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# The importance of atrazine in the integrated management of herbicide-resistant weeds

*Micheal D K Owen*
*Professor of Agronomy*
*Iowa State University*

## 1. Introduction

Weeds have a major impact on agricultural production and represent the most significant pest threat to crop yields in the face of global population growth and increasing demand. It is estimated that the current global population of approximately 7 billion will grow to nearly 9 billion by 2050 (Anonymous, 2004). Currently, herbicide-resistant weed biotypes represent a significant, and increasing, economic threat to U.S. agriculture. Since the first report in the 1950s of herbicide-resistant weeds, 368 herbicide-resistant weed biotypes have been reported in 200 different plant species (Harper, 1956; Heap, 2011; Ryan, 1970). Nevertheless, concerns about genetically-modified (GM) crops, specifically those that have been genetically-modified to be resistant to glyphosate, have dramatically changed how herbicide-resistant weeds are now perceived by the agricultural industry, weed scientists, society and the federal government (Arntzen et al., 2003; Dalton, 2002; Ervin et al., 2010; Gealy et al., 2007; Hails and Kinderlerer, 2003; Hails, 2002; Konig, 2003). Clearly, herbicide-resistant weeds will have a significant impact on future agricultural production of food, feed, fiber and fuel.

The recent major increases in herbicide-resistant biotypes fall within two main mechanisms of action: weeds with evolved resistance to herbicides that inhibit acetolactate synthase (ALS, EC 2.2.1.6) (e.g. imazethapyr) and 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS, EC 2.5.1.19) (e.g. glyphosate). Resistant biotypes have increased dramatically for both mechanisms of action since 1990 and 2000, respectively. In contrast, resistance to herbicides that inhibit photosystem II (PSII) (e.g. atrazine) has not increased much since 1990 (Heap, 2011; Owen, 2008b; Owen and Zelaya, 2005). Considering the more than 50 years of successful use of atrazine and the current situation with increased herbicide resistance in GM crops, maintenance of atrazine as a crop protection tool is essential. Atrazine is a key component of proactive and reactive management systems for herbicide weed resistance, especially for management of weeds resistant to glyphosate. In fact, the number of weeds with evolved glyphosate resistance continues to mount and, more importantly, the number of fields with glyphosate resistant (GR) weed biotypes is escalating at an increasing rate (Owen, 2009b; Owen et al., 2011).

## 2. Management of weeds through herbicide use and other options

The recurrent use of any herbicide imparts selection pressures on a weed population often resulting in the evolution of a resistant biotype (Llewellyn et al., 2001; Owen and Zelaya, 2005). Similarly, the recurrent use of any crop production practice will select for specific weeds or weed biotypes that are ecologically adapted to that particular tactic, resulting in those weeds becoming dominant within the weed community (Owen, 2008b). The inevitable evolution of GR weed biotypes has been ensured by the introduction of crop cultivars with genetic modifications for glyphosate resistance, the unprecedented adoption of GR crops by agriculture over the last 15 years and weed management practices that have narrowed in spectrum to a single herbicide (glyphosate) (Owen, 2010; Young, 2006).

Herbicide use in corn, sorghum and sweet corn in the United States in 2009 represented a major production expenditure. In 2009, 98% of the corn acres were treated with herbicides, and typically each acre was treated with more than two different herbicides (data from GfK Kynetec used with permission). Glyphosate was applied to about 75% of the corn-planted acres, although many of the acres were treated more than once, with an average of 1.3 applications per acre in 2009. Atrazine was applied to about 60% of the corn and sorghum acres. In 2009, 86% of sorghum acres were treated with herbicides. Glyphosate was the second most used herbicide in sorghum as a burndown treatment. There were more than 583,000 acres of sweet corn grown in the United States in 2009, and atrazine was applied to about 80% of the sweet corn acres grown.

In summary, 2009 herbicide use data show atrazine was applied to more than 53 million base acres, and glyphosate was used on almost 70 million base acres of these crops (data from GfK Kynetec used with permission). Approximately 35% of the GR corn acres were treated only with glyphosate for weed management in 2009 (Owen et al., 2010; Owen et al., 2011). This lack of use of diverse weed management tools has significant implications with regard to weed shifts and to the ability of growers to manage these problems (Johnson et al., 2009b; Owen et al., 2010; Owen, 2008b; Shaw et al., 2009).

While atrazine is not labeled for weed management in soybean production, the herbicides used by soybean growers for weed control in corn have a major impact on soybean weed management where corn is grown in rotation with soybeans, as is typical in the Midwest. Lack of herbicide diversity (other than glyphosate being used on greater than 90% of the soybean acres) for weed management in GR soybeans, and the likelihood of the need to make multiple applications of glyphosate in a given year to address mounting weed resistance, will affect weed management in corn rotation (Givens et al., 2009; Johnson et al., 2009b; Owen et al., 2011). Specifically, weeds such as common waterhemp (*Amaranthus tuberculatus syn. rudis*), common lambsquarters (*Chenopodium album*), Palmer amaranth (*A. palmeri*), giant ragweed (*Ambrosia trifida*) and horseweed (*Conyza canadensis*) would likely become more costly to control in soybean without the availability of atrazine, which effectively controls these weeds in corn and sorghum.

### 2.1. Range of weed management choices

There has been a significant decline in the use of herbicides other than glyphosate that is largely attributable to the global adoption of GR crops (Shaner, 2000; Young, 2006). While the lack of diversity in weed management tactics and subsequent changes in weed communities may not eliminate the use of glyphosate as a tool, the effectiveness of glyphosate will be reduced, thereby providing a strong impetus for the development of a variety of weed management strategies (Green, 2007; Swanton and Weise, 1991). This further reinforces the need for glyphosate alternatives and the continued availability of highly effective herbicides such as atrazine. However, it must be considered that there are not a lot of other highly effective herbicides available for weed management in

GR crops in part due to the previous evolution of resistances to herbicides in weeds. Consider that weeds have evolved resistance to 21 herbicide mechanisms of action to date (Heap, 2011). Many of the other herbicides available inhibit ALS, but 113 weed species have evolved ALS resistance, including many agronomically important weeds (Heap, 2011). So despite the plethora of ALS-inhibitor herbicides, they will not provide control of many important weed species. Cross-resistance to different herbicides with the same mechanism of action is common. Furthermore, evolved multiple resistances to several mechanisms of herbicide action within important weeds is increasingly common. In the U.S., there are 14 weed species that have evolved resistance to two or more modes of action (Heap, 2011). Considering just common and giant ragweed, horseweed, common waterhemp and Palmer pigweed, atrazine is needed to control those that are resistant to glyphosate and to the ALS, PPO or PS-I herbicides (e.g. paraquat) (Heap, 2011). This trend reinforces the need to maintain the availability herbicides such as atrazine, as well as to invest in the discovery of new herbicides and importantly, new mechanisms of action (Green and Owen, 2011).

### 2.2. Herbicide resistance: factors and considerations

Weeds have long-demonstrated the genetic flexibility to adapt to all aspects of agriculture, including but not limited to tillage and herbicides (Baker, 1991). Human activities are important in “guiding” this genetic evolution of plant species and will ultimately result in changes in the weedy plants that occupy the agroecosystem (Gressel, 1993). The evolution of herbicide resistant (HR) weed biotypes has increasingly become a significant ecological, environmental and economic problem for global agriculture and society in general (Owen, 2010). Herbicide resistance in weeds has historically been a threat to global food production (Moss and Rubin, 1993). Consider the recent escalation of weed biotypes with evolved resistance to glyphosate. Many weed scientists were not surprised at the discovery of GR weeds, despite early suggestions that it was improbable (Bradshaw et al., 1997). Now weed populations with glyphosate resistance are progressing at an increasing rate and may represent a threat to global agricultural production (Gressel and Levy, 2006; Owen, 2008b; Powles, 2008a). In contrast, the triazine herbicides are typically efficacious on many of the GR weed biotypes that are significant agronomic problems, such as common waterhemp and Palmer amaranth.

### *2.2.1. Herbicide resistance consequences*

Widespread and rapid occurrences of weeds resistant to glyphosate reinforce the need to adopt practices that enhance the long-term viability of GR crops (Powles, 2008b). Indiana growers considered weeds the most important pest complex when compared to diseases and insects (Gibson et al., 2005). However, these same growers were not overly concerned about the evolution of GR weed populations. Only 36% of the Indiana growers surveyed suggested that resistance was a major concern (Johnson and Gibson, 2006). On the other hand, growers in Australia were adopting an integrated approach to managing HR weeds and perceived this strategy had economic value (Llewellyn, 2004). Practices that included alternative herbicides were perceived to have the highest economic return on investment, and growers felt that a stock of new herbicides would be developed in the near term to help them better manage growing HR weed populations (Llewellyn, 2004; Llewellyn et al., 2002). Unfortunately those expected “new” herbicides have not been developed. An herbicide with a novel mode of action has not been commercially introduced for about 20 years. The “new” herbicides introduced in the recent past and those pending commercial introduction all represent older herbicide mechanisms of action to which weeds have already evolved resistance (Green and Owen, 2011).

#### *2.2.2. Herbicide resistance costs*

Herbicides are used on at least 90% of crop acres in the U.S. annually and represent 65% of the pesticide expenditures by growers (Gianessi and Reigner, 2007). If herbicides were not available, U.S. crop productivity was suggested to decline by a minimum of 20%, even with the requisite additional tillage and hand weeding necessary to maintain minimal weed control in crops. It was estimated that herbicides represent the labor of 70 million people if weed control were entirely mechanical (Gianessi and Reigner, 2007). When preferential herbicide use results in the evolution of HR weed biotypes, there are associated costs in reduced production, higher expenditures for herbicides and dramatic increases in the weed seed bank (Peterson, 1999). Given the potentially high seed production of weeds and the potential long-term viability of weed seed, these increased costs attributable to HR weeds represent a long-term prospect. A study of GR weeds in several U.S. crops strongly supports favorable economic returns when glyphosate resistance is proactively managed (Mueller et al., 2005). The difficulty is how to change grower perspectives to make the necessary adjustments in weed management programs. Whether this can be accomplished on the scale necessary to address HR weed populations remains to be seen.

Another repercussion (cost) that must be considered with the increasingly frequent occurrence of GR weed biotypes is the potential decline in conservation tillage practices (Ervin and Welsh, 2010; Ervin et al., 2010; Johnson et al., 2009a). The adoption of GR crops and the use of glyphosate strongly supported the practice of no tillage in conservation tillage crop production systems, especially in soybeans and cotton. However, the need for stewardship of GR crops was not immediately recognized, and selection for GR weeds has occurred. In many instances (i.e. no tillage cotton production), the only management tactic for GR weed populations has been aggressive conventional tillage (Steckel and Gwathmey, 2009; Webster and Sosnoskie, 2010). Over the last four years, the percent of no tillage acres has declined in every year in corn and cotton, and for three years in soybeans (Table 1). Increased tillage has major economic, ecological and environmental implications to growers and to society in general (Ervin et al., 2010). This reinforces the need to maintain effective alternative strategies to manage GR weeds like Palmer amaranth, including alternative herbicides such as atrazine.

### 2.3. Impact of glyphosate-resistant crops on herbicide use

The unprecedented global adoption of GR crops and the concomitant use of glyphosate have dramatically changed herbicide use patterns on millions of acres. The number of herbicide mechanisms of action available for weed control in corn and sorghum has not changed since the introduction of GR crops and is relatively diverse. However, the number of herbicide mechanisms of action used in corn, cotton and soybean has dramatically declined since the introduction of GR crops (Young, 2006). The greatest change is seen in soybean production. By 2002, glyphosate was used on more than 80% and no other herbicide was used on more than 10% of the soybean acres. A similar trend has occurred in the high use of glyphosate in cotton, and glyphosate use in corn continues to increase. While atrazine is used in GR corn, it is not an option in soybean and cotton, where growers reported one to three applications of glyphosate during a growing season while limiting the use of other herbicides (Givens et al., 2009). These changes in herbicide use patterns have affected weed populations and will result in more GR weed biotypes over the long-term, thus emphasizing the need for alternative herbicides (Shaner, 2000). Other changes in herbicide usage in response to herbicide resistance include: 1) herbicide rotation (i.e. alternating herbicides with different mechanisms of action) and 2) herbicide mixtures (i.e. combining herbicides with different mechanisms of action) (Beckie and Reboud, 2009; Wrubel and Gressel, 1994). The use of herbicide mixtures was found to be more effective at managing the evolution of HR weeds than herbicide rotations. A 2009 study in canola demonstrated that ALS-resistant weed populations increased to 89% after four years of herbicide rotation, while the ALS-resistant weed population remained at the original baseline when herbicide mixtures were used (Beckie and Reboud, 2009).

The adoption of an integrated weed management (IWM) program will effectively manage HR weeds and delay the evolution of new HR populations and species (Knezevic et al., 2002; Swanton and Weise, 1991). IWM also provides significant economic, environmental and ecological benefits to growers and the agroecosystem (Owen et al., 2010; Owen, 2010). There are a number of examples showing that IWM programs lessen the impact of HR weed populations and can actually keep these populations from increasing (Llewellyn et al., 2001; Llewellyn et al., 2009; Stephenson et al., 1990). The more varied the measures included in an IWM program, the greater the likelihood of success in mitigating HR weed populations and sustaining the utility of important GM crops and herbicides. To that end, given the inclusion of atrazine with most herbicide products labeled for corn and sorghum, and the fact that many of the broadleaf weeds resistant to other herbicides are susceptible to atrazine, this herbicide is a uniquely important tool that must be available for growers.

## 3. Current state of herbicide-resistant weeds

The current status of HR weeds strongly supports the premise that new HR weed populations continue to evolve at an increasing rate (Heap, 2011). Weeds have evolved resistance to 21 herbicide mechanisms of action globally (Heap, 2011). Most recently, common waterhemp biotypes resistant to *p*-hydroxyphenylpyruvate dioxygenase (HPPD; EC 1.13.11.27) inhibitor herbicides were reported in Illinois and Iowa. In the U.S., 75 weed species are reported to have evolved HR biotypes (Heap, 2011). The current tally of HR weeds globally includes 368 HR biotypes represented by 200 species (Heap, 2011). Many weeds have also evolved resistance to multiple mechanisms of herbicide action (Heap, 2011; Patzoldt et al., 2005; Preston et al., 1996). This phenomenon has become more apparent and dire with the increasing prominence of GR weeds (Powles, 2008a).

## 4. Current state of glyphosate-resistant weeds

There can now be no question that changes in weed populations are occurring more rapidly and are widely distributed in U.S. corn, cotton and soybean production systems despite our knowledge of resistance management (Johnson et al., 2009b; Kruger et al., 2009). Currently 21 weed species are confirmed to have evolved glyphosate resistance globally including 13 in the U.S. involving 27 states (Heap, 2011). Rigid ryegrass (*Lolium rigidum*) was identified in 1998 as the first species to evolve glyphosate resistance in the U.S. (Table 2). Additional species have been reported in 2000 (1), 2004 (3), 2005 (2), 2007 (3), 2008 (1) and 2010 (2) (Tables 2 and 3). A list of states reporting GR weed biotypes shows the rapid yearly increase in GR biotypes and their distribution (Table 3). The 2004-2008 interval had the most rapid increase in reported GR species and infestations into new states.

Generally, glyphosate resistance has evolved in conjunction with GR crop production systems. Historic perspectives demonstrate there is not broad awareness of the factors that affect the expansion of GR weed populations. The level of concern falls well below what most weed scientists believe is necessary to resolve the inevitable problem of evolved glyphosate resistance (Johnson and Gibson, 2006). There have been numerous attempts to engage industry, government and extension academic groups in developing a consensus about how to best manage glyphosate resistance in weeds (Boerboom and Owen, 2007; Owen and Boerboom, 2004). Despite these efforts, the problems associated with GM crops and HR weeds have gone largely without resolution. This lack of resolution is attributable, in part, to a reluctance to recognize the implications of the management choices imposed by decision makers, the marketing perspectives brought forward by some in the herbicide and seed industries, and the erroneous belief that new technologies will be available in the near-term future (Owen et al., 2009; Owen et al., 2011).

Given the predominance of GR corn, cotton and soybean cultivars and the use of glyphosate often as the primary (if not sole) weed control product in these crops, the implications of glyphosate resistance in weed populations are significant. Eight of the 13 weed species identified in the U.S. with GR biotypes have evolved resistance in production systems with GR crops and cause significant economic costs to growers. Historical perspectives of growers regarding the adoption of alternative strategies to provide stewardship for the crop trait and herbicide have increased the frequency of resistance (Boerboom et al., 2009; Owen and Boerboom, 2004; Owen et al., 2009; Owen et al., 2010). The severity of GR weeds is reinforced by the fact that there currently are15 states having more than one glyphosate resistant species and 12 additional states with one weed species with reported resistance to glyphosate (Table 4). It should be noted that the information compiled from the International Survey of Herbicide Resistant Weeds (www.weedscience.org) likely underestimates the HR weed problems; data is based on voluntary participation of weed scientists (Heap, 2011). In addition to the number weed species resistant to glyphosate, these same 15 states also have a number of weed species resistant to more than one herbicide mode of action and the total number of herbicide modes of action to which resistant species are found ranges from three to eight (Table 4). The number of species resistant to the PSII mode of action (e.g. atrazine) is also indicated.

Given the current production systems, it is unlikely that proactive actions will be taken to deter the future evolution of GR weed biotypes (Owen et al., 2011). Furthermore, given the cross and multiple resistances that have evolved in important weeds such as common waterhemp, Palmer amaranth, common and giant ragweed and horseweed, the number of herbicides that will provide effective control is limited. Atrazine is effective in controlling these HR biotypes.

**5. Management of herbicide-resistant weeds**

Given the rapid evolution and expansion of HR weed biotypes, concern for and management of GR weeds has taken on a particularly important perspective in agriculture. Educational programs provided by university extension now focus largely on the management of HR weeds (Scott et al., 2009). It is unfortunate that surveys, while somewhat dated, indicate that growers have not been overly concerned about GR weeds until recently (Johnson et al., 2009b). Importantly, the increasing frequency of GR weeds also has social implications and externalities generally not considered (Marsh et al., 2006). These include, but are not limited to, failure of the current crop production systems based on GR crops and other environmental costs, such as loss of no tillage and conservation tillage acres resulting in increased soil erosion and decreased water quality due to turbidity and sedimentation (Ervin and Welsh, 2010; Marsh et al., 2006).

While agricultural researchers hope to resolve the problem of HR weeds by developing new GM crops with resistances to different herbicides or multiple resistances to several herbicides, this tactic is unlikely to resolve the weed resistance problem in the long term (Green, 2009; Green et al., 2008; Green and Owen, 2011). The management of HR weeds must include as many strategies as possible, but current crop production systems will likely focus on herbicides almost to the exclusion of other strategies. In GR soybean and corn in 2009, glyphosate was used exclusively on approximately 67% and 27% of the acres, respectively (Owen et al., 2011). Growers who assumed there were GR weed biotypes in their production systems suggested that herbicide rotation is a key tactic to manage weed problems (Foresman and Glasgow, 2008). Thus, the opportunities to include alterative herbicides such as atrazine in corn production systems will be positive with regard to the management of many weed biotypes resistant to glyphosate and other herbicides.

Note that atrazine has efficacy on a number of weed biotypes with evolved resistance to other herbicide mechanisms of action (Table 4). An estimate as to the utility of atrazine in aiding control of species in each herbicide group has been made. However, the use of herbicide combinations (Including atrazine) either as tank mixtures or commercially-available prepackage mixtures is a better strategy than herbicide rotation for managing HR weeds (Beckie and Reboud, 2009). Atrazine has tremendous use flexibility, it can be employed as an alternative herbicide or combined in pre-packs or tank mixes to provide an alternative mechanism of action in corn, sweet corn and sorghum.

## 6. Importance and utility of atrazine in the management of herbicide-resistant weeds

Atrazine is used widely for the management of weeds in corn, sweet corn, sorghum and sugarcane, and is second to glyphosate in acres applied. While weeds with atrazine (PSII herbicide) resistance have been reported, the occurrences per year, area infested and severity of infestations have declined since 1984 (LeBaron, 1998). Importantly, many of the agronomically important triazine-resistant weeds demonstrate a significant fitness penalty and thus are not as competitive within the crop production system (Conrad and Radosevich, 1979; Parks et al., 1996; Williams II et al., 1995). The management of triazine-resistant weeds has been accomplished with the adoption of appropriate best management practices (BMPs). These include, but are not confined to, crop rotation, herbicide rotations and mixtures with other herbicides, as well as flexible application timing (Anderson et al., 1996; Beckie, 2006). Triazine-resistant weeds may also demonstrate a negative cross resistance to other herbicides and thus are easier to control with alternative herbicides when compared to the susceptible biotypes (Owen and Gressel, 2001; Parks et al., 1996). The continued use of atrazine as a principle tactic for weed management in corn, sweet corn, sorghum and sugarcane production is testament to the fact that triazine-resistant weeds do not have a major economic impact and can be effectively managed.

Atrazine represents an important herbicide for controlling many economically important weeds with resistance to other herbicide mechanisms of action (Heap, 2011). These other herbicide mechanisms of action include, but are not limited to, the protoporphyrinogen oxidase (PPO; EC 1.3.3.4) inhibitor herbicides, the ALS inhibitor herbicides and EPSPS inhibitor herbicides. The distribution of ALS inhibitor herbicide resistance is considered ubiquitous in the Corn Belt. For example, all common waterhemp in Iowa is reported to be resistant to ALS inhibitor herbicides (Owen, 2009a). Resistance in common waterhemp to PPO inhibitor herbicides is also increasing (Owen, 2009a; Patzoldt et al., 2006). While common waterhemp populations with multiple resistances including resistance to triazine herbicides have been reported, they are not widely distributed and can be effectively managed with the appropriate selection of companion herbicides applied in combination with atrazine (Hugie et al., 2008; Patzoldt et al., 2005). Thus, given the widespread populations of weeds resistant to ALS herbicides, the increasing frequency of weed populations with glyphosate resistance and the likelihood that these biotypes will demonstrate multiples resistances, atrazine continues after 50 years to be fundamental to effective management of weeds in corn, sweet corn, sorghum and sugarcane.

Atrazine has a unique mechanism of action that complements the use of other herbicides with other mechanisms of action. Without atrazine, it is anticipated that a number of weeds could not be effectively managed in corn, sweet corn, sorghum and sugarcane. The inability to manage these weeds may reflect the lack of effective alternatives to atrazine and/or the fact that HR biotypes have evolved. Among the many weeds predicted to become more significant economic problems in the future are velvetleaf (*Abutilon theophrasti*), common lambsquarters, common waterhemp , redroot pigweeds (*A. retroflexus*), Palmer amaranth, giant ragweed, common ragweed (*A. artemisiifolia*), common sunflower (*Helianthus annuus*), horseweed, Asiatic dayflower (*Commelina communis*) and tropical spiderwort (*C. benghalenisis*). It is likely that these weeds would escalate more rapidly in economic importance if atrazine were not available.

## 7. Interaction of atrazine and HPPD inhibitor herbicides

Atrazine in combination with mesotrione can greatly improve weed management and resolve other weed management problems (Kaastra et al., 2008). Interaction between atrazine and mesotrione was reported in tame sunflower (*Helianthus annuus*), velvetleaf and Palmer amaranth (Abendroth et al., 2006). The combination of atrazine and mesotrione also demonstrated better efficacy when these herbicides were applied postemergence for the control of common waterhemp, common lambsquarters and giant ragweed (Woodyard et al., 2009).

Another important consideration involving the combination of atrazine and mesotrione is the improved control of weeds with evolved resistance to PSII and ALS inhibiting herbicides (Sutton et al., 2002). Consider that a redroot pigweed biotype with target site resistance to triazine herbicides was sensitive to a split application of atrazine applied preemergence followed by mesotrione applied postemergence. However, the biomass of a velvetleaf biotype with metabolism-based resistance to triazine herbicides was reduced, reflecting an additive response was demonstrated (Abendroth et al., 2006).

As a general statement, the classes of herbicides that inhibit the HPPD enzyme do not have exceptional levels of efficacy on many agronomically important weeds without the inclusion of atrazine. Furthermore, given the recent reports of evolved resistance in common waterhemp to HPPD-inhibitor herbicides, it is inevitable that HPPD resistance will increase without the availability of atrazine to mitigate these resistant populations (Green, 2011; Hausman et al., 2011; McMullan and Green, 2011). Thus, atrazine is a valuable tank mix companion to the HPPD herbicides.

## 8. Conclusions

Weeds represent the most economically important pest complex in global food production and also significantly impact mankind at all levels, from health perspectives to the pursuit of recreation (Bridges, 1994). Complex weed genomes facilitate continuing adaptation to virtually all forms of selective forces used during plant production (Barrett, 1983; De Wett and Harlan, 1975; Gould, 1991). During the last five decades, herbicides have been the most important component for effectively managing weeds. As a result, biochemical adaptation or mimicry has become an important problem (Gould, 1991). In fact, the intensity of weed management practices, primarily based on herbicide applications, selects for rare mutations in weed genomes that allow those weed biotypes to succeed in the presence of herbicides (Gressel and Levy, 2006).

Recent efforts to manage weeds have focused on the use of herbicides that are selective to GR crops (Duke and Powles, 2008). The use of glyphosate in GR crops has provided exceptional control of many weeds and represents one of the most significant changes in technology in the history of agriculture (Owen, 2009b). Weed management was deemed by growers to be simple and convenient with the use of GR crops, and there were predictions that weeds would be eradicated, causing a loss of biodiversity (Owen et al., 2009; Watkinson et al., 2000). However, it was inevitable that weed populations would eventually adapt and that glyphosate resistance would evolve despite suggestions otherwise (Bradshaw et al., 1997; Neve, 2007). Since GR crops and glyphosate use have seen widespread global adoption, it is not surprising that GR weeds now represent a major threat to a sustainable agriculture (Ervin and Welsh, 2010; Ervin et al., 2010). Certainly the costs of managing GR weeds are important, but there are other environmental costs as well, including the loss of conservation tillage practices, increased soil erosion and declining water quality (Cerdeira and Duke, 2006;

Ervin et al., 2010; Mueller et al., 2005). Proactive management of GR weeds is economically sustaining and provides stewardship for the GR traits (Mueller et al., 2005). However, it is now questionable whether or not proactive management of GR weeds can be accomplished; populations of GR weeds have proliferated across the Midwest, Delta and Southeast US. Thus, it is imperative that weed management options become more diverse, not only with regard to the utilization of other modes of herbicide action, but also in cultural and mechanical tactics (Duke, 2011; Green, 2011; Green and Owen, 2011; Owen, 2008a; Owen, 2011; Owen et al., 2011).

Atrazine is a strong and critically important component of an IWM program to help control herbicide resistant weeds in GR crops. The unavailability of atrazine would severely compromise the economic, environmental and societal benefits of GR corn. (Perry et al., 2004) Atrazine has more than five decades of successful use, and with the current issues involving HR weed populations, it is now more important than ever to the production of corn, sweet corn, sorghum and sugarcane. Given the widespread populations of weeds resistance to ALS inhibitor herbicides, the increasing frequency of weed populations with glyphosate resistance and the likelihood that these biotypes will evolve multiple herbicide resistances, atrazine continues to be fundamental to effective management of weeds in these crops. Atrazine use supports higher yields by effectively and efficiently controlling HR weeds and other weeds in current production systems. The need for higher yields is critical to avoid a Malthusian disaster in agriculture (Trewavas, 2002). Atrazine has a unique and important role in maintaining the sustainability of corn, sweet corn, sorghum and sugarcane production systems in the U.S.

**Table 1. Relative Change in Corn, Cotton and Soybean No Tillage Production Acres from 2007 to 2010 (*Percent Change from the Previous Year: Percent of No-Till Acres Planted Per Crop*)**

| Year | Corn | Cotton | Soybeans |
|---|---|---|---|
| | | | |
| 2007 | Base % | Base % | Base % |
| 2008 | -5.1% | -9.0% | +6.0% |
| 2009 | -5.4% | -12.5% | -12.4% |
| 2010 | -3.1% | -4.2% | -8.0% |

Source: GfK Kynetec

**Table 2. Weed Species with Glyphosate-resistant Biotypes Reported in the US by Year of First US Report**

| Year | Common Name | Species |
|---|---|---|
| | | |
| 1998 | Rigid Ryegrass | *Lolium rigidum* |
| 2000 | Horseweed | *Conyza canadensis* |
| 2004 | Common Ragweed | *Ambrosia artemisiifolia* |
| | Giant Ragweed | *Ambrosia trifida* |
| | Italian Ryegrass | *Lolium multiflorum* |
| 2005 | Palmer Amaranth | *Amaranthus palmeri* |
| | Common Waterhemp | *Amaranthus tuberculatus (syn. rudis)* |
| 2007 | Hairy Fleabane | *Conyza bonariensis* |
| | Johnsongrass | *Sorghum halepense* |
| | Kochia | *Kochia scoparia* |
| 2008 | Junglerice | *Echinochloa colona* |
| 2010 | Goosegrass | *Eleusine indica* |
| | Annual Bluegrass | *Poa annua* |

Source: International Weed Survey Resistant Weeds accessed 07 November 2011 (www.weedscience.org).

**Table 3. Glyphosate-resistant Weeds in the US: Year of First Global Report, States and Years Found**

| Weed species | First Global Report | States | Years |
|---|---|---|---|
| *Amaranthus palmeri* (Palmer amaranth) | 2005 | GA | 2005 |
| | | NC | 2005 |
| | | AR | 2006 |
| | | TN | 2006 |
| | | NM | 2007 |
| | | AL | 2008 |
| | | GA* | 2008 |
| | | MS* | 2008 |
| | | MO | 2008 |
| | | TN* | 2009 |
| | | IL | 2010 |
| | | LA | 2010 |
| | | MI | 2011 |
| | | VA | 2011 |
| *Amaranthus tuberculatus* (*syn. rudis*) (Common waterhemp) | 2005 | MO* | 2005 |
| | | IL* | 2006 |
| | | KS | 2006 |
| | | MN | 2007 |
| | | IN | 2009 |
| | | IA | 2009 |
| | | MS | 2010 |
| *Ambrosia artemisifolia* (Common ragweed) | 2004 | AR | 2005 |
| | | MO | 2006 |
| | | OH* | 2006 |
| | | IN | 2007 |
| | | KS | 2007 |
| | | ND | 2007 |
| | | MN | 2008 |
| *Ambrosia trifida* (Giant ragweed) | 2004 | OH | 2004 |
| | | AR | 2005 |
| | | IN | 2005 |
| | | KS | 2006 |
| | | MN | 2006 |
| | | OH* | 2006 |
| | | TN | 2007 |
| | | MN* | 2008 |
| | | IA | 2009 |
| | | MO | 2009 |
| | | MS | 2010 |
| | | NE | 2010 |
| *Conyza bonariensis* (Hairy fleabane) | 2003 | CA | 2007 |
| | | CA* | 2009 |
| *Conyza Canadensis* (Horseweed) | 2000 | DE | 2000 |
| | | KY | 2001 |
| | | TN | 2001 |

| | | | |
|---|---|---|---|
| | | **IN** | **2002** |
| | | **MD** | **2002** |
| | | **MO** | **2002** |
| | | **NJ** | **2002** |
| | | **OH** | **2002** |
| | | **AR** | **2003** |
| | | **MS** | **2003** |
| | | **MC** | **2003** |
| | | **OH*** | **2003** |
| | | **PN** | **2003** |
| | | **CA** | **2005** |
| | | **IL** | **2005** |
| | | **KS** | **2005** |
| | | **VA** | **2005** |
| | | **NE** | **2006** |
| | | **MI** | **2007** |
| | | **MS*** | **2007** |
| | | **OK** | **2009** |
| | | **IA** | **2011** |
| ***Echinochloa colona* (Junglerice)** | **2007** | **CA** | **2008** |
| ***Eleusine indica* (Goosegrass)** | **1997** | **MS** | **2010** |
| | | **TN** | **2011** |
| ***Kochia scoparia* (Kochia)** | **2007** | **KS** | **2007** |
| ***Lolium multiflorum* (Italian ryegrass)** | **2001** | **OR** | **2004** |
| | | **MS** | **2005** |
| | | **AR** | **2008** |
| | | **OR*** | **2010** |
| ***Lolium rigidum* (Rigid ryegrass)** | **1996** | **CA** | **1998** |
| ***Poa annua* (Annual bluegrass)** | **2010** | **MO** | **2010** |
| ***Sorghum halepense* (Johnsongrass)** | **2005** | **AR** | **2007** |
| | | **MS** | **2008** |
| | | **LA** | **2010** |

Source: International Weed Survey Resistant Weeds, accessed 07 November 2011 (www.weedscience.org).
*Multiple resistances

**Table 4. US States with Herbicide-resistant Weed Species: Total Number of Species, Glyphosate-resistant Species, PSII Species and Number of Herbicide Mechanisms of Action (MOA) Represented**

| State | Weed Species Resistant to at Least 1 MOA | Weed Species Resistant to Glyphosate | Weed Species Resistant to PSII | Herbicide MOA w/at Least 1 Resistant Species |
|---|---|---|---|---|
| **AR** | 12 | 6 | 0 | 8 |
| **CA** | 18 | 4 | 1 | 8 |
| **IL** | 9 | 3 | 4 | 5 |
| **IN** | 11 | 4 | 4 | 3 |
| **IA** | 10 | 3 | 5 | 6 |
| **KS** | 15 | 5 | 4 | 5 |
| **LA** | 6 | 2 | 0 | 5 |
| **MI** | 17 | 2 | 12 | 5 |
| **MN** | 13 | 3 | 3 | 4 |
| **MS** | 9 | 7 | 1 | 7 |
| **MO** | 9 | 6 | 1 | 5 |
| **NC** | 8 | 2 | 3 | 6 |
| **OH** | 10 | 3 | 1 | 5 |
| **TN** | 9 | 4 | 1 | 6 |
| **VA** | 10 | 2 | 4 | 4 |

Source: International Weed Survey for Resistant Weeds. Accessed 07 November 2011 (www.weedscience.org).

## Literature cited


**Abendroth, J. A., Martin, A. R., and Roeth, F. W. 2006. Plant response to combinations of mesotrione and photosystem II inhibitors. Weed Technology 20: 267-274.**

**Anderson, D. D., Roeth, F. W., and Martin, A. R. 1996. Occurrence and control of triazine-resistant common waterhemp (*Amaranthus rudis*) in field corn (*Zea mays*). Weed Technology 10: 570-575.**

**Anonymous. 2004. World Population to 2300. New York, New York: United Nations. 254 p.**

**Arntzen, C. J., Coghlan, A., Johnson, B., Peacock, J., and Rodemeyer, M. 2003. GM crops: science, politics, and communication. Nature Reviews Genetics 4: 839-843.**

**Baker, H. G. 1991. The continuing evolution of weeds. Economic Botany 45: 445-449.**

**Barrett, S. C. H. 1983. Crop mimicry in weeds. Economic Botany 37: 255-282.**

**Beckie, H. J. 2006. Herbicide-resistant weeds: management tactics and practices. Weed Technology 20: 793-814.**

**Beckie, H. J., and Reboud, X. 2009. Selecting for weed resistance: herbicide rotation and mixture. Weed Technology 23: 363-370.**

**Boerboom, C., and Owen, M. 2007. National Glyphosate Stewardship Forum II: A Call to Action. St. Louis, MO. 45 p.**

**Boerboom, C., Sprague, C., and Owen, M. A grower's conundrum: Implementing integrated weed management in a HRC world. Pages 24 in Proceedings of the 6th International IPM Symposium. Portland, Oregon.**

**Bradshaw, L. D., Padgette, S. R., Kimball, S. L., and Wells, B. H. 1997. Perspectives on glyphosate resistance. Weed Technology 11: 189-198.**

**Bridges, D. C. 1994. Impact of weeds on human endeavors. Weed Technology 8: 392-395.**

**Cerdeira, A. L., and Duke, S. O. 2006. The current status and environmental impacts of glyphosate-resistant crops; a review. Journal of Environmental Quality 35: 1633-1658.**

**Conrad, S. G., and Radosevich, S. R. 1979. Ecological Fitness of Senecio vulgaris and Amaranthus retroflexus Biotypes Susceptible or**

**Resistant to Atrazine. Journal of Applied Ecology 16: 171-177.**

**Dalton, R. 2002. Superweed study falters as seed firm deny access to transgene. Pages 655 Nature.**

**De Wett, J. M. J., and Harlan, J. R. 1975. Weeds and domesticates: evolution in the man-made habitat. Economic Botany 29: 99-107.**

**Duke, S. O. 2011. Comparing conventional and biotechnology-based pest management. Journal of Agricultural and Food Chemistry 59: 5793-5798.**

**Duke, S. O., and Powles, S. B. 2008. Glyphosate: a once-in-a-century herbicide. Pest Management Science 64: 319-325.**

**Ervin, D., and Welsh, R. 2010. Genetically engineering crops for a sustainable agriculture. Pages 11 Choices: Agricultural and Applied Economics Association.**

**Ervin, D. E., Carriere, Y., Cox, W. J., Fernandez-Cornejo, J., Jussaume Jr., R. A., Marra, M. C., Owen, M. D. K., Raven, P. H., Wolfenbarger, L. L., and Zilberman, D. 2010. The impact of genetically engineered crops on farm sustainability in the United States. Washington, D.C.: National Research Council. 250 p.**

**Foresman, C., and Glasgow, L. 2008. US grower perceptions and experiences with glyphosate-resistant weeds. Pest Management Science 64: 388-391.**

**Gealy, D. R., Bradford, K. J., Hall, L., Hellmich, R., Raybold, A., Wolt, J., and Zilberman, D. 2007. Implications of gene flow in the scale-up and commercial use of**

**biotechnology-derived crops: economic and policy considerations. Ames, IA. Rep. 37. 24 p.**
**Gianessi, L. P., and Reigner, N. P. 2007. The value of herbicides in U.S. crop production. Weed Technology 21: 559-566.**
**Gibson, K. D., Johnson, W. G., and Hillger, D. E. 2005. Farmer perceptions of problematic corn and soybean weeds in Indiana. Weed Technology 19: 1065-1070.**
**Givens, W. A., Shaw, D. R., Johnson, W. G., Weller, S. C., Young, B. G., Wilson, R. G., Owen, M. D. K., and Jordan, D. 2009. A grower survey of herbicide use patterns in glyphosate-resistant cropping systems. Weed Technology 23: 156-161.**
**Gould, F. 1991. The evolutionary potential of crop pests. American Scientist 79: 496-507.**
**Green, J. M. 2007. Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. Weed Technology 21: 547-558.**
**Green, J. M. 2009. Evolution of glyphosate-resistant crop technology. Weed Science 57: 108-117.**
**Green, J. M. 2011. Outlook on weed management in herbicide-resistant crops: need for diversification. Outlooks on Pest Management 22: 100-104.**
**Green, J. M., Hazel, C. B., Forney, D. R., and Pugh, L. M. 2008. New multiple-herbicide crop resistance and formulation technology to augment the utility of glyphosate. Pest Management Science 64: 332-339.**
**Green, J. M., and Owen, M. D. K. 2011. Herbicide-resistant crops: Utilities and limitations for herbicide-resistant weed management. Journal of Agricultural and Food Chemistry 59: 5819-5829.**
**Gressel, J. Evolution of herbicide resistance in weeds: causes, prevention adn ameliorative-management. Pages 173-188 in Proceedings of the International Symposium of the Indian Society of Weed Science. Hisar: Indian Society of Weed Science.**
**Gressel, J., and Levy, A. A. 2006. Agriculture: the selector of improbable mutations. Proceedings of the National Academy of Science 103: 12215-12216.**
**Hails, R., and Kinderlerer. 2003. The GM public debate: context and communication strategies. Nature Reviews Genetics 4: 819-825.**
**Hails, R. S. 2002. Assessing the risks associated with new agricultural practices. Nature 418: 685-688.**
**Harper, J. L. The evolution of weeds in relation to resistance to herbicides. Pages 179-188 in Proceedings of the 3rd British Weed Control Conference. Farnham, United Kingdom: British Weed Control Council.**
**Hausman, N. E., Singh, S., Tranel, P. J., Riechers, D. E., Kaundun, S. S., Polge, N. D., Thomas, D. A., and Hagar, A. G. 2011. Resistance to HPPD-inhibiting herbicides in a population of waterhemp (*Amaranthus tuberculatus*) from Illinois, United States. Pest Management Science: 4.**
**Heap, I. 2011. The international survey of herbicide resistant weeds. Available at www.weedscience.com. Accessed 21 October 2011.**
**Hugie, J. A., Bollero, G. A., Tranel, P. J., and Riechers, D. E. 2008. Defining the rate requirements for synergism between mesotrione and atrazine in redroot pigweed (*Amarnathus retroflexus*). Weed Science 56: 265-270.**
**Johnson, W. G., Davis, V. M., Kruger, G. R., and Weller, S. C. 2009a. Influence of glyphosate-resistant cropping systems on weed species shifts and glyphosate-resistant weed populations. European Journal of Agronomy 31: 162-172.**
**Johnson, W. G., and Gibson, K. D. 2006. Glyphosate-resistant weeds and resistance management strategies: an Indiana grower perspective. Weed Technology 20: 768-772.**

**Johnson, W. G., Owen, M. D. K., Kruger, G. R., Young, B. G., Shaw, D. R., G., W. R., Wilcut, J. W., Jordan, D. L., and Weller, S. C. 2009b. U.S. farmer awareness of glyphosate-resistant weeds and resistance management strategies. Weed Technology 23: 308-312.**

**Kaastra, A. C., Swanton, C. J., Tardif, F. J., and Sikkema, P. H. 2008. Two-way performance interactions among p-hydroxyphenylpyruvate dioxygenase- and acetolactate synthase-inhbitiing herbicides. Weed Science 56: 841-851.**

**Knezevic, S. Z., Evans, S. P., Blankenship, E. E., Van Acker, R. C., and Lindquist, J. L. 2002. Critical period for weed control: the concept and data analysis. Weed Science 50: 773-786.**

**Konig, A. 2003. A framework for designing transgenic crops - science, safety and citizen's concerns. Science 21: 1274-1279.**

**Kruger, G. R., Johnson, W. G., Weller, S. C., Owen, M. D. K., Shaw, D. R., Wilcut, J. W., Jordan, D. L., Wilson, R. G., Bernards, M. L., and Young, B. G. 2009. U.S. grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. Weed Technology 23: 162-166.**

**LeBaron, H. M. 1998. The role of triazines in managing weeds resistant to other herbicides. Pages 9-23 in L. G. Ballantine, J. E. McFarland, and D. S. Hackett, eds. Triazine herbicide risk assessment. Washington D.C.: American Chemical Society.**

**Llewellyn, R., Lindner, R. K., Pannell, D. J., and Powles, S. 2001. Adoption of integrated weed management to conserve the herbicide resource: review and framework. Available at http://www.agrifood.info/review/2001/Llewellyn.html. Accessed 06 December 2010, 2010.**

**Llewellyn, R., Robert Lindner, David Pannel, Stephen Powles. 2004. Grain grower perceptions and the use of integrated weed management,. Australian Journal of Experimental Agriculture 44: 993-1001.**

**Llewellyn, R. S., D'Emden, F. H., Owen, M. J., and Powles, S. B. 2009. Herbicide resistance in rigid ryegrass (*Lolium rigidum*) has not led to higher weed densities in Western Australian cropping systems. Weed Science 57: 61-65.**

**Llewellyn, R. S., Lindner, R. K., Pannell, D. J., and Powles, S. B. 2002. Resistance and the herbicide resource: perceptions of Western Australian grain growers. Crop Protection 21: 1067-1075.**

**Marsh, S. P., Llewellyn, R. S., and Powles, S. B. 2006. Social costs of herbicide resistance: the case of resistance to glyphosate. Pages 11 50th Annual Conference of the Australian Agricultural and Resource Economics Society. Manly Pacific Sydney, Australia.**

**McMullan, P. M., and Green, J. M. 2011. Indentification of a tall waterhemp (*Amaranthus tuberculatus*) biotype resistant to HPPD-inhibiting herbicides, atrazine and thifensulfuron in Iowa. Weed Technology 25: 514-518.**

**Moss, S. R., and Rubin, B. 1993. Herbicide-resistant weeds: a worldwide perspective. Journal of Agricultural Science 120: 141-148.**

**Mueller, T. C., Mitchell, P. D., Young, B. G., and Culpepper, A. S. 2005. Proactive versus reactive management of glyphosate-resistant or -tolerant weeds. Weed Technology 19: 924-933.**

**Neve, P. 2007. Challenges for herbicide resistance evolution and management: 50 years after Harper. Weed Research 47: 365-369.**

**Owen, M. 2008. Glyphosate resistant crops and evolved glyphosate resistant weeds - the need for stewardship. Pages 51 in Proceedings of the 5th International Weed Science Congress. Vancouver, Canada: IWSS.**

**Owen, M., and Boerboom, C. 2004. National Glyphosate Stewardship Forum. St. Louis, MO. 80 p.**

**Owen, M., Boerboom, C., and Sprague, C. Convenience and Simplicity? An illusion and a detriment to integrated weed management. Pages 127 in Proceedings of the 6th International IPM Symposium. Portland, Oregon.**

**Owen, M., Dixon, P., Shaw, D., Weller, S., Young, B., Wilson, R., and Jordan, D. 2010. Sustainability of glyphosate-based weed management: The Benchmark Study. Pages 1-4 Information Systems for Biotechnology. Blacksburg, VA 24061: Virgina Tech.**

**Owen, M. D. K. 2008b. Weed species shifts in glyphosate-resistant crops. Pest Management Science 64: 377-387.**

**Owen, M. D. K. 2009. The evolution of herbicide resistant weeds in Iowa: Description, implications and solutions. Pages 65-70 in Proceedings of the Intetgrated Crop Management Conference. Ames, IA: Iowa State Univeristy.**

**Owen, M. D. K. 2009b. Herbicide-tolerant genetically modified crops: resistance management. Pages 113-162 in N. Ferry, and A. M. R. Gatehouse, eds. Environmental impact of genetically modified crops. Oxfordshire: CAB International.**

**Owen, M. D. K. 2010. Herbicide resistance. Pages 159-176 in F. Kempken, and C. Jung, eds. Genetic modification of plants; agriculture, horticulture and forestry. Berlin: Springer-Verlag.**

**Owen, M. D. K. 2011. Weed resistance development and management in herbicide-tolerant crops: experiences from the USA. Journal of Consumer Protection and Food Safety 6: 85-89.**

**Owen, M. D. K., and Gressel, J. 2001. Non-traditional concepts of $ynergy for evaluating integrated pest management. Pages 376-396 in J. C. Hall, R. E. Hoagland, and R. M. Zablotowicz, eds. Pesticide biotransformations in plants and microorganisams; similarities and divergences. Washington: Oxford University Press.**

**Owen, M. D. K., Young, B. G., Shaw, D. R., Wilson, R. G., Jordan, D. L., Dixon, P. M., and Weller, S. C. 2011. Benchmark Study on glyphosate-resistant cropping systems in the USA. II. Perspective. Pest Management Science 67: 747-757.**

**Owen, M. D. K., and Zelaya, I. A. 2005. Herbicide-resistant crops and weed resistance to herbicides. Pest Management Science 61: 301-311.**

**Parks, R. J., Curran, W. S., Roth, G. W., Hartwig, N. L., and Calvin, D. D. 1996. Herbicide Susceptibility and Biological Fitness of Triazine-Resistant and Susceptible CommonLambsquarters (*Chenopodium album*). Weed Science 44: 517-522.**

**Patzoldt, W. L., Hager, A. G., McCormick, J. S., and Tranel, P. J. 2006. A codon deletion confers resistance to herbicide inhibiting protoporphyrinogen oxidase. Proceedings of the National Academy of Science 103: 12329-12334.**

**Patzoldt, W. L., Tranel, P. J., and Hagar, A. G. 2005. A waterhemp (*Amaranthus tuberculatus*) biotype with multiple resistance across three herbicide sites of action. Weed Science 53: 30-36.**

**Perry, J. N., Firbank, L. G., Champion, G. T., Clark, S. J., Heard, M. S., May, M. J., Hawes, C., Squire, G. R., Rothery, P., Woiwod, I. P., and Pidgeon, J. D. 2004. Ban on triazine herbicides likely to reduce but not negate relative benefits of GMHT maize cropping. Nature (London) 428: 313-316.**

**Peterson, D. E. 1999. The impact of herbicide-resistant weeds on Kansas Agriculture. Weed Technology 13: 632-635.**

**Powles, S. B. 2008a. Evolution in Action: glyphosate-resistant weeds threaten world crops. Outlooks Pest Management 12: 256-259.**

**Powles, S. B. 2008b. Evolved glyphosate-resistant weeds around the world: lessons to be learnt. Pest Management Science 64: 360-365.**
**Preston, C., Tardif, F. J., Christophers, J. T., and Powles, S. B. 1996. Multiple resistance to dissimilar herbicide chemistries in a biotype of Lolium rigidum due to enhanced activity of several herbicide degrading enzymes. Pesticide Biochemistry and Physiology 54: 123-134.**
**Ryan, G. F. 1970. Resistance of common groundsel to simazine and atrazine. Weed Science 18: 614-616.**
**Scott, B. A., VanGessel, M. J., and White-Hansen, S. 2009. Herbicide-resistant weeds in the United States and their impact on extension. Weed Technology 23: 599-603.**
**Shaner, D. L. 2000. The impact of glyphosate-tolerant crops on the use of other herbicides and on resistance management. Pest Management Science 56: 320-326.**
**Shaw, D. R., Givens, W. A., Farno, L. A., Gerard, P. D., Jordan, D., Johnson, W. G., Weller, S. C., Young, B. G., Wilson, R. G., and Owen, M. D. K. 2009. Using a grower survey to assess the benefits and challenges of glyphosate-resistant cropping systems for weed management in U.S. corn, cotton, and soybean. Weed Technology 23: 134-149.**
**Steckel, L. E., and Gwathmey, C. O. 2009. Glyphosate-resistant horseweed (*Conyza canadensis*) growth, seed production, and interference in cotton. Weed Science 57: 346-350.**
**Stephenson, G. R., Dykstra, M. D., McLaren, R. D., and Hamill, A. S. 1990. Agronomic practices influence triazine-resistant weed distribution in Ontario. Weed Technology 4: 199-207.**
**Sutton, P., Richards, C., Buren, L., and Glasgow, L. 2002. Activity of mesotrione on resistant weeds in maize. Pest Management Science 58: 981-984.**
**Swanton, C. J., and Weise, S. F. 1991. Integrated weed managment: the rationale and approach. Weed Technology 5: 648-656.**
**Trewavas, A. 2002. Malthus foiled again and again. Nature 418: 668-670.**
**Watkinson, A. R., Freckleton, R. P., Robinson, R. A., and Sutherland, W. J. 2000. Predictions of biodiversity response to genetically modified herbicide-tolerant crops. Science 289: 1554-1557.**
**Webster, T. M., and Sosnoskie, L. M. 2010. Loss of glyphosate efficacy: a changing weed spectrum in Georgia cotton. Weed Science 58: 73-79.**
**Williams II, M. M., Jordan, N., and Yerkes. 1995. The fitness cost of triazine resistance in jimsonweed (*Datura stramonium* L.). American Midland Naturalist 133: 131-137.**
**Woodyard, A. J., Bollero, G. A., and Riechers, D. E. 2009. Broadleaf weed management in corn utilizing synergistic postemergence herbicide combinations. Weed Technology 23: 512-518.**
**Wrubel, R. P., and Gressel, J. 1994. Are herbicide mixtures useful for delaying the rapid evolution of resistance? A case study. Weed Technology 8: 635-648.**
**Young, B. G. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technology 20: 301-307.**