Herbicides and Rangeland

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A key objective of weed management systems is to maintain the productivity of rangeland while minimizing the occurrence and impact of weeds. Strategies may include increasing the amount of desirable forage, establishing stable plant communities that prevent erosion or weed invasion, and providing habitat for wildlife. Herbicides have been an integral part of management systems for rangeland weeds since the late 1940s, and have reduced the presence of noxious and common weeds that interfere with grazing, decrease productivity, and lower the aesthetic value of rangeland. Of the 988 million acres of rangeland in the United States, about 25% were treated with herbicides in 1997.

Herbicides decrease growth, seed production, and competitiveness of susceptible weeds. Weeds treated with herbicides use less soil moisture and nutrients, which then become available for more desirable members of the plant community. In addition, decreasing weed growth with herbicides can reduce their canopy cover. Neighboring plants can take advantage of increased light penetration through the canopy, and better compete with weeds.

A key to the long-term success of rangeland weed management systems is to decrease the population of undesired plant species. Even if target weeds are not killed by herbicide applications, their vigor, seed production, and vegetative reproduction (for perennial plants) will usually be reduced. Decreased photosynthesis in leaves and stems results in less energy available for replenishment of root, stolon, and rhizome reserves. Lower energy reserves in vegetative reproductive parts may also cause stress and increase the potential for winter-kill or dessication. Translocated herbicides can also effectively prevent some of the vegetative reproductive parts from sprouting, or perhaps kill them completely.

Herbicides seldom provide long-term control of weeds when used alone and outside the context of an integrated weed management system. Often, weeds dominate in certain areas within a field, especially perennial noxious weeds such as knapweed (*Centaurea* spp.) and leafy spurge (*Euphorbia esula*). In other situations, the stand of desirable grasses and forbs may be stressed by overgrazing or other factors. As a result, annual weeds like cheatgrass (*Bromus tectorum*) are able to become established and further stress the desirable plant community. In these latter cases, herbicides may control existing weeds, but the lack of a healthy community of desirable plants usually allows that weed or another species to become established after the residual effects of the herbicide have dissipated.

This book focuses on managing rangeland weeds using integrated approaches, including the use of herbicides. Successful weed management requires not only the development of a strategy for killing existing weeds, but long-term plans for preventing their reestablishment or the invasion of other weedy species through careful land management. Once a weed management plan is developed, herbicides can be selected that will help meet the initial objective of reducing weed populations to reasonable numbers. To select the proper herbicide for a specific weed management plan, an understanding of how herbicides kill plants, how they are applied, and their fate in the environment is required. Therefore, the objectives of this chapter are: 1) to describe how to apply herbicides; 2) to define the modes of action of rangeland herbicides; and 3) to describe the fate of selected herbicides in the environment.

Herbicide Application

One of the keys to a successful herbicide application is a uniform spread of the product across the desired area. To achieve a uniform herbicide application, one must be aware of the various types of herbicide formulations and the many possible methods of application.

• *Formulations*

The term "formulation" refers to how herbicides are packaged. Herbicide formulations include the active and inert ingredients. The active ingredient is the toxicant or chemical that inhibits growth or kills the plant. Many herbicides in their pure form may not be water-soluble or able to enter the plant, making them essentially useless in the field. Therefore, herbicides are prepackaged or formulated with solvents, diluents, and/or various adjuvants to make them water soluble and able to penetrate leaf tissues. Most rangeland herbicides are formulated so they can be diluted in water and sprayed, although some are applied as dry granular material.

Sprayable formulations are diluted with water, fertilizer, or oil-based carriers, and sprayed on soil or vegetation. Sprayable formulations include water-soluble liquids, water-soluble powders, emulsifiable concentrates, wettable powders, water-dispersible liquids, and water-dispersible granules.

Dry formulations of herbicides are packaged as granules or pellets, and can be applied directly to the field without dilution in water. Dry formulations usually have lower concentrations of herbicide active ingredient. Dry formulations are usually less hazardous to the applicator because of the decreased concentration of the herbicide active ingredient.

Table 1. Herbicide formulations and their description.

Formulation	Formulation Type	Abbreviation	Solubility and Description
Water Soluble Liquid	Sprayable	S, SL	Liquid formulation that dissolves completely in water requiring little agitation. May require wetting agents to allow the spray to spread and stick on the leaf surface.
Water Soluble Powder	Sprayable	SP	Dry formulations that dissolve completely in water. Once in solution requires little agitation. Not widely used today because of fine dusts that become airborne during mixing.
Emulsifiable Concentrates	Sprayable	E, EC	An emulsifier is used to suspend nonpolar herbicides in water. Upon mixing, an emulsion forms and the spray solution has a cloudy appearance. Mild agitation is required.
Wettable Powders	Sprayable	W, WP	Dry herbicide that uses a dispersing agent to suspend insoluble particles in water. Care must be taken to ensure WPs are thoroughly mixed in water. Requires vigorous agitation.
Water Dispersable Liquids	Sprayable	WDL, L, F	Powders suspended in liquid. Like WPs, the herbicide is insoluble in water. Shake herbicide well before dispersing into spray tank. Moderate agitation is required.
Water Dispersable Granules	Sprayable	WDG, DF	Insoluble herbicides ground into a powder mixed with dispersing agents, then formed into granules. Safer than WPs or WDL because they produce less dust when mixing. Agitation is required.
Granules	Dry application	G	Dry herbicide formulated into granules less than 10 mm^3 that is applied directly to the soil. Rainfall is required to leach the herbicide into the soil and activate it.
Pellets	Dry application	P	Pellets are similar to granules, but are larger than 10 mm^3.

• *Carriers*

Carriers are gases, solids, or liquids used to dilute or suspend herbicides during application and allow for proper placement of the herbicide, whether it be to the soil or on foliage. Gas carriers are used for fumigation or soil sterilization, and are seldom used in rangelands.

Liquid carriers include water, liquid fertilizers, diesel, and other similar low-viscosity oils. Water is by far the most widely used carrier because it is universally available, cheap, and is generally effective with a wide range of herbicides. However, problems can be encountered when using hard or dirty water. Hard water (water with high levels of dissolved calcium and magnesium salts) can react or bind with herbicides having an ionic charge, and decrease their activity or cause them to precipitate in the spray tank. Glyphosate and 2,4-D salt or amine formulations are particularly susceptible to problems when applied in hard water. Similarly, these and other herbicides are adsorbed to suspended clay and silt in dirty water, reducing their effectiveness. Dirty water that contains silt, sand, or algae can clog screens, wear out nozzles, and abrade other sprayer parts, resulting in uneven spray patterns and poor weed control.

Liquid fertilizers are rarely used as herbicide spray carriers in rangeland, although diesel or other mineral oils may be used for dormant applications to woody species. Diesel or other mineral oils increase the activity of herbicides because they are phytotoxic, and thus cause injury to the plants directly. The added effect of the carrier may be important for difficult weeds or woody or brushy species.

Dry carriers are used to apply herbicides without further dilution, and are the major components of granules and pellets. In the case of granules or pellets, the formulation also serves as the carrier. The inert ingredients of granules and pellets include attapulgite, kaolinite, or vermiculite clays, dry fertilizers, polymers, starch, and other solid substances.

Dry fertilizer is rarely used as a dry carrier in rangelands. Some herbicide manufacturers have used dry fertilizer in the formulation of lawn and turf herbicides. Dry fertilizer can be impregnated with herbicides. During impregnation, the dry fertilizer is placed in a rolling drum while liquid herbicide formulations are applied and mixed thoroughly with the fertilizer. Uniform applications of the herbicide/fertilizer mixture to the soil should provide control equivalent to applications with liquid carriers. Dry fertilizer impregnated with herbicide may be useful in rangeland revegetation by improving soil fertility and controlling weeds in a single-pass application.

• *Spray Additives*

Spray additives can be included in formulated herbicides, or can be added to the spray mixture to improve the effectiveness of the spray solution. Adjuvants are classified by their uses rather than their chemistry, although chemical properties determine their suitability for use with different herbicides. Adjuvants include surfactants, antifoaming agents, compatibility agents, crop oil or crop oil concentrates, activators, and drift control agents.

• *Application Considerations*

The total volume of spray solution including the actual product, spray additives, and carrier applied per acre is called "spray gallonage." Correct spray gallonage is crucial for ensuring uniform coverage of leaf foliage with foliar-active herbicides. In general, higher spray gallonage results in more and larger spray droplets. As a result, higher spray gallonage results in more spray solution contacting the leaf surface, leading to increased uptake of the herbicide. Minimum spray gallonage required for acceptable herbicide performance is indicated on the herbicide label. In general, systemic herbicides such as 2,4-D or glyphosate require lower spray gallonage than contact herbicides such as paraquat. Soil applied herbicides only require enough spray gallonage to ensure uniform coverage of the soil surface.

Managing weeds successfully involves controlling plants at the time of application and preventing future weed populations. Annual weeds should be treated before they flower to prevent seed set, the source of future generations. In general, the smaller the annual weed, the easier it is to manage with herbicides. More importantly in rangelands, perennial weed management depends on preventing production of seeds and vegetative reproductive parts. To prevent seed set, herbicides must be applied prior to flowering. In addition, herbicides must be applied when they will be translocated to roots or rhizomes. Because phloem-mobile herbicides follow the flow of sugars within plants, they are most effective on perennial weeds when applied to plants storing carbohydrates in the vegetative reproductive tissues. The best application time for perennials is in the late fall prior to frost, and to a lesser extent in late spring prior to flowering.

Timing of herbicides that have soil residual activity (such as picloram) is less critical than herbicides with no residual activity because weeds that emerge and begin to grow within the treated soil zone are still exposed to herbicides through the roots. The central factor for successful weed control with soil-applied herbicides is activation via rainfall or snow melt. Some herbicides are subject to photodegradation or volatilization, so the best application times are in the spring or fall, but not during the heat of summer.

The timing of non-residual systemic herbicide application is much more critical. Because these herbicides enter only through foliar tissue, the weeds must be actively growing to maximize absorption. Herbicide efficacy decreases when plants are stressed. Translocation from the shoots to the roots is essential for perennial weed control, so non-residual systemic herbicides should be applied when plants are actively moving carbohydrates to the root.

• *The Herbicide Label*

The herbicide label is the legal guide for proper use and application of herbicides. Herbicide labels are approved by the U.S. Environmental Protection Agency to ensure

Table 2. Spray additives and their use.

Additive	Purpose	Examples	When to Use
Surfactants	Surfactants improve the emulsifying, dispersing, spreading, and wetting of solutions. In general, they decrease surface tension of water.	Non-ionic surfactant (NIS), Emulsifiers, Dispersing agents, Wetting Agents	Most sulfonylurea herbicides require surfactant for foliar applications. Consult the label.
Antifoaming agents	Antifoaming agents reduce the amount of foam in spray solutions, allowing pumps and nozzles to work better and improving spray uniformity.		Use with surfactants and certain herbicides that produce foam when mixed.
Drift control agents	Drift control agents prevent fine spray droplets and movement of herbicide to non-target sites.		Use when conditions during application are conducive to drift.
Compatibility agents	Compatibility agents aid in the suspension or mixing of herbicides with other herbicides, other pesticides, or liquid fertilizer.		Use when mixing pesticides or fertilizers.
Crop oil	Usually non-phytotoxic and contains NIS to help form emulsions. Activate herbicides by increasing absorption of the herbicide.	Crop oil, Crop oil concentrate (COC), Methylated seed oil (usually from soybean)	Use when weeds are stressed. Consult the label.
Activators	Activators enhance herbicide activity. Herbicides with multiple ionic states benefit most from activators		Improves performance of herbicide salts (i.e., 2,4-D amine and glyphosate).
Fertilizers	Fertilizers used in small doses buffer the pH of spray solutions and bind free ions. Fertilizers also increase absorption of some herbicides.	Ammonium sulfate (AMS), liquid N (28-0-0 or 32-0-0)	Use with glyphosate and herbicide salts.
Dyes	Dyes are used to temporarily color the foliage or ground to aid in application.		Do not use if not approved on the herbicide label.

safety of the applicator and to protect desirable vegetation, non-target areas, wildlife, and the environment. The herbicide label also contains information on the product's mechanism of toxicity, susceptible weed species, grazing restrictions, and proper application techniques. The applicator should read and become familiar with the herbicide label before application, because improper application is against the law.

Herbicide Classification

As of 1998, more than 150 herbicide active ingredients are used for managing weeds. Many of these products are formulated, packaged, or pre-mixed with other herbicides, resulting in several hundred commercial products for sale. Herbicides are classified or grouped by several different methods to distinguish among their uses and activity. Herbicides are often grouped by their chemical structure, how they are used, or how they kill plants. The latter scheme is the most logical from a management standpoint, because modes of action can be targeted to particular weeds, and users can keep track of how often a particular mode of action is used.

• *Herbicide Mode of Action*

A herbicide's mode of action is the mechanism by which it kills plants, and includes all the plant processes affected from the time it is applied until the weed dies. Some of these plant processes are herbicide uptake or absorption, translocation, metabolism, and interference at the site of action. A herbicide must first be taken up or absorbed into the interior of the plant; this can occur through the roots, through the foliage, or both, depending on how the herbicide is applied. Once inside the plant, most herbicides are translocated or moved throughout the plant via the vascular system. Plant metabolism may alter the herbicide by removing or adding essential functional groups, which usually inactivate (but sometimes activate) the molecule. Herbicides eventually kill plants by inhibiting or affecting a single enzyme or enzyme pathway, termed the site of action, which is essential for plant growth.

• *Uptake or Absorption*

Because herbicides are applied to bare soil or to existing plant vegetation, they may enter the plant through roots or shoots. Most rangeland herbicides that persist in soil are absorbed by both roots and shoots.

• *Root Uptake*

Herbicides that persist in the soil and continue to affect newly emerging plants or sprouting perennial shoots are considered residual herbicides. The length of soil residual period varies widely across herbicide families, but plant control can be obtained as long as the herbicide is present in the soil. Most herbicides must be dissolved in the soil solution (water phase) to be taken up by plant roots, although a few enter from the soil vapor phase.

All plant roots are covered with an outer layer of cells called the epidermis. Root hairs are single-celled extensions of epidermal cells which greatly increase the surface area of a root system and are responsible for absorption of water and dissolved compounds (including herbicides) from the soil. To be effective, herbicides must not only be taken up by the roots, but must enter the vascular system of the plant.

Plant roots have a specialized layer of cells inside the root that acts as a barrier between outer cells and the vascular tissue. This barrier ensures that all materials entering the root must pass through a living cell, instead of just moving through intercellular spaces. This layer can exclude herbicides if they are particularly oily or not formulated correctly. Once past this barrier, herbicides can enter the xylem, or water-transporting vascular tissue. Herbicides mobile in the xylem usually travel only upward in the plant, and tend to accumulate in leaf margins.

The other part of the plant vascular system is the phloem, which transports sugars and other nutrients both upward and downward. Herbicides that can enter the phloem have a better chance of accumulating in growing points, or meristems, of the plant, and thus are usually more effective on perennial plants.

• *Foliar Uptake*

To be effective, herbicides applied to vegetation must be applied to actively growing, green vegetation, and not to plants that are drought-stressed or dormant. Foliar absorption occurs mostly through leaves and stems, although small amounts of some herbicides can enter through small openings in the leaf called stomata. In order for herbicides to be effectively absorbed, they must remain in contact with the leaf or stem surface, penetrate into the leaf tissue, and enter living cells.

Herbicides must pass through tissues before they can enter living cells. The first and most effective barrier to herbicide absorption is called the cuticle. This is a waxy layer covering the entire aboveground portion of the plant. The natural function of the cuticle is to protect the plant from excessive water loss through leaf surfaces. Because it is made of several waxy layers, the cuticle can also be very effective at preventing entry of herbicides into the plant. Cuticle thickness varies by plant species and, most importantly, is strongly affected by environmental conditions. Any kind of drought stress, as well as low humidity, high light, and high temperatures will trigger plants to develop thicker cuticles. Therefore, herbicides are usually much less effective on drought-stressed plants, and applications during stressful conditions should be avoided.

Foliar absorption of herbicides is affected by many factors, the most important of which are the type of herbicide, spray solution components, and the species of weed and condition of its leaf surfaces. The key factor for the herbicide is that it remain in solution once the spray droplet is on the leaf surface. If the herbicide crystalizes, it is highly unlikely it will return to solution and penetrate the leaf. For example, amine forms of phenoxy herbicides can react with dust and crystalize on the leaf surface, whereas phenoxy ester formulations are much less likely to do so.

The most important factor of the spray solution is its overall surface tension. Decreasing the surface tension by including spray adjuvants will enhance the amount of spray solution contacting the leaf surface, and can help prevent the spray droplets from drying too quickly. In addition, herbicide absorption is affected by the amount of pubescence (small hairs), cuticle structure, and cuticle composition. A rough cuticle surface and pubescence can decrease the contact between spray droplets and the leaf surface. Cuticle structure and composition refer to a leaf's waxiness and other components, and again vary widely across weed species. The type and amount of waxes in the cuticle can affect herbicide absorption even more than cuticle thickness.

• *Translocation*

Herbicide translocation refers to the movement of a herbicide, once inside the plant. Some herbicides are translocated throughout the plant (systemic), whereas other herbicides have very limited movement (contact herbicides). Complete spray coverage is the key to good management when applying contact herbicides. Contact herbicides effectively burn off the vegetation of perennial weeds, such as spotted knapweed (*Centaurea maculosa*) or leafy spurge, but have no effect on root systems because they are not translocated. In contrast, systemic herbicides are translocated throughout the plant, including root buds and other reproductive structures, and therefore are more effective for controlling perennial weeds. Glyphosate, 2,4-D, triasulfuron, and picloram are systemic herbicides commonly used on rangelands.

Only a few rangeland herbicides (most notably, tebuthiuron) are xylem-mobile. Such herbicides move in the direction of water from the roots to the top of the plant. If a xylem-mobile herbicide is applied only to the lower leaves, new vegetation emerging from the growing point will not show injury. However, xylem-mobile herbicides applied to soil are absorbed through roots and the whole plant will show injury.

Most rangeland herbicides are phloem-mobile and are translocated throughout the plant. Herbicides translocated through the phloem tend to accumulate in meristematic regions, flowers, new leaves, roots, and vegetative propagules. As a result, such herbicides tend to be most effective at managing perennial plants with various mechanisms of vegetative propagation.

• *Metabolism*

Plants have the ability to metabolize many foreign compounds with which they come in contact, including herbicides. However, not all plant species contain the same metabolic enzymes, and thus different species are sensitive to different herbicides.

Plant metabolism can affect a herbicide in one of two ways. Usually metabolism of the herbicide deactivates it to nontoxic products. However, a few cropland herbicides must be metabolized by the plant to become toxic to the plant.

• *Site of Action*

A herbicide's site of action is the specific enzyme or enzyme pathway that is inactivated and causes plant death. By inhibiting an enzyme or pathway, the herbicide prevents the plant from synthesizing critical compounds necessary for life. In other cases, inhibition causes the accumulation of toxic intermediates or highly reactive molecules which destroy cells. The site of action is known precisely for many herbicides, but several are still unknown.

Mode of Action of Rangeland Herbicides

Of the numerous herbicides commercially available, only a handful are widely used in rangeland weed management. Table 3 shows some of the commonly used rangeland herbicides and summarizes their characteristics.

• *Growth-Regulating Herbicides*

Growth-regulating herbicides are chemical mimics of natural plant hormones called auxins. Plants synthesize minute quantities of auxin to regulate their own growth and development, after which they are immediately inactivated by metabolism. However, growth-regulating herbicides, which stimulate the same growth processes, cannot be quickly metabolized by sensitive species, and thus the plants essentially grow themselves to death.

Growth-regulating herbicides are the most widely used herbicides in rangeland. 2,4-D alone is applied on an estimated 4.9 million acres of rangeland per year. Most growth-regulating herbicides are applied directly to the foliage, although several groups within this family have residual activity and are root absorbed. Plant growth-regulating herbicides used on rangeland include phenoxies, benzoic acid, and picolinic acid.

Phenoxies. Phenoxy herbicides include 2,4-D, 2,4-DB (rarely if ever used in rangeland), MCPA, and 2,4,5-T (no longer available). Phenoxy herbicides have numerous trade names, but are usually referred by their common names. They are commonly formulated as amines or esters, and rarely as water-soluble salts. The characteristic chemical structure of phenoxy herbicides is a chlorinated benzene ring.

Phenoxy herbicides are generally applied as foliar sprays and are absorbed through leaves. Phenoxy herbicides can also be absorbed through roots, but are rarely applied to soil because of their very short residual period. Once inside the plant, phenoxy herbicides are translocated in the phloem throughout the plant, and are thus effective on perennial broadleaf weeds. Grass species can metabolize phenoxy herbicides, which is the primary mechanism of selectivity. The site of action of phenoxy herbicides is unclear, since they appear to affect a multitude of enzymes and physiological processes in sensitive plants. Because phenoxy herbicides have relatively low toxicity and are rapidly degraded in soil, they are commonly used for rangeland

Table 3. Commonly used rangeland herbicides.

Common Name	Trade Name	Mode of Action	Weed Spectrum	Soil Residual
glyphosate	Roundup®	amino acid synthesis inhibitor	non-selective	no
picloram	Tordon®	growth regulator	broadleaf species	yes
2,4-D	many	growth regulator	broadleaf species	no
dicamba	Banvel®	growth regulator	broadleaf species	no
triasulfuron	Escort®	amino acid synthesis inhibitor	broadleaf species	yes
tebuthiuron	Spike®	photosynthesis inhibitor	trees and shrubs	yes
clopyralid	Stinger®	growth regulator	broadleaf species	yes
imazapyr	Arsenal®	amino acid synthesis inhibitor	non-selective	yes

weed control in ditches, along streambanks and lakeshores, and for aquatic weed control.

Benzoic acids. Dicamba, the only benzoic acid herbicide used in rangelands, is marketed under the trade names Banvel® or Clarity®. Dicamba is available in liquid or granular formulations. The characteristic structure of benzoic acids is a benzene ring with a carboxylic acid group.

Dicamba is usually applied to foliage as a spray, but can be soil applied as a granule. Dicamba is absorbed through leaves and roots, and is translocated throughout the plant via the phloem. Dicamba has longer soil activity than 2,4-D, with a half-life of about 14 days under most conditions. Monocots are tolerant to dicamba because of rapid metabolism. Dicamba's specific site of action is unknown.

Dicamba is rarely used alone, but instead is applied in a tankmix with other herbicides. Dicamba may be tankmixed with 2,4-D or other phenoxy herbicides to increase its activity and spectrum of weed control, but cannot be applied near open water. Dicamba's relatively short soil residual activity limits its use in rangeland, but it may be mixed with picloram or other longer residual herbicides.

Picolinic acid. Picolinic acid herbicides include picloram, clopyralid, and triclopyr, which are marketed as Tordon®, Curtail® or Transline®, and Garlon® or Remedy®, respectively. All three members are commonly formulated as liquid herbicides. The characteristic structure of picolinic acids is a benzene ring substituted with a nitrogen and a carboxylic acid side chain.

Picolinic acid herbicides can be applied to green vegetation and to soil. These herbicides are absorbed through roots and leaves and translocated via the phloem, similarly with the phenoxy and benzoic acid herbicides. However, picolinic acids are much more persistent in the soil than phenoxy or benzoic acid herbicides. Depending on soil type and environmental conditions, picloram may have soil activity for two to three years or longer, while clopyralid and triclopyr remain active in the soil for two to four months. Picolinic acids are metabolized by grasses and certain broadleaf weeds, which serves as the major mechanism of plant selectivity. The specific enzyme or pathway influenced by picolinic acids is unknown.

Picolinic acid herbicides can be up to 10 times more active than 2,4-D on certain broadleaf weeds, such as knapweed species, leafy spurge, and other perennial broadleaves. For example, clopyralid is very effective for controlling Canada thistle (*Cirsium arvense*), while triclopyr is commonly mixed with 2,4-D or dicamba and used as a brush killer. Increased efficacy combined with long soil residual activity make picolinic acid herbicides a common choice for weed control in rangelands. However, because picolinic acid herbicides are highly mobile in soil and persistent, they can have a high potential for leaching. Care should be taken when picolinic acids are applied to areas with shallow water tables, high rainfall, or near open water.

• *Amino Acid Synthesis Inhibitors*

Amino acid synthesis inhibitor herbicides kill plants by preventing the plant from synthesizing key amino acids. Amino acids are the building blocks of proteins, which are themselves absolutely essential for all life processes. Therefore, depriving the plant of even one or a few amino acids is lethal.

Amino acid synthesis inhibitors are generally used as foliar sprays for killing existing vegetation, and can be used as nonselective sprays or as selective herbicides for killing specific weeds. These herbicides are characterized by very slow action, with plant stunting and yellowing as the first symptoms. Complete plant death may take several weeks.

Amino acid derivatives. Amino acid derivative herbicides include glyphosate and sulfosate, which are marketed as Roundup® or Rodeo® and Touchdown®, respectively. Amino acid derivatives are formulated only as liquid herbicides.

Glyphosate is a nonselective herbicide used only as a foliar spray. Glyphosate has no soil residual properties, because it binds very tightly to soil particles, rendering it inactive. Since it is a systemic herbicide, glyphosate is translocated throughout the plant in the phloem, and accumulates in growing points. As a result, glyphosate is very effective at killing vegetative reproductive organs of certain perennial weeds, particularly grasses. Plants cannot metabolize glyphosate to any appreciable extent, although some species like horsetail (*Equisetum arvense*) are naturally tolerant. Glyphosate can be used selectively using rope-wick applicators to treat weeds that are growing above the desirable plant canopy, or by spraying when weeds are growing but desirable vegetation is still dormant.

Glyphosate inhibits an enzyme that is responsible for synthesis of the aromatic amino acids. By blocking this pathway, glyphosate not only deprives the plant of these essential building blocks, but also a whole host of secondary compounds such as lignin, alkaloids, and flavonoids. The very slow injury symptoms and plant death after glyphosate treatment are a result of starvation for these compounds.

Glyphosate is most often used for total vegetation control in rangeland situations. However, glyphosate will selectively control winter annual weeds such as downy brome if applied early in the spring before desirable grasses and forbs break dormancy. For perennial weeds, glyphosate is most effective if applied in late summer or early fall after seed set. Since glyphosate has no soil residual activity, reseeding or other revegetation practices can be carried out immediately after application.

Sulfonylureas. Sulfonylurea herbicides include metsulfuron, triasulfuron, and a number of other products that are used primarily to control weeds in cropland. Metsulfuron is marketed as Escort® or Ally®, while triasulfuron is marketed as Amber®. Triasulfuron is labeled for some uses in rangeland. Sulfonylureas are commonly formulated as water dispersible granules.

Sulfonylurea herbicides are normally applied as foliar sprays, although they are readily absorbed through roots and leaves. Soil residual periods for sulfonylurea herbicides vary widely among individual members, and range from only a few weeks to three years or more. Sulfonylureas are translocated throughout the plant via the phloem and accumulate in growing points. These herbicides inhibit an enzyme in the pathway responsible for synthesis of the branch chained amino acids leucine, isoleucine, and valine. As with glyphosate, loss of these essential compounds causes sensitive plants slowly to starve to death.

Unlike glyphosate, sulfonylurea herbicides are metabolized by different grass and broadleaf plant species, and the degree of metabolism varies widely. Thus, depending on the individual herbicide, different sulfonylureas can control a wide range of plant species. They can be used selectively to control undesirable rangeland species, particularly perennial broadleaf weeds. Because of the highly variable weed control spectra for individual members, sulfonylureas may have advantages over growth-regulating herbicides such as picloram in certain situations. For example, some desirable broadleaf plants and forbs may be tolerant to certain sulfonylureas, while weeds like spotted knapweed could be controlled.

Imidazolinones. Imidazolinones are a large family of herbicides used for cropland and rangeland weed control. For rangeland, imazapic marketed as Plateau® and imazapyr marketed as Arsenal® are the most commonly used. Imidazolinones are sold as liquid and granular formulations. These herbicides have the same site of action as sulfonylureas, and their translocation patterns are similar.

Plateau® has moderate soil residual activity and will provide one to two years of residual control of winter annual grasses such as downy brome, as well as some perennial broadleaf weeds. Imazapyr has extremely long soil residual activity (sometimes longer than five years) and is typically used as a soil sterilant to control weeds along railroads and in industrial settings.

• *Photosynthesis Inhibitors*

Photosynthetic inhibitors have long been used to selectively control grass, broadleaf and brushy weeds in crops, rangelands, and rights of way. Photosynthetic inhibitors are absorbed through roots and shoots, and usually have long soil residual activity. These herbicides are effective on certain perennial weeds, because shoot death prevents replenishing of food supplies for underground vegetative buds. Photosynthesis inhibitors used in rangelands are mobile only in the xylem, so leaf edges and oldest tissues show injury symptoms first, including leaf yellowing and browning. Unlike some other residual herbicides, photosynthesis inhibitors leave skeletons of dead weeds in the treated area.

Photosynthesis inhibitors block the energy flow in a photosynthetic pathway. The released energy causes the creation of high energy free radical molecules which rapidly destroy cell membranes.

Substituted urea. The only substituted urea used in rangelands is tebuthiuron, marketed under the trade name Spike®. Tebuthiuron is formulated as a granular herbicide and has several years of residual activity. It is primarily used for brush management in rangeland, especially sagebrush. Because of its long soil residual activity, tebuthiuron causes repeated defoliation and eventual death of sensitive brush species. Tebuthiuron is also highly susceptible to leaching via water movement.

Herbicide-Resistant Weeds

Herbicide-resistant weeds are thought to start from one or a few plants present in a field before spraying, so they are not noticed during the first few years a herbicide is used. However, by repeatedly using the same herbicide over several years, the applicator "selects" for those few resistant individuals by killing all the susceptible plants. Each additional year that the applicator uses the same herbicide or herbicides with the same mode of action, the more prevalent resistant weeds become until they become the most predominant form.

The most important factors controlling the appearance of resistant weeds are:

1) Selection Intensity. This term refers to how strongly resistant biotypes will be chosen from a population, and is related to the efficacy of the herbicide and how often the herbicide is applied. If the herbicide is very effective, is applied often, has long soil residual activity, and/or is the only practice for controlling a particular weed, then the selection intensity for resistance is very high. Under these conditions, selection for resistant weeds will be rapid.

2) Weed Biology. Some weed species have substantial amounts of genetic diversity, meaning that a single species consists of many different varieties or hybrids. Generally, weeds like spotted knapweed that outcross (pollen is spread from one plant to another by insects or wind) have more diversity than those that pollinate themselves, like quackgrass (*Agropyron repens*). Weeds with more genetic diversity have a higher potential to develop resistance to herbicides, since the initial incidence of resistant individuals should be higher.

3) Herbicide Mode of Action. Herbicides that kill weeds the same way belong to the same mode of action family. For example, sulfonylurea and imidazolinone herbicides target the same plant enzyme, and so weeds that are resistant to one herbicide are often also resistant to other members of the family. The target enzyme for this herbicide family can exist in many forms, some of which are already herbicide-resistant. Therefore, there is a relatively high proportion of weeds in an unsprayed field that are already resistant (maybe 1 in 10,000). In contrast, resistant forms of the enzyme that glyphosate targets appear to be much more rare (maybe 1 in 100 million).

The most important practice to prevent herbicide resistance is to integrate management methods and rotate among different herbicide modes of action. Applications of the same herbicide (or herbicides with the same mode of action) should not be made in successive years. It is important to remember that residual herbicides are still imposing selection pressure for resistant weeds for however long they persist in the soil. If available, another mode of action should be used, or if not possible, other means of weed control should be substituted in non-application years. Such measures could include burning, mechanical control, timed grazing, or high intensity, short-term grazing.

Herbicide Fate

Herbicides applied in field settings have several fates, including uptake by plants, degradation in plants or soil, off-target movement, and unintended deposition in the environment. In a well-planned management system, herbicides should effectively control weeds with little or no adverse environmental effects. The important characteristics that determine the environmental fate of a particular herbicide include the chemical and physical properties of the herbicide, soil characteristics, climatic conditions, and members of the target plant community.

• *Plant Uptake*

One obvious fate of herbicides is entry into the plant. In general, only a small percentage of applied herbicide enters the plant. Once the herbicide molecule enters the plant it may remain in its active form or can be metabolized into inactive forms. If it is not metabolized, the herbicide may be leached from dead and decaying plant material into the soil.

• *Soil-Herbicide Interactions*

Most herbicides eventually end up in the soil, either through direct application or indirectly through a plant. Once on the soil surface, some herbicides react with sunlight and are photodegraded to nontoxic products, while others are unstable and spontaneously degrade into inactive forms. If they enter the soil, all herbicides are broken down into inactive forms, through chemical or biological processes, or both. However, the rates at which individual herbicides are degraded can vary widely, depending on the chemical properties of the herbicide and the microbial populations in the soil. Herbicide half-lives in soil can range from a few minutes to many years. In general, soils that are fertile and well-watered support substantial microbial populations, and are therefore more likely to degrade herbicides more rapidly. Little microbial activity occurs in dry and nonfertile soils, especially under extreme environments.

Once in the soil, the extent of movement of a particular herbicide depends on a number of factors, most importantly its affinity for organic matter and clay particles and its water solubility. Herbicides like glyphosate bind very tightly to soil components immediately upon contact, thus preventing their further movement and allowing soil microorganisms to begin degradation processes. However, other herbicides have very little affinity for soil, and can be leached extensively if applications are followed by heavy rainfall or surface water movement. Even if bound to soil particles, herbicides can be moved off-site or into surface waters via erosion of treated soil. Excessive water movement can even cause herbicides with reasonable soil affinity to move through subsoil and into groundwater.

Herbicides should always be used so that the likelihood of moving into surface waters or leaching into groundwater is minimized. Some scenarios that may lead to water contamination by herbicides include: 1) using herbicides on soils with very low organic matter content and/or high sand content; 2) using highly persistent herbicides in leachable soils or in high rainfall areas; 3) using herbicides on soils over a shallow water table; 4) using herbicides with low affinity for soil under leachable conditions.

• *Off-Target Movement*

Herbicide volatilization and drift are the primary mechanisms of off-target movement. Off-target movement can result in unintended injury to plant species, contamination of surface waters, and contamination of ecologically sensitive areas.

Volatilization occurs when herbicides become suspended in the atmosphere after application, and can happen within a few minutes of application, or several hours to days later. Under certain environmental conditions, herbicide droplets evaporate from the soil or leaf surfaces and are moved into the air. Again, depending on barometric pressure and wind conditions, volatilized herbicides can affect non-target areas long distances from the application site. Volatilization can be minimized by choosing nonvolatile herbicide formulations (2,4-D amine is much less volatile than 2,4-D ester, for example), using dry carriers when possible, and avoiding applying herbicides during hot summer days.

Herbicide drift occurs when herbicide droplets land on non-targeted areas. Herbicide drift occurs at the time of application and is usually limited to 100 to 200 yards (90 to 180 m). Application conditions that minimize herbicide drift include using low sprayer pressures and nozzles with large orifices that produce larger spray droplets, spraying in calm conditions, adjusting boom height as low as possible, and using windshields on the boom.

Conclusion

Herbicides can be a critical component of weed management systems. The choice of which particular herbicide to use depends on a number of factors, including target weed species, density of weeds, presence of desirable grasses and forbs, soil attributes, proximity to water, and environmental conditions. Because of these interrelated factors, herbicide choices are best made in consultation with experienced Extension specialists, county weed supervisors, field scouts, custom applicators, and others. There are seldom blanket recommendations for individual weed control situations.

Herbicides are likely to be the most expensive component of a rangeland weed management program. Therefore, when using herbicides it is crucial to ensure optimum performance of the product. To improve herbicide performance, use appropriate spray additives and spray gallonage, and apply at the correct time. Finally, choose the right herbicide, know what it will and will not do, use it carefully and according to the label, and use it in rotation with other practices.

In general, herbicides are most effectively used to gain initial control of a new weed invasion or a severe infestation. Herbicides are rarely, if ever, a complete solution to weed problems. Instead, they must be incorporated into long-term management plans that include replacement of weeds with desirable species, proper land use by grazing animals, and prevention of new infestations.

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