

Review

A Review of Chemical Weed Control Practices in Christmas Tree Production in the United States

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Abstract: Christmas trees are sensitive to weed competition, especially during establishment. In initial stages of the tree crop, weeds can utilize available soil moisture and trees may succumb to drought stress. In later stages, weeds can even interfere with production practices. Non-chemical weed control methods alone may not provide effective weed control. Chemical weed management strategies involve the use of preemergence and postemergence herbicides at the right timing and application rates. There are many herbicides that are used in Christmas tree production in the United States, and each has specific application guidelines and weed control spectra. Moreover, crop trees vary in tolerance by species and tree age. Growers need to be careful while applying herbicides as many of these chemicals can cause injury to Christmas trees. Repeated application of herbicides with the same mechanism of action has resulted in development of herbicide resistance among several weed species. Managing herbicide resistance has now become an important issue. More research is required on identifying and managing herbicide resistance among weed species in Christmas tree production. Future research needs to focus on herbicide and mulch combinations, herbicide rotations, and tank mixing different herbicides with different mechanisms of actions and how these affect Christmas tree varieties.

Keywords: Christmas trees; preemergence herbicides; postemergence herbicides; herbicide resistance; glyphosate



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1. Introduction

In the United States, Christmas trees are grown on around 15,000 farms which encompass nearly 350,000 acres [1]. This industry yields an average of \$250 million in sales per year and employs more than 100,000 people [2]. There are many factors contributing to the successful production and profit margins within this industry, and these factors must be correctly implemented. In the United States, typical Christmas tree crops are produced on rotation lengths that vary from 8 to 12 years, depending on species and region of the country. Seedlings and transplants often are grown in nurseries for three to five years and then are transplanted into production fields. Throughout a given rotation, Christmas trees are sensitive to weed competition; therefore, weed control is a very pressing issue in Christmas tree production [3].

One important aspect to consider when planning for successful Christmas tree production is an adequate weed management plan, as weeds must be controlled for both aesthetic and biological reasons to create marketable Christmas trees [4]. There are some benefits to the presence of vegetative cover in Christmas tree plantations. These can include decreased erosion caused by wind and water, reduced nutrient leaching, improved microclimates, and increased biodiversity [5]. Therefore, complete elimination of non-crop

vegetation (including weeds) is not necessary or recommended, but non-crop vegetation needs to be maintained at low densities [4]. The choice of chemical or non-chemical weed control often depends on weed pressure, size, and type of operations (such as wholesale vs. choose and cut), as well as growers' philosophy. Currently, there are few fully organic farms, but many growers are seeking to reduce chemical inputs. Non-chemical methods used to control weeds in Christmas tree production systems include mulching, mechanical control, livestock, cover crops, biological control, and thermal control. In our previous publication [6], we discussed the different non-chemical weed control strategies that can be applied to Christmas tree production. However, non-chemical weed control strategies alone cannot control weeds effectively and the methods are laborious, time consuming, and expensive. Therefore, chemical weed control is an essential component of effective weed management programs in Christmas tree production system. Most of the information related to chemical weed control strategies for Christmas trees is currently available in the form of extension factsheets, bulletins, newsletters, or as blogs, and hence there is strong need of a proper scientific literature review in this area. The purpose of this review is to provide an overview of chemical weed control strategies in Christmas tree production specific to the United States and to identify knowledge gaps where current practices could potentially be improved or on which further research is required. We focus our review and discussion on the United States because restrictions on the use of herbicides and the regulatory environment varies widely between the United States and Europe and between the United States and Canada.

2. Impacts of Weeds in Christmas Tree Production

During all stages of production, weeds can impede tree growth [7]. Problems caused by weeds include competition for water, nutrients, light, and space with the trees. Weeds can also harbor pathogens and pests. Weed control is especially important during the first three years after planting, when transplants are most sensitive to weed competition [7–11]. Weed competition, especially for water, throughout the establishment phase can reduce tree growth and can possibly result in the death of trees [12]. The level of tree growth is directly related to the extent of weed competition in the second and third years of the establishment phase [7]. Christmas trees are often grown in light-textured soils, and in these soils, weeds can take the limited available moisture which can increase tree drought stress. Seedlings and young trees can be shorter than the weeds and weeds can shade these trees this may result in reduced photosynthesis and therefore hinder leaf area development and subsequent growth [13].

For larger trees, weeds can interfere with production practices including spraying and pruning [7]. Weeds can even shade the lower branches of larger trees [14]. Weeds that are problematic in established plantations include broadleaves like horseweed (*Erigeron canadensis* (L.) Cronquist), field bindweed (*Convolvulus arvensis* L.), wild carrot (*Daucus carota* L.), hoary alyssum (*Berteroa incana* (L.) DC.), common ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), and hairy vetch (*Vicia villosa* Roth). In addition, the seed head of grasses can grow into the trees and be difficult to remove. Common grasses include witchgrass (*Panicum capillare* L.), giant foxtail (*Setaria faberi* Herrm.), large crabgrass (*Digitaria sanguinalis* (L.) Scop), and fall panicum (*Panicum dichotoliflorum* Michx.). Vining weeds such as field bindweed, Virginia creeper (*Parthenocissus quinquefolia* (L.) Planch.), poison ivy (*Toxicodendron radicans* (L.) Kuntze), and wild grape (*Vitis* spp. L.) can grow and tangle in Christmas trees, making them difficult to remove. In situations where weeds are tangled within trees, herbicides cannot be used without risking injury to the trees [7]. The low branches of Christmas trees can be scratched by weeds, which can cause those needles to drop and brown and can cause a rough crown growth [15].

The most common means of weed control relied on by Christmas tree growers are mechanical mowing and chemical herbicide applications. However, there are several concerns with herbicides in Christmas tree plantations. Frequent applications of the same herbicides have developed herbicide-resistant weed species. For example, some Michigan Christmas

tree growers have made recent reports of common ragweed resistance to clopyralid, a synthetic auxin herbicide, especially in Montcalm County [16]. Postemergence herbicides can result in severe phytotoxic injuries to Christmas trees including stunted growth, burning, and dropping of needles, chlorosis, and even complete death of the tree, particularly when new shoots have recently emerged [14]. Sensitivity to herbicides is often acute for newly planted seedlings and transplants because they often receive a larger proportion exposure from directed applications. In addition, herbicides can have an adverse environmental effect, such as herbicide leaching, drift, and run-off.

Weeds that are not managed can hinder Christmas trees at all stages of development. During the first three years in the plantation, adequate weed control is imperative to ensure that the trees are able to establish healthy root systems which allow them to withstand drought stress later in life [7]. This is something that needs to be considered because, after transplanting, the trees need to re-establish healthy and full root systems which have been damaged or lost during transplanting [17]. Dry summers and competition with weeds for soil moisture may cause up to an 80% mortality rate of transplants [18]. Weed competition directly relates to the rate of tree growth during their establishment phase. Thus, minimal weed competition during this establishment period will allow the trees to grow well.

When the trees get older, the main problems caused by weeds shift to issues with managing the trees by hindering activities, including spraying for pesticides and pruning the trees [2]. Large and poisonous weeds can pose a threat to the handlers who are performing these activities [7]. Weeds also can have adverse effects on the lower limbs of the trees through light competition, entanglement in the branches, and even by killing the lower branches [7]. Excessive weed growth can provide cover for mammals such as field mice, rabbits, deer, etc., which can have damaging effects on the Christmas trees. Weeds can negatively affect needle characteristics, reducing needle size and color quality (presumably due to nutrient competition) [19]. Weeds can become a potential fire hazard during hot and dry seasons. For farms that market trees on a choose-and-cut basis, too many weeds can negatively affect the customer experience when the trees are being sold, by not allowing the customers to get close enough to the trees and/or posing a threat to the customers through the presence of dangerous weeds [20]. Similarly, weeds can interfere with harvesting operations on wholesale farms, as well.

3. Chemical Weed Control

Solely depending on non-chemical weed control methods may not result in an effective weed management in Christmas tree production. In addition, non-chemical weed control practices can be laborious, time consuming, and expensive. An effective chemical weed control includes weed identification and scouting, choosing, and applying preemergence and postemergence herbicides at their appropriate application rates and times. Growers need to choose the right herbicide product so that it does not cause any injury to the Christmas tree varieties. In this section, some of the important preemergence and postemergence herbicides that can provide effective weed control in Christmas tree production have been discussed.

3.1. Preemergence Herbicides

Preemergence herbicides are applied before the weeds have emerged. Most preemergence herbicides are applied to the soil and provide continuous control over weed emergence for longer periods of time as a residual [21]. These herbicides do not stop seeds from germinating but can prevent germinated weeds from becoming established. Preemergence herbicides work by inhibiting the growth of the roots, shoots, or both. To be effective, the herbicide must be incorporated into the soil and activated by addition of water from either rain or irrigation. These herbicides leave a residual when they are applied and, due to this, can control weeds for 8–12 weeks after application. Therefore, timing of herbicide application is critical to ensure emergence coincides with the residual window. Preemergent herbicides can be beneficial in that they often use different mechanisms of action from

postemergence herbicides. However, preemergent herbicides are not very effective on their own and require combination with other (both chemical and non-chemical) weed control methods [4,22].

Young Christmas trees may be sensitive to preemergence herbicides, but once their roots are established deeper into the soil the risk of injury decreases. Preemergence herbicides should be applied soon after transplanting to reduce weed competition with the young trees. Well-established Christmas trees have a low risk of injury from preemergence herbicides because the herbicide stays near the soil surface and tree roots are much deeper [2]. There is a chance of injury if the herbicide levels build up in the soil and make their way to the root zone of the trees. This possibility can be decreased by using low solubility herbicides and altering mechanisms of action over time [7]. For best results, preemergence herbicides need to be applied to weed-free soils.

Preemergence herbicides that are labeled for use in Christmas tree production in the United States can be found in Table 1. Preemergence herbicides can control both broadleaves (eudicots) and grasses (monocots). The specific herbicide indicates whether it is better utilized with broadleaves or grasses. For example, atrazine, simazine, oxyfluorfen, isoxaben, oxadiazon, and flumioxazin all control broadleaved weeds better than they control grasses, whereas napropamide, pendimethalin, s-metolachlor, oryzalin, and prodiamine all control grasses better than broadleaved weeds. For best results, growers should use a preemergence herbicide from each category [20].

Isoxaben provides excellent control for broadleaved weeds but does not provide good control of grasses. Isoxaben can be used to control triazine resistant weed species. It can be used on firs (*Abies* spp. Mill.), pines (*Pinus* sp. L.), and spruces (*Picea* sp. Mill.). There is little foliar activity, so isoxaben can be applied over the tops of trees [20] and should be applied before annual weeds emerge in the spring [7].

Napropamide, prodiamine, pendimethalin, and oryzalin all move slowly in the soil, meaning they need to be applied a few weeks prior to weed germination so that they can move within the soil before the weeds germinate. These preemergence herbicides can provide exemplary long-term control of annual grasses but will not control perennial grasses growing from rhizomes or stolons or broadleaved weeds. They must be applied when the temperatures are below 7 °C or irrigated in as they degrade in heat and sunlight. Prodiamine must also be applied in temperatures below 7 °C. Prodiamine provides good control of both annual and perennial grasses and some broadleaved weeds [20]. It is recommended to make one application of prodiamine in the fall. Prodiamine, pendimethalin, and oryzalin are all Weed Science Society of America (WSSA) group 3, microtubule inhibiting herbicides, which all require rainfall or other water soon after their application for activation. Oryzalin is safe for use with pine (*Pinus* sp.) and firs (*Abies* sp.), not including Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco). Prodiamine should not be used on trees in the first year after planting [4].

Oxadiazon is a WSSA group 14, protoporphyrinogen oxidase (PPO) inhibiting herbicide. It provides excellent control of annual broadleaves and good control of grasses. Oxadiazon remains on the soil surface for a long time because it has very low water solubility. It works by creating a barrier on the soil surface which kills weeds as they emerge. This works for annual broadleaves but not perennial broadleaves with established root systems. Oxadiazon can control grasses only for the short term, and hence it is recommended to combine this herbicide with one more suited for grasses [20].

Indaziflam is a WSSA group 29, cellulose biosynthesis inhibitor, which needs to be applied in fall or spring prior to weed emergence as a spray directed at the soil. It needs water/irrigation for activation. Indaziflam can cause damage to new tissue if applied over trees. It works to control grasses, sedges, and broadleaves and is persistent [4]. Indaziflam hinders root growth in the top inch of soil. It is persistent and will remain in this location for a relatively long time. It is not effective on established plants, and the presence of existing vegetation can obstruct its activity as a preemergence herbicide [23].

Table 1. Preemergence herbicides labeled in the United States for use in Christmas tree production.

Active Ingredient	Trade Name	Mechanism of Action	WSSA Group ³	Weeds Effective Against	Application Timing	Notes
Prodiamine	Barricade	Inhibits microtubule assembly	3(K ₁) ⁴	Many annual grasses [20]	After transplanting and prior to spring budbreak. Once trees are established, can be applied at any time over top or as directed spray [7].	Not recommended for trees under 1 year [7].
Prodiamine	Kerb	Inhibits microtubule assembly	3(K ₁)	Annual and perennial grasses, common chickweed (<i>Stellaria media</i> (L.) Vill.), and mustard weeds (<i>Sisymbrium officinale</i> (L.) Scop.)	In late fall when soil temperature is below 13 °C. Trees established over 1 year.	
Isoxaben	Gallery	Inhibits cell wall synthesis site B	21(L)	Annual broadleaves [7]	Spring, before annual weeds germinate [7].	
Oxyfluorfen	Goal	PPO ¹ inhibitor	14(E)	Annual small seed broadleaves, established grasses are tolerant [4]	After seeding, or 5 weeks after seedling emergence. To established trees before budbreak or after new growth has hardened [7].	
Simazine	Princep	Photosystem II inhibitor	5(C ₁)	Many annual broadleaves and grasses as well as quackgrass (<i>Elymus repens</i> (L.) Gould) [7]	In fall or spring to dormant trees more than 2 years old [6]. To growing trees before or during rain [4].	
Pendimethalin	Pendulum AquaCap	Inhibits microtubule assembly	3(K ₁)	Annual grasses and broadleaves [7]	Over the top of trees or to soil between trees before weeds germinate. After soil has settled around new transplants [7].	
Dichlobenil	Casoron	Inhibits cell wall synthesis site A	20(L)	Perennials like Canada thistle and horsetail [4]	In midwinter directly before a cold rain. Only use with well-established trees [4].	
Oryzalin	Surflan	Inhibits microtubule assembly	3(K ₁)	Annual grasses and some broadleaves [7]	To bare soil after transplant, requires cultivation or 13 mm rain [4].	Safe for pine and fir (not Douglas-fir) [4].

Table 1. Cont.

Active Ingredient	Trade Name	Mechanism of Action	WSSA Group ³	Weeds Effective Against	Application Timing	Notes
S-metolachlor	Pennant Magnum	VLCFA ² synthesis inhibitor	15(K ₃)	Annual grasses, pigweeds (<i>Amaranthus</i> sp. L.), yellow nutsedge (<i>Cyperus esculentus</i> L.), nightshades (Solanaceae family) [7]	In spring prior to weed emergence [7].	
Indaziflam	Marengo	Inhibits cellulose biosynthesis	29(L)	Grasses, sedges, broadleaves [4]	Use on trees established in the field at least 1 year. As a directed spray to soil at base of trees [7].	
Oxadiazon	Ronstar	PPO inhibitor	14(E)	Many annual broadleaves and some grasses [20]	Before or at least 4 weeks after budbreak [20].	
Napropamide	Devrinol	VLCFA synthesis inhibitor	15(K ₃)	Many annual grasses not good for broadleaves or perennial grasses [20]	In cool season or irrigate into soil [20].	

¹ PPO: Protoporphyrinogen oxidase; ² VLCFA: Very long-chain fatty acids; ³ WSSA stands for Weed Science Society of America. WSSA has classified herbicides based on their different mechanism of actions. ⁴ The number refers to the WSSA classification category and the letter plus subscript next to each number refers to the Herbicide Resistance Action Committee classification system which has both a letter and a subscript sub-category.

S-metolachlor is a group 15, very long chain fatty acid (VLCFA) inhibiting herbicide. It provides good control of annual grasses, but not as good as some others on this list, and provides outstanding control of nutsedge, which sets it apart. It should be applied in early spring, prior to budbreak of the Christmas tree. It can injure plants if sprayed over top, especially white pine (*Pinus strobus* L.) [20].

Dichlobenil is a group 20, cell wall synthesis at site A inhibitor. Dichlobenil is used to control difficult perennials such as Canada thistle (*Cirsium arvense* L.) and horsetail (*Equisetum arvense* L.). It should be applied in midwinter right before a cold rain. It should only be used on established trees and not on trees within one year of transplant [4].

Simazine, which is known under many different trade names, is a group 5, photosystem II inhibiting herbicide. It should only be applied to dormant trees unless it is raining [4]. Simazine controls broadleaved weeds and grasses [20]. Overall weed control can be improved by combining simazine with a preemergence herbicide that controls grasses. Lower rates of simazine can be used on field-grown spruce than on firs or pines [24]. The authors of [25] compared efficacy and conifer seedling mortality of simazine and atrazine. Atrazine, when mixed with simazine, was most successful at controlling weeds and had negligible impact on the seedling mortality rate [26].

3.2. Postemergence Herbicides

Postemergence herbicides are applied after the weeds have already emerged from the soil. They usually do not interact with the soil, instead killing the shoots and leaves of the weeds. Once they are absorbed by the plant, postemergence herbicides usually work by causing cellular membranes to rupture, impeding the production of essential compounds including amino acids or fatty acids, or by altering growth via hormone mimicry [4]. There are two different classifications of postemergence herbicides: systemic and contact. Translocated herbicides work better to kill perennial weeds, while contact herbicides work well against annual weeds but do not work against perennial weeds unless they are applied repeatedly. Annual weeds should be treated with contact herbicides when they are small. Perennial weeds, in contrast, should be treated with translocated herbicides when they are at least 30 cm long to provide greater area for the herbicide to be absorbed into the plant. Systemic postemergence herbicides include glyphosate, 2-4-D, and clopyralid. These herbicides can translocate through the plant and kill underground structures [4]. Examples of contact postemergence herbicides include pelargonic acid and diquat, which work through direct contact with the plant and only kill tissues with which the spray comes into contact [25]. Postemergence herbicides can also be categorized as either selective or non-selective. Selective herbicides will only kill what is on their label. On the other hand, nonselective herbicides will injure or kill nearly all plants [20].

Postemergence herbicides that are labeled for use in Christmas tree production in the United States can be found in Table 2. Postemergence herbicides can be dangerous and phytotoxic to Christmas trees. The relative safety of post-emergence herbicides varies with chemical, tree species, and season, as nearly all trees are sensitive to post-emergence products during active shoot growth. If postemergence herbicides are used in the summer, they need to have good foliar activity, be safe on trees, and the sprays need to be directed to avoid tree injuries. Broadcast application of postemergence herbicides should be avoided between budbreak and the 1st of September [7].

Glyphosate is a systemic, postemergence herbicide that is commonly used in Christmas tree production [20]. Glyphosate is a group 9 Shikimic acid pathway inhibitor which kills most annual and perennial weeds, and even woody weeds with multiple applications. It does not kill field horsetail. This herbicide should only be applied after growth has hardened in the fall and should not contact new growth [7]. For most Christmas tree species, glyphosate can be applied over the top of healthy completely dormant trees, though using directed sprays and avoiding direct contact with trees may be safer. By avoiding contact with trees, higher rates of glyphosate can be used to control deeply rooted weeds. Weeds need to be actively growing when glyphosate is applied, because it is absorbed through

foliage and green stems and translocates throughout the plant. Therefore, it may take time for it to fully affect the weeds, especially in colder conditions. No additives should be included when applying glyphosate over top of dormant trees [15]. Glyphosate can be used with pines, spruces, and firs as well as other conifers [7]. Glyphosate becomes inactivated when it comes in contact with the soil. Therefore, tree roots are safe, and growers can plant into fields that have recently been treated with glyphosate [20]. Christmas trees can have semi directed basal sprays of glyphosate in the fall, late August, or September, or prior to spring budbreak. Douglas-fir and white pine are more vulnerable to glyphosate injury than true firs and spruces; therefore, these species should not have basal foliage sprayed until they are at least 0.6 m tall [24].

Clethodim, fluazifop-P, and sethoxydim are all group 1, Acetyl CoA Carboxylase (ACCase) Inhibitors [27]. They are selective systemic herbicides that work on annual grasses and most perennial grasses. These herbicides do not affect broadleaved weeds and are safe to use near Christmas trees in all periods of growth. They need to be applied to grasses that are actively growing [20].

Triclopyr triethylamine salt, clopyralid, and 2,4-D, are all group 4 synthetic auxin herbicides that are systemic [27]. Triclopyr triethylamine salt and 2,4-D selectively kill herbaceous and woody broadleaved weeds [20]. Clopyralid is selective to kill specific broadleaves, including legumes, composites, plantains, nightshade, thistles, and smartweeds [7]. Clopyralid does not affect grasses, sedges, or woody brush, and it is safe to spray it over established conifers [24]. Herbicides such as the volatile esters of 2,4-D are capable of causing injury to adjacent crops by movement in the vapor phase after the herbicide has dried on the soil or plant surface. The use of low-volatile esters, oil soluble amines, and dormant applications greatly reduces the hazard of injury to adjacent crops [28]. Phenoxy herbicides like 2,4-D and garlon can be dangerous to wine grapes, and considering Christmas trees are often grown with a variety of other crops or places nearby, such as grapes, organic farms, or schools, it is vital to be aware of the other crops or locations near the farm and avoid the drift of herbicides [29].

Glufosinate is a group 10, glutamine synthase inhibitor [27] that is a non-selective contact herbicide. It controls a variety of annual broadleaves and grasses. If grasses are particularly large or well tillered, then control is not as good. Glufosinate also suppresses perennial weeds. This herbicide is not active in the soil and has minimal translocation. It works best when weeds are small and actively growing [30].

Bentazon is a photosystem II site B inhibitor, group 6, selective herbicide [27]. It controls nutsedges as well as some other broadleaved weeds. Bentazon should be applied directly to the weeds as it can burn the needles of conifers, especially spruce and fir, if sprayed over top of them [20].

Asulam is a group 18 inhibitor of 7,8 dihydro-pterolate synthetase (DHP) [27]. Asulam should only be applied after new tree growth has hardened. It provides good control for many annual and perennial broadleaved weeds and grasses as well as dock species (*Rumex* spp. L.) and bracken ferns (*Pteridium aquilinum* (L.) Kuhn.) [27]. There should not be more than one application of asulam made per season [7].

Table 2. Postemergence herbicides that are labeled in the United States for use in Christmas Tree production.

Active Ingredient	Trade Name	Mechanism of Action	WSSA Group ⁵	Weeds Effective Against	Application Timing	Notes
Glyphosate	Roundup	EPSPS ¹ inhibitor	9(G) ⁶	Most annual and perennial weeds, including woody weeds with multiple applications; does not control field horsetail [7]	After new growth has hardened in the fall. Do not contact new tree growth. Can also be applied before spring budbreak [24].	Woody weeds best controlled in September or August [24].
Sethoxydim	Segment	ACCCase ² inhibitor	1(A)	Annual and most perennial grasses [20]	To actively growing grasses [20].	
Clopyralid	Stinger	Synthetic auxin	4(O)	Controls legume, composites, plantains, nightshade, thistle, and smartweeds [7]	To susceptible weeds at 3–5 leaf stage. Canada thistle and spotted knapweed—apply a high rate before weed bud stage. Can be applied over tops of trees at any stage [7].	
2,4-D	Turret	Synthetic auxin	4(O)	Broadleaf, woody, and herbaceous weed species [7]	Before budbreak in spring. Can be applied over the top of Douglas-fir. As directed, spray for all other species. Do not spray tree foliage or apply to diseased or stressed seedlings [7].	
2,4-D	Defy Amine	Synthetic auxin	4(O)	Broadleaf, woody, and herbaceous weed species [7]	Before budbreak in spring or after new growth is hardened in late summer. Late summer applications to control woody weeds. Spray contact with tree foliage may cause injury [7].	Not safe for diseased or stressed seedlings [7].
Asulam	Asulox	DHP ³ (cell division inhibitor)	18(I)	Controls bracken ferns [7]	After hardening of new tree growth. Not by air and a maximum of one application per season [7].	
Clethodim	Envoy Plus	ACCCase inhibitor	1(A)	Grasses [7]	To actively growing grasses [7].	

Table 2. Cont.

Active Ingredient	Trade Name	Mechanism of Action	WSSA Group ⁵	Weeds Effective Against	Application Timing	Notes
Fluazifop-P	Fusilade	ACCCase inhibitor	1(A)	Grasses [7]	To actively growing grasses; perennial grasses may need more than one application for full control [7].	
Triclopyr triethylamine salt	Garlon	Synthetic auxin	4(O)	Broadleaf, woody, and herbaceous weed species [7]	In summer or early fall after conifer growth has hardened. Spray towards tree base, do not apply to trees established under 1 year [7].	Douglas-fir and white pine may be sensitive [7].
Glufosinate	Finale	Glutamine synthase inhibitor	10(H)	Many annual and perennial grasses and broadleaves [28]	Do not apply over tops of trees. Do not apply to actively growing trees [4].	
Bentazon	Basagran	PSII ⁴ site B inhibitor	6(C ₃)	Nutsedge and some broadleaved weeds [20]	Spray directly, do not apply over treetops [20].	

¹ EPSPS: 5-enolpyruvyl- shikimate- 3- phosphate synthase; ² ACCase: Acetyl CoA Carboxylase; ³ DHP: 7,8- dihydro- pterate synthetase; ⁴ PSII: Photosystem II; ⁵ WSSA stands for Weed Science Society of America. WSSA has classified herbicides based on their different mechanism of actions. ⁶ The number refers to the WSSA classification category and the letter plus subscript next to each number refers to the Herbicide Resistance Action Committee classification system which has both a letter and a subscript sub-category.

3.3. Herbicides with Preemergence and Postemergence Activity

Weeds vary in their anatomy and physiology, which means that common herbicides have differing abilities to adequately control them. For example, some annual weeds can be easily controlled with preemergent herbicides; on the other hand, many perennial grasses and weeds, especially horsetails and sedges (Cyperaceae), are more challenging to control. One method to manage both annuals and perennials is to combine more than one herbicide in the spray tank. Often, preemergence herbicides are combined with postemergence herbicides to control both existing weeds and prevent new weeds from growing, however, it must be determined whether the herbicides are compatible with this [31]. Some herbicides can be used as both preemergence herbicides and postemergence herbicides. These herbicides can be applied over longer periods of time than herbicides that only fit into one category [4]. Herbicides with preemergence and postemergence activities that are labeled for use in Christmas tree production in the United States can be found in Table 3.

Atrazine, which is known under many different trade names, is a group 5, photosystem II inhibiting herbicide that should only be applied to dormant trees, unless it is raining [4]. Atrazine is closely related to simazine, but it is more soluble in water and better at controlling perennial weeds. Initially, applicators should treat with a mixture of the two herbicides, but once perennial grasses are under control, it is often better to just use simazine [24]. Atrazine and simazine have remarkably similar characteristics except for water solubility, as atrazine has shorter residual activity and can be absorbed by leaves, while simazine has longer residual activity but is less readily absorbed by leaves [20]. Atrazine and simazine provide excellent control of broadleaved weeds and fair control to grasses. Atrazine is most active in soils with a pH between 6.5 and 7.5. Breakdown of atrazine is slow when soil pH is below 6.5. If soil pH is raised, e.g., by liming, residual atrazine may be activated and cause injury to trees [20].

Flasulfuron is a group 2 acetolactate synthase (ALS) inhibiting herbicide and provides for both preemergent and postemergent weed control. Flasulfuron needs to be applied directly to avoid injury to actively growing trees, and it should not be applied within the first year of growth [4]. Flasulfuron controls both annual grasses and annual broadleaves. This herbicide can be applied over top to dormant conifers and there must be a minimum of three months wait in between treatments [7].

Hexazinone, which is a group 5 herbicide, can be used on newly planted trees, but injuries have been observed. Hexazinone can be a groundwater hazard, therefore growers should apply it in early spring, rather than late winter, to reduce the likelihood of leaching. At high rates, this herbicide can be effective against trailing blackberries [4]. Hexazinone controls annual broadleaves and grasses well, including common ragweed, horseweed, and annual bluegrass (*Poa annua* L.) [7]. Like atrazine, hexazinone is absorbed by foliage and is only safe on most conifers during the dormant season—either before bud burst of tolerant firs, spruces, and Douglas-firs or after terminal growth has slowed in tolerant pines [32].

Hexazinone + sulfometuron is a combination of 68.6% hexazinone, a photosynthesis inhibitor, WSSA group 5% and 6.5% sulfometuron-methyl, and an acetolactate synthase inhibitor group 2. It works well with firs and Douglas-fir. Hexazinone + sulfometuron should only be applied through broadcast to dormant trees; if trees are not dormant, then applications must be directed so that the herbicide does not come into contact with new growth. This herbicide can also cause a groundwater hazard [4]. It provides good control of broadleaves and grasses as it is a combination of two herbicides [20]. It provides good control of most annual weeds, such as horseweed, common ragweed, and large crabgrass, for three to four months. Hexazinone + sulfometuron should only be used on trees that are at least four years old and have been established for at least one year, as it can stunt tree growth [7]. Metribuzin + flufenacet is a group 5 and group 15 herbicide. For Douglas-fir and true firs it should only be applied when trees are dormant and should not be applied until one year of growth has occurred [4].

Table 3. Herbicides with preemergence and postemergence activity that are labeled in the United States for use in Christmas Tree production.

Active Ingredient	Trade Name	Mechanism of Action	WSSA Group ⁴	Weeds Effective Against	Application Timing	Notes
Hexazinone	Velpar	Photosystem II inhibitor site A	5(C ₁) ⁵	High rates effective against trailing blackberries [4]	In early April [4].	
Metribuzin + flufenacet	Axiom	Inhibits photosystem II site A and inhibits synthesis of VLCFA ¹	5(C ₁) 15(K ₃)	Chickweed (<i>Stellaria media</i> (L.) Vill.) and annual grass	To firs, including Douglas-fir, only. When trees are dormant. For trees established at least 1 year. Very early POST use only [4].	
Oxyfluorfen	Goaltender	PPO ² Inhibitor	14 ^(E)	Many annual grasses and annual broadleaves [7]	Before spring budbreak and after new growth has hardened in fall. Can spray over trees unless actively growing [4]. Do not apply to stressed trees [7].	
Flumioxazin	SureGuard	PPO Inhibitor	14 ^(E)	Selected grass and broadleaf weeds [4]	Must be applied prior to spring budbreak or after trees have hardened in fall [4].	Not safe for conifers before 2 years of emergence [4].
Flazasulfuron	Mission	ALS ³ inhibitor	2 ^(B)	Many broadleaves and grasses less than 10 cm tall	Do not apply within 1 year of seeding trees. May be applied over the top in spring or after new growth has hardened in fall. As directed spray during growth.	
Hexazinone + sulfometuron	Westar	Photosystem II Inhibitor site A and ALS inhibitor	5(C ₁) 2 ^(B)	Many broadleaves, annual grasses, and several perennial weed species	Broadcast to dormant trees. Out of dormancy must do directed applications to avoid contact with new growth [4].	Recommended for various firs including Douglas-fir [4].
Atrazine	Many	Inhibits Photosystem II Site A	5(C ₁)	Many broadleaf weeds and some grasses [7]	To soil before or after new transplants, or to dormant established trees in late fall or early spring [7].	
Lactofen	Cobra	PPO Inhibitor	14 ^(E)	Many annual broadleaves up to 10 cm tall [7]	After seeding or transplanting and prior to budbreak. Not when conifers are stressed [7].	

¹ VLCFA: Very long-chain fatty acids ² PPO: Protoporphyrinogen oxidase. ³ ALS: Acetolactate synthase. ⁴ WSSA stands for Weed Science Society of America. WSSA has classified herbicides based on their different mechanism of actions. ⁵ The number refers to the WSSA classification category and the letter plus subscript next to each number refers to the Herbicide Resistance Action Committee classification system which has both a letter and a subscript sub-category.

Triazine herbicides (atrazine, simazine) have been largely responsible for the abundant supply of high-quality Christmas trees in the United States, as well as the success and improvement of reforestation in western coniferous forests. Due to its absorption by plant foliage as well as by roots, atrazine at agricultural use rates is not tolerated by most ornamental deciduous woody plants during active growth. Depending on dosage and plant species, atrazine can also injure actively growing conifers [33]. Since Christmas trees require several years from planting to harvest, the low cost of triazine herbicides is extremely important to the economics of Christmas tree production. The more recent herbicides registered for Christmas tree production cost 3–10 times as much as simazine or atrazine [34].

Source [35] found that hexazinone + sulfometuron can provide decent acceptable control of most weeds through July of each year. However, it did not provide adequate control of horseweed, which emerged in midsummer each year. Horseweed does well when there is less competition from other weeds, therefore horseweed increased more when weeds were controlled by hexazinone + sulfometuron plots than in the presence of other treatments, including untreated control. Hexazinone + sulfometuron treatments provided good weed control but reduced Fraser fir (*Abies fraseri* (Pursh) Poir.) height significantly when used for three years at 0.65 L Ha⁻¹ at a site in Gobles, Michigan and at 0.43, 0.54, and 0.659 L Ha⁻¹ at a site in Horton, Michigan [35].

Oxyfluorfen, lactofen, and flumioxazin are all WSSA group 14, protoporphyrinogen oxidase (PPO) inhibiting herbicides. Oxyfluorfen, lactofen, and flumioxazin should be applied right after transplanting, prior to budbreak, over the top of the tops of the trees or as a directed spray [4,7]. Flumioxazin and oxyfluorfen can also be applied after growth has hardened in the later season [6]. Source [36] found that many species of common Christmas tree weeds were controlled by flumioxazin, however, it showed poor control of white campion (*Silene latifolia* Poir.), dandelion (*Taraxacum* sp. Munz and I.M. Johnst.), and horseweed. There was also commercially adequate tolerance of Fraser fir and Colorado blue spruce (*Picea pungens* Engelm.) in all the trials [36].

3.4. Herbicide Resistance Management

Herbicide resistance is becoming a major problem in all crops, including Christmas trees. For example, there are reports from Michigan that common ragweed has become resistant to the clopyralid herbicide in Christmas tree production [16]. Herbicide resistance is the inherited capability of a plant to survive an herbicide application which would normally kill that plant, whereas herbicide tolerance is the ability of a species to survive and reproduce following a normal use rate of herbicide application. A species of weeds is considered resistant when an herbicide that previously controlled that weed no longer works. Herbicide resistance is more likely to occur when a singular mechanism of action of the herbicide is applied repeatedly [37]. Resistant weeds are a result of fundamental evolutionary processes. When there are certain resistant individuals in a population, upon application of that herbicide, the susceptible will die and the resistant will survive and reproduce. As the same herbicide is used increasingly, the resistant weeds will rapidly expand to become the majority population under selection pressure [38]. Herbicides (such as group 2, 9, and 5) that are only acting on a singular site of action are more likely to have weeds develop resistance than those that act on multiple sites of action. This can cause herbicide resistance to develop because it is only necessary for one gene in the plant to change in order to disrupt the binding potential of the herbicide. Not all herbicides that have the same mechanism of action will have cross resistance, because there may be different specific sites of action. As a result, it is not possible to predict if there will be cross resistance between herbicide families [39]. Weeds have developed resistance to 167 different herbicides, including 23 out of the 26 known mechanisms of action. There are herbicide resistant weeds that have been reported in 94 different crops in 71 countries [40].

Herbicide resistance can be prevented by integrating different weed control methods using chemical and non-chemical approaches. Another method to reduce the likelihood

of developing herbicide resistance is to rotate among different mechanisms of action of herbicides. Using a tank mixture or combination of different mechanisms of action of herbicides together is another way to manage herbicide resistance among weed species. The speed at which resistance develops depends on the mechanism of action. For example, some group 2 herbicides are rather quick to develop resistance. Another method of resistance prevention is to monitor the weeds that are not killed by herbicides and to not let them mature and produce seed. Growers should clean equipment to prevent the spread of resistant weed seeds between areas [7]. Ground cover and mulches are another good method of weed control to manage herbicide resistance, as hard fescues (*Festuca trachyphylla* (Hack.) Krajina, nom. illeg.) have worked well for Christmas tree growers [18]. Rotating crops with different life cycles is another good method to avoid herbicide resistance, but this may not be very feasible on Christmas tree farms. Primary tillage, mechanical weed control, and field scouting for weeds are all good ways to reduce the chances of weeds becoming herbicide resistant.

Some primary examples of herbicide resistant weeds include weeds that are resistant to glyphosate, triazine herbicides, and ALS inhibiting herbicides. Glyphosate resistance is becoming a problem in annual ryegrass (*Festuca perennis* Lam.). A method to avoid glyphosate resistance is using different nonselective herbicides such as glufosinate or PPO inhibitors [19]. If glyphosate is used where there are resistant weeds, then it should be tank mixed with a different mechanism of action of herbicide and applied to the weeds while they are still small. Weeds with resistance should also not be allowed to produce seeds [19]. The triazine herbicides are another family to which resistance has developed. This includes atrazine and simazine. Weeds with resistant strains to these herbicides include pigweeds (*Amaranthus* sp. L.), lambsquarter (*Chenopodium album* L.), and horseweed. This resistance can be dealt with by using SureGuard. SureGuard can be alternated with triazine herbicides for resistance management [41]. ALS inhibiting herbicides have more plants that are resistant to them than any other mechanism of action. These herbicides are used often, and they also have a lot of soil residual. This combination lends to them being ideal targets for herbicide resistance [20]. The recurrent rate of weed populations becoming resistant to ALS inhibitors can be credited to the extensive use of these herbicides, how they are used, the strong selection pressure they employ, and the unique resistance mechanism [42]. Table 4 lists the herbicides with different mechanisms of action that are commonly used in Christmas tree production in the United States.

Table 4. Common herbicides with their mechanisms of action used in Christmas trees and some common weeds that have developed resistance to respective mechanism of action. Adapted from [40].

WSSA Group ¹	Mechanism of Action	Herbicide Common Name	Resistant Weed Species
1	ACCase ² Inhibitors	Clethodim, fluazifop-P, sethoxydim	Green Foxtail (<i>Setaria viridis</i> (L.) Beauv.) Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)
2	ALS ³ Inhibitors	Flazasulfuron	Prickly lettuce (<i>Lactuca serriola</i>), Common Ragweed (<i>Ambrosia artemisiifolia</i> L.), Giant Ragweed (<i>Ambrosia trifida</i> L.), Common Lambsquarters (<i>Chenopodium album</i> L.), Horseweed (<i>Erigeron canadensis</i> (L.) Cronquist), Yellow Nutsedge (<i>Cyperus esculentus</i> L.), Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.), Perennial Ryegrass (<i>Lolium perenne</i> L.)
3	Microtubule Inhibitors	Prodiamine, oxyfluorfen, pendimethalin, oryzalin	Green Foxtail (<i>Setaria viridis</i> (L.) Beauv.), Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)
4	Synthetic Auxins	2,4-D, clopyralid, triclopyrtriethylamine salt	Wild Radish (<i>Raphanus raphanistrum</i> L.), Smooth Pigweed (<i>Amaranthus hybridus</i> L.), Wild Carrot (<i>Daucus carota</i> L.), Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.), Prickly Lettuce (<i>Lactuca serriola</i> L.)
5	Photosystem II site A Inhibitors	Atrazine, hexazinone, simazine	Smooth Pigweed (<i>Amaranthus hybridus</i> L.), Common Ragweed (<i>Ambrosia artemisiifolia</i> L.) Common Lambsquarters (<i>Chenopodium album</i> L.), Horseweed (<i>Erigeron canadensis</i> (L.) Cronquist), Large Crabgrass (<i>Digitaria sanguinalis</i> (L.) Scop) Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.), Green foxtail (<i>Setaria viridis</i> (L.) Beauv.)
6	Photosystem II Site B inhibitor ^{6(C3)}	Bentazon	Smooth Pigweed (<i>Amaranthus hybridus</i> L.)
9	EPSPS ⁴ Inhibitor ^{9(G)}	Glyphosate	Annual Ryegrass (<i>Festuca perennis</i> Lam.), Horseweed [<i>Erigeron canadensis</i> (L.) Cronquist], Bentgrasses (<i>Agrostis</i> spp. L.), Perennial Ryegrass (<i>Lolium perenne</i> L.), Common Ragweed (<i>Ambrosia artemisiifolia</i> L.), Smooth Pigweed (<i>Amaranthus hybridus</i> L.), Horseweed (<i>Erigeron canadensis</i> (L.) Cronquist), Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.), Prickly Lettuce (<i>Lactuca serriola</i> L.), Perennial Ryegrass (<i>Lolium perenne</i> L.)

Table 4. Cont.

WSSA Group ¹	Mechanism of Action	Herbicide Common Name	Resistant Weed Species
10	Glutamine synthase inhibitor 10 ^(H)	Glufosinate	Perennial Ryegrass (<i>Lolium perenne</i> L.)
14	PPO ⁵ Inhibitors	Oxyfluorfen, flumioxazin, lactofen, oxadiazon	Smooth Pigweed (<i>Amaranthus hybridus</i> L.), Common Ragweed (<i>Ambrosia artemisiifolia</i> L.)
15	VLCFA ⁶ Synthesis inhibitor 15 ^(K₃)	S-metolachlor, napropamide	Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)
20	Inhibits cell wall synthesis site A 20 ^(L)	Dichlobenil	Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)
21	Inhibits cell wall synthesis site B 21 ^(L)	Isoxaben	Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)
29	Inhibits cellulose biosynthesis 29 ^(L) ⁷	Indaziflam	Barnyardgrass (<i>Echinochloa crus-galli</i> (L.) Beauv.)

¹ WSSA stands for Weed Science Society of America. WSSA has classified herbicides based on their different mechanism of action. ² ACCase: Acetyl CoA Carboxylase. ³ ALS: Acetolactate synthase. ⁴ EPSPS: 5-enolpyruvyl- shikimate- 3- phosphate synthase. ⁵ PPO: Protoporphyrinogen oxidase. ⁶ VLCFA: Very long-chain fatty acids. ⁷ The number refers to the WSSA classification category and the letter plus subscript next to each number refers to the Herbicide Resistance Action Committee classification system which has both a letter and a subscript sub-category.

4. Conclusions

While chemical weed control can be highly effective in Christmas tree production, herbicide resistance is becoming a more pressing issue in all agricultural fields, and Christmas tree production is no exception. Currently, more research is focusing on herbicide resistance issues for agronomic crops only. However, there is a huge knowledge gap or little research is being conducted on herbicide resistance issues for Christmas tree production system. While there is research related to avoiding development of herbicide resistant weeds, there is little research on ways to manage herbicide resistance in Christmas tree production specifically. More research must be done on identification and confirmation of herbicide resistant weed species in Christmas tree farms and methods of avoiding herbicide resistance. One method that needs more research is combining multiple herbicides with different mechanisms of action to reduce the onset of herbicide resistance. New combinations or tank mixes of various herbicides with different mechanisms of action need to be tested for various weed control efficacies and their phytotoxic effects on the different Christmas tree varieties. Field trials conducted by Saha et al. (unpublished data) at Michigan commercial Christmas tree farms in 2021 showed that a tank mix of oxyfluorfen + clopyralid + glyphosate can cause injury to the Fraser fir variety of Christmas trees, whereas organic mulch combined with herbicides (oxyfluorfen + glyphosate) can provide an effective weed control in Christmas tree production. Comparing the newer herbicide formulations with the older ones in terms of weed control efficacies is another area which has a significant knowledge gap and requires more research.

Successful weed management in Christmas tree production requires integration of chemical and non-chemical approaches. Among chemical weed control, applicators need to include and integrate preemergent and postemergent products as well as multiple mechanisms of action. In the future, research needs to focus on an integrated approach, as well. A study conducted by [43] on different organic mulch types, depths, and irrigation volume on common landscape weed control showed that pine bark mulch, when combined with a liquid formulation of preemergence herbicides at depths of 5 cm or more, can provide excellent weed control. Combining organic mulch with herbicides and understanding how these combinations interact with different Christmas tree varieties during their establishment stages require an in-depth study. Furthermore, the effects of mulch depths and particle size on herbicide leaching, efficacy, and residual effects need to be investigated for Christmas tree production.

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