UNIVERSITY OF GEORGIA
Warnell School of Forestry & Natural Resources

Publication WSFNR-22-31A

September 2022

Forestry and forestry-related herbicide modes of action

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INTRODUCTION

Herbicide mode of action (MOA) is important for vegetation management in forestry, agriculture, and other uses as it dictates how herbicides control susceptible plants. Understanding MOA can make herbicide applications more effective in the control of undesirable plants, avoid monetary loss with ineffective herbicide applications, decrease environmental impacts and increase awareness of potential weed resistance. Essentially, MOA represents the manner in which an herbicide affects a plant at the tissue or cellular level. Herbicides with the same mode-of-action will have the same translocation (movement) pattern and produce similar injury symptoms such as the onset of chlorosis or foliage yellowing (Figure 1) and/or necrosis (brown or black coloration and death of cells) (Figure 2). Each herbicide is placed into a specific group based on their MOA. This information can be extremely important to know when planning an herbicide prescription for forest vegetation management. Herbicide groups follow the Weed Science Society of America (WSSA) and Herbicide Resistance Action Committee (HRAC) classification system. Herbicide MOAs with labeled forestry applications are much fewer than the current total number of herbicide MOAs (see Shaner 2014). The purpose of this paper is to provide descriptions of each herbicide mode of action commonly used in forestry vegetation management. In addition, information on potential tank mixes with other forestry herbicides, average herbicide soil persistence information, and available product trade names are provided with each mode of action.

Figure 1: *Example of foliage chlorosis (foliage yellowing) caused by an herbicide application on waxmyrtle and loblolly pine seedlings/saplings.*

Figure 2: *Foliage and stem necrosis (brown or black coloration) caused by a recent glyphosate application approximately four days prior.*

GROUP 1(^{A}), ACETYL COA CARBOXYLASE (ACCASE) INHIBITORS

These herbicides are commonly used for annual and perennial grass control in pine and hardwood stands. They are applied as first or second year banded, broadcast, or directed spray (fluazifop-P-butyl) herbaceous weed control. Group 1(A) herbicides inhibit fatty acid synthesis preventing the production of new cell membrane growth/cell growth. Broadleaf species are resistant because they contain an insensitive ACCase enzyme. After treatment, the plants will stop growing, form leaf chlorosis and eventually leaf or sheath necrosis will develop between one and three weeks, starting with younger tissue. It is important to note that these herbicides generally cannot be tank mixed with any other herbicide groups that are used for forest vegetation management without potential antagonism or incompatibility. Soil persistence of herbicides in this group is minimal and is typically less than 15 days. Three herbicides in this group have forestry or natural areas labels. These include: clethodim, fluazifop-P-butyl, and sethoxydim. Common trade names of clethodim products include: Arrow® 2EC, Cleanse™ 2 EC, and Envoy Plus™. Fusilade® DX is the only fluazifop-P-butyl product registered for forestry use (check label by state). Common trade names of sethoxydim products include Poast Plus® and Segment® II.

GROUP 2(^{B}), ACETOLACTATE SYNTHASE (ALS) INHIBITORS

ALS inhibitors are commonly used for several forestry vegetation management scenarios. They are essential for site preparation, post-plant herbaceous weed control, hack and squirt, basal bark, individual plant foliar applications, and mid-rotation release for planted pines, and some hardwood species. Herbicides in this group inhibit acetolactate synthase (ALS), which is an enzyme in the synthesis of branched chain amino acids. Symptoms of ALS inhibitors include growth stunting as soon as a few hours after treatment to within a couple of months after initial treatment (onset of symptoms depends on the herbicide, application method (e.g. foliar versus hack and squirt application), foliar chlorosis and necrosis, and leaves or herbaceous plant stems may exhibit reddish-purple coloration, vein discoloration and necrosis of terminals. Many of these products have more than one labeled use, so be sure to pay close attention to the product label for your intended use. These chemicals can persist in the soil for 20 days (sulfometuron methyl) to 90+ days (imazapyr) depending on the product and rate used, soil texture and chemical properties, as well as climate factors. Plant-back wait periods with ALS inhibitors can be very important for some products and application scenarios such as imazapyr when used at chemical site preparation rates (see Dickens et al. 2020 for more on this subject). Group 2 herbicides can be tank mixed with several other herbicide groups, but check the label of a specific product for compatible tank mixtures or conduct a jar test if needed. Sulfometuron methyl is a commonly used ALS inhibitor with several available products such as Oust® XP, Spyder®, and SFM 75. Metsulfuron methyl products include: Escort® XP, Patriot®, and MSM 60. Some products in this group contain a mixture of both chemicals such as Oust® Extra. Four-pound acid equivalent (ae) imazapyr are available for a variety of forestry application methods and uses and include: Arsenal® Applicators Concentrate, Polaris® AC Complete, and Imazapyr 4 SL. These 4 lb. ae products lack a built-in surfactant. Two-pound ae products more commonly used for site preparation such as Chopper® Gen2™, ecomazapyr 2SL, etc. are also available. These products sometimes have a built-in surfactant. Imazapyr products may have different formulations and intended uses, so pay close attention to the label. An aquatic labeled imazapyr product called Habitat® is also available. Herbicides also included in this group with more specific forestry-related labeled uses (e.g. noncropland or Conservation Reserve Program areas) are imazamox (e.g. Clearcast®) and imazapic with several available products such as Plateau®, Journey®, and Cadre®.

GROUP 3(^{K_1}), MICROTUBULE ASSEMBLY INHIBITORS

The Group 3(^{k_1}) herbicides are not commonly used for forestry, but are labeled for use in tree plantations, noncropland areas, conifer Conservation Reserve Program land, and similar areas when applied as pre-emergence applications. These herbicides bind to the tubulin protein causing loss of cell structure and function, misaligning and separation of chromosomes during mitosis, and disruption of cell wall functions. These herbicides do not work on established plants and are used as preemergent herbicides to control germinating weeds. Grasses and broadleaf weeds generally do not emerge after application due to secondary lateral root deformation, thickening, and growth stunting. Soil persistence is moderate and averages 44-days across a range of different soil types and local climates. There are not many herbicides available for forestry-related applications in this group, but a common one is pendimethalin under the trade name Pendulum® 2G.

GROUP 4(°), SYNTHETIC AUXINS

Synthetic auxins are some of the most commonly used herbicides in forest vegetation management and are widely available for purchase. They mimic the natural plant growth hormone auxin and disrupt growth hormone balance in plants. Growth hormones affect cell division, cell elongation, and protein synthesis, and the killing action of auxin herbicides is caused the by disruption of several growth processes in susceptible plants. Visual symptoms of auxin herbicides include bending and twisting of stems and petioles, leaf cupping and curling, stunted growth, chlorosis at growing points, wilting, and finally necrosis. Application methods of these herbicides include: broadcast applications, hack and squirt (injection), basal bark sprays, and individual plant control treatments. It usually takes 3-5 weeks for plant mortality. Some common herbicides in this group are 2,4-D, aminopyralid, picloram, triclopyr, fluroxypyr, aminocyclopyrachlor, florpyrauxifen-benzyl, and clopyralid. Many companies produce some of these herbicides, such as 2,4-D and triclopyr. Triclopyr and 2,4-D also come in different formulations such as amine, ester, free acid (or acid), dimethylamine or DMA (2,4-D) and choline salt. These different formulations have advantages and disadvantages for certain application scenarios, and some formulations may have different labeled application methods. For instance, triclopyr amine is labeled for hack and squirt applications and triclopyr ester is labeled for basal bark applications, while both products are labeled for cut stump treatments. Aquatic labeled products of some herbicides (e.g. triclopyr—Renovate® 3) in this group are also available. Synthetic auxins can be tank mixed with a variety of other forestry herbicides depending on label restrictions, and some herbicides in this group may be tank mixed in pre-mixed products for specific application types. Soil persistence is typically low but can be short or long-term ranging from 1 week (2,4-D) to a year or longer (aminocyclopyrachlor) depending on the herbicide, soil texture, and climate. Fewer purchasing options are available with some of the less commonly used or new synthetic auxins such as aminopyralid (e.g. Milestone®), clopyralid (Transline® and Clopyralid 3), aminocyclopyrachlor (Method® 240SL), aminopyralid + florpyrauxifen-benzyl (TerraVue®), and fluroxypyr (Vista® XRT and Flagstaff™).

GROUP 5(C_1), PHOTOSYNTHESIS INHIBITORS OF PHOTOSYSTEM II SITE A

Photosynthesis inhibitors of photosystem II site A have many varied uses in forestry depending on the herbicide used. Herbicides in this group block photosynthesis or the food production process in plants. These herbicides quickly cause a loss of chlorophyll and carotenoids while drying cell membranes and cell organelles causing them to disintegrate. Hexazinone causes foliar chlorosis, then necrosis. Atrazine causes distinctive interveinal (leaf vein) and leaf margin (leaf edges) chlorosis. Symptoms are more prevalent on older leaves, with leaf browning at the tips occurring. Some Group 5 herbicides are used for broadleaf weed control with loblolly and slash pines only (atrazine), while hexazinone has more varied uses that include: hardwood control (oaks and sweetgum especially), conifer site preparation (spring application), stem injection, basal (soil) single stem treatment, soil grid applications with a metered spotgun, herbaceous weed control (southern pines and yellow-poplar plantations), woody release, and spot control applications. Atrazine is used primarily for broadleaf weed control and offers control of some grasses. Hexazinone is very effective on oaks and some other hardwood species but is weak on sassafras, blackgum, yellow-poplar, red maple, and most conifer species. There are fewer available products for forestry use in this group than in some other groups, but these products are important in some application scenarios. Atrazine and hexazinone can be tank mixed for specific uses and with herbicides as stated on each product's label (e.g. hexazinone and sulfometuron methyl for southern pine post-plant herbaceous weed control). Soil persistence with this group is moderately long and depends on the herbicide used. Average soil half-life for atrazine is 60 days while hexazinone is 90 days. An atrazine product with a forestry label is Atrazine 90 DF. Some products with the active ingredient hexazinone include Velpar® L VU (liquid product) and Velpar® DF VU (dry flowable product) as well as Velossa™ (dry flowable product).

GROUP 7(C_2), PHOTOSYNTHESIS INHIBITORS AT PHOTOSYSTEM II SITE A; DIFFERENT BINDING BEHAVIOR THAN GROUP 5

Herbicides in this group are used at low rates along fence rows, industrial sites, rangeland, pastureland and non-cropland areas for broad spectrum control of broadleaf and woody species. They are usually applied as soil treatments or bands to small areas or around individual woody plants. Herbicides in this group can kill most vegetation, and if used at high rates can maintain soil activity and limit plant growth for many years. They may occasionally be used as soil sterilants. These herbicides prevent CO2 fixation, which halts the production of energy sources for plant growth and leads to chlorophyll and carotenoid loss and cell membrane leakage, which leads to cell drying and disintegration. Symptoms begin with discoloration of the foliage. Eventual foliage browning or blackening occurs before plant mortality. Tebuthiuron is not tank mixed with other forestry herbicides, and it is not commonly used in forestry but may have more applications in pasture and rangeland management. Long soil persistence is an important consideration when deciding to use this herbicide. Average soil half-life is 12-15 months in areas that receive 40 to 60 inches of precipitation per year and can be considerably longer in dryer areas or in soils with high organic matter content. Common trade names such as Spike® 80DF, Spike® 20P, Tebuthiuron 80 WG, and Tebuthiuron 20 P are available.

GROUP 9(G), INHIBITOR OF 5-ENOLYPYRUVYL-SHKIMATE-3-PHOSPHATE SYNTHASE (EPSPS)

The only herbicide in this group, glyphosate, is used for spot applications, individual plant control, and site preparation and is one of the most common herbicides used in forestry and all of agriculture. The herbicide causes EPSPS inhibition leading to amino acid depletion causing protein synthesis to halt and stopping biosynthetic pathways that lead to new plant growth. After treatment, the plants will stop growing and chlorosis and necrosis will appear as soon as four to seven days after application for some species. Other symptoms may include discoloration (red to purple) of the leaves and regrowth of woody species being deformed with white markings or striations. Some affected species will not show symptoms for 10-20 days. Though glyphosate is a broad-spectrum herbicide that controls grasses, broadleaf weeds, vines, shrubs, and trees, there are some species it does not control, such as hickory spp., greenbrier spp., Virginia creeper, or trumpet creeper. Glyphosate is sold under many common trade names. Be sure to check the herbicide label for the active ingredient amount and proper application rates for your intended use, as glyphosate products often have differing active ingredient amounts. Aquatic labeled glyphosate products such as Rodeo® are also available. A variety of glyphosate tank mixes are possible, but glyphosate is most often tank mixed with synthetic auxins (Group 4) and ALS inhibitors (Group 2). Be sure to check the label of all potential tank mix herbicides for compatible mixes and conduct jar tests if unsure of compatibility. Soil persistence averages 47 days, but glyphosate adsorbs strongly to soil making planting immediately after application feasible. Common products used in forestry applications include: Razor® Pro, Touchdown® HiTech, Roundup Promax®, Cornerstone® Plus, and Accord® XRT II.

GROUP 10(H), GLUTAMINE SYNTHETASE INHIBITORS

The single herbicide in this group (glufosinate) is used for nonselective weed control generally in a farm setting, but some products do have forestry site preparation, brush control, natural areas, and Conservation Reserve Program labels. Other related labeled application areas include fencerows, shelterbelts, and Christmas tree farms. Glufosinate inhibits the activity of glutamine synthase, which stops the binding of glutamate and ammonia that forms glutamine, and causes a buildup of ammonia in cells. This causes cell mortality and reduces or stops photosynthesis. Glufosinate symptoms develop quickly after most applications and begin with chlorosis and wilting 3-5 days after treatment and necrosis 1-2 weeks later. Information on compatible forestry herbicides for tank mixes is limited. Soil persistence is a week or less. Weather is a factor in the efficacy of this herbicide, so pay close attention to weather conditions listed on the label for application. Products with forestry-related labels include: Cheetah®, Finale® XL T&O, and Interline®.

GROUP 14 (^{E}), PROTOPORPHYRINOGEN OXIDASE (PROTOX, PPO) INHIBITORS

These herbicides are used for preemergence and postemergence broadleaf weed control in conifer nursery stock and Christmas tree production areas. In addition, they can be valuable for herbaceous weed control with some hardwood species on sites that are prone to flooding. These chemicals affect chlorophyll production by oxidizing lipids in proteins causing cell membranes and organelles to dry and disintegrate. Symptoms with this group are conspicuous and occur quickly. Treated leaves begin bleaching (white coloration), desiccating, and finally necrosis spots develop where foliage is contacted. Full leaf necrosis occurs within one to two days after treatment. Herbicides in this group tend to be weak on grasses and most woody species. Depending on the herbicide, soil persistence ranges from none (flumioxazin) to approximately 30 days (oxyfluorfen). There are two herbicides labeled for forestry-related applications in Group 14 (^{E}), including oxyfluorfen (Goal® 2XLand Oxyflo 2EC) and flumioxazin (Lock Down™ SC and Flumigard™).

GROUP 27 (^{Z}), ENZYME INHIBITOR

The lone forestry herbicide in this group is fosamine. Fosamine inhibits mitosis and the effects are seen during the following spring after a fall application, as affected plants do not develop buds or leaves. What leaves do appear will be small or misshapen. It offers broad spectrum control of many deciduous trees, southern pines, and shrubs along with some difficult to control herbaceous species such as bracken fern. Fosamine may be applied as a conifer site preparation application (often as a burndown application to promote a subsequent site preparation burn), individual plant treatments, and as cut stump applications. Tank mixtures of fosamine with metsulfuron methyl, imazapyr, or picloram can be utilized to broaden the spectrum of control. Fosamine and constituent components have limited soil persistence, which is typically less than a month. Fosamine or fosamine ammonium is the active ingredient in Krenite® S and Fosamine 41.5% SC.

GROUP 29(^{L}) INHIBITION OF CELLULOSE BIOSYNTHESIS

Group 29(^{L}) is a relatively new (first products introduced in 2010) mode of action (Shaner 2014), and this group contains one herbicide that can be used for forestry applications. Indaziflam inhibits cellulose biosynthesis and prevents weed seedling growth. If applied post-emergence it causes growth stunting and root swelling or clubbing. Indaziflam is used primarily as a pre-emergent herbicide for site preparation and herbaceous weed control in conifer and hardwood plantations pre-bud swell stage. For forestry site preparation, it may be applied as a post-emergence application. Rainfall of 0.25 in or greater is required within a few weeks after application to activate Group 29 herbicides. Indaziflam may be tank mixed with a variety of other common forestry herbicides such as triclopyr, imazapyr, hexazinone, glyphosate, and others (see label) to improve the spectrum of control. Soil persistence can last over 150 days with this herbicide. Indaziflam is sold under trade names such as Esplanade® F and Marengo®.

CONCLUSIONS

Understanding the MOA of each chemical group can help a producer determine which herbicides might work best for a particular application and save valuable time and money. Not all of the modes of action mentioned here are frequently used in forestry applications primarily due to costs, but applicators should be aware of their availability. Always consult the label of a product you are considering for purchase, and determine if it has a forestry label that meets your application objectives, corresponds with your intended application method, and can be legally used in your state (e.g. picloram cannot be used in Florida). Always follow label instructions (remember the label is the law) and wear proper personal protective equipment with any application. When applicators can pinpoint a mode of action that best meets their vegetation management objective and selected application method, they can choose the correct herbicide to better accomplish objectives, apply less herbicide yet maintain efficacy, save money and time, and reduce environmental impacts.

CITATIONS AND SUGGESTED READINGS

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APPENDIX. FORESTRY AND FORESTRY-RELATED HERBICIDE MODES OF ACTION SUMMARY TABLE.

Group	Mechanism of Action	Herbicides	Common Trade Names[1]
Group 1(A)	Acetyl CoA Carboxylase (ACCase) Inhibitors	Clethodim Fluazifop-P-Butyl Sethoxydim	Arrow® 2EC, Clean-up™ 2 EC, and Envoy Plus™ Fusilade® DX Poast® and Segment® II
Group 2(B)	Acetolactate Synthase (ALS) Inhibitors	Sulfometuron methyl Metsulfuron methyl Imazapyr Imazamox Imazapic	Oust® XP, Spyder®, and SFM 75 Escort® XP, Patriot®, and MSM 60 Arsenal® Applicators Concentrate, Polaris® AC Complete, Imazapyr 4 SL, Chopper® Gen2™, ecomazapyr 2SL, Habitat®, etc. Clearcast® Plateau®, Journey®, and Cadre®
Group 3(K1)	Microtubule Assembly Inhibitors	Pendimethalin	Pendulum® 2G
Group 4(O)	Synthetic Auxins	2,4-D Aminocyclopyrachlor Aminopyralid Clopyralid Florpyrauxifen-benzyl Fluroxypyr Picloram Triclopyr	Freelexx™, Weedone® LV6 EC, plus many others Method® 240SL Milestone® Transline® and Clopyralid 3 TerraVue® Vista® XRT and Flagstaff™ Tordon® RTU, Picloram 22K, Tordon™ 22K, Triumph® 22K Garlon® 4 Ultra, Relegate®, Triclopyr 4, Garlon® 3A, Forestry® Garlon XRT, Renovate® 3, Vastlan™, Trycera®, plus many others
Group 5(C1)	Photosynthesis Inhibitors of Photosystem II Site A	Atrazine Hexazinone	Atrazine 90 DF Velpar® L VU, Velpar® DF VU, Velossa™
Group 7(C2)	Photosynthesis Inhibitors at Photosystem II Site A; Different Binding Behavior than Group 5	Tebuthiuron	Spike® 80DF, Spike® 20P, Tebuthiuron 80 WG, and Tebuthiuron 20 P
Group 9(G)	Inhibitor of 5-Enolpyruvyl-Shikimate-3-Phosphate Synthase (EPSPS)	Glyphosate	Razor® Pro, Touchdown® HiTech, Roundup Promax®, Cornerstone® Plus, Accord® XRT II, plus many others
Group 10(N)	Glutamine Synthetase Inhibitors	Glufosinate	Cheetah®, Finale® XL T&O, and Interline®
Group 14 (E)	Protoporphyrinogen Oxidase (Protox, PPO) Inhibitors	Flumioxazin Oxyfluorfen	Flumigard™ and Lock Down™ SC Goal® 2XL and Oxyflo 2 EC
Group 27 (H)	Enzyme Inhibitor	Fosamine	Krenite® S and Fosamine 41.5% SC
Group 29(L)	Inhibition of Cellulose Biosynthesis	Indaziflam	Esplanade® F and Maxengo®

[1]Mention of a specific trade or product name does not endorse that product by the authors or the University of Georgia.