

Weed Management

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Numerous plant species are considered weeds in agronomic cropping systems. Weeds have many attributes undesirable to crop producers, not the least being the ability to reduce crop yields through competition for resources such as sunlight, water, nutrients, and space. Weeds also may harbor insects and provide a host for certain plant pathogens. Some weed species, such as wild garlic and eastern black nightshade, can reduce the quality of the harvested crop. Eliminating or reducing the deleterious effects of weeds on agronomic crops is the ultimate goal of weed management. Integrated weed management includes all practices that enhance a crop's competitive ability and decrease weeds' ability to reduce yield.

Successful weed management requires identifying relevant species and understanding their biological characteristics so that management can be tailored to the weeds present in individual fields. Accurate identification is critical: identification of seedling weeds is necessary for selecting an appropriate postemergence herbicide, while identifying mature weeds often indicates

which species will populate a particular field the following season. Most weed species in Illinois agronomic cropping systems are either broadleaves or grasses. Broadleaf species are generally easier to differentiate than grasses, especially at early growth stages. Many excellent identification references are available, including the several listed here; one or more should be part of every weed management practitioner's library.

Weeds of the North Central States (B772). Available from the University of Illinois (www.pubsuplus.illinois.edu)

Weeds of the Great Plains (ISBN-10: 0939870002; ISBN-13: 978-0939870004). Available from the Nebraska Department of Agriculture, (402) 471-2394

Weeds of the Northeast (ISBN-10: 0801483344; ISBN-13: 978-0801483349). Available from Cornell University Press.

Most weeds of agronomic cropping systems are herbaceous, but a few species that can become established in reduced-tillage fields are woody (such as maple trees). Weeds can be categorized according to their life cycle, or how long they live: annual, biennial, and perennial (Table 12.1). Knowledge of life cycles is important to reducing the potential for weeds to produce

Annuals		Biennials	Perennials	
Winter	Summer		Simple	Spreading
butterweed	barnyardgrass	bull thistle	common milkweed	Canada thistle
common chickweed	burcucumber	common burdock	curly dock	hemp dogbane
downy brome	common cocklebur	musk thistle	dandelion	Jerusalem artichoke
field pennycress	common lambsquarters	poison hemlock	field bindweed	johnsongrass
henbit	common ragweed	teasel	hedge bindweed	perennial sowthistle
horseweed	crabgrass	wild carrot	honeyvine milkweed	quackgrass
little barley	giant foxtail		horsenettle	swamp smartweed
prickly lettuce	giant ragweed		pokeweed	trumpet creeper
purple deadnettle	green foxtail		smooth groundcherry	wirestem muhly
shepherd's-purse	jimsonweed			yellow nutsedge
yellow rocket	kochia			
	shattercane			
	smartweed			
	smooth pigweed			
	tall morningglory			
	velvetleaf			
	waterhemp			
	yellow foxtail			

Table 12.1. Examples of weed species by life cycle.

Weed type	Duration of life cycle	Overwintering state	Method of reproduction
Annual	1 yr	Seed	Seed
Biennial	2 yr	Rosette	Seed
Perennial	>2 yr	Seed, vegetative propagule	Seed, vegetative propagule

viable seed or vegetative structures that aid in weed dispersal (Table 12.2).

Annual plants complete their life cycle (from seed to seed) in one year; they are sometimes further divided into winter annuals and summer annuals. Summer annual weeds emerge in the spring, grow in spring and summer, then flower and produce seed during late summer or early fall (Figure 12.1). These species are the most common weeds that grow in agronomic crops. Summer annual weeds can be controlled by various soil-applied herbicides before they emerge; they are easiest to control with post-emergence herbicides when they are small (about 4 inches or less). In general, most weeds become progressively harder to control with herbicides as they become larger.

Winter annual weeds emerge during late summer or fall, overwinter in a vegetative state, then flower and produce seed the following spring (Figure 12.2). They are common in fields where no tillage is done after harvest and in fall-seeded small grains and forages. Controlling winter annual weeds with herbicides may be accomplished during late fall or early spring. It is best to control all existing weed vegetation (including winter and summer annuals) before planting corn or soybean in the spring or before fall-seeding small grains or forages.

Biennial plants complete their life cycle over two years. Biennials emerge in the spring or summer, overwinter in a vegetative stage (often referred to as a rosette), then resume growth the following spring (Figure 12.3). Elongation of the flowering stalk (bolting) and seed production can vary by species; it occurs during the spring, summer, or fall of the second year. Biennial

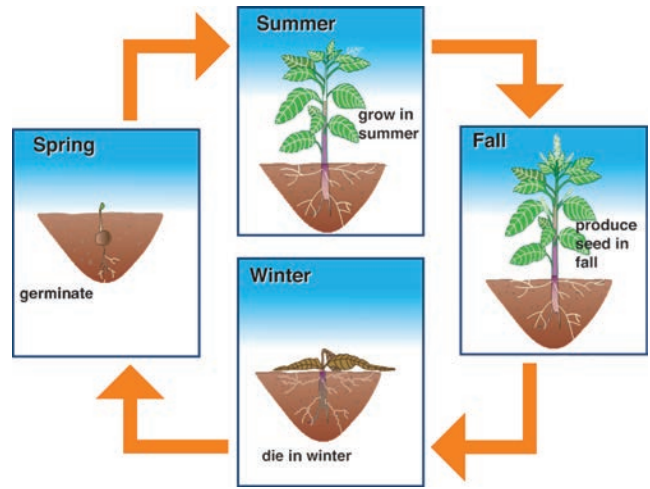


Figure 12.1. Summer annual weed life cycle.

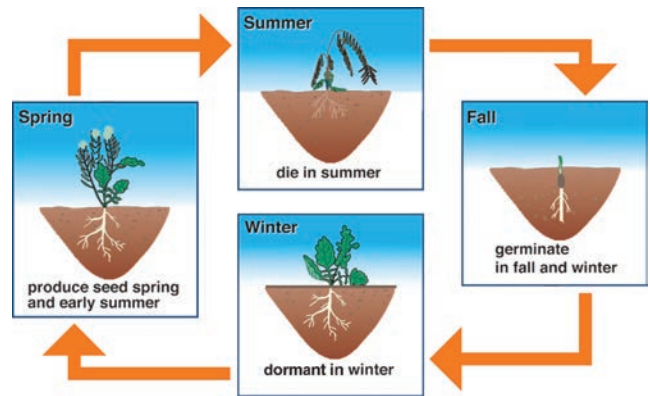


Figure 12.2. Winter annual weed life cycle.

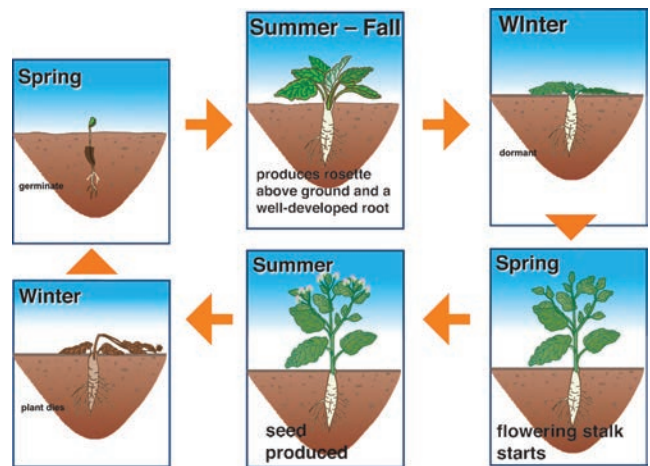


Figure 12.3. Biennial weed life cycle

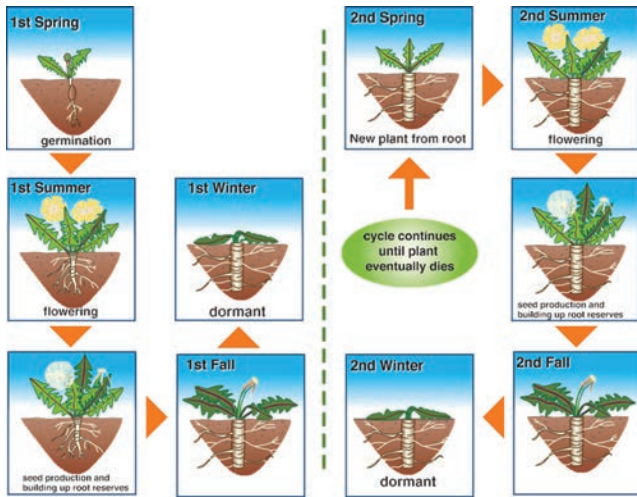


Figure 12.4. Perennial weed life cycle

weeds are often best controlled with postemergence herbicides during the rosette stage of growth. Their susceptibility to herbicides generally decreases rapidly after the onset of bolting.

Perennial species live longer than two years— theoretically, indefinitely (Figure 12.4). Some species reproduce almost exclusively by seed and are referred to as simple perennials. Other species can reproduce by both seed and various types of vegetative propagules (creeping roots, rhizomes, tubers, etc.). These types of perennials are referred to as creeping, or spreading, perennials.

Perennial weed species often become established in no-till production fields and can cause great frustration with respect to how best to control or eradicate them. Without the option of mechanical weed control (i.e., tillage), perennial weed species are generally best controlled with post-emergence translocated herbicides. Which translocated herbicide is used, as well as when the application is made, can impact the success achieved.

Perennial weed species are frequently difficult to control because they store food reserves in their root systems or underground storage structures. Controlling only what is above ground is usually not sufficient for satisfactory, long-term control; what is underground must be controlled as well. Translocated herbicides (those that can move into the roots) are usually the most effective chemical option to control perennial weeds, but when they are applied is very important. In the spring, perennials rely on stored food reserves to initiate

new growth, so most of the food at this time of year is moving upward from the roots to support new vegetative development. Because of this upward movement, it is often difficult to get sufficient herbicide into the root when applications are made in early spring.

Better control of perennial broadleaf species can be achieved when postemergence translocated herbicides are applied about the time the plants begin to flower. Another good time to treat perennial weed species is early to mid-fall. As day length shortens and temperatures fall, perennial plant species begin to move food back into their roots, and more translocated herbicide moves to the root as well.

Figure 12.5 depicts a generalized representation of post-emergence herbicide effectiveness on annual, biennial, and perennial weeds as influenced by stage of weed growth at application.

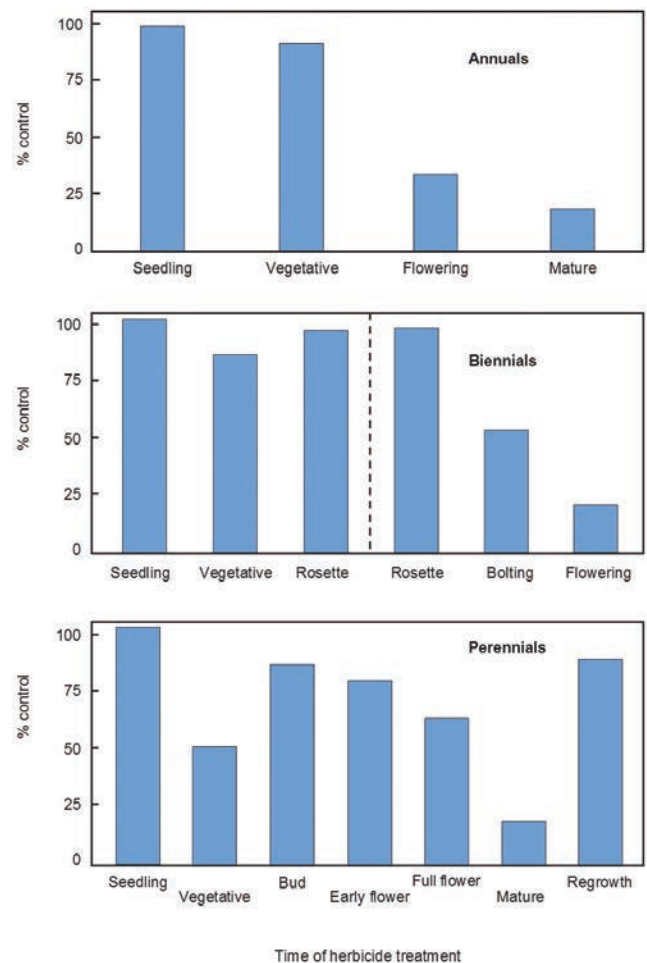


Figure 12.5. Postemergence herbicide effectiveness on annual, biennial, and perennial weeds as influenced by stage of weed growth at the time of application.

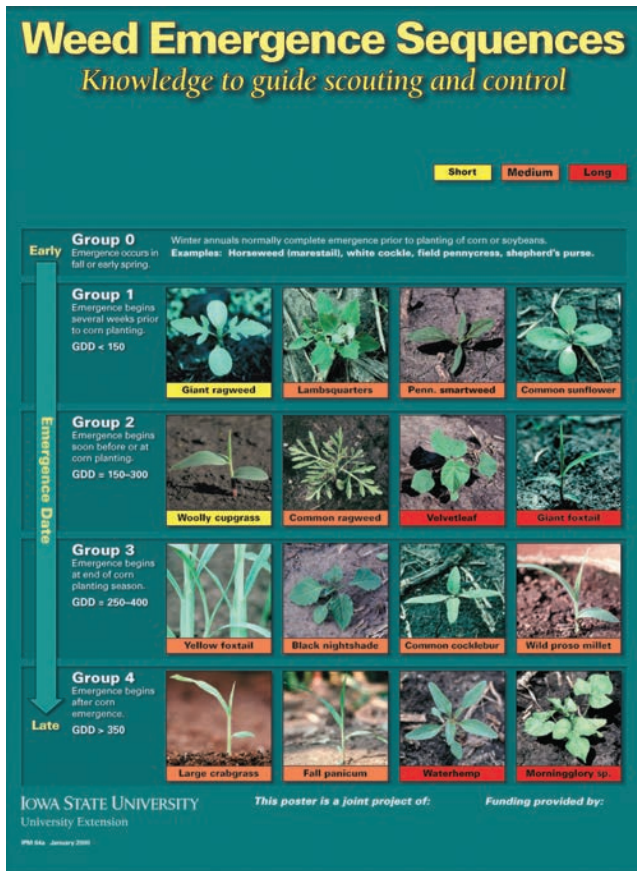


Figure 12.6. Emergence sequences for weed species common in midwestern corn and soybean

Scout agronomic production fields for weeds several times each season. In no-till fields, determine which winter annual or early-emerging summer annual species are present prior to any herbicide application so that herbicide selection and application rates can be optimized for the species present before planting. Knowing when weed species begin to emerge can vastly improve your management program if you practice timely scouting and subsequent control tactics. Weed emergence can, and often does, vary somewhat from year to year. Weeds such as smartweed and kochia emerge during early spring, while morningglory species can emerge during mid-summer (see Figure 12.6 for emergence sequences for weed species common in corn and soybean). Some species, such as velvetleaf, tend to have a relatively short period of emergence, whereas others, such as waterhemp, tend to emerge over a relatively long part of the growing season.

Weed Interference¹

Weed management strategies attempt to limit the deleterious effects weeds have when growing with crop plants. Most common is competition with the crop for available growth factors (light, water, etc.). Whatever quantities weeds use are unavailable for use by the crop. If weeds can use a sufficient amount of some growth factor, crop yield can be, and often is, adversely impacted.

Currently, the most common method of managing weeds is herbicides. Many options are available, each with distinct advantages and disadvantages. There are also several methods by which herbicides can be applied. Whatever the herbicide or method of application, the goal is to prevent weeds from contributing to crop yield loss by reducing the amount of competition exerted by the weeds.

The concept of competition between weeds and crops has received a great deal of attention from farmers and herbicide manufacturers alike. A particular point of interest focuses on when competition (from weeds) should be removed so that yields (of corn and soybean primarily) are not adversely impacted. Soil-applied residual herbicides can be used to eliminate any early-season weed competition, but some farmers would rather use only postemergence herbicides to control weeds.

Is one method better than another at reducing weed interference? What research is needed to determine how and when competition reduces crop yield? How should results of such research be interpreted?

Those involved in managing weeds have long recognized their harmful effects on crop growth and productivity through competing for light, moisture, nutrients, and space as well as hampering harvest operations, reducing quality of the harvested crop, and producing propagules that lead to future problems. Numerous experiments over the years have compared weed species and densities in various crops and assessed the importance of the duration of competition and the time of weed

1 Some text in the "Weed Interference" section has been modified from L. M. Wax, 1998, "Factors to consider when interpreting crop-weed competition studies," Proceedings of the Illinois Agricultural Pesticides Conference (<https://hdl.handle.net/2142/89666>)

removal. From those studies, some general guidelines evolved regarding the relative competitiveness of weeds with various crops, the weed-free time needed following crop emergence, and the appropriate time of weed removal with postemergence treatments to preclude loss of crop quantity and quality. However, as tillage, planting, and weed management practices have changed over the years, the once-accurate guidelines regarding crop–weed competition should be revisited, and in some instances modified, as new findings are reported. The following text reviews crop–weed competition research, both past and present, and offers guidelines for interpreting related data.

Cropping and Cultural Practices.

Crops vary greatly in their ability to compete with weeds, from providing essentially no competition to competing very aggressively. This text focuses on the major field crops of Illinois, corn and soybean. Early studies, with a variety of weed species, tended to show nearly equal competitive ability of corn and soybean, with some differences. Very tall-growing weeds, if left for the entire season, were sometimes less competitive in corn than in soybeans, mainly because they could overtop soybeans and cause greater losses from shading. Weeds that rarely grew taller than soybeans often caused less yield loss in soybeans than in corn, again due to the excellent shading provided by a healthy stand of soybean.

Crop varieties and hybrids can vary substantially in response to weed competition, with those that canopy earlier and provide more shading being the most competitive. For the most part, this aspect has not been exploited to any great degree, but it is currently being investigated in crops where a limited number of herbicide options exist, such as sweet corn. A number of studies have shown that increasing crop populations within the row, up to a point, can increase the competitive ability of the crop, with no deleterious effect on crop growth or yield.

Row spacing and time of planting can greatly influence a crop's competitive ability. Especially for soybean, narrow row spacings have enhanced the ability to compete with weeds, so that under current production practices, soybean may be more competitive than

corn. When planted in wide rows, soybeans and corn are probably closer to equal in their competitiveness. Time of planting for both corn and soybeans is earlier now than several decades ago, but this does not always enhance competitive ability. Very early planting, combined with reduced or no tillage, allows for greater weed competition as well as for a different suite of weed species to be present than historically has been common. Clearly, weeds that are established at the time of crop emergence begin to compete with the crop earlier than weeds that emerge only after the crop emerges.

With modern production practices and herbicides, do corn and soybeans differ in the ability to compete with weeds? Conclusive evidence is lacking, but many speculate that there is probably not much difference in most instances. However, soybeans, especially when vigorous varieties are grown at high populations in narrow rows, usually have an edge over corn in competitive ability, assuming that complete weed control is achieved with herbicides prior to crop canopy closure and that neither crop will be cultivated.

Weed Variables.

Weeds have been able to reproduce, survive, and compete for centuries, at least partly due to their diversity. Species of weeds, and sometimes biotypes within species, can vary greatly in growth habits and ultimately in their ability to compete with crops. Germination patterns differ markedly and sometimes erratically, causing differences in potential for competition, which can vary from year to year. Emergence and growth also vary from slow to even rapid and almost unpredictable. Different species and biotypes appear to respond differentially to various environmental conditions—only some years are a so-called “nightshade year” (or smartweed year or nutsedge year), whereas in most areas of Illinois, every year is a foxtail or velvetleaf year. Most recent years could be described as lambsquarters and pigweed years, and few could dispute the increased prevalence of waterhemp years across much of the state.

Obviously, as demonstrated in many competition studies, weeds produce markedly differing amounts of growth per individual plant and reach widely varying heights.

These studies have allowed the development of relative competitive indices that can be somewhat helpful in determining the severity of problems presented by stands of various weed species. For example, it obviously requires more foxtail plants than cocklebur or giant ragweed plants to produce the same degree of competition with corn or soybean.

The density or population of weeds required to cause a consistent yield reduction in crops has been difficult to establish. Many research studies have addressed this issue and helped establish some of the thresholds and guidelines currently available. In general, corn and soybeans can withstand low populations of weeds throughout the season without suffering yield or harvest losses; losses tend to increase linearly with increases in weed population up to some population level above which further yield reductions tend to subside (see Figure 12.7 for an illustration of the impact of giant ragweed density on soybean yield).

Establishing consistent thresholds or numbers of weeds that cause a specific yield reduction is difficult across many locations, years, and weather patterns. A synthesis of competition experiments conducted across several states and over many years suggests that improved techniques may be needed to establish and refine thresholds, since variation across locations and years almost always occurs and can be considerable. This should not be surprising, and it is most likely due to differences in environmental conditions, with special emphasis on weather patterns. General threshold guidelines would be possible, as long as a range of likely responses is given, and could cover a majority of situations.

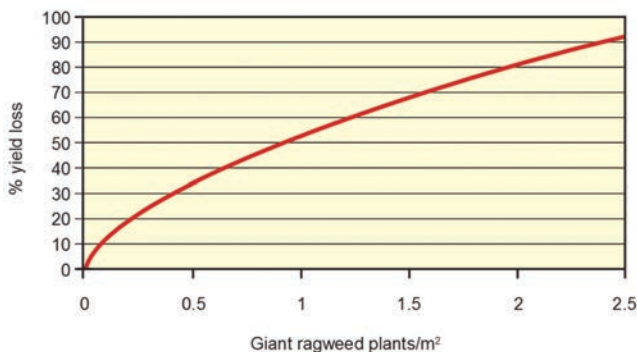


Figure 12.7. The impact of giant ragweed density on soybean yield

Lessons from Research. Numerous experiments over the years have attempted to define the critical duration of weed competition in corn and soybean and to determine the optimal time to implement weed management practices. One type of experiment is designed to determine the early-season weed-free interval needed before the crop can effectively compete with later emerging weeds and then progress independently for the remainder of the season, with no crop quantity, quality, or harvesting losses. Such experiments are especially useful in determining how much time a soil-applied herbicide needs in order to be effective after planting.

In general, for many of the weed species encountered in corn and soybean production systems of the northern U.S., the interval ranges from 3 to 6 weeks, with 4 to 5 weeks being the most frequent range needed. It is important to note that some of these studies initiated the interval at planting, while others began at crop emergence (a potentially significant difference, depending on the season and the weather). Most studies were conducted with healthy crop stands in 30 to 40-inch rows, with the objective being to obtain 4 to 5 weeks without weed competition, after which the weeds were kept under control by crop shading and one or more “lay-by” cultivations. In sharp contrast, cultivators are not used today nearly as much as they once were, and weed management after crop emergence is administered in the form of postemergence herbicides if soil-applied treatments do not last sufficiently long.

It is also important to note that these rules of thumb were developed with good crop stands and, for the most part, with the most common row crop weeds, most of which tend to emerge fairly uniformly, not in multiple flushes well into the season. As mentioned here and again later, a review of available data indicates that in most studies, there has been considerable variation from year to year, probably due to differing environmental conditions, so *it is very difficult, if not impossible, to set a specific weed-free interval that is acceptable with all species and across all locations and years.*

Another factor to consider is that many of these studies were conducted either by seeding unimbibed weed

seeds at various times after crop planting or by removing natural weed populations as needed for a specified period. These two methods effect different results, and how these results compare with a herbicide treatment that lasts the same amount of time is not defined. Does a lower dosage of a herbicide still cause some growth inhibition of later emerging weeds? These and other unanswered questions suggest extreme caution about pronouncing exact periods that are to apply over a wide variety of conditions.

Another type of experiment is designed to determine how long weeds can remain in the crop and eventually be removed with no resultant deleterious effects on quantity and quality of crop yield. In previous years this was important so that producers would know how early one needed to cultivate between the rows, as many older herbicides were applied only in a band over the row. With the growing prevalence of broadcast, selective postemergence herbicides, these types of studies became relatively more important for providing guidelines in timing postemergence herbicide applications. Until fairly recently, such competition studies were often conducted by growing various populations of weeds from crop and weed emergence until the weeds were removed either mechanically or by hand. The weeds were removed at some time after either crop planting or emergence or until certain weed heights or stages. As a general guideline, many of these studies tended to show that a moderate population of weeds could remain growing with the crop for up 3 to 6 weeks after planting, and once removed, cause little or no crop yield loss. These types of experiments also have considerable variation in results, so *again it is difficult to set specific intervals that will be valid over widely diverse conditions.*

In assessing these experiments, one needs to consider the weed species involved and their respective populations. In general, denser weed populations should be removed earlier, while less dense populations can be left to compete longer. From an applied standpoint, a problem with many competition studies is that only one weed species is considered, whereas producers' fields often contain a number of species with varying populations. Experience would suggest that more emphasis should be placed on total weed biomass

present at crop flowering and fruiting as the best indicator of loss likely to result from competition. However, this is generally well past the stage when control is possible or even feasible, and herbicides undoubtedly should be applied before this stage in most instances. *To reiterate, these types of studies are influenced greatly by the environment, which makes establishing concrete intervals arduous.*

The results of these experiments should also be closely examined with respect to how the competition (weeds) was removed. Some removed the weeds by hand but allowed any weeds that emerged afterward to grow, while others were hand-weeded throughout the season to simulate season-long control. Modern-day studies tend to focus on controlling either single species or a mixture growing at whatever population is present in the field, by applying selective postemergence herbicides at various weed sizes or growth stages. In interpreting the results of these studies, it is important to note whether the herbicide(s) used possessed any soil bioactivity that may have provided some control of weeds emerging following application. Additionally, the population and mixture of weeds are important to note; of particular importance is to note how effectively the weeds were controlled. This is important since any yield reduction noted and attributed to pre-application competition stress might actually have been partially due to post-application stress from weeds that were not controlled or from weeds that emerged after application.

Invariably, these experiments lead to a range of intervals for weed removal that work effectively under various conditions. Recommendations often tend to suggest removing competition at the average or even slightly earlier time because potentially adverse conditions might cause delays in herbicide application, resulting in weeds that would be very difficult to control. This may become especially important when dealing with weed species where later emergence might be a problem with herbicides that lack soil residual activity. Under this scenario, the conservative approach might involve adding a herbicide with soil residual activity to the mixture. As will be noted in the next section, *environmental conditions can cause significant variation in the results of these types of experiments.*

More than any other factors, soil and air temperature and soil moisture and rainfall before, during, and after initiation of competition experiments probably contribute most to the variation in results. Even the best-planned and best-conducted studies can vary considerably from location to location and year to year, often because of environmental conditions. These conditions affect weed emergence and growth, herbicide effectiveness, the competitive interaction between crop and weed, and the ability of the crop to recover from early weed competition once the weeds have been removed. *Primarily because of environmental conditions, one should be very cautious in setting precise guidelines for crop/weed competition, including thresholds for density, duration of weed-free intervals, and times of competition removal.* It would seem prudent to establish ranges of densities, times, and the like and/or to operate on the conservative side in these matters.

The total effect of weeds on crop plants is more correctly termed interference, which is the total of competition plus allelopathy. Allelopathy (the suppression of plant growth due to release of natural plant-derived substances) can and has been demonstrated, but with most of the soils and cropping situations in the Corn Belt, it is thought to be relatively minor and is very difficult to demonstrate. Thus this discussion has focused primarily on weed competition, which many consider significantly more important because it deals with plants competing for light, moisture, nutrients, and perhaps space. However, in dense infestations of weeds (such as grasses in corn), allelopathy could be a contributing factor to yield loss in addition to competition.

Competition for light may be one of the most important factors in reducing yields, especially with weeds that grow taller than the crop. Moisture stress, especially during and after removal of a very dense population of weeds, may be extremely important in how well the crop is able to recover. Many do not consider nutrient stress to be as important in the rich, fertile soils across much of the Corn Belt, but in coarse-textured soils and soils with low fertility, it may be more significant. Some research has demonstrated that weeds can exhibit “luxury consumption” of certain nutrients, such as nitrogen, to the detriment of the crop.

Those involved with developing weed management systems need to remember that the whole subject of crop–weed competition, while seemingly not simple, is even more complex in the marketplace. The fact that weed management decisions are made not only based on true crop–weed competition but on other factors as well is widely recognized. Yield and quality loss are not the only issues being considered by decision makers. Harvest difficulties and additions of weed seed to the soil seedbank are genuine concerns often not addressed in traditional competition research. Esthetic thresholds, as related to landowner perceptions, often necessitate weed control at much higher levels than what is required based simply on yield losses. Product guarantees and respray programs have also contributed to extraordinarily high levels of weed management expectations.

In summary.

Numerous experiments have investigated crop–weed competition from a variety of aspects. The results of these studies can be helpful to those making decisions about weed management, as guidelines can be prepared that indicate in general the relative competitive ability of various weeds at various densities in the major crops of the Midwest. These experiments also provide guidance for the duration of weed-free conditions needed after crop emergence and for when weeds should be removed with postemergence herbicides. Other concerns, such as producer, neighbor, and landlord perceptions, may be as important as yield loss indications from crop–weed competition studies in determining the types of weed management systems implemented.

Weed Management Practices

Effective weed management practices include those that reduce the potential for weeds to adversely impact crop growth and yield. These practices often allow the crop to utilize all available resources necessary to achieve its yield potential. Weeds require many of the same resources for growth as crop plants, and any resource utilized by the weed is unavailable for use by the crop. The most common weed management practices in Illinois agronomic crops include cultural, mechanical, and chemical approaches.

Cultural weed management practices allow the crop to become established without experiencing any negative effects of weed interference. Proper crop variety selection and planting date, adequate soil fertility and pH, and crop row spacing are examples of factors that can be manipulated to improve the competitive ability of the crop.

Mechanical weed management involves physical disturbance of the weeds, through activities including pulling weeds, tilling the soil before or after weeds emerge, and mowing.

Chemical Weed Control

Herbicides are often the primary tools of choice for weed management across most acres of the Midwest. Many different herbicides and herbicide formulations are commercially available, including soil-applied and foliar-applied products, selective and nonselective products, products with long soil persistence, and products with no soil residual activity. The selection of which herbicide to use should be based on multiple factors, including soils, cropping rotations, tillage practices, and weed species. Sole dependence on herbicides may not necessarily provide the most economical or sustainable weed management. Integrating multiple practices reduces the likelihood of poor weed control due to unfavorable environmental conditions and reduces the intensity of selection for herbicide-resistant weeds.

Product Labels. Every herbicide product commercially available is required by law to have a label. The label provides a great deal of information about the product, including how it is to be applied, where, and in what quantity. The label is considered a legal document; using a herbicide in a manner inconsistent with its labeling is illegal. Herbicide labels change frequently, so be sure to consult the most current label when using a product. All pesticide products for sale in Illinois must be registered with the state government.

Application Rates. Herbicides applied at labeled rates should provide good weed control during the season of use while minimizing the potential for in-season crop injury and carryover into the following season. Herbicide application rates can vary according to many factors.

Rates for soil-applied herbicides are greatly influenced by soil characteristics, such as organic matter content, texture, and pH. In general, heavy-textured soils high in organic matter often require a higher application rate than coarse-textured soils lower in organic matter. Application rates of postemergence herbicides are often determined by weed species and weed and crop size. For some postemergence products, higher application rates are suggested when certain weed species are present and/or when one or more weed species exceed a specified height or number of leaves.

Often several different commercially available formulations or premixes contain the same herbicide active ingredient. Much of the following text will demonstrate how to determine product equivalents and how to calculate amounts of active ingredient applied. Keep in mind that just because two or more products contain the same ingredient(s) does not necessarily mean they are applied at the same rates. Always consult the respective product label to determine the appropriate application rate.

Nomenclature. Across its lifetime a herbicide active ingredient may be sold by one or more companies and identified by one or more names. The three most common categories of names are trade, common, and chemical.

Trade names. The trade name is the name under which a product is commercially sold; it is often the name most familiar to users. Examples of trade names include Valor, Raptor, Yukon, Basagran, and Cobra. These names are typically trademarked by the manufacturer so that no other company can use them. Trade names come and go, and sometimes they are recycled (for example, Option was once the trade name of a soybean herbicide but then became the trade name of a corn herbicide). You thus cannot always rely on the trade name to know what active ingredient(s) a product contains.

Common names. Each common name is unique to a particular active ingredient. Common names are listed on the product label, usually in the active ingredient section. Flumioxazin, imazamox, halosulfuron plus dicamba, bentazon, and lactofen are the common names of the active ingredients contained in the commercial

products Valor, Raptor, Yukon, Basagran, and Cobra, respectively. While more than one trade name may be used for a particular active ingredient, common names remain constant irrespective of trade names.

Chemical names. Herbicide chemical names may not be as familiar as trade names or common names. Like common names, a chemical name is unique to a particular active ingredient, describing its chemical composition. For example, Salvo is the trade name of a herbicide with the active ingredient known by the common name 2,4-D, whose chemical name in turn is 2,4-dichlorophenoxyacetic acid.

Active Ingredients. The active ingredient of a pesticide formulation is the component responsible for its toxicity (phytotoxicity in the case of herbicides) or its ability to control the target pest. The active ingredient is always identified on the pesticide label, either by common name (for example, atrazine) or chemical name (for example, 2,4-dichlorophenoxyacetic acid). The active ingredient statement may also include information about how the product is formulated and the amount of active ingredient contained in a gallon or pound of formulated product. For example, the Basagran label indicates that the active ingredient (bentazon) is formulated as the sodium salt, and 1 gallon of Basagran contains 4 pounds active ingredient.

Usually when a herbicide trade name is followed by a number and letter designation (4L, 75DF, 7EC, etc.), the number indicates the pounds of active ingredient in a gallon (for liquid formulations) or a pound (for dry formulations) of the formulated product. So, for example, Basagran 4L contains 4 pounds of active ingredient (bentazon) per gallon of formulated product, AAtrex 90DF contains 0.90 pounds of active ingredient (atrazine) per pound of formulated product, and Prowl 3.3EC contains 3.3 pounds of active ingredient (pendimethalin) per gallon of formulated product.

Many herbicide labels restrict the maximum amount of product to be used per application and/or per year. These maximum rates are generally presented in terms of the total amount of active ingredient that can be applied per acre and/or per year. Several calculations can be used to

determine the amount of active ingredient applied at a given product use rate. This is one of the easiest:

$$\begin{aligned} & \text{lb active ingredient applied per acre} \\ &= \frac{\text{gal of lb of product applied}}{\text{acre}} \times \frac{\text{lb active ingredient}}{\text{gal or lb of product}} \end{aligned}$$

So, if we apply this equation to Basagran 4L, the amount of active ingredient (bentazon) applied at 2 pints (0.25 gallon) of product per acre is:

$$\begin{aligned} & \text{lb of bentazon (active ingredient) applied per acre} \\ &= \frac{0.25 \text{ gal of product applied}}{\text{acre}} \times \frac{4 \text{ lb active ingredient}}{\text{gal of product}} \\ &= 1 \text{ lb active ingredient per acre} \end{aligned}$$

Types of Formulation. There are several ways to define formulation, but in essence it consists of the active ingredient and all associated components that make up the commercially available product. The active ingredient is responsible for controlling target weeds, but it rarely is the only component in a gallon or a pound of commercial herbicide. Other ingredients serve various functions, such as making the active ingredient safer and easier to handle, allowing the active ingredient to easily mix with water, and aiding herbicide uptake through plant leaves. These other components of a herbicide formulation are generally listed as inert ingredients on the product label, although they have important functions in making the active ingredient work as intended.

Several types of herbicide formulations are available, and a given herbicide active ingredient may be available in more than one formulation. Formulations are often designated on product labels as single or two-letter abbreviations. The more common herbicide formulations, along with their abbreviations, are presented in Table 12.3.

Acid equivalents. In some instances, the number preceding the formulation designation (L, EC, DF, etc.) indicates not pounds of active ingredient per gallon or pound, but rather acid equivalent per gallon or pound. Acid equivalent may be defined as that portion of a formulation (as in the case of 2,4-D ester, for example) that theoretically could be converted back to the corresponding or parent acid. Another definition is the theoretical yield

Table 12.3. Common examples of herbicide formulations.

Type of formulation	Description of formulation
Flowable or aqueous suspension (F, L, or AS)	Liquid formulation containing finely ground solids suspended in a liquid
Water-soluble concentrate	Liquid formulations that form a true solution when added to water
Emulsifiable concentrate (EC or E)	Liquid formulation containing solvents and emulsifiers that disperse the active ingredient in water
Water-dispersible granule or dispersible granule (WDG or DG)	Dry formulation in which the active ingredient is sorbed onto aggregated granular particles
Dry flowable (DF)	Dry formulation very similar to water-dispersible granules
Wettable powder (WP or W)	A finely ground dry formulation (often mineral clays) onto which the active ingredient is sorbed
Granule (G)	Dry formulation in which the active ingredient is coated onto an inert granule, ready to use without diluting in a liquid carrier
Capsule suspension (CS)	A stable suspension of capsules in a fluid, normally intended for dilution with water

of parent acid from a pesticide active ingredient that has been formulated as a derivative (esters, salts, and amines are examples of derivatives). For example, the acid equivalents of the isooctyl and ethyl acetate ester formulations of 2,4-D are 66% and 88%, respectively. Why would a herbicide (one that has the acid as the parent molecule) be formulated as a derivative of the parent acid? An illustration using 2,4-D follows.

The herbicide active ingredient 2,4-D, originally discovered in the 1940s, continues to show utility across a diversity of landscapes. The herbicide is a popular tool among homeowners for selectively controlling certain broadleaf weed species in turf, and it is frequently a component of burndown herbicide applications in no-till agronomic cropping situations. Many commercially available 2,4-D formulations and trade names exist, but not all formulations and products are identical.

One characteristic of 2,4-D-containing products of particular importance is the type of formulation. Most often, 2,4-D products are available as one of three formulations: acid, amine, or ester. Each type has unique characteristics that can influence where and how a particular product is used.

Figure 12.8 illustrates the chemical structure of 2,4-D. The molecule is considered a weak acid because the carboxyl hydrogen atom (the one to the far right) can dissociate, imparting a net negative charge to the molecule. In the dissociated (negatively charged) form,

the acid molecule is very soluble in water but is not readily absorbed through a plant leaf. The waxy cuticle that covers the leaf surface is composed of many non-charged substances that reduce the ability of a charged molecule to penetrate and enter the plant. Somehow altering the parent acid form can influence how quickly and thoroughly it enters a plant through the leaf. These alterations produce derivatives that have physical and chemical properties different from the parent acid, such as increased ability to penetrate through a waxy leaf or increased water solubility for enhanced root uptake. The two most common derivatives of 2,4-D acid are amines and esters.

Esters are formed by reacting the parent acid with an alcohol, while amine salts are formed when the parent acid is reacted with an amine. The isooctyl ester is a very common ester formulation of 2,4-D, and the ammonium salt is perhaps the most common amine formulation. Other esters and amine salt formulations, however, are commercially available.

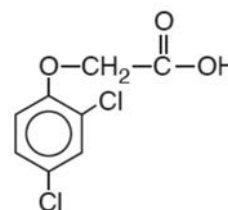


Figure 12.8. 2,4 D parent acid.

Table 12.4. Comparisons between amine and ester formulations of 2,4-D.

Amine salt	Ester
High water solubility	Generally insoluble in water
Low solubility in oils and waxes	Higher solubility in oils and waxes
Slow absorption into plant leaves	Faster absorption into plant leaves
No or very low volatility potential	Low to high volatility potential
Clear or slightly amber colored in water	Milky when mixed in water
Does not mix well with liquid fertilizers	More compatible with liquid fertilizers
Less preferred formulation for no-till burndown applications	Preferred formulation for no-till burndown applications
Reduced probability of crop injury following postemergence application	Greater probability of crop injury following postemergence application
Preferred formulation for in-crop (i.e., corn) applications when air temperatures exceed 85 °F	Less preferred formulation for in-crop (i.e., corn) applications when air temperatures exceed 85 °F

As previously mentioned, these different types of derivatives impart different characteristics to the formulation. For example, the isooctyl ester formulation is more soluble in hydrophobic (“water-avoiding”) substances, like waxes, while amines are more soluble in hydrophilic (“water-loving”) substances. In practical terms, esters are better able than amines to penetrate the waxy leaf surface of weeds, whereas amines are more easily moved into the soil by rainfall for root uptake (an important characteristic in certain brush-control applications). Table 12.4 provides some general comparisons between the amine and ester formulations of 2,4-D. These comparisons are somewhat relative since the specific type of amine salt or ester chain length can influence some characteristics. For example, ester formulations are considered more volatile (the change from a liquid state to a vapor state) than amine formulations, but the actual volatility potential of the ester formulation is influenced by the length of the ester chain (the number of carbon atoms). Also, remember that different derivatives can impact the amount of active ingredient contained in a quantity of formulated product. To accurately compare among various products, calculations of “equivalency” should be based on the amount of acid equivalent contained in the formulation rather than the amount of active ingredient. An example follows of how to calculate acid equivalents, using ester formulations of 2,4-D as examples.

2,4-D can be formulated as various esters. The chain length of the ester can vary, but it is most commonly eight carbon atoms long (isooctyl ester). For this example, consider two ester formulations of 2,4-D: the first has only two carbon atoms forming the ester, and the second has eight carbons forming the ester. The parent acid is the same in these two formulations; the only difference is the length of the ester. These can be visualized in several diagrams.

Figure 12.8 illustrates the parent acid of 2,4-D; Figure 12.9 shows the parent acid formulated with a two-carbon side chain, and Figure 12.10 shows an eight-carbon side chain. While the carbon atoms of the side chain may modify some aspect of herbicide performance, it is the parent acid (Figure 12.8) that acts at the target site within the plant. The additional carbon atoms of the ester side chain add weight to the formulation and may increase the amount of active ingredient of a formulation, but these atoms do not increase the amount of parent acid in the formulation. If these formulations were commercially

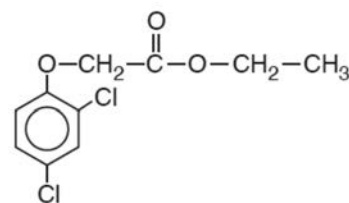


Figure 12.9. 2,4-D ethyl acetate ester.

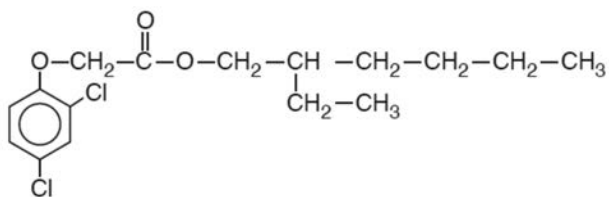


Figure 12.10. Isooctyl ester of 2,4 D.

available, and someone wanted to know how much of the parent acid each contained, the calculation would be based on the acid equivalents, not the active ingredients, of the formulations.

Assume that both the two-carbon and eight-carbon ester formulations (Figures 12.9 and 12.10, respectively) are commercially available and that each formulation contains 4 pounds of active ingredient per gallon. The application rate for both products is 1 pint per acre. Since the application rates and the pounds of active ingredient per gallon are identical for the two formulations, the amount of active ingredient applied would be the same for each. Verify this by performing the calculations previously illustrated for determining the amount of active ingredient applied. Even though the amounts of active ingredient applied are the same for the two formulations, the amounts of acid applied are not the same. Remember, it is the parent acid that binds to the target site to control the weed; the ester portion of the formulation is not involved in binding to the target site. What, then, is required to determine the amount of acid applied (i.e., the acid equivalent)?

The first step is to determine the amount of acid equivalent in a gallon of formulated product. Some labels indicate the amounts of both active ingredient and acid equivalent in a formulation, while others list only active ingredient. If the pounds acid equivalent is specified on the product label, all one need do to determine the pounds acid equivalent applied per acre is to substitute pounds acid equivalent for pounds active ingredient in the equation presented previously for calculating the pounds active ingredient applied. For this example, assume that neither 2,4-D label indicates the amount of acid equivalent.

The formula that can be used to calculate the amount of acid equivalent in a gallon of formulated product is:

$$\text{acid equivalent} = \frac{\text{molecular weight of the acid} - 1}{\text{molecular weight of the salt or ester}} \times 100$$

Some molecular weights (i.e., how much the molecule weighs) are needed to complete these calculations. The molecular weight of the parent 2,4-D acid is 221.04. The molecular weight of the two-carbon ester formulation is 29.02 (weight of the two carbons and five hydrogens) + 221.04 (weight of the parent acid) = 250.06. The molecular weight of the eight-carbon ester formulation is 333.25. The acid equivalent of the **two-carbon** ester formulation is:

$$\text{acid equivalent} = \frac{221.04 - 1}{250.06} \times 100 = 88\%$$

Thus, the amount of *acid equivalent* in one gallon of formulated product is:

$$88\% \text{ acid equivalent} \times \frac{4 \text{ lb active ingredient}}{\text{gal}} = 3.52 \text{ lb ae}$$

The acid equivalent of the **eight-carbon** ester formulation is:

$$\text{acid equivalent} = \frac{221.04 - 1}{333.25} \times 100 = 66\%$$

Thus, the amount of *acid equivalent* in 1 gallon of formulated product is:

$$66\% \text{ acid equivalent} \times \frac{4 \text{ lb active ingredient}}{\text{gal}} = 2.64 \text{ lb ae}$$

Again, each product is applied at 1 pint (0.125 gallon) per acre, and because each formulation contains 4 pounds active ingredient per gallon, the amounts of *active ingredient* applied are equal. The amounts of *acid* (that part of the formulation that actually controls the weed) applied for each formulation are *not* equal.

The amount of *acid* applied per acre with the **two-carbon** ester formulation is:

$$\begin{aligned} & \text{lb of acid equivalent applied per acre} \\ &= \frac{0.125 \text{ gal of product applied}}{\text{acre}} \times \frac{3.52 \text{ lb ae}}{\text{gal of product}} \\ &= 0.44 \text{ lb ae per acre} \end{aligned}$$

The amount of *acid* applied per acre with the **eight-carbon** formulation is:

$$\begin{aligned} & \text{lb of acid equivalent applied per acre} \\ &= \frac{0.125 \text{ gal of product applied}}{\text{acre}} \times \frac{2.64 \text{ lb ae}}{\text{gal of product}} \\ &= 0.33 \text{ lb ae per acre} \end{aligned}$$

This example demonstrates that more 2,4-D acid is applied with the two-carbon ester formulation than with the eight-carbon formulation. In practical terms, more of the part of the formulation that actually controls the weeds was applied with the two-carbon ester formulation. To compare the herbicidally active portion of two ester, salt, or amine formulations, product equivalents should be calculated on the *acid equivalent*.

If only one formulation of a salt or ester product is commercially available, it would not really matter if one calculated active ingredient or acid equivalent. For example, Pursuit is formulated as the ammonium salt of imazethapyr, but currently this is the only salt formulation commercially available for use in agronomic crops. There are, however, several commercial formulations of 2,4-D and glyphosate. Not all of these formulations contain the same amount of *acid equivalent*, so to determine equivalent rates among different formulations, calculations should be based on acid equivalent rather than active ingredient.

Since the commercialization of glyphosate-resistant soybean varieties in 1996, the number of glyphosate-containing products commercially available has increased dramatically. More than 50 such products are registered for use in Illinois agronomic crops, and that number is expected to continue increasing. Keeping track of product names and formulations can be daunting.

When selecting one of these products for weed control, keep several important considerations in mind: How

much acid equivalent (ae) does the formulation contain? Should a spray additive (such as nonionic surfactant) be added to the tank, or does the formulation contain a “built-in” additive system? Are factors such as rain-free interval and toxicity category similar in the products you are considering? Once these questions have been answered and you have narrowed down the list of products you are interested in purchasing, how can you compare costs? Should price comparisons be based simply on cost per gallon of formulated product? As in determining equivalent application rates, producers should compare prices on an acid equivalent basis.

To compare prices among glyphosate-containing products you need to do a few simple calculations. First, determine what rate to apply based on weed spectrum and size. For well-timed applications, a rate of 0.75 lb ae/acre can be very effective on many broadleaf and grass species. Once you have determined the application rate, calculate how many fluid ounces of each product are needed for this rate. Next, convert the price per gallon for each product to price per fluid ounce. Finally, multiply the number of fluid ounces needed to achieve the 0.75 lb ae/acre rate for each product by the cost per fluid ounce. An example to illustrate these calculations follows.

You decide to apply a glyphosate-containing product at 0.75 lb ae/acre when most broadleaf weeds are 4 inches tall. You are deciding between two glyphosate-containing products and want to know which offers the lowest cost per acre (for purposes of this example, assume additive requirements, if any are required by label, are identical for each product). “Glyfo A,” a potassium salt, contains 4 lb ae per gallon and costs \$23 a gallon. “Glyfo B,” an isopropylamine salt, contains 3 lb ae per gallon and costs \$21.75 a gallon.

Start by calculating how many fluid ounces are needed for an application rate of 0.75 lb ae/acre:

Glyfo A:

$$\frac{0.75 \text{ lb ae}}{\text{acre}} \times \frac{1 \text{ gal}}{4 \text{ lb ae}} \times \frac{128 \text{ fl oz}}{\text{gallon}} = 24 \text{ fl oz}$$

Glyfo B:

$$\frac{0.75 \text{ lb ae}}{\text{acre}} \times \frac{1 \text{ gal}}{3 \text{ lb ae}} \times \frac{128 \text{ fl oz}}{\text{gallon}} = 32 \text{ fl oz}$$

Next, divide the price per gallon by 128 to determine price per fluid ounce:

Glyfo A:

$$\frac{\$23.00}{128 \text{ fl oz}} = \$0.1797 \text{ per fl oz}$$

Glyfo B:

$$\frac{\$21.75}{128 \text{ fl oz}} = \$0.1699 \text{ per fl oz}$$

Finally, multiply cost per fluid ounce by the number of fluid ounces needed to achieve an application rate of 0.75 lb ae/acre:

Glyfo A:

$$\frac{\$0.1797}{\text{fl oz}} \times \frac{24 \text{ fl oz}}{\text{acre}} = \$4.31 \text{ per acre}$$

Glyfo B:

$$\frac{\$0.1699}{\text{fl oz}} \times \frac{32 \text{ fl oz}}{\text{acre}} = \$5.44 \text{ per acre}$$

So, while a gallon of Glyfo A costs \$1.25 more than a gallon of Glyfo B, calculating costs on an acid equivalent basis reveals that the per-acre cost is \$1.13 less with Glyfo A than with Glyfo B.

Determining how many pounds of acid equivalent are contained in a given formulation may seem the most daunting part of this exercise, but several references are available that list the amount of acid equivalent in many commercially available glyphosate formulations. Table 12.5 compares a number of glyphosate-containing products based on the amount of acid equivalent per gallon. The table also lists the amount of product (in fluid ounces) needed to apply a range of acid equivalents (0.375-1.5 lb per acre).

Herbicide isomers. Herbicide isomers may not be very familiar to weed management practitioners, but they are becoming increasingly common in the marketplace. In essence, herbicide isomers are variations of a molecule, put together in slightly different arrangements. One isomer of a particular active ingredient is generally much more herbicidally active than the other isomer. A small amount of chemistry can help explain stereoisomers and how they are relevant in today's weed management arena.

A good starting point might be to define the term *stereoisomer*. Stereoisomers are molecules that have the same atoms bonded to each other but differ in how the atoms are arranged in space. Figure 12.11 and Figure 12.12 will serve as examples for the following

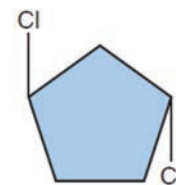


Figure 12.11. A 5-carbon ring with two chlorine atoms, one positioned above the plane of the ring and the other below.

Table 12.5. Glyphosate-containing herbicides.

Active ingredient/ gal	Acid equivalent/ gal	Product rate equivalent to (lb acid equivalent/A)				
		0.375	0.56	0.75	1.13	1.5
		fl oz				
4	3	16	24	32	48	64
5	3.68	13	19.5	26	39	52
5.4	4	12	18	24	36	48
5.14	4.17	11.5	17	23	35	46
5.5	4.5	11	16	21	32	43
6.16	5	10	14	19	29	38

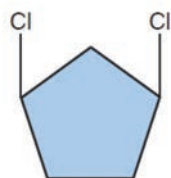


Figure 12.12. The same 5-carbon ring as shown in Figure 12.11, but here both chlorine atoms are positioned above the plane of the ring.

discussion. Figure 12.11 illustrates a 5-carbon ring molecule with two chlorine atoms attached to it; one chlorine atom is positioned above the plane of the ring, while the other is positioned below. Figure 12.12 shows the same 5-carbon ring with the same two chlorine atoms, but here both chlorine atoms are positioned above the plane of the ring. Each molecule contains the same number of atoms—5 carbon and 2 chlorine—but the spatial arrangement of the chlorine atoms differs, which is what differentiates this pair of stereoisomers. An analogy of stereoisomers is a person's two hands; each hand consists of the same components, but they are assembled differently. You cannot rotate your right hand to make it a left hand, and vice versa.

So how is a differential orientation of atoms or substituent groups (i.e., stereoisomers) relevant to weed management? Even though two molecules may have the same types and numbers of atoms and differ only in the orientation of one or more atoms or groups, differential orientations can greatly affect the biological activity of the molecules. If, for example, the molecules depicted in Figure 12.11 and Figure 12.12 were herbicides, the orientation of the chlorine atoms in Figure 12.11 might cause that isomer to bind much more effectively at the herbicide target site within the plant, whereas the orientation of the chlorine atoms in Figure 12.12 might not allow this isomer to bind the target site at all. One might reason that if the molecule depicted in Figure 12.11 is more herbicidally active than the molecule depicted in Figure 12.12, it would be better to manufacture or use a product containing the Figure 12.11 molecule only. While this notion is valid, the process used to manufacture certain herbicides results in a combination of isomers (that is, a mixture of the two molecules) in the commercially available formulation. An example of stereoisomer chemistry in weed management is the active ingredient metolachlor.

Metolachlor first became commercially available during the 1970s and was sold under the trade name Dual. The process used to manufacture Dual resulted in two isomers of metolachlor present in the commercial formulation. One isomer, designated the S-isomer, is much more herbicidally active than the other, designated the R-isomer. Dual and the subsequent product Dual II each contained a 50:50 mixture of the active (S) and inactive (R) isomers of metolachlor. (Dual became Dual II when a safener was added to the original formulation to reduce the potential for adverse crop response.) Application rates for these “nonresolved” formulations were determined based on this 50:50 mixture of active and inactive isomers.

In the 1990s, improvements in technology allowed manufacturers to increase the amount of active (S) isomer in a formulation, and Dual II became Dual II Magnum. The “Magnum” formulations (Dual II Magnum, Bicep II Magnum, Bicep Lite II Magnum) still contain the same active ingredient(s) as always, but they now contain a higher proportion of the active or resolved (S) isomer compared with the older formulations (Dual and Dual II, Bicep and Bicep II, Bicep Lite and Bicep Lite II). Specifically, the Magnum formulations contain an 88:12 mixture of the active (S):inactive (R) isomers compared with a 50:50 mixture of the active (S):inactive (R) isomers found in the Dual and Dual II formulations. So what is a practical implication of having a formulation containing more of the active isomer? Since a higher proportion of the active isomer is present in the Magnum formulations, application rates are reduced approximately 35% compared with the original formulation.

Perhaps another illustration will be of value. Say, hypothetically, you were to count out 100 molecules from a container of Dual II and 100 molecules from a container of Dual II Magnum. Assuming the rules of probability hold, the 100 molecules of Dual II would be 50 active molecules (the S or resolved isomer) and 50 inactive molecules (the R or unresolved isomer). The 100 molecules of Dual II Magnum would be 88 active and 12 inactive molecules.

Assuming the unresolved isomer does not contribute

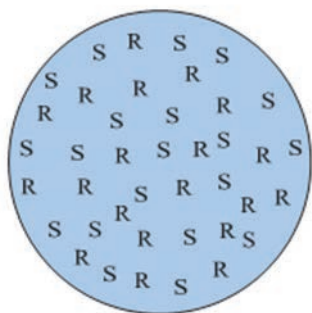


Figure 12.13. A droplet taken from a container of a non- resolved metolachlor-containing herbicide (50:50 mixture of S and R isomers). Note the equal numbers of S and R letters.

much to weed control, it takes less Dual II Magnum than either Dual or Dual II to obtain the critical number of S-metolachlor molecules needed for weed control. For example, if 50 molecules of S-metolachlor (the active isomer) are needed to achieve control of a particular weed species, how many total molecules of Dual/Dual II and Dual II Magnum would you need in order to apply at least 50 molecules of S-metolachlor? You would need 100 total molecules of Dual or Dual II (50:50 mixture) to get 50 molecules of S-metolachlor, whereas you would need only 57 total molecules of Dual II Magnum (88:12 mixture) to get 50 molecules of S-metolachlor. Stated another way, if you were to apply the same product rate of Dual and Dual II Magnum, you would apply less active isomer per acre from the Dual formulation.

Figure 12.13 and Figure 12.14 illustrate this concept. The circles represent equal volumes of herbicide. Figure 12.13 was taken from a container of a nonresolved metolachlor-containing herbicide (50:50 mixture of S and R isomers) while Figure 12.14 was taken from a container of a resolved metolachlor formulation (88:12 mixture

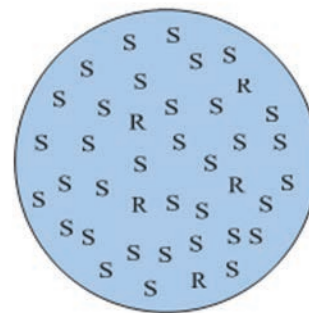


Figure 12.14. A droplet taken from a container of a re- solved metolachlor-containing herbicide (88:12 mixture of S and R isomers). Note the higher proportion of S letters relative to R letters.

of S and R). Each circle contains the same number of total molecules (designated S and R), but a different proportion of S and R isomers.

This information should help those who purchase herbicides made up of stereoisomers better understand some of the differences among commercially available products. Currently there are many metolachlor and S-metolachlor products on the market, and there appears to be some confusion about product equivalents among these many formulations. For example, equivalent rates may be defined several ways, including equivalent amounts of active ingredients, equivalent amounts of active isomers, or simply the rates allowed by the respective product label. These are not always synonymous or interchangeable.

Table 12.6 lists several examples of products containing metolachlor or S-metolachlor. One should not assume that applying the same rate of each product necessarily results in applying the same amount of active ingredient or active isomer. In particular, it should be noted

Table 12.6. Metolachlor- and S-metolachlor-containing herbicides.

Product	Active ingredient	Active ingredient/ gal	R:S mixture (ratio)	If you apply (product/A):	You have applied	
					Lb/ai	Lb active isomer
Dual	metolachlor	8 lb	50:50	2.5 pt	2.5	1.25
Dual II	metolachlor	7.8 lb	50:50	2.5 pt	2.43	1.218
Dual Magnum	S-metolachlor	7.62 lb	88:12	1.67 pt	1.59	1.399
Dual II Magnum	S-metolachlor	7.64 lb	88:12	1.67 pt	1.59	1.403
“Generic I” brand	metolachlor	8 lb	50:50	1.67 pt	1.67	0.835
“Generic II” brand	metolachlor	7.8 lb	50:50	1.67 pt	1.62	0.814

Table 12.7. Metolachlor- and S-metolachlor-containing herbicides.

Herbicide	Components (ai/gal or lb)	If you apply/A:	You have applied (ai):	Product equivalents:
Bicep II Magnum 5.5L	S-metolachlor = 2.4 lb atrazine = 3.1 lb	2.1 qt	S-metolachlor = 1.26 lb atrazine = 1.63 lb	Dual II Magnum 7.64E = 1.32 pt AAtrex 4L = 3.26 pt
Harness Xtra 5.6L	acetochlor = 3.1 lb atrazine = 2.5 lb	2.5 qt	acetochlor = 1.94 lb atrazine = 1.56 lb	Harness 7E = 2.21 pt AAtrex 4L = 3.13 pt

that while applying the same product rates of an S-metolachlor-containing product and metolachlor-containing product can provide similar amounts of total active ingredient, the amounts of the active isomer applied can vary considerably.

Herbicide premixes. Herbicide premixes are commercially formulated products containing more than one herbicide active ingredient. Combining two or more active ingredients in a formulated product can provide several advantages, including a broader weed control spectrum than any individual component has alone, reduced potential for physical or chemical incompatibility problems, and reduced cost compared with purchasing the components separately and mixing them.

Herbicide premixes can be confusing with respect to components, product equivalents, application rates, and other factors. Table 12.7 compares two commercially available corn herbicide premixes used in Illinois. The first column lists the trade name and formulation of the herbicide, and the second provides the common names for the components. For example, Harness Xtra (trade name) 5.6L (formulation) is composed of the active ingredients acetochlor (common name) and atrazine (common name). The second column also indicates the amount of active ingredient (or sometimes acid equivalent) of each component per gallon or pound of formulated product.

The third column lists an application rate for each premix, and the fourth column indicates how much of each active ingredient is applied at that application rate. For example, 2.5 quarts of Harness Xtra 5.6L provides 1.94 lb acetochlor active ingredient and 1.56 lb atrazine

active ingredient. Note here that while application rates of commercial products are usually expressed in ounces, pounds, pints, or quarts of product per acre, active ingredients are usually expressed in units of pounds active ingredient or acid equivalent per acre.

The last column lists product equivalents for each premix component when applied at the application rate listed in the third column. The 2.5-quart rate of Harness Xtra 5.6L provides the same amount of acetochlor and atrazine contained in 2.21 pints of Harness 7E and 3.13 pints of AAtrex 4L, respectively.

The application rate of Harness Xtra 5.6L listed in Table 12.7 is 2.5 quarts per acre. Instead of 2.5 quarts, suppose someone would like to know how much acetochlor and atrazine are applied at a 2-quart rate of Harness Xtra 5.6L.

First, convert 2 quarts to gallons:

$$\frac{2 \text{ qt}}{\text{acre}} \times \frac{1 \text{ gal}}{4 \text{ qt}} = 0.5 \text{ gal}$$

Next, calculate how much acetochlor and atrazine active ingredient are contained in 0.5 gallon of Harness Xtra 5.6L.

$$\frac{0.5 \text{ gal}}{\text{acre}} \times \frac{3.1 \text{ lb ai acetochlor}}{\text{gal}} = 1.55 \text{ lb ai acetochlor per acre}$$

Finally, determine product equivalents based on these active ingredient amounts:

$$\frac{0.5 \text{ gal}}{\text{acre}} \times \frac{2.5 \text{ lb atrazine}}{\text{gal}} = 1.25 \text{ lb ai atrazine per acre}$$

Principles of Soil-Applied Herbicides. Soil-applied herbicides remain an important part of weed management programs in corn and soybean production systems. Early preplant (EPP), preplant incorporated (PPI), and preemergence (PRE) surface are the most common types of herbicide applications to soil. EPP applications are typically made several weeks prior to planting and are more common in corn fields than soybean fields. PPI applications were once very common, but they have declined in recent years with the growing adoption of conservation tillage. PRE applications are generally made within one week of crop planting. Regardless of when or how a herbicide is applied to the soil, the effectiveness of soil-applied herbicides is influenced by several factors.

For a soil-applied herbicide to be effective, it needs to be available for uptake by the weed seedling (usually before the seedling emerges, but some soil-applied herbicides can control small, emerged weeds under certain conditions). Processes such as herbicide adsorption to soil colloids or organic matter can reduce the amount of herbicide available for weed absorption. Soil-applied herbicides do not prevent weed seed germination; rather, they are first absorbed by the root or shoot of the seedling and then exert their phytotoxic effect. Generally, this happens before the seedling emerges from the soil. For a herbicide to be absorbed by weed seedlings, the herbicide must be in the soil solution or vapor phase (i.e., an available form). How is this achieved? The most common methods for herbicides to become dissolved into the soil solution are by mechanical incorporation or precipitation. EPP applications in no-till systems attempt to increase the likelihood that sufficient precipitation will be received before planting to incorporate the herbicide. If, however, no precipitation is received between application and planting, mechanical incorporation (where feasible) will, in most instances, adequately move the herbicide into the soil solution. Herbicide that remains on a dry soil surface after application may not provide much effective weed control and is subject to various dissipation processes, some of them described in subsequent paragraphs.

Many weed species, in particular small-seeded ones, germinate from fairly shallow depths in the soil. The

top 1 to 2 inches of soil is the primary zone of weed seed germination and should thus be the target area for herbicide placement. Shallow incorporation can be achieved by mechanical methods or precipitation. Which method is more consistent? Precipitation provides for fairly uniform incorporation, but mechanical incorporation reduces the absolute dependence on receiving timely precipitation. How much precipitation is needed and how soon after application it should be received for optimal herbicide performance depends on many factors, but generally 1/2 to 1 inch of rain within 7 to 10 days is sufficient.

Herbicides remaining on the soil surface, or those placed too deeply in the soil, may not be intercepted by the emerging weed seedlings. Herbicides on the soil surface are subjected to several processes that reduce their availability. Volatility (the change from a liquid to gaseous state) and photolysis (degradation due to absorption of sunlight) are two common processes that can reduce the availability of herbicides remaining on the soil surface. Volatility potential is determined by several properties of the soil and the herbicide formulation, while photolysis is dependent primarily on herbicide properties.

Dry soil conditions are conducive for planting, but they may also reduce the effectiveness of soil-applied herbicides. If herbicide applications are made prior to planting and no precipitation is received between application and planting, a shallow mechanical incorporation prior to planting may help preserve much of the herbicide's effectiveness.

Principles of Postemergence Herbicides.

Postemergence herbicides are a key part of an integrated weed management program. Applications made after crops and weeds have emerged allow for identifying the weed species present and assessing the severity of infestation so that herbicide selection can be tailored to the particular field. Postemergence herbicide applications minimize the interactions of the herbicide with factors associated with soil (such as texture and organic matter content), but they often magnify interactions between the herbicide and prevailing environmental conditions.

To achieve weed control with postemergence herbicides, the herbicide must come in contact with the target, be retained on the leaf surface prior to absorption into the plant, be able to reach the site of action within the plant, and finally induce some phytotoxic response. If for any reason one or more of these steps is restricted or limited, the level of weed control can be expected to decline.

The plant cuticle serves as an outer protective layer, or “barrier,” that restricts the amount of water lost by the plant through transpiration. It also serves a variety of other functions, and the cuticle is often considered the primary barrier that limits herbicide absorption. The cuticle is composed primarily of waxes and cutin, substances that effectively limit water movement out of the leaf (transpiration) or into it (absorption). The type and amount of wax that comprises the cuticle influences the degree of wetting that can be achieved, and this composition can change with plant age and in response to changes in the environment. Older plants and plants under environmental stress generally have more wax or a different structure of the wax comprising their cuticles and are thus more difficult to wet. One of the main functions of certain spray additives is to enhance herbicide penetration through the cuticle.

Plant age and size, relative humidity, soil moisture, and temperature are other factors that influence absorption of postemergence herbicides. Younger, smaller plants usually absorb herbicide more rapidly than older, more mature plants. Many postemergence herbicide labels recommend applications be made when target weeds are small and caution about reduced effectiveness if applications are made to larger plants. Labels of postemergence herbicides may also suggest that users delay applications if weeds are under “adverse environmental conditions.” Examples of such adverse environmental conditions may include prolonged periods without significant precipitation (resulting in dry soil) or low air temperatures. On the other hand, high relative humidity, adequate soil moisture, and moderate to warm air temperatures all favor enhanced herbicide absorption. Remember that if conditions occur that enhance herbicide absorption into weeds, conditions also are favorable for enhanced absorption into the crop, which may result in crop injury.

Postemergence herbicides vary in their mobility within the plant. Some demonstrate very limited movement following absorption and are commonly referred to as “contact” herbicides. Others can move extensively within the vascular elements of the plant and are referred to as “translocated” herbicides. Contact herbicides do show some movement following absorption, but they do not move nearly as extensively as translocated herbicides. Thorough spray coverage of the plant foliage is very important with contact herbicides but somewhat less important with translocated herbicides.

Almost every postemergence herbicide has a preharvest interval specified on the label or a crop developmental stage beyond which applications should not be made. Labels of some products indicate both a developmental stage and a preharvest interval. A preharvest interval indicates the amount of time that must elapse between herbicide application and crop harvest. Such intervals are established to allow sufficient time for the herbicide to be broken down or metabolized in the plant. Additionally, the preharvest interval reduces the likelihood of herbicide residue remaining on the harvested portion of the crop. Failure to observe the preharvest interval may result in herbicide residue in the crop in excess of established limits. In addition to preharvest intervals, there are restrictions on many postemergence herbicides labels about whether the treated crop may be used for livestock feed or whether treated fields may be grazed as forage.

Another interval that is important to observe is the rotational crop interval. Nearly all herbicide labels, both soil-applied and postemergence, list rotational crop intervals that specify the time that must elapse between herbicide application and planting a rotational crop. This becomes particularly important with late-season herbicide applications. Such intervals are established to reduce the likelihood that sufficient herbicide residues will persist in the soil that could adversely affect the rotational crop. Some herbicide rotational restrictions are based solely on time, while others are influenced by different factors, such as soil pH and the amount of precipitation received after herbicide application.

Additives for postemergence herbicides. Additives are compounds added to a herbicide formulation or spray mixture that in some way modify the characteristics of the spray solution. Additives either are included in the commercial herbicide formulation or are added to the spray mixture prior to application. Different types of spray additives perform different functions, such as improving herbicide uptake into the target vegetation, reducing the number of very small droplets so as to reduce physical drift, and enhancing herbicide performance on certain weed species. Some of the most common additives for postemergence herbicides are nonionic surfactants (NIS), crop oil concentrates (COC), and ammonium fertilizer salts. These are used to increase the effect of the herbicide on the target plants.

Nonionic surfactants lower the surface tension of spray droplets, thus increasing spray coverage, so they are frequently referred to as spreaders or wetting agents. Herbicide labels often specify that the NIS should contain a minimum of 75% to 80% active ingredient or otherwise use a higher rate of NIS. NIS is usually applied at 0.5 to 1 pint per acre, or 0.125% to 0.5% on a volume basis.

Ammonium fertilizer adjuvants are added to increase herbicide activity on certain weed species, including velvetleaf. The two most common ammonium fertilizers used are ammonium sulfate (AMS) and urea ammonium nitrate (UAN) solution (28-0-0). AMS is used at 8.5 to 17 pounds per 100 gallons of spray solution. UAN is used at 2 to 4 quarts per acre, or 2% to 4% by volume. Contact herbicide labels may specify that fertilizer adjuvants replace NIS or COC, while translocated herbicides often specify the addition of UAN or AMS to NIS or COC.

Crop oil concentrates are phytobland oils with emulsifiers added to allow mixing with water. The oil may be of petroleum (POC) or vegetable (VOC) origin. Oils increase spray penetration through the leaf cuticle. Most herbicide labels allow POC or VOC, but some may specify one or the other only. COCs are used at 1 to 2 pints per acre, or 0.5% to 1% by volume.

Compatibility agents are spray additives that improve mixing, especially for soil-residual herbicides that are applied with a liquid fertilizer spray carrier. Herbicide

labels often specify a “jar test” to determine the need for a compatibility agent when mixing herbicides with liquid fertilizer. The rate is usually 1 to 4 pints per 100 gallons of spray mix.

Drift reduction agents are added to the spray tank to reduce small droplet formation and thus minimize drift potential. The use rate per 100 gallons of spray is generally 2 to 10 fluid ounces of concentrated forms and 2 to 4 quarts of dilute forms (1% to 2% active ingredient).

Buffer-surfactants or buffer-compatibility agents contain organic phosphatic acids that provide an acidifying effect on spray mixes where a pesticide is affected by alkaline water. Most herbicides do not need a buffering agent, and some sulfonylureas should not be acidified because herbicide degradation is accelerated.

How Herbicides Work. Herbicides are frequently categorized into families according to various similarities. Examples of classification categories include mode of action, application timing, and chemical structure. Herbicide mode of action describes the metabolic or physiological plant process impaired or inhibited by the herbicide. Essentially, mode of action refers to how the herbicide acts to inhibit plant growth. Herbicide site of action describes the specific location(s) within the plant where the herbicide binds. Site of action thus identifies the herbicide target site within the plant. Though the most common herbicide classification schemes utilize mode of action, much ambiguity exists with respect to that herbicide classification.

While understanding herbicide mode of action is beneficial, classifying herbicides by site of action may be more useful from the standpoint of resistance management. Herbicide resistance in plants is often due to an alteration of the binding site in the target plant. Selecting herbicides based on these different binding sites or sites of action may provide for more reliable classification, in contrast with the ambiguity of classification based on herbicide mode of action, whose systems include anywhere from seven to 13 different categories. Some of these systems describe mode of action categories as “cell membrane disruptors,” “seedling growth inhibitors,” and “amino acid synthesis

Table 12.8. Weed species in Illinois that include herbicide-resistant biotypes and the herbicide families to which the biotypes are resistant.

Species		Resistant to herbicide(s)
Common name	Scientific name	
Common lambsquarters	<i>Chenopodium album</i>	Triazine
Smooth pigweed	<i>Amaranthus hybridus</i>	Triazine, ALS inhibitors
Kochia	<i>Kochia scoparia</i>	Triazine, ALS inhibitors
Common waterhemp	<i>Amaranthus rudis</i>	Triazine, ALS inhibitors, PPO inhibitors, glyphosate, HPPD inhibitors, Auxins, VLCFA inhibitors
Giant ragweed	<i>Ambrosia trifida</i>	ALS inhibitors
Common ragweed	<i>Ambrosia artemisiifolia</i>	ALS inhibitors
Common cocklebur	<i>Xanthium strumarium</i>	ALS inhibitors
Shattercane	<i>Sorghum bicolor</i>	ALS inhibitors
Giant foxtail	<i>Setaria faberi</i>	ALS inhibitors, ACCase inhibitors
Horseweed	<i>Conyza canadensis</i>	Glyphosate, ALS inhibitors
Palmer amaranth	<i>Ameranthus palmeri</i>	ALS inhibitors, PPO inhibitors, glyphosate

inhibitors.” Selecting herbicides based on these categories could cause confusion among growers. For example, the mode-of-action category “amino acid synthesis inhibitors” would place the herbicides Pursuit (imazethapyr) and Roundup (glyphosate) in the same family, whereas classification by site of action would place these two herbicides into two distinctly different families, allowing growers to more accurately select herbicides for resistance management.

The United Soybean Board Take Action publication *Herbicide Classification* presents a color-coded herbicide classification system based on 17 sites of action. The system is intended to enhance growers’ ability to select herbicides based on site of action, in order to slow further development of herbicide-resistant weed biotypes. The table, reproduced here on the next page, separates herbicide sites of action into 17 “primary” colors. Herbicide chemical families sharing a particular site of action are coded in shades of the same color. The table also can be used to determine the sites of action of individual herbicide premix components.

Weed Resistance to Herbicides. Herbicide-resistant weed biotypes continue to plague farmers across much of Illinois. Biotypes are populations within a species that possess characteristics not common to the species as a whole. In this case, the “uncommon characteristic” is resistance to a particular herbicide. Understanding how herbicide resistance develops is an important initial step in designing effective weed-management strategies that deter the selection for resistant biotypes. Table 12.8 provides a listing of weed species in Illinois that have biotypes resistant to particular herbicides.

The terminology used when discussing herbicide resistance can be confusing. The most common terms are defined as follows:

Herbicide resistance: the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.

Herbicide tolerance: the inherent ability of a plant species to survive and reproduce after herbicide treatment.

Notice in the definition of resistance, the word “plant” is used, whereas “species” is used in the definition of tolerance. Stated another way, a resistant plant is a member of a species that, as a whole, is susceptible to a given herbicide. The resistant plant is a biotype of that species that is no longer susceptible to the herbicide. Tolerance implies that a species has never been susceptible to a given herbicide.

Origin of resistance. To slow the selection of herbicide-resistant weeds, one should have a basic understanding of how a resistant weed population develops. The natural-selection theory is widely regarded as the most plausible explanation for the development of resistance. The theory states that herbicide-resistant biotypes have always existed at extremely low numbers within particular weed species. When a herbicide effectively controls the majority of susceptible members of a species, only those plants that possess a resistance trait can survive and produce seed for future generations.

What is meant by “selection pressure” in regard to herbicide-resistant weeds? Herbicides are used to control a wide spectrum of weeds. By controlling susceptible members of a weed population, we are essentially using herbicides as agents to “select for” biotypes that are naturally resistant to the herbicide. When most of the susceptible members of a weed population are controlled, the resistant biotypes are able to continue growing and eventually produce seed. The seed from the resistant biotypes ensures that the resistance trait carries into future seasons. If the same herbicide is used year after year, or several times during a single season, the resistant biotypes continue to thrive, eventually outnumbering the normal (susceptible) population. In other words, relying on the same herbicide (or herbicides with the same site of action) for weed control creates selection pressure that favors the development of herbicide-resistant weeds.

The development of a herbicide-resistant weed population can be summarized by the following principle: *The appearance of herbicide-resistant weeds is often favored by using a herbicide with a single site of action year after year or by repeating applications of a herbicide during the growing season to kill a specific weed*

species not controlled by any other herbicide or in any other manner. This principle has three key components:

1. A herbicide with a single site of action.
2. Repeated use of the same herbicide.
3. The absence of other control measures

By understanding these components and developing weed-control systems with them in mind, producers can greatly reduce the probability that herbicide-resistant weeds will develop in their fields.

Management Strategies to Minimize Herbicide-Resistant Weeds. The best solution for minimizing herbicide-resistant weeds is to reduce the intensity of their selection. In the past, as new weed problems were discovered, the usual solution has been to develop new herbicides. Today, the high cost of developing a new herbicide makes good management practices the best method for dealing with herbicide-resistant weeds. The following strategies may help slow selection for herbicide resistance:

- Scout fields regularly to identify resistant weeds. Respond quickly to changes in weed populations to restrict the spread of plants that may have developed resistance.
- Apply herbicides in tank-mixed, prepackaged, or sequential mixtures that include multiple sites of action. Both herbicides in the mixture must have substantial activity against potentially resistant weeds, as well as similar soil persistence.
- As new herbicide-resistant and herbicide-tolerant crops become available, their use should still not result in more than two consecutive applications of herbicides with the same site of action against the same weed unless other effective practices are included in the management system.
- Combine mechanical control practices (such as rotary hoeing, cultivating, and even hand weeding) with herbicide treatments for a near-total weed-control program.
- Clean tillage and harvest equipment before moving from fields infested with resistant weeds to fields that are not infested.

- Railroads, public utilities, highway departments, and similar organizations using total-vegetation-control programs should be encouraged to use practices that do not lead to the development of herbicide-resistant weeds. Resistant weeds resulting from areas of total vegetation control frequently spread to cropland. Chemical companies, state and federal agencies, and farm organizations can help in this effort.

Several criteria may be used to diagnose a herbicide-resistant weed problem correctly:

- All other causes of herbicide failure have been eliminated.
- Other weeds on the herbicide label (besides the one in question) were controlled effectively.
- The field has a history of continuous or repeated use of the same herbicide or herbicides with the same mode of action.
- The weed species was controlled effectively in the past. Weed control in the field has been based entirely on herbicides, without mechanical control.

With these management strategies and diagnosis criteria in mind, how does one go about correctly identifying a resistant weed population? We know that initially resistant weed biotypes are present at extremely low frequencies within a particular population. It stands to reason, then, that because of such a low initial frequency, resistance will most likely first be noticed within a particular field as a few individual weeds that were not controlled. In other words, resistant weeds do not usually infest an entire field within 1 year. Typically, the resistant weed population is initially confined to small, isolated patches. If the same herbicide-control program is followed repeatedly, these patches begin to encompass a larger and larger proportion of the field, until finally the resistant weeds appear as the dominant species. Therefore, a producer who encounters an entire field of resistant weeds has most likely had a resistant population in the field for more than 1 year.

Crop Injury and Herbicides. Crop response, meaning injury, caused by herbicides applied for in-crop weed control can range from no visible response to nearly complete crop loss. Determining the reason or reasons

for observed crop injury can be challenging, as several interacting factors may contribute to the severity of response. If the cause is readily discernible, the explanation and prognosis also may be straightforward, but if multiple factors contribute to crop injury, the process of assessment and prognosis may become less precise.

Crop genetics can influence the degree of injury response. Certain corn hybrids, for example, are sensitive to 2,4-D (and other herbicides, for that matter) and may exhibit a great deal of injury following herbicide application. The labels of many corn herbicides, especially postemergence herbicides, have precautionary statements about the potential for certain hybrids to be more sensitive than others to a particular active ingredient. If you are concerned that a particular hybrid may be sensitive to a certain herbicide or herbicide family, contact the seed company representative for information.

If more than one formulation of a particular active ingredient is commercially available, the choice of formulation, especially for postemergence applications, also can influence the occurrence of corn injury. For example, ester formulations of 2,4-D tend to be absorbed through the leaf surface faster than amine formulations. Applying 2,4-D esters postemergence with additives such as COC, or tank-mixing herbicides with formulations that can “behave” similarly to a spray additive, can increase the rate of 2,4-D uptake into the corn, potentially leading to enhanced corn injury.

The environment has a large influence on the severity of crop injury symptoms from both soil-applied and post-emergence herbicides. High air temperatures and relative humidity levels favor enhanced absorption of postemergence herbicides. Adequate soil moisture levels and low relative humidity can enhance uptake of soil-applied herbicides. Rapid herbicide absorption into the crop plant may temporarily overwhelm the plant’s ability to break down the herbicide, leading to injury symptoms.

Apart from enhancing herbicide uptake, environment-induced crop stress can enhance crop injury from herbicides. Cool air temperatures and wet soil conditions are good examples of environmental conditions that can induce stress. Why is a crop under stress more likely to be

injured by a selective herbicide? In most cases, herbicide selectivity arises from the crop's ability to metabolize (break down) the herbicide to a nonphytotoxic form before it causes much injury. For example, a grass-control herbicide used in corn cannot discriminate between giant foxtail and a corn plant; the herbicide attempts to control the corn just as it attempts to control the giant foxtail. When the corn is growing under favorable conditions, it rapidly metabolizes the herbicide before excessive injury occurs. If, however, the corn plant is under stress (which could be caused by a variety of factors), its ability to metabolize the herbicide may be slowed enough that injury symptoms develop.

The herbicide itself can influence the severity of crop injury, and spray additives applied with a postemergence herbicide or tank-mix combinations may enhance crop response. Always read all label suggestions and precautions related to spray additives that should be either included or avoided when applying herbicides postemergence.

