

Forest Herbicide Characteristics¹

Anna Osiecka and Patrick J. Minogue²

The effectiveness and safe use of the numerous brand name and generic herbicides registered for forest vegetation management requires developing site-specific herbicide prescriptions made with careful consideration of site factors and knowledge of herbicide characteristics. Familiarity with chemical and physical properties of herbicides and their effects on biological systems enables the selection of appropriate herbicide products, application methods, rates, and timing.

In addition to understanding herbicide characteristics, it is helpful to understand terminology used on herbicide labels. These labels are legally binding documents for herbicide use. The single most important rule in employing herbicides is to always read and follow the label instructions, which are provided on the herbicide container and are also available at numerous websites, such as Crop Data Management Systems (CDMS) (<https://www.cdms.net/label-database>).

Herbicide characteristics, such as:

- mode of action
- selectivity
- activity
- mobility in soil
- volatility
- persistence in the environment

- toxicity

are determined by the active ingredients as well as by the formulations of the herbicide products in which the active ingredients are “packaged.” Herbicides contain one or more active ingredients and several inert ingredients:

- a carrier/solvent
- possibly one or more adjuvants

Herbicide Components

The term **active ingredient** refers to the chemical substance in the herbicide product that disrupts plant metabolism and produces the herbicidal effect. The active ingredient has the greatest influence on the properties and behavior of the herbicide and is the primary factor to consider when selecting an herbicide product for a particular application. The active ingredient may be referred to by the **common name** (e.g., triclopyr) or its **chemical name** (e.g., for triclopyr: 3,5,6-trichloro-2-pyridinyloxyacetic acid). Many herbicidally active compounds are acids that can be formulated as salts (mostly amine salts) or esters. Once an herbicide enters the plant, the salt or ester is disassociated, and the parent acid may be transported throughout the plant to the site of action where the herbicidal effect is produced. The amount of an active ingredient in an herbicide product is reported either as the **amount of active ingredient (a.i.)** or the free acid portion of the active ingredient known as the **acid equivalent (a.e.)**. The latter is especially useful when comparing herbicides containing different derivatives of

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2. Anna Osiecka, senior biological scientist (retired); and Patrick J. Minogue, associate professor of silviculture; UF/IFAS North Florida Research and Education Center, Quincy, FL 32351.

the same parent acid. The amount of active ingredient in an herbicide product is usually expressed as the pounds of active ingredient or acid equivalent per gallon (or grams per liter) and also as the percentage a.i. or a.e. by volume or mass. Several active ingredients are available in both salt and ester formulations (e.g., triclopyr as Garlon® 3A and Garlon® 4, respectively). When choosing between a salt and an ester formulation, the following characteristics should be considered.

Salts

- water-soluble; polar (ionic—separate into negative and positive ions when mixed with water)
- typically require a surfactant to facilitate penetration through the waxy leaf covering (cuticle)
- low volatility (less likely to move as a vapor) and thus preferable near sensitive sites, especially in hot weather

Esters

- low water-solubility; generally require an emulsifying agent or agitation to maintain dispersion in water-based carriers
- oil-soluble; can penetrate the outer oil-loving, or lipophilic, tissues of plants such as the waxy cuticle of the leaf surface or the suberin-rich material of the bark
- varying degrees of volatility, but generally more volatile than salts
- generally more toxic to plants and animals than salts

Adjuvants

Adjuvants are chemicals included in an herbicide product or added to a tank mix immediately preceding an application to enhance herbicide effectiveness, stability of the spray preparation, or to improve application efficiency. Adjuvants improve herbicide performance by increasing efficiency of spray deposition to target vegetation and improving plant uptake. Adjuvants include surfactants (see below), pH buffers and acidifiers, drift mitigation agents, spray colorants, anti-foaming agents, and compatibility agents. Before adding adjuvants to an herbicide spray preparation, refer to the labels of all products to ensure their compatibility. While adjuvants may improve herbicide performance, they may also affect non-target species tolerance. For instance, some surfactants increase herbicide absorption by pines, resulting in injury, thus decreasing selectivity.

Surfactants

Surfactants (surface-active agents) are the most commonly used adjuvants and include several groups of products

described as spreaders, stickers, emulsifying agents, and crop oil concentrates. However, the term “surfactants” is often used in a narrower sense referring to spreaders, or wetting agents, which work by reducing the surface tension of water and causing a larger portion of each spray droplet to come into contact with the surface of the target vegetation. Reducing surface tension results in enhanced wetting and penetration by an herbicide. **Ionic surfactants** separate into negative and positive ions when mixed with water and may react unfavorably with ionic herbicides. **Non-ionic surfactants** do not separate into ions when mixed with water and therefore are not likely to react with herbicides. Since many herbicides are ionic, many herbicide labels specify the use of non-ionic surfactants.

Carriers/Solvents

Carriers, or solvents, are the inert liquid or solid materials in an herbicide product that serve as delivery vehicles for the active ingredients. Carriers are also used to dilute or suspend an herbicide product for the application. The most common liquid carrier is water because of low cost and ease of use. Petroleum and plant oils as well as liquid fertilizers are also used as herbicide carriers. Solid (dry) carriers include attapulgite, kaolinite, vermiculite, bentonite, polymers of starch, and dry fertilizers.

Herbicide Products or Formulations

Herbicide products or formulations are commercial preparations of herbicides. They may contain one or more active ingredients, adjuvants, and a carrier/solvent. Formulated herbicide products are registered and marketed under various trade names intended for uses specified on the product label. Forestry herbicides are manufactured as liquid or solid formulations. Because of the multitude of existing herbicide formulations, one has to make sure that the selected formulation is appropriate for the desired application. The important determining factors include application method, target weed species, crop tree species, and environmental considerations. Knowing the formulation helps the applicator to properly dispense herbicides in an appropriate carrier, add appropriate adjuvants if necessary, and select the appropriate application method.

Liquid Formulations

May be used undiluted, as in the case of “ready-to-use (RTU)” herbicide products (e.g., Pathfinder® II), mixed with water to form a solution, mixed with oil, or mixed with water plus oil carriers to form an emulsion. In a solution, herbicide product is dissolved in water and is dispersed uniformly in the spray preparation. In an emulsion, the

herbicide is suspended in minute globules of oil (micelles) in a predominantly water carrier through the use of an emulsifier. The water and oil phases will separate over time without agitation. Invert emulsions are a suspension of water droplets containing herbicide in a predominantly oil carrier, are very thick in nature, and provide some drift mitigation because they produce a larger droplet size.

- **Water-soluble liquids** are designated as L, SL, or WS in herbicide product names such as Velpar® L, the liquid formulation of hexazinone.
- **Emulsifiable concentrates** are commonly designated as EC in the product names such as Pendulum® EC, the emulsifiable concentrate formulation of pendimethalin.

Solid Formulations

May be mixed with water to form solutions or suspensions, or applied as a solid.

- **Soluble powders** form a homogenous solution in water.
- **Wettable powders** such as Aatrex® 80 W are suspended in water through constant agitation.
- **Water-dispersible granules**, also known as **dry flowables**, such as Velpar® DF, typically disperse (but do not fully dissolve) in water, and generally require agitation to prevent precipitation in the spray tank. They are similar to wettable powders, but formulated as small, easily measured granules.
- **Granules** and pellets (e.g., Pendulum® 2G) consist of one or more active ingredients embedded in an inert solid material. When applied to the soil they slowly dissolve, gradually releasing the active ingredients.

Herbicide Characteristics

Mode of Action is the mechanism by which an active ingredient interferes with the metabolism of a plant in order to kill or suppress it. It largely determines the effectiveness of an herbicide in controlling a particular species, and thus the **selectivity** of the herbicide product (see Table 1). An herbicide's mode of action includes the nature by which it is absorbed by plants (**activity**), the pattern of movement within the plant (**translocation**), and the physiological processes that are affected by the herbicide (**site of action**). The site of action is generally determined by the chemical structure and properties of an active ingredient. Herbicide active ingredients that are chemically similar belong to the same "chemical family" and tend to have the same site of action. However, active ingredients belonging to different families may also exhibit the same site of action. For example, triclopyr and clopyralid in the pyridine family,

and 2,4-D within the phenoxy family, are all auxin analogs and mimic this plant hormone physiologically. Alternating between herbicides with different sites of action helps prevent the creation of herbicide-resistant weed populations. The most common sites of action among forestry herbicides are:

- Auxin analogs (e.g., 2,4-D, aminopyralid, clopyralid, and triclopyr) mimic the plant growth hormone auxin, resulting in disorganized growth through many physiological processes.
- Photosynthesis inhibitors (e.g., atrazine and hexazinone) interfere with electron transport in photosynthesis.
- Amino acid synthesis inhibitors (e.g., glyphosate, imazapic, imazapyr, metsulfuron methyl, and sulfometuron methyl) prevent the synthesis of amino acids (the building blocks of proteins).
- Lipid biosynthesis inhibitors (e.g., fluazifop-p-butyl) prevent the synthesis of lipids, crucial elements of cell membranes.

Selectivity refers to an herbicide's capability to affect different categories of plants to different extents due to physiological or morphological differences between species, and is largely dictated by the herbicide's mode of action. Ideally, differences between crop plants and weed species are exploited. **Selective** herbicides have a specific range of susceptible species and often target a particular class of plants, such as broadleaf plants (e.g., 2,4-D and aminopyralid) or grasses (e.g., fluazifop-P-butyl and clethodim). **Non-selective** or **broad-spectrum** herbicides (like glyphosate) negatively affect most species by impacting metabolic processes common to many plant groups. Non-selective herbicides, therefore, are normally not used over-the-top of crop trees, especially during periods of active growth. Selectivity may also be achieved by manipulating application method, rate, and timing. For example, one can control undesirable trees by applying a non-selective herbicide directly to their stems or foliage without spraying desired vegetation. Also, some herbicides applied at lower rates may selectively control unwanted vegetation without affecting crop trees or other desired plant species. Non-selective herbicides can sometimes be applied with selectivity over-the-top of crop trees during their dormancy.

Activity refers to the way an herbicide enters treated plants.

Foliar-active herbicides are absorbed by leaves and stems, and typically require herbicide spray coverage to most of the crown in order to be effective in controlling woody plants. Herbicides absorbed by foliage may translocate to

the roots in the phloem. Some foliar-active herbicides can also be applied to stems and absorbed through bark and epidermal tissues. Many foliar-active herbicides can be injected directly into tree stems or applied to cuts made in the stem to expose cambium and vascular tissues. This approach also includes treating surfaces of cut tree stumps. Foliar herbicides exhibit **post-emergent** weed control, meaning they have to be applied directly to established plants.

Soil-active herbicides are taken up from the soil solution by roots and are transported in the xylem to the upper parts of the plant. They generally require adequate soil moisture for activation of herbicidal properties. For annual and perennial herbaceous plant control, soil active herbicides such as sulfometuron methyl are effective with **pre-emergent** application timing, meaning before plants emerge, or with early post-emergent timing, when weeds are only a few inches tall. Pre-emergent herbicides disrupt germination or kill germinating seedlings. Other long-residual soil-active herbicides such as hexazinone and imazapyr are more effective in controlling established plants such as perennial herbaceous plants, shrubs and trees and are usually applied during the growing season.

Herbicide mobility in soil, volatility, persistence, and toxicity are very important in environmental considerations (see Table 2).

Herbicide mobility in soil is determined by its water solubility and potential for soil sorption, both important characteristics for predicting the potential for off-site movement through leaching and runoff. The potential for soil sorption is assessed primarily through two measures, usually reported for the active ingredient and sometimes for the parent acid and the salt and ester formulation, if applicable:

- K_d (Soil sorption coefficient) is defined as the ratio of sorbed herbicide to dissolved herbicide at equilibrium in water/soil slurry at a given temperature and pH.
- K_{oc} (Soil organic carbon sorption coefficient) is calculated as K_d divided by the weight fraction of organic carbon present in the soil at a given temperature and pH.

Herbicides with small K_{oc} values are more likely to be leached compared with those with large K_{oc} values. However, K_{oc} values should be used with caution, since they may be significantly affected by soil properties and environmental factors.

Volatility refers to an herbicide's tendency to go into a gaseous phase during or after application and is primarily determined by its molecular weight and presence of cyclic hydrocarbons. High volatility may result in herbicide movement off-site with negative impacts on nearby sensitive crops. The danger of herbicide volatilization increases with increasing air temperatures during and immediately following application. Of the common forestry herbicides, only triclopyr and 2,4-D can pose significant volatilization risk. In general, ester formulations are more volatile than salts.

Persistence defines the “lasting power” of an herbicide and is measured in half-life. **Half-life** ($T_{1/2}$) can be defined as the expected time after application during which half of the applied herbicide would be degraded. The half-life values for herbicide active ingredients are derived from field and laboratory experiments. These values give only a rough estimate of the persistence in the environment, since an actual half-life of a particular herbicide product also depends on the formulation and can vary significantly depending on soil characteristics, weather (especially temperature and soil moisture), and vegetation at the site. Nonetheless, average half-life values, based on herbicide active ingredient deactivation in surface soils, provide some means of comparing the relative persistence of herbicide products. The $T_{1/2}$ values in subsoils and ground water are usually much larger and often not available.

Herbicide toxicity refers to the potential to cause injury, illness, or other undesirable effects in mammals, birds, fish, honeybees, or other organisms. Toxicity studies measure short-term (**acute**), mid-term (**subchronic**), and long-term (**chronic**) effects. Since most herbicides affect physiological processes exclusive to plants (like photosynthesis or plant-specific hormones or enzymes), the majority of forestry herbicides have very low toxicity to humans and animals.

The United States Environmental Protection Agency (EPA) requires results of six acute toxicity studies (acute oral, acute dermal, acute inhalation, primary eye irritation, primary skin irritation, and dermal sensitization) performed with the herbicide product formulation to determine the safety language appearing at the beginning of each herbicide label: an appropriate signal word, “Hazards to Humans and Domestic Animals,” “Personal Protective Equipment,” and “First Aid” statements. An herbicide is assigned a toxicity category for the results of each acute toxicity study, with exception of dermal sensitization (see Table 3). The signal word is determined by the most severe toxicity category.

The commonly used acute toxicity measures include the median lethal dose (LD_{50}) for oral and dermal exposure and median lethal concentration (LC_{50}) in air or water.

LD_{50} is the dose (quantity) of an herbicide that kills 50% of a population of test animals through oral or dermal exposure and is expressed in milligrams of the herbicide per kilogram of the test animal body weight.

LC_{50} is the herbicide concentration in the air (inhalation toxicity) or in the water (aquatic toxicity) that kills 50% of a population of test animals and is expressed in milligrams of the herbicide per liter of air or water (parts per million).

Chronic mammalian toxicities are determined by long-term (12–24 month) feeding studies, which evaluate the potential for long-term negative effects on test animals including:

- Carcinogenicity, the potential to cause cancer.
- Potential for adverse effects on reproduction.
- Teratogenicity, the potential to cause birth defects.
- Mutagenicity, the potential to cause genetic changes.

In addition, wildlife toxicity is determined using various test organisms, including quail, duck, honeybees, *Daphnia* (water flea), rainbow trout, and bluegill.

Acute and chronic toxicity studies are required for the registration of an active ingredient, and most often toxicities are reported for the technical grade of the active ingredient (or the parent acid), as in Table 2. However, the formulated herbicide product may have greater or lower toxicity, depending on the concentration and formulation of the active ingredient, as well as the adjuvants and carriers. For example, some ester formulations (e.g., Garlon® 4) are much more toxic to aquatic organisms than the salt formulations (e.g., Garlon® 3A). Surfactants may also increase herbicide toxicity to aquatic organisms. For example, glyphosate formulations with surfactants (e.g., Accord® XRT II) are more toxic to aquatic organisms than formulations containing no surfactants (e.g., Foresters®).

Detailed herbicide toxicity characteristics (including ecotoxicity) are included in Safety Data Sheets (SDSs) available at <https://www.cdms.net/label-database> and in Pesticide Information Profiles (PIPs) in EXTOTOXNET available at <http://extotoxnet.orst.edu/pips/ghindex.html>.

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Table 1. Forest herbicide characteristics relative to effectiveness.

Active Ingredient	Trade Name Examples	Chemical Family	Site of Action	Selectivity (target weeds)	Activity
2,4 D salt	Weedar® 64	Phenoxy	Growth regulator (auxin analog)	Annual and perennial broadleaves; woody plants	Foliar
2,4 D ester	Barrage® HF	Phenoxy	Growth regulator (auxin analog)	Annual and perennial broadleaves; woody plants	Foliar
Aminopyralid	Milestone®	Pyridine	Growth regulator (auxin analog)	Woody plants; annual and perennial broadleaves	Foliar, some soil
Atrazine	AAtrex® 4L	Triazine	Photosynthesis inhibitor	Annual broadleaves and grasses	Soil
Clopyralid	Transline®	Pyridine	Growth regulator (auxin analog)	Annual and perennial broadleaves; woody plants; vines	Foliar
Fluazifop-p-Butyl	Fusilade® DX	Aryloxyphenoxy-propionate	Lipid synthesis inhibitor	Annual and perennial grasses	Foliar
Fosamine	Krenite® S	Phosphonic acid	Unknown	Woody plants	Foliar
Glyphosate	Accord® XRT II, Foresters'®	Glycine	Amino acid synthesis inhibitor	Annual and perennial broadleaves and grasses; woody plants	Foliar
Hexazinone	Velpar® L	Triazine	Photosynthesis inhibitor	Annual and perennial broadleaves and grasses; woody plants	Soil, some foliar
Imazapic	Plateau®	Imidazolinone	Amino acid synthesis inhibitor	Annual and perennial grasses and broadleaves; vines	Foliar and soil
Imazapyr	Arsenal® AC	Imidazolinone	Amino acid synthesis inhibitor	Annual and perennial grasses and broadleaves; woody plants; vines	Foliar and soil
Metsulfuron methyl	Escort® XP	Sulfonylurea	Amino acid synthesis inhibitor	Annual and perennial grasses and broadleaves; woody plants	Foliar and soil
Sulfometuron methyl	Oust® XP	Sulfonylurea	Amino acid synthesis inhibitor	Annual and perennial grasses and broadleaves	Foliar and soil
Triclopyr salt	Garlon® 3A	Pyridine	Growth regulator (auxin analog)	Annual and perennial broadleaves; woody plants	Foliar
Triclopyr ester	Garlon® 4	Pyridine	Growth regulator (auxin analog)	Annual and perennial broadleaves; woody plants	Foliar

Table 2. Forest herbicide characteristics relative to environmental and safety concerns according to *Herbicide Handbook* (Senseman 2007; Shaner 2014).

Active ingredient	Water solubility (mg/L)	Behavior in soils			Toxicity		Environmental and safety concerns
		Soil sorption average K_{oc} (mL/g)	Mobility	Soil half-life average (range) (days)	Oral LD ₅₀ Rat (mg/kg)	Dermal LD ₅₀ Rabbit (mg/kg)	
2,4 D DMA salt	729,000 (20°C)	20	Moderate	10 (7–28)	949	1,829	Severe eye irritant
2,4 D 2-EHE ester ¹	0.087 (20°C)	100	Moderate	10 (7–28)	896	>2,000	Volatility concerns
Aminopyralid	212,000 (pH 5); 203 (pH 9)	10.8	Low	32 (6–74)	>5,000	>5,000 (rat)	
Atrazine	33 (22°C, pH 7)	100	Low	60	3,090	>3,100	Restricted-use herbicide because of ground water contamination potential
Clopyralid ²	300,000 (25°C)	6 (6–60)	Moderate	40 (12–70)	>5,000	>2,000	Selective herbicide developed as an alternative to picloram
Fluazifop-P-butyl	1.1 (25°C)	5,700	Low	not available	>5,000 ³	>2,000 ⁴	
Fosamine	1,790,000 (25°C)	150	Low	8	24,400	>1,683	
Glyphosate	900,000 (25°C, pH 7) ⁵	24,000	Very low	47	5,600	>5,000	Tightly bound to soil
Hexazinone	33,000 (25°C)	54	Moderate-high	90	1,690	>6,000	Potential for ground water contamination, especially on sandy soils; eye danger
Imazapic	2,200 (25°C)	112	Low	120	> 5,000	>2,000	Long residual
Imazapyr	11,272 (25°C, pH 7)	poor, K_{oc} not available	Moderate	25–142 days	> 5,000	>2,000	Long residual; hardwood trees may be injured if their roots extend into treated area
Metsulfuron methyl	(25°C): 548 (pH 5) 2,790 (pH 7)	35 (pH 7)	Moderate	30 days (7–42)	> 5,000	>2,000	
Sulfometuron methyl	(25°C): 10 (pH 5) 300 (pH 7)	78 (pH 7)	Moderate-high	20–28 (pH 6–7)	> 5,000	>2,000	Solubility increases greatly and crop tree tolerance decreases at soil pH above 6.1
Triclopyr salt ⁶	2,100,000 (25°C)	20	Moderate	30 (10–46)	2,574	>5,000	Eye danger
Triclopyr ester ⁷	23 (25°C)	780	Low	30 (10–46)	1,581	>2,000	Volatility concerns

¹ 2-EHE = 2-ethylhexyl ester
² As monoethanolamine salt
³ As Fusilade DX
⁴ As a parent acid
⁵ Isopropylamine salt
⁶ Triethylamine salt (Garlon® 3A)
⁷ Butoxyethyl ester (Garlon® 4)

Table 3. Pesticide toxicity categories according to US EPA Label Review Manual (as of July 2014).

Study	Category I	Category II	Category III	Category IV
Acute Oral	Up to and including 50 mg/kg	> 50–500 mg/kg	> 500–5000 mg/kg	> 5000 mg/kg
Acute Dermal	Up to and including 200 mg/kg	> 200–2000 mg/kg	> 2000–5000 mg/kg	> 5000 mg/kg
Acute Inhalation ¹	Up to and including 0.05 mg/L	> 0.05–0.5 mg/L	> 0.5–2 mg/L	> 2 mg/L
Primary Eye Irritation	Corrosive (irreversible destruction of ocular tissue) or corneal involvement or irritation persisting for more than 21 days	Corneal involvement or other eye irritation clearing in 8–21 days	Corneal involvement or other eye irritation clearing in 7 days or less	Minimal effects clearing in less than 24 hours
Primary Skin	Corrosive (tissue destruction into the dermis and/or scarring)	Severe irritation at 72 hr (severe erythema or edema)	Moderate irritation at 72 hr (moderate erythema)	Mild or slight irritation at 72 hr (no irritation or slight erythema)
Signal Word	DANGER	WARNING	CAUTION	CAUTION (optional)
¹ 4 hr exposure				