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Avoiding Weed Shifts and Weed Resistance in Roundup Ready Alfalfa Systems

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OVERVIEW

Weeds present a continual challenge for profitable alfalfa production. The Roundup Ready (RR) production system, using transgenic alfalfa, has the potential to simplify weed management by improving broad-spectrum control of both annual and difficult-to-control perennial weeds. The use of glyphosate, in combination with transgenic crops, has proven to be a reliable weed control strategy.

However, weed species shifts and the selection for glyphosate-resistant weeds can result from the increased use of this technology if the crop is not managed properly from the outset. Aspects of the alfalfa production system both favor and discourage the occurrence of weed shifts and the evolution of resistant weeds. Alfalfa is a competitive perennial crop that is cut multiple times per year, making it difficult for most weeds to become established. On the other hand, the RR alfalfa system may be vulnerable to weed shifts and resistant weeds for several reasons: tillage typically only occurs between crops, alfalfa is produced over a wide geographical area and in large fields with a great diversity of weeds, and there is potential for long-term repeated use of a single herbicide because it is a perennial crop. In this publication we recommend an integrated weed management system designed to prevent the proliferation of tolerant or resistant weeds. Elements include crop rotation, rotations with herbicides of different modes of action (preferably soil-residual herbicides), tank mixtures, and irrigation and harvest timing. Successful adaptation of these concepts into production systems would assure the long-term effectiveness and sustainability of the Roundup Ready system in alfalfa. A preemptive approach is warranted; these strategies should be employed before weed shifts and weed resistance occur.

IMPORTANCE OF WEED CONTROL IN ALFALFA

Alfalfa, the queen of forages, is the principal forage crop in the United States and frequently the third most important crop in value. It is a vital component of the feed ration for dairy cows and is a principal feed for horses, beef cattle, sheep, and other livestock. Because animal performance depends upon the palatability and nutritional value of alfalfa, livestock managers, especially those in the dairy and horse industry, expect high-quality hay. Although many factors influence quality, the presence of grassy and broadleaf weeds (of low forage quality) plays a significant role in reducing the feeding value of hay throughout the United States. Weeds that accumulate nitrates or are poisonous to livestock are also a major concern in alfalfa, since poisonous weeds sicken or kill animals every year (Puschner 2005). Most livestock producers demand weed-free alfalfa for optimum quality and maximum animal performance.

Weed-free alfalfa can be difficult to achieve, whether using nonchemical methods or conventional herbicides. Typically, no single herbicide controls all weeds present in a field, and some weeds—especially perennials—are not adequately controlled with any of the currently registered conventional herbicides. Cultural practices such as modifying harvest schedules, grazing, time of planting, and use of nurse crops such as oats (*Avena sativa* L.) help suppress weeds; however, these practices are almost never entirely effective and some of them suppress alfalfa seedling growth. In addition to being difficult to achieve, complete weed control in alfalfa is costly. Alfalfa growers continually seek ways to enhance the level of weed control while minimizing costs.

Roundup Ready technology was a major development in alfalfa weed control, providing growers with a useful weed management tool and a means to deal with some of the most difficult-to-control weed species.

THE ROUNDUP READY ALFALFA TECHNOLOGY

Glyphosate (Roundup) is generally considered the most effective broad-spectrum post-emergence herbicide available. The first commercially available glyphosate-resistant crops were soybean, canola, cotton, and corn, which were released in 1996, 1997, 1997, and 1998, respectively. Glyphosate-resistant or Roundup Ready alfalfa (RR alfalfa) was developed through biotechnology in late 1997 and became commercially available in the fall of 2005. This technology imparts genetic resistance to glyphosate by inserting a single gene from a soil bacterium into alfalfa. These biotechnology-derived alfalfa plants have an altered enzyme that allows them to tolerate a glyphosate application while susceptible weeds are killed. Glyphosate resistance is the first commercially available, genetically engineered (GE) trait in alfalfa.

This technology was a major development in alfalfa weed control, providing growers with a useful weed management tool and a means to deal with some of the most difficult-to-control weed species. Researchers have evaluated its effectiveness as a weed control strategy (Canevari et al. 2007; Sheaffer et al. 2007; Steckel et al. 2007, Van Deynze et al. 2004). The advantages and disadvantages of this technology have been reviewed (Van Deynze et al. 2004). Glyphosate was found to be especially effective for weed control in seeding alfalfa (Canevari et al. 2007). Glyphosate typically causes no perceptible crop injury, is much more flexible and less restrictive in application, and provides superior weed control across a range of weed species when compared with other currently used herbicides. One of the greatest advantages of this technology is that it provides a tool for suppressing perennial weeds such as dandelion (*Taraxacum officinale*), yellow nutsedge (*Cyperus esculentus* L.), bermudagrass (*Cynodon dactylon* (L.) Pers.), and quackgrass (*Elytrigia repens* (L.) Nevski) that have not been adequately controlled with conventional practices.

After deregulation of this trait in 2005, over 300,000 acres of RR alfalfa were planted in the United States, about 1.4 percent of U.S. acreage. (For equivalents between U.S. and metric systems of measurement, a conversion table is provided at the end of this publication.) However, in the spring of 2007, further plantings were suspended pending the outcome of a legal challenge and further environmental analysis by the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS). There were two key issues in this process: the possibility of contamination of organic and conventional alfalfa through the adventitious presence of the gene, and the possibility of a greater level of weed resistance due to the adoption of the Roundup Ready technology in alfalfa (USDA 2008).

Grower experience in commercial fields following deregulation confirmed many of the benefits that early research had suggested in terms of the efficacy and safety of the RR system (Van Deynze et al. 2004). Growers have generally found that this technology is easy to use and provides superior weed control and improved forage quality in many cases compared with conventional herbicides. However, no new technology is a panacea, and, like other weed control strategies, RR alfalfa has its limitations. An important limitation of this new weed-management system is the potential for weed shifts and weed resistance. This publication discusses techniques that are available to manage the possibility of weed shifts and weed resistance occurring in Roundup Ready alfalfa weed control systems.

WEED SHIFTS AND WEED RESISTANCE

Change in weed populations as a result of repeated use of a single herbicide is not a new phenomenon. Such changes result from shifts in the weeds present from susceptible to tolerant species, or conversion of a population within a species to resistant individuals, as a consequence of selection pressure (Holt and LeBaron 1990; Prather et al. 2000).

Weed Shift

A weed shift refers to a change in the relative abundance or type of weeds as a result of a management practice (fig. 1). The management practice could be herbicide use or any other practice such as tillage, manure application, or harvest schedule that brings about a change in weed species composition.

In the case of chemical weed control, no single herbicide controls all weeds, as weeds differ in their susceptibility to an herbicide. Susceptible weeds are largely eliminated over time with continued use of the same herbicide. This allows inherently tolerant weed species to remain, which often thrive and proliferate with the reduced competition. As a result, there is a gradual shift to tolerant weed species when practices are continuously used that are not effective against those species. A weed shift does not necessarily have to be a shift to a different species. For example, with a foliar herbicide without residual activity like glyphosate, there could also be a shift within a weed species to a late-emerging biotype that emerges after application. In the case of weed shifts, the total population of weeds does not necessarily change as a result of an herbicide or an agronomic practice; these practices simply favor one species (or biotype) over another.

Weed Resistance

In contrast to a weed shift, weed resistance is a change in the population of weeds that were previously susceptible to an herbicide, turning them into a population of the same species that is no longer controlled by that herbicide (fig 2).

Figure 1. Weed shifts due to herbicide application. A weed species shift occurs when both susceptible and tolerant weed species are present in a field. After continued use of a single herbicide, the susceptible weed species is nearly eliminated. The tolerant weed species survives and proliferates, eventually becoming the prevailing species. In this example, a shift to a broadleaf weed is favored by use of a grass herbicide.

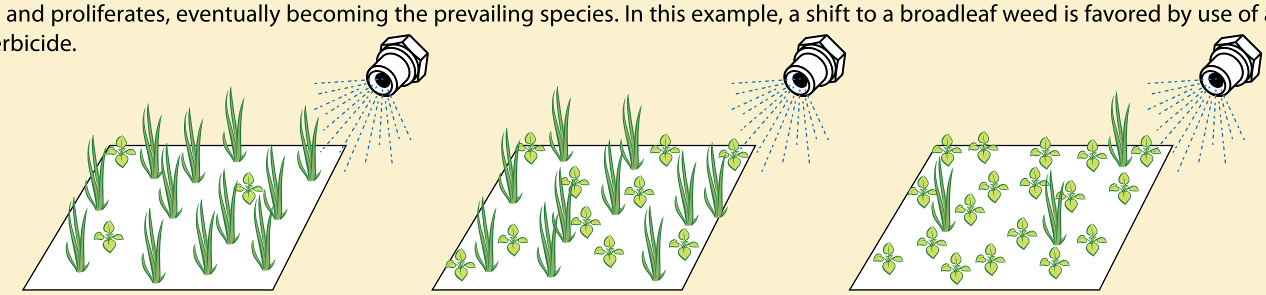
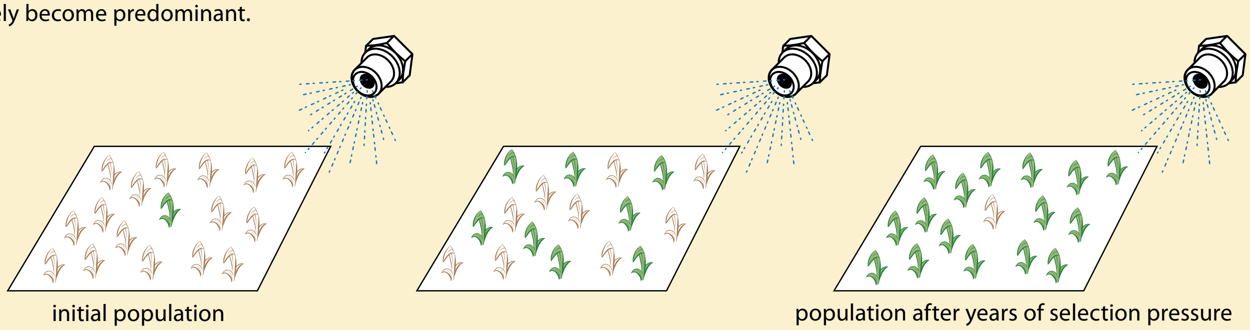


Figure 2. Evolution of herbicide resistance due to selection pressure. An herbicide controls susceptible weeds, preventing them from reproducing and leaving only those individuals carrying the genes for resistance. Typically an extremely small percentage of the weed population initially possesses the genes for resistance. These altered genes are thought to exist in weed populations at very low frequencies. As repeated use of an herbicide controls the susceptible individuals, the resistant weeds continue to multiply and ultimately become predominant.



While weed shifts can occur with any agronomic practice (crop rotation, tillage, frequent harvests, or use of particular herbicides), the evolution of weed resistance is only the result of continued herbicide application. The use of a single class of herbicides continually over time creates selection pressure so that resistant individuals of a species survive and reproduce, while susceptible ones are killed.

Which Is More Important, Weed Shifts or Weed Resistance?

A weed species shift is far more common than weed resistance, and ordinarily takes less time to develop. If an herbicide does not control all the weeds, the tendency is to quickly jump to the conclusion that resistance has occurred. However, a weed shift is a far more likely explanation for weed escapes following an application of glyphosate. See table 1 for a list of weeds sometimes found in alfalfa fields that are tolerant to or difficult to control with glyphosate.

Table 1. Annual weeds encountered in alfalfa fields that are potential candidates for weed shifts in continuous glyphosate systems

Latin name	Common name
*Brassica nigra**	black mustard
Chenopodium album†	lambsquarters
Echinochloa colona†	junglerice
Epilobium	Willowherb, panicle
*brachycarpum**	willowherb, panicle
*Eragrostis**	lovegrass
Erodium spp.†	filaree
Lamium amplexicaule†	henbit
Lolium multiflorum†‡	ryegrass
*Malva parviflora**	malva (cheeseweed)
Polygonum convolvulus†	wild buckwheat
Polygonum spp.†	knotweeds
Portulaca oleracea†	purslane
Sonchus oleraceus†	annual sowthistle
*Trifolium spp.**	clover
*Urtica urens**	burning nettle

Note: This table includes weeds that are listed as susceptible on the label but are difficult to control and weeds which are not controlled by glyphosate.
*Glyphosate-tolerant weeds—not listed as controlled on product label.
†Difficult to control weeds.
‡Glyphosate-resistant biotype has been confirmed.

Are Weed Shifts or Weed Resistance Linked Only to Genetically Engineered Crops?

A common misconception is that weed resistance is intrinsically linked to genetically engineered (GE) crops. However, this is not correct. The occurrence of weed shifts and weed resistance is not unique to genetically engineered crops. Weed shifts and resistance are caused by the practices that may accompany a GE crop (for example, repeated use of a single herbicide), not the GE crop itself. Similarly, some people believe that herbicide resistance is transferred from the GE crop to weed species. However, unless a crop is genetically very closely related to a naturally-occurring weed, weed resistance cannot be transferred from crop to weed. In the case of alfalfa, there are no known wild plants that cross with alfalfa, so direct transfer of herbicide resistance through gene flow to weedy species will not occur. However, the glyphosate-tolerant genes from RR alfalfa can be transferred to feral (wild) alfalfa plants if cross pollination occurs.

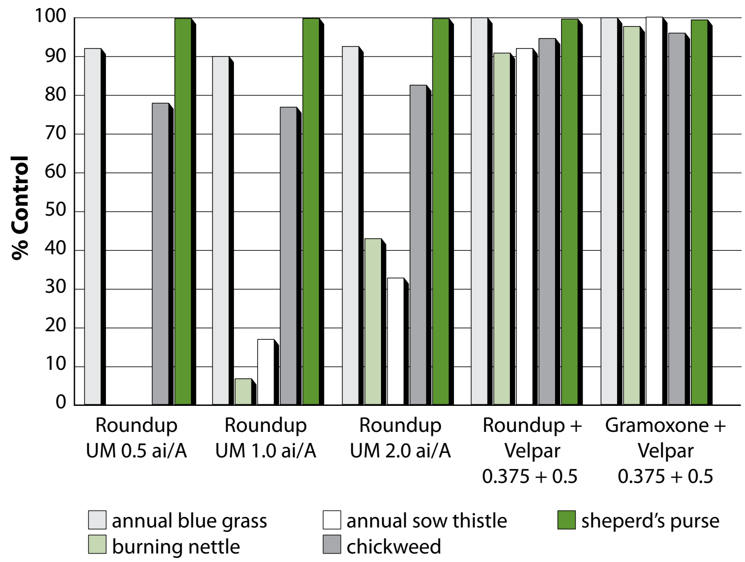
Link to Management Practices

The development of weed shifts or the evolution of weed resistance in cropping systems is primarily a result of management practices, not the crop itself. Continued use of the same management practice, in this case the use of a single herbicide, increases the probability of a weed shift or the evolution of resistant weeds as a result of constant selection pressure. For example, if the herbicide diuron (Karmex) is used alone for several years in established alfalfa, susceptible weeds are controlled. However, there is likely to be an increase in tolerant weeds such as common groundsel (*Senecio vulgaris*), Persian speedwell (*Veronica persica*), and others. Similarly, if imazethapyr (Pursuit) is used repeatedly for several years without rotating with other herbicides, there is likely to be an increase in the population of prickly lettuce (*Lactuca serriola*), annual sowthistle (*Sonchus oleraceus*), and many grassy weeds that are not controlled by this herbicide. Rigid ryegrass (*Lolium rigidum*) and horseweed (*Conyza canadensis*) resistance to glyphosate was the outcome of repeated glyphosate applications in California orchards and noncrop settings, respectively. Weed shifts and weed resistance are not new; evolved resistance was first reported in the 1970s and now occurs with a range of herbicide classes (Holt and LeBaron 1990; Heap 1999; Heap 2008).

RR Crops Present a Challenge

Transgenic herbicide-resistant crops do, nonetheless, have greater potential to foster weed shifts and resistant weeds since a grower is more likely to use a single herbicide repeatedly in herbicide-resistant crops such as RR alfalfa. Additionally, the accumulation of acreage of different RR crops (corn, soybean, and cotton) could increase the potential for weed shifts or weed resistance in cropping systems utilizing RR crops. This is because the probability of repeated use of the

Figure 3. Weed control 69 days after treatment in an established stand of Roundup Ready alfalfa, San Joaquin County, California, 2004.



same herbicide is higher and the potential applied acreage (and therefore the size and genetic diversity of the weed population) is greater. Fortunately, there are simple methods available to prevent weed shifts and weed resistance from occurring.

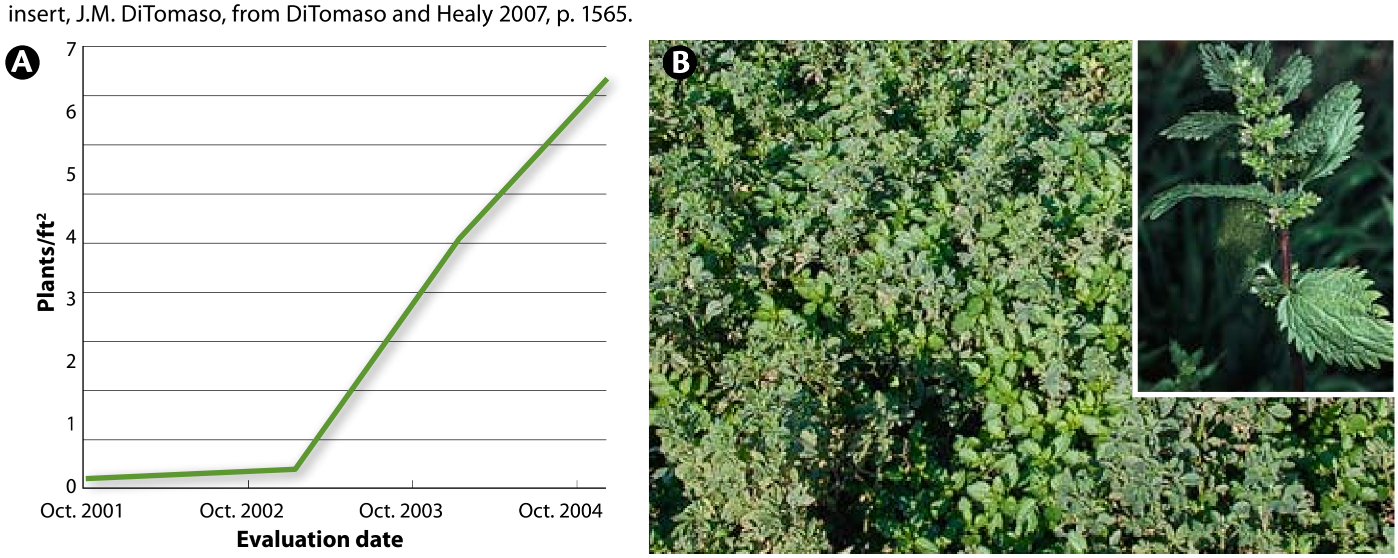
In studies conducted in San Joaquin County, California, weeds shifts were found to occur during the first few years of use when glyphosate-tolerant weeds were present (Van Deynze et al. 2004). Annual bluegrass and shepherd's purse were adequately controlled with glyphosate, whereas chickweed control was about 80 percent and burning nettle and annual sowthistle were not adequately controlled with any of the glyphosate rates (fig. 3). During the 3 years of this field trial, when glyphosate was used repeatedly, there was a gradual weed species shift away from annual bluegrass and shepherd's purse to higher populations of burning nettle and annual sowthistle (figs. 4A and 4B). A tank mix of glyphosate and Velpar, or a rotation to Velpar and Gramoxone, was needed to adequately control all weed species at this location.

To our knowledge there have been no documented cases of weed resistance in alfalfa during the first 3 years of RR alfalfa production (2005 to 2008) in the United States.

WEED SHIFTS AND RESISTANCE WITH RR ALFALFA

The possibility of weed shifts and weed resistance is a concern with RR alfalfa. This is due to its perennial growth habit, its long stand life, and the potential for repeated use of a single herbicide over several years without crop rotation. Although some stands last 3 to 4 years, it is common in many areas of the United States to keep an alfalfa stand in production for 5 to 7 years or longer. If the rotation crop (e.g. a grain crop) is not treated with an herbicide, an even longer period of time without herbicide diversity could occur. In this instance, weed populations could slowly return to preglyphosate composition, but the new species or resistant biotypes would not disappear. In areas where alfalfa is rotated with transgenic RR corn, cotton, or soybean varieties, this

Figure 4. (A): Increase in burning nettle population in Roundup Ready alfalfa with repeated annual applications of glyphosate alone, San Joaquin County, California, 2006. **(B):** Plot overtaken with burning nettle after 3 years of continual glyphosate use. *Photos:* Mick Canevari; insert, J.M. DiTomaso, from DiTomaso and Healy 2007, p. 1565.



again could result in a prolonged time period where a single herbicide is used repeatedly.

There are aspects of the alfalfa production system that both favor and discourage the development of weed shifts and the evolution of resistant weeds.

Attributes of Alfalfa That Favor Weed Shifts and Resistance

First, crop rotation opportunities with a perennial crop like alfalfa are significantly reduced compared with annual cropping systems. Mechanical weed control, such as cultivation, is impractical in a solid-seeded perennial crop like alfalfa, and hand weeding is not economical. Alfalfa is grown over extensive acreage in the United States and fields can be large in size; therefore, the overall weed flora available for selection of resistant traits or for weed shifts is plentiful. Perennials like alfalfa, if sprayed repeatedly with the same herbicide, are likely candidates for weed shifts and weed resistance.

Attributes of Alfalfa That Discourage Weed Shifts and Resistance

On the other hand, many weeds do not flourish in an alfalfa field due to its perennial nature and the competitiveness of the crop after establishment. Alfalfa is an aggressive competitor with most weeds, which fail to establish in alfalfa fields due to the crop's vigorous growth and shading ability. In addition, many weed species do not tolerate the frequent cutting that occurs in alfalfa fields. The lack of soil disturbance once the alfalfa stand is established also reduces opportunities for germination of some weed species. Furthermore, the interval between alfalfa cuttings is short enough that seed production for many weeds is reduced compared with annual crops that allow completion of the weeds' life cycles.

Risk of Resistance Generally Lower with Glyphosate Than with Other Herbicides

Weed shifts or resistant weeds are unavoidable and will occur eventually with any herbicide used repeatedly, and the same is true with the use of glyphosate (Heap 1999). Fortunately, resistance to glyphosate is not as common as resistance to many other herbicides, such as acetolactate synthase (ALS) and acetyl-CoA carboxylase (ACCase) herbicides that have a single binding site and single target enzyme mechanisms of action (Heap 2008). The relatively low rate of resistance in weeds to glyphosate relative to the widespread use of this chemical has not been fully explained, but may be due to the number or frequency of mutations that may be required to confer resistance to glyphosate. Two resistance mechanisms, a weak target site mutation, and a reduced glyphosate translocation mechanism have been documented in weed species that have evolved resistance to this herbicide (Powles and Preston 2006).

Regardless of the mechanism, weed resistance to glyphosate is not as common as resistance to other herbicides. However, cases of weed resistance to glyphosate have been documented and are increasing. There is a range of species across the world with documented resistance to glyphosate (table 2). Fortunately, most of these species are not common in alfalfa fields. Two weed species in particular have evolved resistant populations in California: *Lolium* spp. (ryegrass) and *Conyza* sp. (marestail). The latter is not important in alfalfa, but ryegrass is frequently found in alfalfa fields. Glyphosate-resistant ryegrass is increasing in the Sacramento Valley and northern San Joaquin Valley of California and may become problematic during fall stand establishment of RR alfalfa.

Weed shifts and/or weed resistance have occurred with the other transgenic RR crops released before RR alfalfa (Duke and Powles 2008). Weed resistance is of greater concern than weed shifts and has occurred in RR soybean, cotton, and corn in less than a decade after their initial release (see table 2). Alfalfa growers can learn from experience with these crops and in noncrop areas as a preemptive measure to avoid, or at least minimize, the problems with weed shifts and weed resistance. These problems are sure to occur in alfalfa if proper weed management practices are not followed.

Alfalfa growers can learn from experience with other RR crops and in noncrop areas as a preemptive measure to avoid, or at least minimize, the problems with weed shifts and weed resistance.

WEED MANAGEMENT PRINCIPLES TO REDUCE WEED SHIFTS AND RESISTANCE IN ALFALFA

Glyphosate-resistant crops have provided growers with an easy-to-use, low-cost, and effective weed management tool. However, the effectiveness of weed control systems using RR crops can make growers complacent in their weed control practices. Even though this technology is highly effective, growers must follow sound weed management principles to prevent short- or long-term weed shifts or weed resistance from occurring. This includes weed identification, crop rotation, attention to application rate, proper timing of application, herbicide rotation, and tank mixtures.

Weed Identification

Effective weed management practices begin with proper identification to assess the competiveness of the weeds present and to select the proper herbicide if one is needed. A weed management strategy to prevent weed shifts and weed resistance requires knowledge of the composition of weeds present. Identification of young seedlings is particularly important because seedling weeds are easier to control. Resources for weed identification can be found at the UC IPM Web site (http://www.ipm.ucdavis.edu/PMG/weeds_common.html) and at the UC Weed Research and Information Center Web site (http://wric.ucdavis.edu/information/information.html).

Table 2. Glyphosate-resistant weed populations

Resistant weed	Common name	Location of resistant populations	Situation(s)	Year first reported
UNITED STATES			**(In the U.S.)**	
Amaranthus palmeri	Palmer amaranth	Arkansas, Georgia, North Carolina, Mississippi, Tennessee	corn, cotton, soybean	2005
Amaranthus rudis	common waterhemp	Illinois, Kansas, Minnesota, Missouri	corn, soybean	2005
Ambrosia artemisiifolia	common ragweed	Arkansas, Kansas, Missouri	soybean	2004
Ambrosia trifida	giant ragweed	Arkansas, Indiana, Kansas, Minnesota, Ohio, Tennessee	cotton, soybean	2004
Conyza bonariensis	hairy fleabane	California	roadsides	2007
Conyza canadensis	horseweed (marestail)	17 states including California	cotton, nurseries, road-sides (in CA), soybean	2000
Lolium multiflorum	Italian ryegrass	Mississippi , Oregon	cotton, orchards, soybean	2004
Lolium rigidum	rigid ryegrass	California	orchards	1998
Sorghum halepense	Johnsongrass	Arkansas	soybean	2007
WORLD			**(in the world)**	
Conyza bonariensis	hairy fleabane	Brazil, Colombia, South Africa, Spain	corn, orchards, soy-bean, vineyards, wheat	2003
Conyza canadensis	horseweed (marestail)	Brazil, China, Czech Republic, Spain	orchards, soybean, railways	2005
Digitaria insularis	sourgrass	Brazil , Paraguay	soybean	2006
Echinochloa colona	junglerice	Australia (New South Wales)	cropland	2007
Eleusine indica	goosegrass	Colombia , Malaysia	cropland , orchards	1997
Euphorbia heterophylla	wild poinsettia	Brazil	soybean	2006
Lolium multiflorum	Italian ryegrass	Argentina, Brazil, Chile, Spain	cropland orchards, soybean	2001
Lolium rigidum	rigid ryegrass	Australia, France, South Africa, Spain	asparagus, orchards, railways, sorghum, vineyards, wheat	1996
Plantago lanceolata	buckhorn plantain	South Africa	orchards, vineyards	2003
Sorghum halepense	Johnsongrass	Argentina	soybean	2005
Urochloa panicoides	liverseedgrass	Australia (New South Wales)	sorghum, wheat	2008

Source: International Survey of Herbicide Resistant Weeds, adapted from Heap 2008.

Frequent Monitoring for Escapes

It is difficult to detect an emerging weed shift or weed resistance problem if fields are not frequently monitored for weeds that escape current weed management practices. Identification and frequent monitoring can detect problem weeds early and guide management practices, including herbicide selection, rate, and timing.

Herbicide Rate and Timing

It is important to use the appropriate rate and timing for the weeds present. For example, some weeds that are considered somewhat tolerant to glyphosate (cheeseweed, filaree, and purslane) can be controlled effectively in seedling alfalfa with glyphosate, provided the proper rate is used and the application is made when the weeds are very small. Research in Nebraska over a 7-year period (Wilson 2004) demonstrated a rapid increase in lambsquarters when a low rate of glyphosate (0.5 lb ai/acre) was applied, but a higher rate (1.0 lb ai/acre) successfully controlled this weed. Just like with traditional weed management programs, the grower must be sure to use the recommended rate for the weed species present and treat at the appropriate time when the weeds are still small.

Crop Rotation

One of the most effective practices for preventing weed shifts and weed resistance is crop rotation, which allows growers to modify selection pressure imposed on weeds. Continuous (also called back-to-back) alfalfa is not recommended for other agronomic reasons, but especially would be ill advised when it comes to management of resistance and weed shifts. Crops differ in their ability to compete with weeds; some weeds are a problem in some crops, while they are less problematic in others. Rotation therefore would not favor any particular weed spectrum. Crop rotation also allows the use of different weed control practices, such as cultivation and application of herbicides with different sites of action. As a result, no single weed species or biotype should become dominant. The effectiveness of crop rotation to manage weed shifts and resistance is substantially reduced if another RR crop (such as corn or cotton) is planted in rotation with RR alfalfa, since the same herbicide and selection pressure would likely occur.

Using an effective herbicide with a different mode of action from the one to which the weeds are resistant controls both the susceptible and resistant biotypes, thus preventing reproduction and slowing the spread of the resistant biotype.

Agronomic Practices

In addition to crop rotation, several management practices may have an impact on the selection of problem weed populations. If problem weeds germinate at a specific time of year, crop seeding date can be shifted to avoid these weed populations, allowing a vigorous alfalfa crop to develop that is capable of outcompeting weeds. Delaying irrigation after alfalfa cutting can reduce germination of certain summer annual weeds. However, this practice only works on some soil types, and water stress in alfalfa can reduce yields. Harvest management can, in some cases, assist in eliminating or suppressing problem weed populations, but harvests must occur before weed seed production to prevent weed proliferation.

Rotation of Herbicides

Weed shifts occur because herbicides are not equally effective against all weed species and herbicides differ greatly in the weed spectrum they control. A weed species that is not controlled will survive and increase in density following repeated use of one herbicide. Therefore, rotating herbicides is recommended. Rotation of herbicides reduces weed shifts, provided the rotational herbicide is highly effective against the weed species that is not controlled with the primary herbicide. The grower should rotate to an herbicide with a complimentary spectrum of weed control, along with a different mechanism of action and therefore a different herbicide binding site. Weed susceptibility charts are useful to help develop an effective herbicide rotation scheme (Canevari et al. 2006). In addition, publications on herbicide chemical families are available to assist growers in choosing herbicides with different mechanisms of action (Retzinger and Mallory-Smith 1997).

Rotating herbicides is also an effective strategy for resistance management. Within a weed species there are different biotypes, each with its own genetic makeup, enabling some of them to survive a particular herbicide application. The susceptible weeds in a population are killed, while the resistant ones survive, set seed, and increase over time. Using an effective herbicide with a different mode of action from the one to which the weeds are resistant, however, controls both the susceptible and resistant biotypes. This prevents reproduction and slows the spread of the resistant biotype.

Herbicide Tank Mixtures

For the same reasons that rotating herbicides is effective, tank mixing herbicides is also recommended. The key is to select tank mix partners that have different target sites and that compliment each other so that, when combined, they provide complete or nearly complete weed control.

RECOMMENDED WEED MANAGEMENT PROGRAM FOR RR ALFALFA

The cost of RR alfalfa seed, including the technology fee, is generally twice or more than that of conventional alfalfa seed. Naturally, growers will want to recoup their investment as quickly as possible. Therefore, considerable economic incentive exists for the producer to rely solely on repeated glyphosate applications alone as a weed control program. Some producers may even be inclined to shave the rates to the minimum amount that would provide acceptable weed control. While relying solely on glyphosate and shaving rates may provide satisfactory results in the short term, it is a risky practice in the long run as it will accelerate weed species shifts and the evolution of resistant weeds. Sound weed management practices should be employed to maintain the effectiveness of the RR technology.

Roundup Ready alfalfa is still a relatively new technology, so there has been limited field experience with it to date. The following are some suggestions to consider based upon proven resistance management strategies, our understanding of alfalfa production practices, and our initial experience with RR alfalfa. Ultimately, growers and pest control advisors hold the key to avoiding weed shifts and resistance by reducing selection pressure, which is accomplished by developing a weed management program that does not rely solely on the continuous use of glyphosate. Any management practice that reduces the selection pressure (in this case, the selection pressure imposed by continual use of the same herbicide) will help avoid weed species shifts and resistance.

For Seedling Alfalfa, Use Glyphosate Alone or in a Tank Mix Combination

Seedling alfalfa is most vulnerable to weed competition because weeds are often more vigorous and competitive than young alfalfa. Additionally, complete weed control in seedling alfalfa is often difficult to achieve and frequently requires tank mixes of different herbicides to control the broad spectrum of weeds found in an individual field. Yield and stand loss from weed competition, and injury from conventional herbicides, are usually far greater in seedling than in established alfalfa. Numerous field trials throughout the United States have proven the effectiveness of RR alfalfa for stand establishment. Superior weed control with no perceptible alfalfa injury has occurred in most studies. Therefore, it is only logical to use glyphosate for weed control in RR seedling alfalfa for the cost savings, improved weed control, reduced crop injury, superior stand establishment, and the elimination of the small percentage of alfalfa seedlings (commonly called nulls) that do not carry the RR gene. Delayed removal of these nulls may cause weed control problems in the future by creating open spaces for weeds to grow.

Ordinarily, 1.0 pound per acre active ingredient of glyphosate is sufficient for weed control during the seedling period. However, a higher rate may be needed if the field contains some of the more tolerant weeds listed in table 1. A tank mix may be advised if especially-difficult-to-control weeds are present. For example, a tank mix of glyphosate with imazamox (Raptor) or imazethapyr (Pursuit) may be advised if burning nettle is present, or a tank mix with clethodim (Prism) will be necessary if the field or surrounding area is known to have glyphosate-resistant ryegrass.

Rotate or Tank Mix Herbicides at Least Once During the Life of an Alfalfa Stand

Alfalfa stand life varies considerably throughout the western United States depending on the production area, grower practice, and the existence of profitable rotation crop options. A stand life of 3 to 5 years is common in the Central Valley of California and other warm, long growing-season areas of the Southwest. A stand life of 5 to 7 years is common in much of the Northwest, and some alfalfa stands remain in production in excess of 10 years. As suggested by the principles outlined above, it is unwise to rely solely on glyphosate applications for weed control throughout the life of a transgenic alfalfa field. This practice would encourage weed shifts and resistance, and over time weed control would diminish in most cases. Once an herbicide is rendered ineffective as a result of resistant weeds, its usefulness as a weed control tool may be greatly diminished. After a resistant weed population has gained a foothold, it is practically impossible to eliminate it due to the presence of a weed seedbank.

Most alfalfa producers apply an herbicide to alfalfa during the dormant season to control winter annual weeds that infest the first cutting. It is strongly recommended that growers not rely solely on glyphosate for their winter weed control program for the duration of the stand. They should rotate to another herbicide or tank mix at least once in the middle of the life of a stand, and perhaps twice if the stand life is over 5 years (table 3).

Use an Herbicide with a Different Mode of Action

Fortunately, all of the herbicides currently registered in alfalfa—and there are several to choose from—have

Table 3. Comparison of weed management strategies for glyphosate-resistant alfalfa using continuous glyphosate applications versus a recommended approach where glyphosate is rotated with other herbicides during a 4-year alfalfa stand

Year	Objective	Season	Continuous glyphosate strategy	Rotational herbicide strategy
Seedling	control weeds that compete during stand establishment	fall	glyphosate	glyphosate
1	control late-emerging weeds during establishment	winter (late)	glyphosate	glyphosate*
	summer annual weed control may not be needed first year	spring		
		summer		
		fall		
2	control winter annual weeds and/or pre-emergence control of summer weeds	winter	glyphosate	soil residual herbicide or tank mix* of soil residual herbicide with glyphosate†
	summer annual weed control/dodder	spring		
		summer	glyphosate	
		fall		
3	control winter annual weeds and/or pre-emergence control of summer weeds	winter	glyphosate	soil residual herbicide or tank mix* of soil residual with glyphosate†
	control summer annual grassy weeds/ dodder	spring	glyphosate	
		summer (mid)	glyphosate	
		fall		
4	control winter annual weeds	winter	glyphosate	glyphosate
	control summer annual grassy weeds/ dodder	spring	glyphosate	
		summer (mid)	glyphosate	glyphosate
	(stand take-out)	fall (late)	tillage and/or 2,4-D + dicamba as necessary	tillage and/or 2,4-D + dicamba as necessary
(4 years)	**Total number of glyphosate applications**		**10**	**4–6**

Note: A combination of soil residual herbicides and different modes of action is recommended to prevent weed shifts and herbicide resistance. These are examples only—appropriate strategies should be modified for different regions and weed pressures.

*Tank mixing with another herbicide is advised if significant populations of glyphosate, tolerant weeds such as burning nettle are present.

†Soil residual herbicide (depending on location and weed spectrum, use hexazinone, diuron, or metribuzin) for pre-emergence control of winter annual weeds. An application of a dinitroaniline herbicide (pendimethalin or trifluralin) applied at this time will control summer annual grassy weeds.

a different target site of action than does glyphosate. The soil-residual herbicides applied during the dormant season to established alfalfa [such as hexazinone (Velpar), diuron (Karmex), metribuzin (Sencor), and pendimethalin (Prowl)] would be appropriate herbicides for a rotation or tank-mix partner. The rotation herbicide or tank-mix partner of choice depends on the weeds present in the field and their relative susceptibility to the herbicides. Paraquat (Gramoxone) is another candidate for rotation, but paraquat, like glyphosate, lacks residual activity and is applied late in the dormant season. By rotating paraquat with glyphosate, growers could potentially be selecting for early-emerging weeds that may be too large to control at the typical timing for these herbicides. In addition, they could be selecting for late emerging weeds that germinate after the application.

Rotate Herbicides Early in Stand Life So Glyphosate Remains Effective

Weed control during the last year of an alfalfa stand is often challenging because the stand is typically less dense and competitive and also there are fewer herbicide options from which to choose. There are significant plant-back restrictions associated with many of the soil-residual herbicides used in alfalfa, so glyphosate is a good choice for controlling weeds in the final year of RR alfalfa field. The preference to use glyphosate in the final year of an alfalfa stand underscores the importance of rotating herbicides earlier so that glyphosate will remain effective and continue to control the majority of the weeds.

Consider a Soil-Residual Herbicide for Summer Annual Weed Control

Summer annual grass weeds such as yellow and green foxtail (Setaria spp.), barnyardgrass (*Echinochloa crus-galli*), cupgrass (*Eriochloa* spp.), and jungle rice (*Echinochloa colona*), and less frequently, broadleaf weeds like pigweed (*Amaranthus* spp.) or lambsquarters (*Chenopodium album*), can be problematic in established alfalfa. These weeds emerge over an extended time period whenever soil temperatures and moisture are adequate, typically from late winter or early spring (as early as February in the Central Valley) throughout the summer. Weeds may emerge between alfalfa cuttings, so several applications may be necessary in California's Central Valley for a foliar herbicide without residual activity like glyphosate to provide season-long control.

Multiple applications of a single herbicide during a season is cited as promoting weed resistance. Therefore, growers should not rely solely on glyphosate for summer grass control for multiple seasons. It remains to be seen how many applications of glyphosate will be required for season-long summer grass control. In some of the long growing-season areas of California, as many as two to three applications per season may be needed in older, thinner stands. Rather than making multiple applications of glyphosate, a better approach may be to apply a pre-emergence soil-residual dinitroaniline herbicide like trifluralin (Treflan) or pendimethalin (Prowl), or possibly EPTC (Eptam), and follow up with glyphosate later in the season as needed for escapes. Not only is this approach more in line with management practices to avoid weed shifts and resistance, but it may be more economical as well, compared with multiple applications of glyphosate.

The practice of rotating herbicides or applying tank mixtures is recommended for both dormant applications aimed at winter annual weeds and for spring/summer applications intended to control summer annual weeds. For example, rotating to hexazinone (Velpar) for winter annual weed control for a year does nothing to prevent weed species shifts or the evolution of resistance in the summer annual weed spectrum. Herbicides for summer annual weed control should be rotated as well.

Frequency of Rotation Depends on Weed Species and Escapes

There is no definitive rule on how often herbicides should be rotated. Our suggestion to rotate or tank mix at least once in the middle years of the life of a stand (or more often for long-lived alfalfa stands) may need to be modified depending upon actual observations of evolving weed problems. The key point, which cannot be overemphasized, is the importance of diligent monitoring for weed escapes. Producers should stay alert to the appearance of weed species shifts and evolution of resistant weeds. If the relative frequency of occurrence of a weed species increases dramatically, chances are that it is tolerant to glyphosate and immediate rotation of herbicides or a tank mix is advised. If a few weeds survive among a weed species that is normally controlled easily with glyphosate, it could be an indication of weed resistance, assuming misapplication and other factors can be eliminated as possible causes. Weed resistance should be confirmed by controlled studies conducted by a weed scientist. However, in these situations, it is imperative to prevent reproduction of a potentially resistant biotype. Treat weed escapes with an alternative herbicide or other effective control measure.

CONCLUSIONS

The Roundup Ready alfalfa production system has the potential to simplify weed management, while also improving the spectrum of weed control. However, growers should learn from the experience gained in other crops and stay alert to the occurrence of weed shifts and evolution of resistant weeds. The key is for growers to reduce selection pressure, not to rely on repeated applications of glyphosate year after year, application after application. Well-known management principles are available to manage weed shifts and weed resistance in RR alfalfa. Rotate crops, rotate herbicides, and utilize tank mixes as needed, depending on the weed species and weed escapes present. A grower should not wait for a problem to occur before he or she employs these practices; a preemptive approach is strongly encouraged.

METRIC CONVERSIONS

English	Conversion factor for English to metric	Conversion factor for metric to English	Metric
pound (lb)	0.454	2.205	kilogram (kg)
acre (ac)	0.4047	2.47	hectare (ha)
pound per acre (lb/ac)	1.12	0.89	kilogram per hectare (kg/ha)

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WARNING ON THE USE OF CHEMICALS

Pesticides are poisonous. Always read and carefully follow all precautions and safety recommendations given on the container label. Store all chemicals in their original labeled containers in a locked cabinet or shed, away from foods or feeds, and out of the reach of children, unauthorized persons, pets, and livestock.

Recommendations are based on the best information currently available, and treatments based on them should not leave residues exceeding the tolerance established for any particular chemical. Confine chemicals to the area being treated. THE GROWER IS LEGALLY RESPONSIBLE for residues on the grower's crops as well as for problems caused by drift from the grower's property to other properties or crops.

Consult your county agricultural commissioner for correct methods of disposing of leftover spray materials and empty containers. Never burn pesticide containers.

PHYTOTOXICITY: Certain chemicals may cause plant injury if used at the wrong stage of plant development or when temperatures are too high. Injury may also result from excessive amounts or the wrong formulation or from mixing incompatible materials. Inert ingredients, such as wetters, spreaders, emulsifiers, diluents, and solvents, can cause plant injury. Since formulations are often changed by manufacturers, it is possible that plant injury may occur, even though no injury was noted in previous seasons.

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