RESEARCH ARTICLE

For. Sci. 67(1):43–48
doi: 10.1093/forsci/fxaa039

Forest Management

Mixture of Triclopyr and Imazapyr More Effective than Triclopyr Alone for Hardwood Forest Stand Improvement

Mark A. Turner, William D. Gulsby, and Craig A. Harper

Treatment of individual trees in hardwood stands typically is conducted with herbicides that have no soil activity, such as triclopyr. However, triclopyr is not effective on some tree species. Applying a mixture of triclopyr and imazapyr would broaden the spectrum of species controlled, but nontarget mortality may be problematic as imazapyr may affect other trees through soil activity. We applied herbicide via girdle-and-spray as part of a forest stand improvement treatment in four upland hardwood stands in the Upper Coastal Plain of Alabama. We compared effects of using triclopyr alone with a mixture of triclopyr and imazapyr 18 months posttreatment. Only one untreated sweetgum (*Liquidambar styraciflua*) out of 440 trees was killed in the stands treated with the herbicide mixture (0.5 percent nontarget mortality rate). Nontarget mortality did not differ between treatments. However, the herbicide mixture controlled hickory (*Carya* spp.) and sourwood (*Oxydendrum arboreum*) better than triclopyr alone, with 56 percent of hickory treated with triclopyr still alive 18 months later, compared with 0 percent of hickory treated with the mixture. Our results indicate a mixture of triclopyr and imazapyr provides better control than triclopyr alone, and there is minimal risk to nontarget tree species in hardwood stands when used according to label recommendations.

Study Implications: Forest stand improvement (FSI) is a noncommercial practice typically conducted by cutting and using herbicide to kill undesirable trees. Consideration must be given to herbicide selection, which is based on efficacy on target species while minimizing nontarget mortality of residual trees. We found that a mixture of triclopyr and imazapyr applied via girdle-and-spray was more effective for FSI than triclopyr alone, which failed to control a significant proportion of treated hickory, and resulted in essentially no nontarget mortality in mixed hardwood stands 18 months after application.

Keywords: herbicide efficacy, vegetation management, canopy reduction, habitat management

Selective removal of individual trees in hardwood forests may be used to accomplish a variety of silvicultural and wildlife habitat-related objectives. For example, oak (*Quercus* spp. L.) regeneration depends on sunlight provided by canopy gaps (Hannah 1987, Brose and Van Lear 1999), and growth rates of crop trees are greater following release from competition (Wendel and Lamson 1987, Lamson et al. 1990, Kochenderfer et al. 2001). Additionally, sunlight availability influences forest understory development, and silvicultural techniques that reduce canopy coverage can improve conditions for various wildlife species (Masters et al. 1993, Mixon et al. 2009, Lashley et al. 2011, McCord et al. 2014).

Overstory reduction often is accomplished with a commercial timber harvest, such as a thinning or shelterwood harvest. However, the ability to conduct a commercial harvest depends on the availability of markets for harvested timber. If trees are not merchantable because of species composition, size class, or volume, noncommercial techniques may be used to reduce canopy coverage (Nyland 2002). These techniques collectively are referred to as forest stand improvement (FSI) and can be applied to manipulate both economic and ecological conditions in a forest (Wendel and Lamson 1987, Nyland 2002, Lashley et al. 2011, McCord et al. 2014). Commonly, FSI is conducted by killing trees using herbicide introduced into the cambium (Pariona et al. 2003, Ohlson-Kiehn et al. 2006, Lewis and McCarthy 2008, McCord et al. 2014).

An important consideration when conducting FSI is herbicide selection, as various chemicals may have differential efficacy on certain

Manuscript received August 6, 2020; accepted August 24, 2020; published online September 26, 2020.

Affiliations: *Mark A. Turner (mat0073@auburn.edu) and William D. Gulsby (wdg0010@auburn.edu), School of Forestry and Wildlife Sciences, Auburn University, 602 Duncan Drive, Auburn, AL 36849. Craig A. Harper (charper@utk.edu), Department of Forestry, Wildlife, and Fisheries, University of Tennessee, Knoxville, TN 37996.*

Acknowledgments: *We would like to thank A. Pritchett, D. Nix, W. Gray, and the Barbour Wildlife Management Area staff for their critical contributions to this project. We would also like to thank A. Neilan, D. Knowles, and S. Cain for their assistance in treatment implementation and data collection. Funding was provided by the Wildlife Section of the Alabama Division of Wildlife and Freshwater Fisheries through the Federal Aid in Wildlife Restoration Program.*

species (Kochenderfer et al. 2001, DiTomaso et al. 2004, DiTomaso and Kyser 2007). Triclopyr and imazapyr are two of the most commonly used forestry herbicides, and they often are introduced into the tree following mechanical treatment to the cambium (Ezell et al. 1999, DiTomaso and Kyser 2007, Alkire et al. 2012). However, Arsenal Applicators Concentrate (BASF Corporation 2017; hereafter, Arsenal AC), which contains imazapyr, is not effective for control of elm (*Ulmus* spp. L.), hornbeam (*Carpinus caroliniana* Walter), or leguminous species. Garlon 3A (Dow AgroSciences 2016), which contains triclopyr, is not effective for control of hickory (*Carya* spp. Nutt.) or sourwood (*Oxydendrum arboreum* L.). Use of an herbicide that will not control various undesirable species that may be present in a forest stand is inefficient, and it is not practical to apply different herbicides based on individual tree species. Therefore, using an herbicide mixture may be most efficient and effective in forest stands with a diverse species composition.

FSI often is applied to increase crop tree growth or mast production within the stand (Wendel and Lamson 1987, Brooke et al. 2019), so it is critical to minimize nontarget mortality among nontreated trees. Multiple factors influence the likelihood of nontarget mortality, including tree diameter, distance to treated trees, species of tree, soils, and the herbicide used (Kochenderfer et al. 2001, DiTomaso and Kyser 2007, Lewis and McCarthy 2008). Triclopyr is often used for FSI because it has a shorter half-life, is more selective than imazapyr, has no soil activity, and results in little nontarget mortality (Kochenderfer et al. 2001, DiTomaso and Keyser 2007). In contrast, nontarget mortality rates associated with use of imazapyr in FSI operations vary widely. For example, Alikre et al. (2012) reported only 0.7 percent crown reduction to nontreated midstory sweetgum (*Liquidambar styraciflua* L.) 12 months after treatment of midstory trees with imazapyr in Mississippi. They applied a solution of 20 percent Arsenal AC via hack-and-squirt to all nonoaks in the midstory and used 1 ml per 7.5 cm diameter at breast height (DBH). However, Lewis and McCarthy (2008) observed 57 percent mortality in black cherry (*Prunus serotina* Ehrhart) and 0 percent mortality in pawpaw (*Asimina triloba* Dunal) trees adjacent to 7.5 to 12.5 cm DBH tree-of-heaven (*Ailanthus altissima* Swingle) that had been injected with four 1 g capsules containing 83.5 percent imazapyr. Site-specific variables also may influence nontarget damage. Kochenderfer et al. (2001) reported 0–66 percent of nontarget black cherry and yellow-poplar (*Liriodendron tulipifera* L.) trees were damaged following treatment of various hardwood competitors with imazapyr. Their study was focused on crop tree release via hack-and-squirt, and they had a target application of 1.5 ml of 7.5 percent concentration Arsenal AC per 7.5 cm DBH. However, there have been no previous evaluations of the trade-off between nontarget mortality and herbicide efficacy when imazapyr and triclopyr are applied in a mixture via girdle-and-spray to control a variety of species.

Despite the potential benefits of using a mixture of triclopyr and imazapyr in an FSI operation, concerns associated with nontarget mortality when using imazapyr should be evaluated. In addition, previous work has suggested that triclopyr amine formulations may be antagonistic when tank mixed with imazapyr for foliar control (Lawrie and Clay 1993, Ezell et al. 1994, Minogue and Quicke 1999), but information is lacking on efficacy or antagonism when applied as a mixture to the stem. We designed a study to measure the efficacy and nontarget mortality rates associated with triclopyr alone compared with a mixture of triclopyr and imazapyr when implementing FSI. We hypothesized that we would see greater control of target trees with a mixture of triclopyr and imazapyr compared with triclopyr alone, and that we would not see widespread nontarget mortality rates following application of either treatment.

Materials and Methods

Study Area

We conducted our study within four upland hardwood-dominated stands on Barbour Wildlife Management Area (WMA). Barbour WMA is located in Barbour County at 31° 59' 37.788" N, 85° 27' 36.144" W, and it is within the Upper Coastal Plain physiographic region of Alabama. The WMA is managed by the Alabama Department of Conservation and Natural Resources. Overstory species composition included southern red oak (*Quercus falcata* Michx.), white oak (*Quercus alba* L.), yellow-poplar, sweetgum, water oak (*Quercus nigra* L.), red maple (*Acer rubrum* L.), hickory, and sourwood. Mean stand pretreatment overstory basal area was approximately 27.5 m^2 ha^{-1}. Midstory species composition included sparkleberry (*Vaccinium arboretum* Marsh), wax myrtle (*Morella cerifera* L.), and sweetgum. Prior to treatment, understory species composition was primarily Virginia creeper (*Parthenocissus quinquefolia* Planch.), spike uniola (*Chasmanthium laxum* L.), low panicgrass (*Dichanthelium* spp. Gould), and greenbriar (*Smilax* spp. L.).

Study stands all had northern aspects, and all were located within different drainages. The climate in Barbour County is subtropical, with a mean annual temperature of 18° C and mean annual precipitation of 133 cm (NOAA 2019). Soils in the northern replicate are well drained and consist primarily of Luverne-Springhill complex and Luverne sandy loam. Soils in the two central replicates are well drained and consist primarily of Luverne-Springhill complex and Blanton-Bonneau complex. Soils in the southern replicate are well drained, consisting primarily of Springhill-Lucy complex, Cowarts loamy sand, and Springhill-Troup complex (NRCS 2017).

Experimental Design and Treatments

We randomly assigned treatments to two 1.6-hectare treatment units within each study stand. FSI treatments reduced canopy closure to allow approximately 30 percent sunlight into the stands by girdle-and-spray or felling trees. We marked trees in each stand prior to treatment. In the triclopyr treatment, we applied a 50 percent Garlon 3A–50 percent water mixture to the treated trees. In the herbicide mixture treatment, we applied a mixture of 50 percent Garlon 3A, 40 percent water, and 10 percent Arsenal AC, mixed in that order to prevent gelling (Table 1). We retained trees within the stand based on species, crown class, and form. We favored species that produced mast valuable for white-tailed deer (*Odocoileus virginianus* Zimmermann) and wild turkeys (*Meleagris gallopavo* L.), such as oaks, persimmon (*Diospyros virginiana* L.), and black cherry, for retention. Common treated species included sweetgum, red maple, yellow-poplar, hickory, and water oak.

We felled trees with a DBH of <10 cm and applied herbicide with a spray bottle to the cambium of each stump. We girdled trees with DBH of >10 cm with a chainsaw just deep enough to sever the cambium layer 1 m above the ground and applied herbicide with a spray bottle all the way around the cut. For both girdled and felled trees, we applied approximately 0.5 ml of solution per 2.54 cm DBH. At this rate of solution, we applied 0.25 ml of Garlon 3A per 2.54 cm DBH to treated trees in the triclopyr treatment units and 0.25 ml of Garlon 3A and 0.05 ml

Table 1. Trade name, common name, active ingredient, and percent active ingredient of herbicides used in efficacy and nontarget mortality trial in upland hardwoods in the Upper Coastal Plain of Alabama.

Trade name	Garlon 3A	Arsenal Applicators Concentrate
Common name	Triclopyr amine	Imazapyr
Active ingredient	2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5- oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylicacid	2-[(3,5,6-trichloro-2-pyridinyl) oxy] acetic acid, triethylamine salt
Percent active ingredient	44.4%	53.1%

of Arsenal AC per 2.54 cm DBH to treated trees in the mixture treatment units. We applied treatments during January and February 2018 and evaluated efficacy during July and August 2019.

Data Collection

Two growing seasons after herbicide application, we documented tree response to treatments using 10 randomly placed 0.04-hectare fixed-radius plots in each treatment unit during July/August. Herbicide efficacy and nontarget mortality were only monitored on trees >10 cm DBH, although smaller stems within the stand were treated with cut-stump treatments. We measured and identified trees >10 cm DBH within each fixed-radius plot and recorded whether they had been girdled and treated with herbicide. We classified each tree to one of three crown reduction classes based on ocular evaluation in a manner similar to Alkire et al. (2012). We classified trees as alive if they had <25 percent crown reduction and no visible herbicide damage to the leaves. We classified trees as dying if they had 25–75 percent crown reduction and visible herbicide damage to the leaves. We classified trees as dead if they had >75 percent crown reduction. If mortality was present in nontreated trees, we measured the distance to the nearest treated tree and recorded the species of both trees. In total, we treated approximately 2,000 trees with herbicide via girdle-and-spray across the four stands. We evaluated herbicide efficacy on 546 treated trees (Table 2) and nontarget mortality among 440 nontreated trees.

Statistical Analysis

We used a chi-square test to compare the proportion of treated trees that were alive, dying, and dead between herbicide treatments, across species. We also examined those data to determine differences in herbicide susceptibility for a given genera or species. If so, we used a chi-square test to determine whether the proportion of those trees alive, dying, or dead differed between herbicide treatments within genera or species. Finally, we used a mixed-effects analysis of variance in package "nlme" (Pinheiro et al. 2017) in the program R (R Core Team 2018) with herbicide treatment as the fixed effect, percent nontarget mortality in each treatment unit as the response variable, and stand as a random effect to examine the effects of each herbicide treatment on nontarget mortality.

Results

Efficacy differed between herbicide treatments (χ^2 = 34.15, degrees of freedom [DF] = 2, p < .001). Specifically, 9 percent of

Table 2. Number of alive, dying, and dead trees in Upper Coastal Plain hardwood stands treated with triclopyr and a mixture of triclopyr and imazapyr that was applied via girdle-and-spray. Trees were treated in January–February 2018 and evaluated 18 months later.

	Triclopyr			Mixture		
	Alive	Dying	Dead	Alive	Dying	Dead
Acer rubrum L.	0	0	9	0	0	34
Carpinus caroliniana Walter	0	0	2	0	1	5
Carya spp. L.	22	2	21	0	1	24
Celtis laevigata Wild.	0	0	0	0	0	1
Fraxinus pennsylvanica Marsh.	1	1	7	0	0	2
Liquidambar styraciflua L.	0	0	63	0	0	77
Liriodendron tulipifera L.	0	5	20	0	3	43
Magnolia virginiana L.	0	0	0	0	0	1
Nyssa sylvatica L.	0	3	5	0	0	7
Ostrya virginiana Mill.	0	0	0	0	0	2
Oxydendrum arboreum L.	2	0	1	0	1	6
Pinus glabra Walter	0	0	2	0	0	0
Pinus taeda L.	0	0	20	0	0	40
Prunus serotine Michx.	0	0	0	0	0	1
Quercus alba L.	0	0	16	0	1	19
Quercus coccinea Münchh.	0	0	0	0	1	0
Quercus falcata Michx.	0	0	5	0	0	8
Quercus nigra L.	0	0	28	0	0	16
Quercus stellate Wangenh.	0	0	4	0	0	0
Ulmus alata Michx.	0	0	6	0	0	7

trees treated with triclopyr were alive following treatment, compared with 0 percent of trees treated with the mixture (Figure 1). Of the trees that were alive, 88 percent were hickory species (Table 3). More than half of the hickory trees treated with triclopyr were alive (Figure 1), and the mixture achieved greater control of hickory than triclopyr alone (χ^2 = 18.3, DF = 2, p < .001). Although our sample size was insufficient to observe statistically significant differences for other species, it is likely that sourwood also had lower vulnerability to triclopyr alone, with 67 percent of treated stems alive (χ^2 = 5.9, DF = 2, p = .052) (Table 3). We observed one nontarget stem mortality: a nontreated 49.5 cm DBH sweetgum in a stand treated with the herbicide mixture that was 1.5 m from a 24.4 cm sweetgum that had been treated via girdle-and-spray. Thus, we recorded an overall nontarget mortality rate of 0.5 percent (1 of 217) for the herbicide mixture, which did not differ from the nontarget mortality rate of 0 percent for the triclopyr treatment (Table 4).

Discussion

Susceptibility to various herbicides differs among tree species, which we documented when comparing triclopyr with a mixture of triclopyr and imazapyr. However, triclopyr alone resulted in sufficient control of nearly all trees except for hickory and sourwood. Nearly half of the treated hickory and a third of treated sourwood were alive 18 months posttreatment, which is not surprising given that triclopyr is not labeled for control of hickory or sourwood. Nonetheless, triclopyr is still widely recommended for FSI operations in mixed hardwood stands. Hickory and sourwood comprised approximately 15 percent of the stems we targeted for removal in the Coastal Plain of Alabama. Elsewhere, Goode et al. (2018) reported 11 percent relative dominance of hickory and sourwood in the Cumberland Plateau of Alabama, and Rose and Rosson (2007) reported basal area of hickory was 2.4 m^2 ha^{-1} in forest inventory and analysis plots in Virginia where hickory was

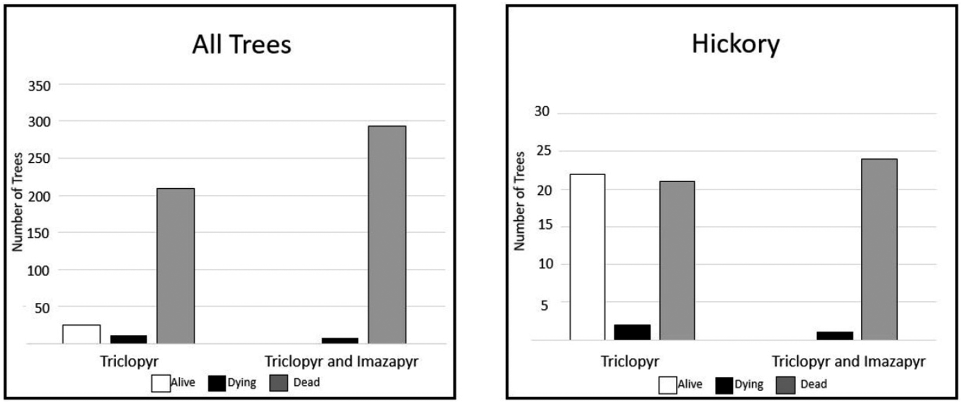

Figure 1. Status of trees treated with triclopyr and a mixture of triclopyr and imazapyr in upland hardwood stands in the Upper Coastal Plain of Alabama. We applied herbicide in January–February 2018 via girdle-and-spray and evaluated the status of the treated trees 18 months later.

Table 3. Percent of treated trees in upland hardwood stands in the Upper Coastal Plain of Alabama still alive following application of triclopyr herbicide via girdle-and-spray. We applied herbicide during January–February 2018 and evaluated the treated stems during July–August 2019.

	Percent Alive	Number Alive	Total Treated
Hickory (*Carya* spp. L.)	55.5%	25	45
Sourwood (*Oxydendrum arboreum* L.)	66.6%	2	3
Green ash (*Fraxinus pennsylvanica* Marsh.)	11.1%	1	9

Table 4. Parameter estimates (β), standard errors (SE), 95% lower and upper confidence limits (LCL and UCL), and *p*-values predicting herbicide-associated nontarget mortality rates for residual trees in upland hardwoods stands in Alabama treated with forest stand improvement. We applied the different herbicide mixtures via girdle-and-spray during January–February 2018 and evaluated nontarget mortality 18-months later.

	β	SE	LCL	UCL	*p*-Value
Triclopyr	0	0.004	-0.01	0.01	1
Triclopyr and Imazapyr	0.005	0.005	-0.01	0.02	0.39

present. Thus, hickory and/or sourwood are well represented in many eastern hardwood stands, and failure to control these species may diminish success of FSI efforts. If managers plan to remove a portion of the hickory and sourwood trees within a forest stand, using a herbicide or herbicide mixture with greater efficacy than we documented for triclopyr alone should be considered.

Although including imazapyr in the mixture increased our control of hickory and sourwood, imazapyr is not labeled to control legumes, such as black locust (*Robinia pseudoacacia* L.), honeylocust (*Gleditsia triacanthos* L.), or eastern redbud (*Cercis canadensis* L.). Imazapyr also fails to control other species relatively common in some areas, including elm and hornbeam (Ezell et al. 1999). Thus, applying a mixture of the two herbicides may be necessary to ensure management objectives are met in stands with a diverse mixture of tree species. Although others have noted antagonism between imazapyr and triclopyr mixtures in foliar applications (Lawrie and Clay 1993, Ezell et al. 1994, Minogue and Quicke 1999), we achieved 100 percent control of all species injected with this mixture in our study, despite the fact that the mechanism of action of these herbicides is the same regardless of application method. Further research using different rates of imazapyr and triclopyr mixtures, or using an ester formulation of triclopyr mixed with imazapyr (which has shown less antagonism potential in foliar applications) could further refine application protocols using imazapyr and triclopyr mixtures applied to girdled trees. One limitation of our study is that we did not evaluate the efficacy of imazapyr alone. Others have reported that wide-spacing injections of a 20 percent solution of imazapyr resulted in >90 percent control of many species treated in our study (Ezell et al. 1999, Alkire et al. 2012). However, those studies did not evaluate treatment efficacy on several of the species included in our study, nor did they evaluate cut-stump treatments. In addition, Ezell and Self (2016) note that some species are naturally resistant to imazapyr. As such, they recommended injecting species susceptible to imazapyr, followed by a broadcast application of triclopyr in stands with significant representation of resistant species. Instead, we combined these herbicides, greatly reducing treatment costs.

We documented only one nontarget tree killed following application of the triclopyr and imazapyr mixture using girdle-and-spray and cut-stump treatments. Combined use of these techniques within each stand allowed us to assess nontarget mortality risk to trees >10 cm DBH when FSI is conducted in forest stands that require treatment of both large and small stems. Nontarget tree mortality from herbicide use is most likely to occur when residual trees are in close proximity to trees of the same species (DiTomaso et al. 2004), especially when the tree species is clonal (DiTomaso and Keyser 2007). The nontarget mortality we recorded was in close proximity to a treated sweetgum, and sweetgum root sprouting is extremely common (Burns and Honkala 1990). Therefore, it is possible that herbicide transfer occurred through root connections and not through the soil. Similarly, Alkire et al. (2012) reported limited nontarget damage to sweetgum, which they attributed to either herbicide spillage or poor injection technique. This highlights the importance of proper herbicide application, especially when treating cut stumps where inadvertent application to the soil is more likely. Nonetheless, we documented only a single sweetgum mortality among hundreds of nontreated trees, suggesting that the probability of root or soil transfer of our herbicide mixture to nontarget trees following girdle-and-spray and treatment of cut stumps is extremely low.

Soil composition is commonly considered an important factor associated with nontarget herbicide mortality when soil-active herbicides are used. Soils with lower clay and organic matter content, as found in our stands, allow greater herbicide movement than those with greater clay and organic matter contents (Anderson 1996). Kochenderfer et al. (2001) reported limited damage associated with imazapyr applied during crop tree release treatments on two sites, but observed 66 percent nontarget mortality on a third site with lower clay and organic matter content. This led the authors to recommend against the use of imazapyr for single-tree treatments, regardless of soil type. However, we did not observe widespread nontarget herbicide mortality on four sites with soils that were low in clay and organic matter, despite examining a wider suite of tree species and giving more time for nontarget herbicide mortality to manifest than Kochenderfer et al. (2001).

The disparity in application rates likely is the primary difference between our results and previous studies. For example, Kochenderfer et al. (2001) applied 0.11 ml of Arsenal AC per 2.54 cm DBH, and Lewis and McCarthy (2008) applied 0.8 g of imazapyr per 2.54 cm DBH. In contrast, we only applied 0.05 ml of Arsenal AC or 0.2 g of imazapyr per 2.54 cm DBH. Given the high efficacy we observed with the triclopyr and imazapyr mixture, it is clear that using higher rates of imazapyr is unnecessary. Our study provides evidence that wide-scale nontarget mortality concerns associated with the use of imazapyr in mixed hardwood stands are likely unwarranted if similar herbicide rates and application techniques are used.

Literature Cited

Alkire, D.K., A.W. Ezell, A.B. Self, S. Demarais, and B.K. Strickland. 2012. Efficacy and non-target impact of midstory injection in bottomland hardwoods. P. 3–6 in *Proceedings of the 16th Biennial Southern Silvicultural Research Conference.* USDA Forest Service, Southern Research Station, Ashville, NC.

Anderson, W.P. 1996. *Weed science: Principles and applications.* West Publishing Company, St. Paul, MN.

BASF Corporation. 2017. *Arsenal® applicators concentrate label.* BASF Corporation, Research Triangle Park, NC.

Brooke, J.M., P.S. Basinger, J.L. Birckhead, M.A. Lashley, J.M. McCord, J.S. Nanney, and C.A. Harper. 2019. Effects of fertilization and crown release on white oak masting and acorn production. *For. Ecol. Manage.* 433(2019):305–312.

Brose, P., and D. Van Lear. 1999. Effects of seasonal prescribed fires on residual overstory trees in oak-dominated shelterwood stands. *South. J. Appl. For.* 23(2):88–93.

Burns, R.M., and B.H. Honkala. 1990. *Silvics of North America.* US Department of Agriculture, Washington, DC.

DiTomaso, J.M., and G.B. Keyser. 2007. Control of *Ailanthus altissima* using stem herbicide application techniques. *Arboric. Urban For.* 33(1):55–63.

DiTomaso, J.M., G.B. Keyser, and E.A. Fredrickson. 2004. Control of black oak and tanoak in the Sierra Cascade range. *West. J. Appl. For.* 19(4):268–276.

Dow AgroSciences. 2016. *Garlon® 3A label.* Dow AgroSciences, Indianapolis, IN.

Ezell, A.W., J. Lowery, B. Leopold, and P.J. Minogue. 1999. Use of imazapyr injection to promote oak regeneration and wildlife stand improvement in bottomland hardwood stands. P. 151–153 in *Proceedings of 10th Biennial Southern Silvicultural Research Conference.* USDA Forest Service, Southern Research Station, Asheville, NC.

Ezell, A.W., and A.B. Self. 2016. Herbicide options for hardwood management. P. 377–382 in *Proceedings of the 18th Biennial Southern Silvicultural Research Conference.* USDA Forest Service, Southern Research Station, Asheville, NC.

Ezell, A.W., J. Volmmer, P.J. Minogue, and B. Zutter. 1994. A comparison of herbicide tank mixtures for site preparation – evaluation of treatment efficiency and possible antagonism. P. 98–101 in *Proceedings of the 8th Biennial Southern Silvicultural Research Conference.* USDA Forest Service, Southern Research Station, Asheville, NC.

Goode, J.D., C.R. Barefoot, J.L. Hart, and D.C. Dey. 2018. Disturbance history, species diversity, and structural complexity of a temperate deciduous forest. *J. For. Res.* 31(2):397–414.

Hannah, P.R. 1987. Regeneration methods for oaks. *North. J. Appl. For.* 4:97–101.

Kochenderfer, J.D., S.M. Zedaker, J.E. Johnson, D.W. Smith, and G.W. Miller. 2001. Herbicide hardwood crop tree release in central West Virginia. *North. J. Appl. For.* 18(2):46–54.

Lamson, N.I., H.C. Smith, A.W. Perkey, and S.M. Brock. 1990. *Crown release increases growth of crop trees.* USDA Forest Service Res. Pap. NE-RP-635, Northeastern Forest Experiment Station, Radnor, PA.

Lashley, M.A., C.A. Harper, G.E. Bates, and P.D. Keyser. 2011. Forage availability for white-tailed deer following silvicultural treatments in hardwood forests. *J. Wildl. Manage.* 75(6):1467–1476.

Lawrie, J., and V. Clay. 1993. Effects of herbicide mixtures and additives on *Rhododendron ponticum*. *Weed Res.* 33(1):25–34.

Lewis, K., and B. McCarthy. 2008. Nontarget tree mortality after tree-of-heaven injection with imazapyr. *North. J. Appl. For.* 25(2):66–72.

Masters, R.E., R.L. Lochmiller, and D.M. Engle. 1993. Effects of timber harvest and prescribed fire on white-tailed deer forage production. *Wildl. Soc. Bull.* 21(4):401–411.

McCord, J.M., C.A. Harper, and C.H. Greenberg. 2014. Brood cover and food resources for wild turkeys following silvicultural treatments in mature upland hardwoods. *Wildl. Soc. Bull.* 38(2):265–272.

Minogue, P.J., and H.E. Quicke. 1999. Early-season forest site preparation with imazapyr and combinations of imazapyr and glyphosate or triclopyr in oil emulsion carrier: second-year response for planted pines and associated woody and herbaceous vegetation. P. 307–311 in *Proceedings of the 10th Biennial Southern Silvicultural Research Conference*. USDA Forest Service, Southern Research Station, Asheville, NC.

Mixon, M.R., S. Demarais, P.D. Jones, and B.J. Rude. 2009. Deer forage response to herbicide and fire in mid-rotation pine plantations. *J. Wildl. Manage.* 73(5):663–668.

National Oceanic and Atmospheric Administration (NOAA). 2019. *Climate at a glance: County time series.* Available online at www.ncdc.noaa.gov/cag/; last accessed August 21, 2019.

Natural Resource Conservation Service (NRCS). 2017. *Web soil survey.* Available online at www.websoilsurvey.sc.egov.usda.gov/; last accessed November 5, 2017.

Nyland, R.D. 2002. Improvement, salvage, and sanitation cuttings. P. 506–223 in *Silviculture: Concepts and applications.* Waveland Press, Long Grove, IL.

Ohlson-Kiehn, C., W. Pariona, and T.S. Fredericksen. 2006. Alternative tree girdling and herbicide treatments for liberation and timber stand improvement in Bolivian tropical forests. *For. Ecol. Manage.* 225(1–3):207–212.

Pariona, W., T.S. Fredericksen, and J.C. Licona. 2003. Tree girdling treatments for timber stand improvement in Bolivian tropical forests. *J. Trop. For. Sci.* 15(4):583–592.

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and R Core Team. 2017. *nlme: Linear and nonlinear mixed effects models. R package version 3.1-131*. Available online at https://CRAN.R-project.org/package=nlme; last accessed October 15, 2019.

R Core Team. 2018. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. Available online at http://www.R-project.org; last accessed October 15, 2019.

Rose, A.K., and J.F. Rosson. 2007. *The importance and distribution of hickory across Virginia.* USDA Forest Service e-Gen. Tech. Rep. SRS-101, Southern Research Station, Knoxville, TN.

Wendel, G.W., and N.I. Lamson. 1987. *Effects of herbicide release on the growth of 8- to 12-year-old hardwood crop trees.* USDA Forest Service Res. Pap. NE-RP-589, Northeastern Forest Experiment Station, Broomall, PA.