erosion of soil is the primary concern, 1,120 kilograms per hectare (ha^{-1}; 1,000 pounds per acre) of small grain residue equivalent must be left on the soil surface during the critical wind erosion period.

Conservation tillage includes no-till, ridge-till, mulch-till, and noninversion tillage. No-till, also called direct seeding, describes the technique of planting crops directly into the previous crop's residue without tillage. With no-till, no more than 25%

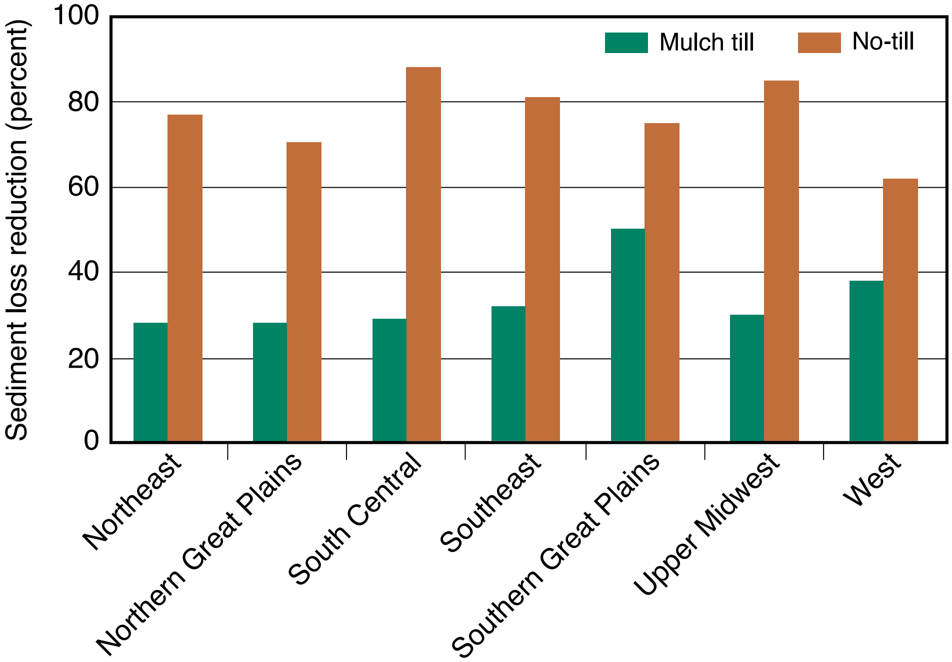

Figure 1. Reductions in sediment losses by U.S. region, compared to conventional tillage, with mulch tillage and no-till systems from 1989 to 2008 (CTIC 2011).

of the soil surface can be disturbed for nutrient injection or planting (Hoeft et al. 2000). Noninversion tillage techniques are common where equipment or naturally occurring compaction occurs and include within-row subsoiling or use of a *paratill* to disrupt soil compaction while minimally disturbing the soil surface (Raper and Reeves 2007). Herbicides are used to replace tillage and may be applied before, at, or after planting, but inter-row cultivation can be used in some conservation systems to provide in-crop weed control.

Weed seeds remain near the soil surface in the absence of tillage and become mixed with crop residue. Crop residues can provide a microenvironment near the soil surface that is moist and supports germination of many weed species. This usually results in a shift toward annual grass and small-seeded broadleaf weeds, as well as perennial species. Especially in drier environments, however, high amounts of plant residue on the soil surface may prevent seed-soil contact and the germination of some species of weeds (Cardina, Herms, and Doohan 2002).

When weed seed production is effectively suppressed during the first few years of no-till production, the active weed *seed bank* will decline. Without tillage, weed seeds positioned deeper in the soil are not moved to the soil surface where they can germinate and replenish the weed seed bank if the plants are allowed to produce seed. In practice, researchers have shown that small-seeded annual grass species and perennials become more difficult to manage as tillage is decreased, whereas large-seeded broadleaf weeds become easier to manage in production systems with less tillage (Frick and Thomas 1992). Winter annual and biennial weeds, and some brush species that were not problematic with conventional tillage, can increase with no-till. Moldboard plowing followed by disking cuts, buries, and desiccates roots of creeping perennials like Canada thistle (*Cirsium arvense*), whereas no-till leaves the roots undisturbed and Canada thistle populations can increase. A no-till corn monoculture rotation had 45% higher soil weed seed bank population density of specific weeds compared to a more diverse crop rotation, and this difference was attributed to the lowered competitive effect of the monoculture as well as the no-till system (Cardina, Herms, and Doohan 2002). More *edaphic* variability exists in conservation tillage systems, thus allowing greater niche diversity and facilitating a more diverse weed community.

Conservation tillage is a major component of many, if not most, modern-day cropping systems. A recent report from the U.S. Department of Agriculture (USDA) Economic Research Service entitled *No-Till Farming Is a Growing Practice* indicates that 35% of U.S. cropland was farmed using no-till production practices (Horowitz, Ebel, and Ueda 2010). Of the major crops—corn, soybean, wheat, cotton, and rice—44% of the area was farmed using conservation tillage practices. Soybean and corn had the greatest percentage of the acreage farmed, with conservation tillage and cotton the least. Similar trends have been noted in other countries as well.

Perhaps the most far-reaching effect of *genetically engineered* (GE), herbicide-resistant (HR) crops, specifically glyphosate-resistant (GR) crops, on the *agroecosystems* was the recognition by growers that these crops, in conjunction with almost exclusive use of glyphosate for weed management, represented an effective, efficient, and consistent "system" for weed control with less tillage (Carpenter and Gianessi 1999). Thus, crop production in no-till and other conservation tillage practices was supported by glyphosate-based systems and resulted in dramatic increases in conservation tillage agriculture.

Figure 2 demonstrates these changes; conventional tillage has been declining for some time, with substantial increases in no-till cropping systems. These trends were evident before the introduction of HR crops; however, the trends have accelerated since their introduction. In 1997, more area was planted to GR soybean using conservation tillage than

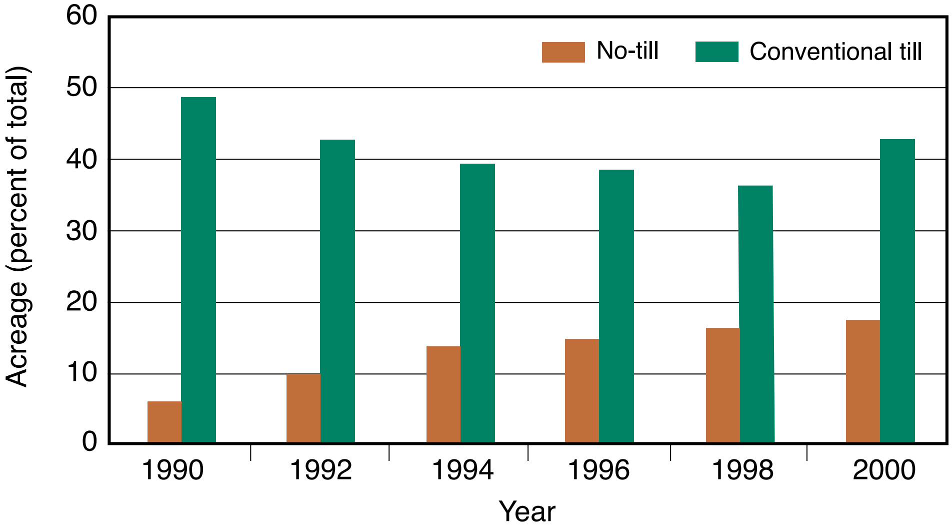

Figure 2. Changes in no-till and conventional tillage in U.S. corn, cotton, and soybean crops for the period 1990 to 2000 (CTIC 2011).

was planted to conventional soybean (Fernandez-Cornejo and McBride 2002), and this trend has accelerated. Cotton production using conservation tillage increased almost threefold between 1997 and 2002 (NRCS 2004); however, recent developments in herbicide resistance have threatened this progress, with tillage becoming a more common practice in GR cotton due to the evolution of GR weeds (Dill, Cajocob, and Padgette 2008). In fact, conventional tillage is now the dominant tillage practice in GR cotton primarily because of the evolution of GR weeds. Weed shifts favoring GR horseweed (*Conyza canadensis*), Palmer amaranth in the southeastern United States, and kochia in the western United States have increased production costs and environmental concerns while decreasing time-management efficiency.

Selection pressure for weeds more tolerant to a given production system is inherent with the utilization of that system. A number of factors come into play as a producer determines the specifics of a production system, including economics, crop suitability, time demands, and experience with production practices. In addition, federal policies and programs in many instances play a significant role in the selection of crops and conservation programs that are implemented. These governmental programs in turn can play a major role in weed selection and weed management practices chosen in response to these weed populations.

Government Programs and Tillage

Natural Resources Conservation Service

The USDA Natural Resources Conservation Service (NRCS) is the federal agency responsible for providing science-based policy development and technical and monetary assistance to U.S. farmers implementing conservation on private land. The NRCS traces its agency roots back to the Soil Erosion Service, which was congressionally funded in 1933 and renamed the Soil Conservation Service in 1935 and NRCS in 1994. This agency assisted the Civilian Conservation Corps and the Works Projects Administration during the Great Depression, furnishing equipment, seed, seedlings, and technical expertise to farmers and ranchers in efforts to prevent soil erosion from wind and water. Historically, the NRCS worked with landowners on a voluntary basis. The U.S. Food Security Act of 1985, however, changed the NRCS scope of work by introducing compliance monitoring, in which field staff are required to make determinations as to whether or not producers are compliant with USDA highly erodible land (HEL) and wetlands requirements. Natural Resources Conservation Service programs generally are administered at the state level—technical assistance information is accumulated at the state level from federal and institutional research and extension programs locally and regionally. Thus, conservation programs and recommendations can and usually do vary by state and state NRCS leadership uses local, regional, and national expertise to determine recommended practices.

Soil and Water Conservation Districts

First formed in 1937, soil and water conservation districts (SWCDs) were developed as independent local governmental organizations (usually delineated by county map or watersheds) that organized and supervised soil and water conservation projects within district boundaries. There are more than 3,000 SWCDs across the United States, and they are further organized under the National Association of Conservation Districts (NACD). Independent of NRCS, SWCDs formally agree to collaboratively promote NRCS goals and set locally led conservation priorities for the distribution of a portion of NRCS funding to landowners within the district. Implementation of projects by SWCDs is determined and approved by a local board of directors. Soil and water conservation district activities include "conducting surveys and research, disseminating information, conducting demonstrations, carrying out prevention and control measures, acquiring land and property, and promulgating land-use regulations"—in effect, broadening NRCS agency impact (NRCS 2004). Concerning crop production practices, SWCDs determine priorities and practices, participants, and cost-share rates within districts.

Resource Conservation and Development

Resource Conservation and Development (RC&D) council areas were established by the U.S. Agricultural Act of 1962 and generally are composed of three or more counties. These grassroots organizations bring rural people together to work toward protecting and enhancing cultural, economic, and environmental resources. The NRCS provides each RC&D council a full-time coordinator who helps participants locate project funding resources, including research and demonstration grants and in-kind assistance from NRCS and other USDA agencies. Resource Conservation and Development council activities are very broad and include anything that fits within the council's long-range plans and goals for the area, such as conducting research and extension, grant writing and administration, and soil and water resource projects.

Most NRCS in-field programs focus on promoting soil and water quality. Soil quality is loosely defined as "the ability of soil to function" and is composed of three major components: sustained biological productivity, environmental quality, and plant and animal health (Karlen et al. 1997). Other definitions referenced by Doran and Parkin (1994) include chemical, physical, biological, erodibility attributes, and sustainable use. As stated previously, to be eligible to participate in USDA Farm Service Agency (FSA) and NRCS programs, farmers must be in compliance with the HEL (calculated by using rainfall, inherent erodibility, and slope angle and length) and wetland conservation provisions of the 1985 Farm Bill (as amended). Historically, FSA and NRCS programs encouraged transition of HEL to grass and timber systems to promote soil conservation as well as decrease commodity surpluses to alleviate government price-support payments.

Currently, as commodity prices increase, the likelihood of bringing HEL back into production is increasing, as well as the likelihood of increasing soil erosion. Many soils will have excessive soil erosion without conservation tillage, cover crops, and proper crop rotations. Loss of FSA eligibility forfeits participation in direct and cyclical payment programs, deficiency payments, consolidated farm and rural development loans, crop disaster payments, and conservation payments, among other USDA benefits (NRCS 2002).

Environmental Quality Incentives Program

Through the Environmental Quality Incentives Program (EQIP), the NRCS "provides assistance to agricultural producers in a manner that will promote agricultural production and environmental quality as compatible goals, optimize environmental benefits, and help farmers and ranchers meet Federal, State, Tribal, and local environmental requirements." National priorities include reduction of non-point source pollution, reduction of emissions, reduction in soil erosion and sedimentation, and promotion of at-risk species habitat conservation. The Conservation Security Program (CSP) is the NRCS flagship program that provides incentives to keep conservation-managed land in such systems as well as enhance environmental and sustainability concerns. Priorities (developed by the USDA, SWCDs, and other stakeholders) are used by the NRCS chiefly to allocate available EQIP funds to state conservationists and SWCDs through partnership agreements.

The state conservationist, following guidance from the State Technical Committee, SWCDs, and other stakeholders, identifies priority natural resource concerns in the state that will be used in a competitive process to decide which applicants are awarded EQIP or CSP assistance. A competitive process is used to prioritize contracts within NRCS at the local level. Again, EQIP and CSP programs and practices can be different between states and even between counties within states.

Herbicide Resistance in Weeds

Evolution

The Weed Science Society of America defines herbicide resistance as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type" (WSSA 1998). Herbicide resistance has been documented as far back as 1970, when a common weed called groundsel (*Senecio vulgaris*) *biotype* was identified that was resistant to triazine herbicides. More than 350 confirmed instances of weed resistance have been reported in 197 weed species globally (Heap 2011), and more than one-third of these are found in the United States. Resistance to herbicides that inhibit the acetolactate synthase (ALS) enzyme occurs in the highest incidences, followed by resistance to the triazine herbicides. Glyphosate resistance was first noted before the development of GR crops and was the result of exclusive use of glyphosate repeatedly for vegetation control in orchard settings. In the United States, glyphosate resistance was first noted in horseweed, again not due to GR crops because horseweed is a weed problem before planting numerous crops (Figure 3).

The rapid adoption of GR crops was primarily due to the effectiveness of glyphosate on most economically important weeds and the simplicity of using glyphosate alone for weed control. The effectiveness of weed control in GR crops supported the widespread adoption of no-till systems that improved the utilization of soil and energy resources (Gianessi 2008). Functionally, weed control in GR crops (e.g., alfalfa, canola, corn, cotton, soybean, and sugarbeet) has minimized the need for aggressive tillage and mechanical tactics previously necessary. Given the economic, environmental, and time-management implications of tillage, and herbicide

Figure 3. Glyphosate-resistant horseweed in a Tennessee conservation tillage field. (Photo courtesy of Lawrence Steckel.)

complexity in non-HR crops, GR crops utilizing glyphosate supported the wide-scale grower adoption of conservation tillage. With the evolution of HR weeds and the resultant inability to maintain weed control, however, the continued inclusion of conservation tillage systems is threatened.

The evolution of glyphosate resistance has further threatened global food production and reinforced the need to adopt practices to protect the sustainability of the GR crops and glyphosate (Powles 2008). Whereas academia and farm consultants are suggesting tactics to proactively mitigate the evolution of GR weeds, in many agroecosystems prevention is no longer an option. Given the prominence of evolved resistance to glyphosate, concerns about resistances to other herbicide sites of action have become less. These resistances to alternative herbicides, however, are still a significant component of agroecosystems and should be monitored and understood when developing mitigation strategies to manage HR weed populations. Regardless of the strategies adopted by growers, the costs must be considered against the benefits of these strategies.

Selection pressure in agriculture, regardless of the specific source of the selective differential, will inevitably result in shifts in weed communities. In HR crop production systems using conservation tillage, the weed community must first "adjust or adapt" to the tillage system given that tillage has a greater overall impact on the agroecosystem than herbicides (Buhler, Hartzler, and Forcella 1997). For HR weeds, however, the selection pressure is also attributable to the recurrent use of herbicides. The greater the frequency of specific herbicide use, the less the diversity of management tactics; the greater the efficacy of the herbicide on the target weeds, the faster the evolution of the HR biotype (Gressel and Segel 1978). Herbicide-resistant weed biotypes are an inevitable consequence of herbicide use, and in the case of glyphosate resistance, more opportunities exist for resistance than originally thought (Bradshaw et al. 1997; Gressel 1996; Owen 2008).

Given the almost universal use of herbicides for weed control, and specifically the use of glyphosate almost to the exclusion of other herbicides in GR crops, it is not surprising that resistance to glyphosate has evolved in a number of weed species. Furthermore, the evolution of multiple and cross-resistances reflects the importance of herbicides as selective differentials in impacting the evolution of HR weed biotypes.

Genetic variability coding for herbicide resistance must pre-exist in natural weed populations for the evolution of HR biotypes; spontaneous evolution of herbicide resistance has not been documented (Jasieniuk, Brule-Babel, and Morrison 1996). There are two primary mechanisms by which herbicide resistance can evolve. One, and perhaps the most widely documented, is target-site resistance where high rates of an herbicide have been used repeatedly. The other has been labeled "creeping resistance" and is attributable to using low herbicide rates. Creeping resistance may result from different genes conferring a low level of resistance and a fairly rapid reduction in the response of the weed population to the herbicide (Gressel 2009). Most current GR weeds have evolved a relatively low level of glyphosate resistance. There is evidence of creeping resistance in two *Conyza* species (Dinelli et al. 2006, 2008). There is also documentation, however, that increasing the rate of glyphosate may expedite the evolution of GR weeds where the resistance is controlled by a single partially dominant nuclear gene (Zelaya, Owen, and VanGessel 2004).

Present Use

Generally, most of the herbicides that are currently important in weed management inhibit or affect a single essential plant enzyme or process and are controlled by a single gene (Gressel 2011)—glyphosate resistance in horseweed is controlled by a single gene (Zelaya, Owen, and VanGessel 2007); paraquat resistance in rigid ryegrass (*Lolium rigidum*) is the result of a single nuclear gene (Yu et al. 2009). *Polygenic control* of glyphosate resistance, however, is suggested in tall waterhemp (*Amaranthus tuberculatus*) and Palmer amaranth (Gaines et al. 2010; Zelaya and Owen 2005). Inheritance of glyphosate resistance in the California rigid ryegrass biotype is also apparently governed by more than one gene (Simarmata, Kaufmann, and Penner 2003). Triazine resistance in velvetleaf (*Abutilon theophrasti*) is the result of a single gene, whereas in tall waterhemp more than one gene is likely involved (Andersen and Gronwald 1987; Patzoldt, Dixon, and Tranel 2003).

Herbicide resistance is typically a single, dominant or partially dominant, paternal characteristic. As previously suggested, there are examples of herbicide resistance that are not conferred by a single gene; regardless, the characteristic for herbicide resistance is typically dominant or semi-dominant and paternally heritable. Maternally heritable resistance to triazine herbicides, however, is known (Souza-Machado et al. 1978). Furthermore, there are documented herbicide resistances conferred by a single recessive nuclear-coded gene (Sabba et al. 2003). Interestingly, interspecific hybridization between indigenous weedy plants has been commonly reported and natural hybridization in *Conyza* spp. has been documented in numerous instances (McClintock and Marshall 1988; Stace 1975; Thebaud and Abbot 1995). Typically, these hybrids do not evolve into significant weed problems. The implication of hybridization, however, between HR and sensitive weed populations and the introgression of the HR trait is potentially agronomically important.

One of the more important characteristics that influence the evolution of HR weed biotypes is the relative fitness (biological success) of the HR biotype in the absence of the herbicide-based selective pressure. Assessing plant fitness is difficult and often misrepresented in the literature (Gressel and Segel 1978). Generally, there does not seem to be a consistent fitness response for HR weed biotypes. Though it is clear that resistance to triazine herbicides imparts a significant fitness penalty (Holt and Thill 1994), the fitness of weed biotypes with evolved resistance to ALS-inhibiting herbicides is less clear and variable. Generally, it is accepted that there is a minimal fitness penalty for ALS-resistant biotypes. The impact of glyphosate resistance in weeds is similarly less than clear. There is evidence that evolved resistance to glyphosate imparts a fitness penalty in rigid ryegrass; however, other studies suggest a minor or no fitness implication on GR weed biotypes (Pedersen et al. 2007; Preston and Wakelin 2008; Preston et al. 2009; Zelaya, Owen, and VanGessel 2004).

Although HR weeds have evolved against most mechanisms of herbicide action, none have threatened advances in conservation tillage to the extent of GR weeds. The need for tillage in these GR cropping systems was replaced with herbicides, primarily glyphosate, which led to increased grower dependence on a single herbicide mechanism of action (Young 2006). The selection pressure arising from this unprecedented use of glyphosate over space and time subsequently led to the evolution of GR weed biotypes such as horseweed, Palmer amaranth, common waterhemp (*Amaranthus rudis*), and kochia (Al-Khatib et al. 2010; Culpepper et al. 2006; Duke and Powles 2009; Heap 2011; Legleiter and Bradley 2008; Stahlman and Geier 2011; VanGessel 2001). Glyphosate-resistant weeds pose the greatest threat to conservation tillage since its adoption and in some instances have caused farmers to change their conservation tillage practices or, in a few more limited situations, have eliminated conservation tillage where it once thrived (Ervin et al. 2010; Price et al. 2011).

Glyphosate-resistant horseweed was first reported to infest no-till GR soybean fields in Delaware in 2000 (VanGessel 2001) and has since been confirmed in 16 U.S. states (Heap 2011). Initially when resistance evolved, growers who previously had used effective glyphosate-based systems had to re-adjust their management programs. In some states growers reverted back to tillage to control escaped GR horseweed in certain fields; area devoted to conservation tillage was decreased by as much as 25% in some Tennessee counties (Steckel and Culpepper 2006). The biological attributes of horseweed, such as its intrinsic genetic variability, prolific seed production, ease and great distance of seed dispersal, and lack of dormancy mechanisms, led to the need for tillage. Fortunately, by 2007 herbicide programs were developed or reintroduced that used dicamba and 2,4-D to control emerged plants resistant to glyphosate, but these applications also included flumioxazin or fluometuron to provide residual control of plants that emerged after burndown, thereby avoiding the need for tillage (Davis et al. 2007). Although these programs are more costly than glyphosate only-based programs, growers were able to resume practicing conservation tillage (Steckel, Main, and Mueller 2011; USDA–NASS 2010).

The GR *Amaranthus* species (e.g., Palmer amaranth and common waterhemp) has had an even greater impact on crop production in general, and conservation tillage specifically. Its impact has increased each year since discovery in Georgia during 2004. Beginning in 2005, many Georgia growers were forced to abandon cotton production because of their inability to manage GR Palmer amaranth using herbicide programs that had previously provided excellent weed control. In contrast to the case of GR horseweed, herbicide systems by themselves are not sustainable for the control of GR amaranth in numerous areas, with herbicide costs alone often exceeding \$150 ha^{-1} (\$60 per acre) (Culpepper et al. 2011). In areas infested with this pest, integrated management practices that combine the use of cultural, mechanical, and chemical tactics have proved to be the only economically effective option for managing GR Palmer amaranth. In areas not infested with resistant *Amaranthus*, some growers have been able to prevent/slow the invasion of this resistant pest through practices such as rotating herbicide chemistry and crops, using effective residual herbicides throughout the season, and, most importantly, removing any escaped plants before seed production.

In some heavily infested areas, conservation tillage has been nearly eliminated because inversion tillage was the most effective option to supplement other tactics for Palmer amaranth control (Culpepper, York, and Kichler 2009; Leon and Owen 2006). Palmer amaranth emergence was decreased 46 to 60% without the use of residual herbicides by inverting the soil with a moldboard plow. Even when effective residual herbicide programs were implemented, control improved 17% with moldboard plow tillage (Culpepper et al. 2011). Similarly, GR Palmer amaranth control can be improved at least 10% by either in-row cultivating or incorporating dinitroaniline herbicides into the soil rather than applying these herbicides on the soil surface. Although tillage can often improve control of GR *Amaranthus*, greater input costs and potential soil erosion are significant challenges for growers. Thus, there is a pressing need for effective management strategies that both lower production costs and have minimal environmental impacts.

Although the agriculture community is committed to conservation tillage systems because of the environmental benefits, preservation of the economic viability of the farming operation is critically important. Understanding how tillage can fit into effective HR weed management programs with minimal or no impact on the conservation benefits is essential.

Balancing Conservation Tillage and Herbicide-resistant Weed Management

Primary tillage and inter-row cultivation can provide indiscriminate weed control regardless of weed susceptibility to herbicides. The fundamental conflict facing many producers with HR weed management issues today is the choice between using tillage or land stewardship practices that protect soil and water resources. Integration of high-residue cover crop systems, inversion of the weed seed bank profile, and effective residual herbicides are beneficial for herbicide resistance management. Secondary tillage is required to optimize preplant incorporated and preemergence (PRE) herbicide efficacy, and these herbicides are extremely useful tools as alternative mechanisms of action. These tillage practices, however, may exclude producers from participating in government programs designed to promote land stewardship and protect soil and water quality.

Through NRCS EQIP funding opportunities, producers can apply for funds to assist in herbicide resistance management planning and practice implementation. The conservation activity plan (CAP) is a provision within EQIP that allows NRCS to assist producers with payment to an NRCS-certified consultant for the development of a specific herbicide resistance activity farm plan, among others. In 2011, NRCS offered 11 activities available nationwide for CAPs; however, individual states determine which CAPs receive funding. In 2011 a herbicide weed resistance CAP was added to the nationwide available activity list, and four states—Arkansas, Florida, New Mexico, and North Carolina—funded herbicide resistance CAPs. The number of participating states likely was limited as much by the lack of certified consultants to develop CAPs as it was by the lack of identification of herbicide resistance as a resource concern by stakeholders (Hardee, G. Personal communication).

In addition, an integrated pest management (IPM) CAP was funded by 19 states in 2011; plans to address herbicide resistance can also be developed through the IPM CAPs. The IPM CAP, however, requires that the prevention, avoidance, monitoring approach be followed; that all likely pests of the crop be addressed; and that environmental hazards of target pest suppression activities be assessed and mitigated. These requirements are likely viewed as daunting by NRCS technical staff, NRCS-certified consultants, and producers. Producers can also make application for EQIP funding for practices to control herbicide resistance in combination with numerous resource concerns or as the singular resource concern. In general, IPM CAP practices are consistent with environmental resources protection and Cooperative Extension System recommendations within the state and may include integration of cover crops and conservation agriculture crop management practices.

Conservation Regulations

Conservation program eligibility requirements are determined when farmers participating in NRCS programs submit crop management plans for each field. Growers must explicitly state what equipment and crop rotations will be used on their farm. Natural Resources Conservation Services staff then estimate the soil loss potential for individual fields, which is used with other information to rank contract awards. Farmers using practices that minimize soil loss and decrease off-site environmental risks rank relatively higher and get contract approval before those who provide less stewardship.

Historically, NACD, NRCS, FSA, and agricultural research and extension have worked in a close partnership in developing and funding sound conservation programs. This partnership will be critically important as HR weed management practices are developed that can sustain yields and farm profitability while at the same time remain in compliance with conservation stewardship programs. In some cases, especially Palmer amaranth in cotton, researchers recognize that integrated weed management (IWM) strategies that include tillage may be necessary, especially as control in some instances is virtually impossible without tillage

Textbox 2. Palmer amaranth Case Study.

Palmer amaranth Case Study

For purposes of this paper, a case study of one of the most high-profile problems—Palmer amaranth in cotton—is used (see Figure 4). Many southeastern and mid-south producers are currently implementing university recommendations to combat HR Palmer amaranth. In 2010, the Georgia NRCS began offering an HR weed management pilot program utilizing EQIP funding through an SWCD in a limited number of counties (NRCS 2011a). The program in Georgia required using a high-residue cover crop system, minimal residue disturbance, crop rotation, and rotation of herbicide mechanisms of action. Producers also had the option of using inversion tillage as long as a high-residue cover crop system was established within two weeks of the tillage operation (see Figures 5 and 6). The following variance was also stated in Georgia's NRCS pilot program (NRCS 2011a): "Documentation will be provided to the landowner and FSA in cases where accepted acreage is designated as HEL that will allow tillage practices the first year of the contract."

Natural Resources Conservation Service EQIP guidelines to address HR Palmer amaranth were developed in 2010 in Alabama and Tennessee, with implementation starting in 2011. To discourage use of tillage, the USDA and FSA eligibility requirements prominently state that "participants must be on record with the Farm Service Agency and meet all eligibility requirements including producer and land eligibilities" and "all fields must maintain HEL compliance" in Alabama (NRCS 2011b) and Tennessee (NRCS 2011c), respectively.

Alabama requirements additionally state that "all crops in rotation must currently be in a conservation tillage system." Tennessee requirements include that an herbicide resistance CAP be developed. Alabama and Tennessee practices require, for minimum payment, herbicide mode of action rotation, control of weeds after crop harvest, and maintenance or enhancement of current conservation practices. In addition to these requirements, producers are expected to implement scouting, mechanically remove HR weeds to prevent seed production, minimize in-row residue disturbance, use shielded sprayers, increase crop residue, and clean equipment. To receive the highest payment, producers are required to also implement a high-residue cover crop system and, in Alabama, use a mechanical roller that flattens the cover crop and facilitates planting. A sod-based rotation option, in which perennial forage crops are rotated with agronomic crops, is available in Tennessee.

Figure 4. Glyphosate-resistant Palmer amaranth infesting Georgia cotton. (Photo courtesy of Stanley Culpepper.)

Figure 5. Decreased Palmer amaranth infestation in Georgia cotton following inversion tillage and mulching. The nontreated control is in the background. (Photo courtesy of Stanley Culpepper.)

Figure 6. Palmer amaranth infestation with strip tillage. (Photo courtesy of Stanley Culpepper.)

because of extraordinarily high seed bank numbers.

Because HR weed management has no simple solutions, disagreement among organizations about the use and value of tillage in HR weed management is inevitable. In addition, as commodity prices increase, producers may be reluctant to participate in USDA programs if their programs are inflexible with regard to tillage and HR weed management. Producers should not be forced to choose between government program compliance and unacceptable yield losses due to inadequate HR weed control. Instead, more collaboration between all parties is essential. Research should target identifying effective HR weed management tools while at the same time meeting land stewardship requirements.

Regulations for conservation compliance also state that "USDA participants may request using experimental cropping systems, conservation systems, or component practices on a field trial basis." This provision could allow experimental tillage for GR Palmer amaranth management in the Georgia NRCS pilot program. In addition, variances and exemptions for compliance can also be granted because of "good faith, economic hardship, expedited variances for weather, pests, and disease related incidents, and exemptions provided when violations are found during the regular provision of USDA technical assistance" ("The FSA State Committee may grant this exemption when a farmer or rancher's conservation system is economically prohibitive to apply and maintain, the technology needed to apply the conservation system is not available within the area, and there are no other conservation alternatives available") (NRCS 2005).

Variances for specific pest management problems are considered based on percentage of expected crop production compared to normal production, documentation of weed or insect infestations, or other special circumstances. The NRCS provides out-of-compliance producers with the technical assistance necessary to move back into compliance within 45 days of the violation. According to the NRCS fact sheet, a producer has one year to return to FSA compliance before losing participation eligibility.

Mitigating the Impact of Herbicide-resistant Weeds on Tillage Options

Diversity is Key

Strategies can mitigate and manage herbicide resistance in weeds. Importantly, a key consideration is the need for diversity of strategies. Strategies to consider include, but are not limited to, alternative tillage including mechanical strategies, using alternative herbicides, and cultural approaches. Collectively, these strategies are beneficial from the perspective that management of HR weed populations is improved. This benefit, however, must be balanced against the concomitant risks of the strategies. These risks may represent greater economic costs, time requirement, petroleum fuel consumption, and environmental decline. Alternative mitigation tactics to lessen the impact of HR weed populations are critical to effective crop production, particularly in systems based on GR crops and glyphosate. The greater the number of alternative mitigation tactics that are included in a crop production system, the greater the impact on the evolution of HR weed populations.

Johnson and colleagues (2009) noted that three herbicide use patterns that were largely abandoned given the wide-scale adoption of GR-based systems include herbicide tank-mixtures, rotation of alternative herbicides with glyphosate, and preemergence-applied residual herbicides. The changes in herbicide use were attributable to the initial effectiveness of glyphosate, the marketing message for the technology, and the belief by many that glyphosate resistance in weeds would never be a major concern. Rotation of herbicides, however, specifically when the mechanisms of herbicide action (MOA) are considered, is an important tactic to mitigate and manage HR weed populations. If only rotation of herbicide modes of action is practiced as the tactic to manage HR weed populations, however, the evolution of HR weed populations will only be delayed (Beckie and Reboud 2009; Diggle, Neve, and Smith 2003; Powles et al. 1997).

Generally, the benefit of crop traits for the mitigation and management of herbicide resistance reflects the opportunity to use alternative herbicides such as glufosinate where GR weed biotypes have been selected and glyphosate applied recurrently. The risk attributable to alternative herbicide resistance traits reflects the likelihood that the new trait/herbicide system will be used by growers recurrently, resulting in the evolution of new resistances. Again, diversity is the key to effective mitigation of herbicide resistance.

Transgenic and Nontransgenic Herbicide-resistant Crops

A number of transgenic and nontransgenic HR crops have been available since 1984. These HR crops include alfalfa, canola, corn, cotton, rice, sorghum, soybean, sugar beet, sunflower, and wheat; the HR cultivars generally both eliminated concerns for crop injury and provided new herbicide options with potentially better weed control and environmental safety. Seven herbicide MOAs are represented in the HR crop cultivars, with new crops and MOAs anticipated in the future. New HR traits include auxinic herbicides, 4-hydroxyphenyl pyruvate dioxygenase (EC 1.13.11.27) inhibitor herbicides, and protoporphyrinogen oxidase (EC 1.3.3.4) inhibitor herbicides. These new HR traits may be important in the management of GR weed biotypes; however, the evolution of herbicide resistances, either multiple or cross-resistances, in agronomically important weeds to some of these MOAs already threatens the utility of the new traits.

Multiple Herbicide Resistance

Another important opportunity exists regarding HR crops with multiple resistances to herbicides. As reinforced by the evolution of GR weeds, no single HR trait will be sustainable if only one herbicide or MOA is used recurrently. The development of HR crops with multiple resistances may provide better weed management and support sustainable systems, but only if these cultivars and herbicides are used in a diverse management program. Weed biotypes with multiple and cross-resistances, however, are already problematic, and populations of these HR weed biotypes are likely increasing faster than the development of multiple HR crops (Owen 2009).

The rotation of traits that code for different herbicide resistances does not, in itself, provide any benefit to the management of HR weeds. Likewise there is no relationship between the traits that code for herbicide resistance in crops and the naturally occurring traits that confer resistance in weed species. The genetic traits that confer herbicide resistance in crops with currently available HR cultivars are functionally benign in the environment and thus by themselves have no impact on HR weed biotypes. When HR traits are in a rotation system that includes the use of the specific herbicide (i.e., glufosinate), however, there is potential benefit for the management of HR weeds. This assumes, of course, that the trait/herbicide combination has efficacy on the target HR weed species.

Alternative Herbicides

The benefits and risks of using alternative herbicides reflect how growers adopt and use the strategies; if diversity of herbicide use (i.e., herbicide combinations) is lacking and growers emphasize simple and convenient use of alternative herbicides (i.e., using only glufosinate instead of glyphosate), there is a significant risk that new herbicide resistances will evolve. Furthermore, the adoption of alternative herbicides has been reported to be a reactive rather than a proactive strategy for the management of herbicide resistance and, as such, less functional with regard to mitigating and managing HR weed biotypes (Beckie 2007). Importantly, given that resistant weed biotypes exist to most of the herbicide MOAs used in row crops, care must be taken in the development of the alternative herbicide practices to ensure that these alternatives have benefits in the crop production system (Heap 2011).

Rotation of herbicide MOAs can be a beneficial strategy to mitigate and manage HR weed populations. Furthermore, this strategy is viewed as simple and convenient by growers and reflects the availability of alternative (to glyphosate) HR crops. To that end, the adoption of rotating MOAs is a common strategy to mitigate and manage herbicide resistance in weeds. If, however, rotation of herbicide MOAs is the only strategy employed to mitigate and manage the evolution of HR weed biotypes, it will inevitably fail and there is a high probability of resistances to both herbicide MOAs.

Herbicide Tank Mixtures

The use of herbicide tank mixtures is a better strategy to mitigate and manage herbicide resistance than MOA rotation and other alternative herbicide practices. Importantly, this strategy can be used, in many instances, regardless of crop herbicide resistance traits. It is critical, however, to recognize the implications of multiple herbicide resistances in weed populations and to correctly select appropriate herbicides for the tank mixtures; the herbicides selected with different MOAs must be efficacious on the target weeds. Consider that many of the commercially available tank mixtures include herbicides to which HR weed biotypes already exist; the use of these herbicide mixtures would not provide any benefit for the mitigation and management of HR weed biotypes.

One other important consideration about the utility of herbicide tank mixtures for mitigation and management of HR weed biotypes is the relative selective differential that the herbicide components provide. Theoretically, for herbicide tank mixtures to have the maximum benefit for mitigating and managing HR weed biotypes, the components should provide equal (redundant) selection pressures (Wrubel and Gressel 1994). This includes the relative efficacies that the components demonstrate on the target species and residual characteristics for control. If differences in control or residual properties exist for the components, differential selection pressures are imposed on the weed community and HR weed biotypes will inevitably evolve.

Other alternative herbicide practices include the use of rates that are lower than labeled and recommended as well as application timings and the inclusion of *synergists*, alternative products, and *adjuvants*. The use of below-labeled herbicide rates should be considered relatively risky from the perspective that lower herbicide rates may not consistently control the target weed population and may contribute to the evolution of herbicide resistance in weeds (Sammons et al. 2007). There is merit to alternative application timing (i.e., PRE applications) if combined with alternative herbicides and practices. Given the current system that focuses on postemergence applications of glyphosate, the inclusion of a soil-applied residual herbicide would be of particular value if the herbicide of choice has efficacy on the target weed species and a different MOA. The use of alternative application timing of herbicides, however, is likely only to be adopted as a reactive, not proactive, strategy and viewed by growers as an approach that increases the cost of weed management. Although numerous products that allegedly improve herbicide performance are recognized and these alternative products and adjuvants are readily available, it is suggested that these products are generally of little value for the mitigation and management of HR weed populations.

Mechanical Weed Control and Cultural Strategies

Mechanical weed control strategies are historically important components of an IWM program (Swanton and Weise 1991). The current scale of production agriculture, concerns for increased soil erosion, time management issues, and higher production expenses due to increasing cost of petroleum fuels, however, all contribute to the unwillingness of some growers to consider mechanical weed control strategies. If HR weed problems (i.e., multiple herbicide resistances) are such that no other approach is feasible, growers may consider mechanical control strategies. The utility of mechanical control strategies in the Midwest crop production systems, however, is minimal because of the aforementioned risks. But it is suggested that the adoption of site-specific mechanical control strategies may serve to resolve many of the barriers and thus allow growers to effectively use this approach for the mitigation and management of HR weed populations.

The use of cultural strategies to more effectively manage HR weeds has considerable merit; however, typically there are significant obstacles and/or risks associated with these approaches. Cultural strategies are available that include, but are not limited to, variable planting time and crop seeding rate; crop rotation sequence; planting configuration; choice of crop cultivar; nutrient management optimization; and cover crops, mulches, and intercrop/relay crop systems (Green and Owen 2011; Owen 2001). Generally, the likely adoption of these cultural strategies is assessed to be fair to poor. Approaches such as crop rotation sequence and cultivar selection are correlated with herbicide selection and may have generally less risk with regard to the mitigation and management of HR weeds than many other cultural strategies. Typically, the contribution of any cultural strategy to the management of HR weeds is small, and several approaches should be considered (Liebman and Dyck 1993; Westerman et al. 2005). The risks that must be considered include the inconsistency of the strategy for the management of HR weeds (e.g., cover crops or nutrient use), economic risks (e.g., crop rotation sequence), and implications on other weed management tactics (e.g., planting configuration and mechanical control options).

Crop Rotation

Crop rotation can be an effective means of managing a number of pest complexes. In theory, crop rotation decreases weed population densities and maintains weed species diversity by introducing ecological niches supporting the crops in rotation. Liebman and Dyck (1993) suggested that differing crop rotations create an ecosystem that would minimize weed shifts due to the ecological variability that exists with diverse rotations. The effectiveness of crop rotation to impact weed population densities, however, is dependent on the characteristics of the different crops and the resultant management tactics used to produce the crops. For example, the increased diversity found in complex crop rotations (e.g., corn, soybean, small grain, forage) dilutes the selection pressure that ecologically favors specific weeds and subsequently decreases the potential for weed population shifts.

Other researchers have shown the general effect that the more diverse the rotation, the more diverse the community of weed species (Cardina, Herms, and Doohan 2002; Heggenstaller and Liebman 2005; Teasdale, Parthan, and Collins 2005). Conversely, simple crop rotations and management tactics (e.g., continuous corn and recurrent applications of glyphosate) will result in weeds that are well adapted to the specific agroecosystem and thus more difficult to manage effectively. Crop systems based on GE crops are generally ecologically simple and unlikely to include a complexity of production tactics, thus favoring rapid adaptation (weed shifts) by specific weeds.

The benefits and risks of crop rotations on weeds, however, are difficult to quantify considering the other management tactics that are typically included in crop production systems. When considering the benefits of crop rotations on the mitigation and management of HR weeds, it is important to consider factors such as herbicide use and tillage, given their major impacts on the weed population dynamics in conjunction with crop rotations. It is often difficult or impossible, however, to separate the effects of crop rotation from other strategies on HR weeds. Regardless, crop rotations that impact soil disturbance and resource competition potentially will have an important role in decreasing the likelihood of weed shifts such as the evolution of HR weed biotypes.

Conclusions

- Herbicide-resistant weeds pose one of the most significant threats to soil conservation since the inception of the USDA NRCS.
- Some weed species have resistance to herbicides such that they have forced growers to include or intensify tillage if they are to remain economically viable in their farming operation. In most soil conservation tillage situations, however, the objectives of conservation tillage can still be met even in the presence of HR weeds.
- The NRCS and NACD must realize and support the value of developing integrated management programs, perhaps including tillage, for the management of GR weeds. Additionally, the NRCS and NACD should assist in determining when and how to implement tillage to complement conservation tillage systems, thus having minimal impacts on soil quality and the environment.
- The NRCS and NACD should work to qualify and promote HR weed

best management practices (BMPs) in the suite of existing conservation programs such as the EQIP.

- The NRCS and NACD should strongly encourage HR weed BMPs to be high-priority practices qualifying for land stewardship programs.
- Stronger educational programs are needed that demonstrate how HR weeds can be best managed without losing the tremendous conservation gains attained in recent decades.
- More research is needed on how to best meet the needs of HR weed management, while at the same time meeting soil conservation compliance goals.

Glossary

Adjuvant. An ingredient that modifies the action of the principal ingredient.

Agroecosystem. A system in which communities of plants, microbes, and animals inhabiting farmed land interact with each other and their physical environment and are affected by agricultural management.

Biotype. Populations of organisms sharing an identical genotype.

Crop residue. Organic material left in the field after harvesting the crop—e.g., leaves, stalks, stubble, roots, hulls.

Dormancy. A temporary period during which viable seeds will not germinate under favorable conditions.

Edaphic. A condition of soil—whether physical, biological, or chemical—that influences the organisms and processes that occur in soil.

Genetically engineered. Having undergone direct modification of the gene component of an organism by techniques such as altering the DNA, substituting genetic material, transplanting whole nuclei, transplanting cell hybrids, etc.

Paratill. A subsurface tillage implement that loosens compacted soil.

Photoreceptors. Proteins in living organisms that sense and respond to light.

Polygenic control. The determination, controlled by a group of genes, of a number of an organism's characteristics.

Seed bank. All seeds present in the soil.

Synergist. An enhancement for the effectiveness of an active agent.

Tilth. The overall physical character of soil regarding its suitability for crop production.

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