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Novel basal bark and cut stump herbicide treatments for Brazilian peppertree (*Schinus terebinthifolia*) management

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Research Article

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Abstract

Brazilian peppertree (*Schinus terebinthifolia* Raddi) is an aggressive shrub that infests more than 280,000 ha in Florida. Individual plant treatments (IPT), including basal bark and cut stump application with triclopyr butoxyethylester and triethylamine formulations, respectively, have been used for decades. While they are both effective, resprouting can occur, which requires retreatment for control. Recent research on other woody invasive plants has indicated additional non-crop herbicides used in natural areas can be effective with these IPT techniques and therefore warrant testing on *S. terebinthifolia*. In 2018 and 2019, basal bark and cut stump studies were conducted at Cape Canaveral Air Force Station in natural areas infested with *S. terebinthifolia*. In the basal bark application studies, we found aminocyclopyrachlor applied at 12 and 24 g L^{-1} and triclopyr acid applied at 34 and 69 g L^{-1} each provided 100% defoliation of multistemmed *S. terebinthifolia* individuals with a mean root collar diameter up to 20.2 cm at 360 d after treatment (DAT). These were not different from triclopyr ester applied at 96 g L^{-1}. Imazamox applied at 30 g L^{-1} resulted in 86% defoliation at 360 DAT. However, we observed formulation incompatibility when imazamox was mixed with basal bark oil which may limit its utility. In cut stump studies, we found aminocyclopyrachlor and aminopyralid each individually applied at 6, 12, and 24 g L^{-1}, resulted in stump mortality that was not different from the commercial standard triclopyr amine applied at 180 g L^{-1}. Similar results were found for a triclopyr acid formulation applied at 86 and 172 g L^{-1} and imazamox applied at 60 g L^{-1}. For both treatment techniques, we found that alternative treatments provided control at lower herbicide concentrations than triclopyr ester and amine commercial standards. These results advance our understanding of IPT and expand access to additional effective herbicide options for *S. terebinthifolia* management.

Introduction

Brazilian peppertree (*Schinus terebinthifolia* Raddi) is a multistemmed shrub or small tree that is one of the most troublesome invasive plants in Florida. Introduced into south Florida in the mid-1800s as an ornamental, it has since escaped into natural areas and has expanded across much of the state, infesting more than 280,000 ha (Ferriter et al. 2006). *Schinus terebinthifolia* invades a wide range of natural areas such as mangrove forests, coastal strands, rangelands, seasonal wetlands, and upland scrub habitat (Ewel 1986) (red mangrove [*Rhizophora mangle* L.], black mangrove [*Avicennia germinans* (L.) L.], white mangrove [*Laguncularia racemosa* (L.) C.F. Gaertn.], and buttonbush [*Conocarpus erectus* L.]). Like other species in the Anacardiaceae family, such as poison ivy [*Toxicodendron radicans* (L.) Kuntze], the plant's sap can cause skin rashes and dermal irritation in susceptible individuals (Morton 1978).

Although it can form small single-stemmed trees, its primary growth habit consists of multistemmed trunks with drooping branches that form dense tangled thickets. *Schinus terebinthifolia* effectively crowds out many native species (Doren and Whiteaker 1990; Gordon 1998) and produces allelopathic substances that can inhibit germination and growth of surrounding vegetation (Donnelly et. al 2008; Morgan and Overholt 2005; Nickerson and Flory 2015). In many habitats, it is known to increase year-round litter moisture, reduce the amount of fire-prone litter, and exclude pyrogenic species, ultimately transforming systems to fire-excluded areas (Doren et al. 1991; Gordon 1998; Loope and Dunevitz 1981).

Approaches to control *S. terebinthifolia* often involve chemical and mechanical control with basal bark and cut stump herbicide treatments (Ferriter et al. 2006). Basal bark application generally uses the triclopyr butoxyethyl ester formulation applied in an oil carrier to penetrate the bark and successfully control the target woody species. Basal bark treatment is highly effective on

Management Implications

Schinus terebinthifolia (Brazilian peppertree) is an aggressive invader in Florida and threatens remnant coastal scrub habitat that several protected species in Cape Canaveral depend on. Management of *S. terebinthifolia* is often costly and herbicide intensive. We evaluated new herbicide active ingredients and formulations at reduced rates compared with the standard triclopyr ester and triclopyr amine treatments with basal bark and cut stump treatments, respectively. We found that for basal bark application, aminocyclopyrachlor (Method® 240SL at 10% v/v) and triclopyr acid (Trycera® at 10% v/v) were 100% effective at 360 d after treatment (DAT) with less active ingredient used than the standard recommendation of triclopyr ester (Garlon® 4 Ultra at 20% v/v). Cut stump treatment with aminocyclopyrachlor (Method® 240SL at 2.5%, 5%, and 10% v/v), aminopyralid (Milestone® at 5% and 10% v/v), and triclopyr acid (25% v/v) resulted in similar efficacy compared with the commercial standard triclopyr amine (Garlon® 3A at 50% v/v). These studies indicate an opportunity to expand *S. terebinthifolia* individual plant treatment options with lower herbicide use through alternative herbicide treatments.

S. terebinthifolia (Doren and Whiteaker 1990) and is widely used on trees and shrubs less than 15 cm in diameter and where dead standing individuals are acceptable. Cut stump treatments are often applied with the water-soluble triethylamine formulation of triclopyr, glyphosate, or imazapyr. Although very labor-intensive, cut stump treatment is used during habitat restoration, especially when restoring open habitat that was previous occupied by dense shrub or forest cover (Harms and Hiebert 2006). Cut stump treatments are also widely used when complete removal of trees is required due to safety concerns with dead standing trees. Both triclopyr formulations are generally effective but have limitations for successful *S. terebinthifolia* management. For example, basal bark treatment with the ester formulation can easily exceed maximum labeled rates in dense stands of woody vegetation (Holmes and Berry 2009). Stump sprouting is common following cut stump treatments with triclopyr amine or glyphosate, and these must be subsequently treated for complete control. Imazapyr soil residual activity often limits its utility in natural areas, even when applied as a cut stump treatment.

In recent years, a limited number of new herbicides have been labeled for treating woody species in natural areas. Two key herbicides include the auxin-type herbicides aminopyralid and aminocyclopyrachlor. A growing body of literature indicates these auxin-type herbicides are extremely effective on many very difficult to control invasive plants, including Chinese tallowtree [*Triadica sebifera* (L.) Small] (Enloe et al. 2015), tropical soda apple (*Solanum viarum* Dunal) (Ferrell et al. 2006), kudzu [*Pueraria montana* (Lour.) Merr.] (Minogue et al. 2011), skunkvine (*Paederia foetida* L.) (Marble and Chandler 2019), and mile-a-minute (*Mikania micrantha* Kunth) (Sellers et al. 2014). Foliar applications of aminopyralid and aminocyclopyrachlor have also effectively controlled *S. terebinthifolia* (Enloe et al. 2020).

Additionally, a relatively new acid formulation of triclopyr has been shown to be comparable to and better than the triclopyr amine formulation on Tahitian bridal veil [*Gibasis pellucida* (M. Martens & Galeotti) D.R. Hunt] (Yu et al. 2022) and hen's eyes (*Ardisia crenata* Sims) (Cristan et al. 2019), respectively. The triclopyr acid formulation warrants additional testing, as it is labeled for aquatic use and, operationally, has been shown to be effective at lower use rates than current rates recommended for triclopyr ester for basal bark treatment of *S. terebinthifolia* (Bell 2019).

Finally, imazamox is a herbicide used to control several troublesome aquatic and wetland plants, including *T. sebifera* (Enloe et al. 2015), that is also labeled for basal bark use (Anonymous 2016). In previous studies, Enloe et al. (2021) also found imazamox applied at 0.56 kg ha^{-1} resulted in 97% defoliation of *S. terebinthifolia*. Given that it is labeled for basal bark application, its testing on *S. terebinthifolia* with this application technique is warranted.

Given the utility of these newer herbicides for invasive plant management, the objective of this research was to compare their performance as basal bark and cut stump treatments with commercial rates of triclopyr ester and amine, which are widely used for *S. terebinthifolia* management. If effective, these would be additional tools in the treatment toolbox for this difficult to control species.

Materials and Methods

Two field studies were conducted in 2018 and 2019 at Cape Canaveral Air Force station, located on the Atlantic Coast of Florida in a cluster of coastal barrier islands. These barrier islands are predominantly open coastal scrub and strand habitats with low-lying vegetation communities influenced by high winds and salt spray (Sweet et al. 1980). Historically, these were successional pyrogenic ecosystems naturally cycled by lightning fires. However, fire has been widely suppressed due to the highly sensitive nature of aerospace rocket launches for several decades (Duncan et al. 2011). Mean annual temperatures (22.1 C) were slightly above normal for 2018 (22.6 C) and 2019 (23.2 C), and mean annual precipitation (137.1 cm) was near normal in 2018 (135.6 cm) and well above average in 2019 (170.5 cm).

The first experimental runs for the basal bark and cut stump studies were conducted in February and March 2018, respectively, on a 4-ha coastal scrub restoration site (28.51°N, 80.577°W). Soils were classified as a mix of Welaka sand and Canaveral Urban land complex (Hyperthermic, uncoated Aquic Quartzipsamments) (Soil Survey Staff n.d.). In 2016. the site was a monospecific stand of large, old-growth *S. terebinthifolia*, approximately 5 to 10 m in height, that was masticated with heavy machines. Shortly after, numerous stumps resprouted at the root collar, reestablishing a stand of scattered, multistemmed shrubs that were approximately 3 m in height. Across this site, individual shrubs spaced at least 3 m apart were randomly selected along transects and served as experimental units. There were 10 replicate shrubs per treatment, which resulted in 70 and 120 experimental units for Run 1 of the basal bark and cut stump studies, respectively. Shrubs in Run 1 of the basal bark experiment had 2 to 4 stems with root collar diameters (RCDs) from 3.0 to 4.3 cm (Table 1). For the cut stump study, there were 3 to 8 stems per shrub, with an average RCD of 2.2 to 3.8 cm.

The second experimental runs for the basal bark and cut stump studies were conducted in December 2018 and January 2019, respectively, on a 4-ha coastal strand that had largely transformed to dense old-growth *S. terebinthifolia* (28.4698°N, 80.5341°W). Soils were a Canaveral-Anclote complex composed of deep sands on marine terraces (Sandy, siliceous, hyperthermic Typic Endoaquolls) (Soil Survey Staff n.d.). Other vegetation included Surinam cherry (*Eugenia uniflora* L.), oaks (*Quercus* spp.), and saw palmettos [*Serenoa repens* (W. Bartram) Small]. Across this site,

Table 1. *Schinus terebinthifolia* pretreatment and application time data for the basal bark application study at Cape Canaveral Air Force Station, FL.[a]

		Stem count		Mean RCD[b]		Circumference		Application time/ circumference	
no. plant^{-1}	cm	s cm^{-1}							
	g L^{-1}	LMU21	CX36	LMU21	CX36	LMU21	CX36	LMU21	CX36
Aminocyclopyrachlor	12	2.2 a	1.6 a	4.2 a	15.4 a	25.4 a	65.8 a	1.4 a	1.1 a
Aminocyclopyrachlor	24	3.0 a	2.3 a	4.3 a	9.3 a	32.7 a	61.0 a	1.3 a	1.0 a
Imazamox	30	3.0 a	1.7 a	3.0 a	12.5 a	26.5 a	60.2 a	1.8 a	1.4 a
Triclopyr acid	34	3.9 a	2.1 a	3.6 a	11.5 a	39.4 a	80.2 a	1.7 a	1.5 a
Triclopyr acid	69	2.5 a	3.4 a	4.2 a	10.3 a	28.4 a	93.8 a	1.6 a	1.4 a
Triclopyr ester	96	3.1 a	1.9 a	4.0 a	10.1 a	33.1 a	59.0 a	1.3 a	1.1 a
Nontreated, oil only	—	2.9 a	1.8 a	3.5 a	15.7 a	28.1 a	67.4 a	1.2 a	0.7 a

[a]Means within columns followed by the same letter are not different using Tukey's adjustment.
[b]RCD, root collar diameter.

Table 2. *Schinus terebinthifolia* response to basal bark herbicide treatments over time at Cape Canaveral Air Force Station, FL.

		60 DAT[a]		180 DAT		360 DAT		360 DAT	
	g L^{-1}	LMU21[b]	CX36	LMU21	CX36	LMU21	CX36	LMU21	CX36
		——— % Defoliation[c] ———						——% Sprouting[d]——	
Aminocyclopyrachlor	12	100	32 cd	100	86 a*	100	100 a	0	10 (3–31)
Aminocyclopyrachlor	24	100	34 c	100	100	100	100	0	0 (0–17)
Imazamox	30	88	55 bc	100	86 a*	100	86 a*	0	30 (14–53)
Triclopyr acid	34	100	53 bc	100	98 a	100	100	0	0 (0–17)
Triclopyr acid	69	100	79 ab	100	98 a	100	100	0	0 (0–17)
Triclopyr ester	96	100	90 a	100	100	100	100	0	0 (0–17)
Nontreated, oil only	—	4	7 d	2.1	10 b*	2	51 b*	0	0 (0–17)

[a]DAT, days after treatment.
[b]Mean comparisons were not performed for this site, as almost all herbicide treatments were 100% effective.
[c]Old growth defoliation means within columns followed by the same letter are not different using Tukey's adjustment. Old growth 180 and 360 DAT defoliation means followed by an asterisk (*) are at least 2 SE less than 100% defoliation.
[d]Wilson's 85% confidence interval for percent of rootstocks with epicormic sprouting based on sample size are given in parentheses.

individual treelike shrubs spaced at least 3 m apart were randomly selected along transects and served as experimental units. There were 10 replicates per treatment, which again resulted in 70 and 120 experimental units for the basal bark and cut stump Run 2 studies, respectively. The *S. terebinthifolia* individuals in the repeated basal bark study were larger, approximately 5 to 7 m in height with 1.6 to 3.4 stems and an RCD of 9.3 to 15.7 cm (Table 1). For the repeated cut stump study, there were 1.0 to 1.11 stems per shrub with an average RCD of 20.2 to 21.5 cm.

For both experimental runs, *S. terebinthifolia* was phenologically in the post-fruiting period. In south and central Florida, the species remains evergreen with actively growing leaves throughout the year. We were not concerned with potential treatment response to variation in phenology, which is common in the study of more temperate deciduous species. Rather, our focus was on herbicide effects at multiple locations, which also encompassed a range of shrub sizes.

Treatments for the basal bark studies included aminocyclopyrachlor at 12 and 24 g ae L^{-1} (Method® 240SL, Bayer, Research Triangle Park, NC 27709), triclopyr acid at 34 and 69 g ae L^{-1} (Trycera®, Helena AgriEnterprises, Collierville, TN 38017), imazamox at 30 g ae L^{-1} (Clearcast®, SePRO, Carmel, IN 46032), triclopyr ester at 96 g ae L^{-1} (Garlon® 4 Ultra, Dow AgroSciences, Indianapolis, IN 46268) as the commercial standard, and a nontreated control with basal oil only (Table 2). All herbicide formulations were mixed with a basal oil carrier (Impel™ Red Oil, Helena AgriEnterprises). The oil carrier was formulated with a combination of aliphatic hydrocarbon oils, surfactants, and non-ionic emulsifiers that were expected to be compatible with the diversity of herbicides tested. We did not use comparable acid equivalent concentrations for the two triclopyr products tested, given that the recommended concentrations and application approaches varied between the two formulations.

Basal bark applications were administered using 1.5-L hand sprayers with an adjustable cone nozzle (Flo-Master® spray bottle, Home Depot, 2433 Paces Ferry Road NW, Atlanta, GA 30339). Treatments were applied to the lower bark from the root collar of the tree up to ~30 cm in a spray-to-wet pattern, ensuring complete coverage around the circumference of each stem, but not dripping off and pooling around the base of the trunk. For multistemmed individuals, all stems in the clump were treated.

The treatment design of cut stump studies included aminocyclopyrachlor at 6, 12, and 24 g L^{-1}, aminopyralid at 6, 12, and 24 g L^{-1} (Milestone®, Dow AgroSciences), triclopyr acid at 86 and 172 g L^{-1}, imazamox at 30 g L^{-1}, triclopyr amine at 90 and 180 g L^{-1} (Garlon® 3A, Dow AgroSciences) as the commercial standard, and a nontreated control that included water. All treatments contained a non-ionic surfactant at 0.5% v/v (Induce®, Helena AgriEnterprises).

Cut stump herbicide applications were performed with 750-mL spray bottles (Ace® Hand Sprayer, Ace Hardware, 2200 Kensington Court, Oak Brook, IL 60523) with an output of 0.89 ± 0.1 ml stroke^{-1}. Trees initially were limbed using a chainsaw and cut to a stump height of approximately 5 cm. Debris was quickly removed from the stump surface, and herbicide solutions were applied to the entire phloem and vascular cambium tissues in a band around the circumference of the stump. Treatments were applied within 1 to 2 min of cutting. For multistemmed individuals, all cut stems were treated.

For all studies, baseline data included RCD and number of stems for each experimental unit. At application, we recorded the time necessary to treat each individual. For the basal bark experimental runs, this included the time required to apply the herbicide treatment to the base of each experimental unit. For the cut stump experimental runs, this included the time required to both cut and apply the herbicide treatment to each experimental unit. We also recorded herbicide applied per individual for the basal bark study by subtracting the final spray volume from the initial spray volume after each treatment. The total volume applied was then normalized across experimental units to the total amount of herbicide applied per centimeter of RCD.

Posttreatment data for the basal bark study included visual estimates of canopy defoliation on a 0 to 100 scale, where 0 equals no defoliation and 100 equals no live green leaves remaining. For the cut stump study, new stump and lateral root sprouts were counted at 360 d after treatment (DAT). Lateral root sprouts were quantified within a 30-cm-wide radius around each tree. Lateral sprouts were easily discerned from seedlings, as they were present on exposed lateral roots or originating from lateral roots just below the soil surface. Seedlings were also removed around the stump to reduce confusion with lateral sprouts (Enloe et al. 2015). Similar to Harmoney (2016), we defined cut stump resprouts as any new green leaf tissue not present before cut stump treatment.

Analysis of the basal bark and cut stump studies was performed for each location separately. Baseline pretreatment ANOVA was performed for rootstock stem count, average rootstock RCD, circumference of stems in rootstock, and application time per circumference. The baseline analysis included application volume and application volume per circumference for the cut stump study. Stem count was analyzed as count data using the Poisson distribution with a log link function, with the exception that no analysis was performed for the cut stump old growth (CX36) location with mostly single-stem rootstocks.

Basal bark studies were evaluated in terms of percent defoliation at 60, 180, and 360 DAT and proportion of rootstocks with epicormic branching. Many treatments included in the basal bark experiment achieved 100% defoliation. A posttreatment statistical analysis was not performed for the mulched (LMU21) location due to lack of variation when all treated stems have 100% defoliation. The arcsine square-root transformation was used to normalize variance for old-growth (CX36) location percent defoliation with modifications suggested by Seedorf et al. (2022) for treatments with complete defoliation. The ANOVA was performed by evaluation date and excluded treatments with 100% defoliation to accurately estimate the random block and residual error effects. Means included in the analysis were compared using Tukey's adjustment for multiplicity and were denoted as less than 100% defoliation if the difference was greater than 2 SE (calculated using ANOVA residual error for differences on the transformed scale). The Wilson score interval (Wilson 1927) was used to calculate an 85% confidence interval for proportion of rootstocks with epicormic sprouts at 360 DAT to describe the limits of inference with respect to sample size.

Cut stem studies were evaluated in terms of rootstock total sprouts (stump + lateral sprouts) and rootstock mortality at 360 DAT. The analysis of total sprout count was performed using the negative binomial distribution with a log(circumference) offset to account for overdispersion of the Poisson model and reduce the variation due to different rootstock size. This compares treatments in terms of total sprout count per unit of rootstock circumference (n cm^{-1}). The analysis of rootstock mortality was performed using a logistic model. Treatments with no sprouts were excluded from these analyses and mean comparisons. Means included in each analysis were compared using Tukey's adjustment for multiplicity. Treatment mortality was denoted to be less than 100% if below the Wilson 85% confidence interval for 100% mortality based on sample size.

Data were analyzed using SAS® 9.4 (SAS Institute, Cary, NC 27513) software. The ANOVA was performed with PROC GLIMMIX (Littell et al. 2006). The old-growth location was a randomized complete block design with block included as a random effect. The mulched location was analyzed as a completely random design. Wilson score intervals were computed using the R Base package v. 4.2.2 (2022) with the BINOM package v. 1.1-1.1 (2014).

Results and Discussion

Basal Bark Study

Application time did not differ among treatments and ranged from 1.2 to 1.8 s cm^{-1} of stem circumference at LMU21 and 0.7 to 1.5 s cm^{-1} of stem circumference at CX 36 (Table 1). Across treatments, application volumes averaged 2.2 and 2.4 ml cm^{-1} of stem circumference at LMU21 and CX36, respectively. These data indicate a strong consistency in the application technique across the range of *S. terebinthifolia* shrub sizes evaluated. The application volume values are slightly lower than those tested for tree of heaven [*Ailanthus altissima* (Mill.) Swingle] (Burch and Zedaker 2003) and slightly higher than previous basal bark application studies on *T. sebifera* (Enloe et al. 2015) and Chinese privet (*Ligustrum sinense* Lour.) (Enloe et al. 2016) However, variation in bark thickness, stem architecture, and the presence of exposed lateral roots may influence application volume on a species basis.

At 60 DAT, all herbicide treatments resulted in 88% to 100% *S. terebinthifolia* defoliation at LMU21 (Table 2). This was in contrast to CX36, where defoliation of larger trees was lower and varied by treatment. At CX36, triclopyr ester was the only treatment that resulted in 90% defoliation at 60 DAT. This was significantly greater than for all other treatments, except triclopyr acid applied at 69 g L^{-1}. Defoliation in the triclopyr acid (69 g L^{-1}) treatment was significantly higher than both concentrations of aminocyclopyrachlor, which both resulted in 34% or less defoliation. Imazamox was intermediate in defoliation and did not differ from the low concentration of triclopyr acid or both concentrations of aminocyclopyrachlor.

At 180 DAT, *S. terebinthifolia* defoliation was 100% across all herbicide treatments at LMU21. At CX36, defoliation ranged from 86% for the low concentration of aminocyclopyrachlor and imazamox to 100% for all other herbicide treatments. Out of all treatments, defoliation in the aminocyclopyrachlor (12 g L^{-1}) and imazamox (30 g L^{-1}) treatments was more than 2 SE below100%, suggesting less herbicidal activity and considerably greater variation in herbicide performance at that sample time. *Schinus terebinthifolia* defoliation in the nontreated control was 10% and was less than in all herbicide treatments.

At 360 DAT, all herbicide treatments except imazamox resulted in 100% defoliation at both locations. Imazamox provided 100% defoliation at LMU21 and 86% at CX36. Defoliation in the imazamox treatment at CX36 was again more than 2 SE below 100% defoliation, indicating more variable performance. Epicormic sprouting at 360 DAT was not observed at LMU21 and was limited to the low concentration of aminocyclopyrachlor and imazamox treatments at CX36. However, Wilson's 85% confidence interval approach did not result in any significant differences in epicormic sprouting between any treatments due to the high variation in sprouting in those two treatments. While epicormic sprouting has been reported for *S. terebinthifolia*, the high degree of herbicide efficacy across both studies clearly prevented it, and 100% defoliation coupled with no epicormic sprouting likely indicates mortality in those treatments.

Just before final data collection at 360 DAT for Run 2 of the basal bark study, four untreated controls experienced considerable unexpected defoliation. This had not been observed at previous sampling dates but was likely caused by salt spray, as the plots were less than 400 m from the coastline. *Schinus terebinthifolia* is known to tolerate limited salinity but experiences significant reductions in shoot quality following exposure to moderate brackish conditions (Tootoonchi et al. 2022). We checked the spatial data for patterns of aminocyclopyrachlor-treated tree presence near these experimental units and did not find any pattern indicating a potential issue. Given we did not see any issues at any other sampling date and the fact that we checked for auxin-type symptomology in the young twigs and did not find any symptoms, we could not attribute this to herbicide injury. Essentially all herbicide-treated trees in the study were defoliated by 180 DAT and did not leaf out through the termination of the study at 360 DAT, so they could not be impacted by salt spray in terms of defoliation.

Overall, these data indicate excellent control of *S. terebinthifolia* with the commercial standard triclopyr ester treatment, both concentrations of triclopyr acid, and the high concentration of aminocyclopyrachlor. Across sites, these treatments were effective on a range of shrub sizes from 3.0- to 15.7-cm RCD. This size range for control agrees with the general recommendations for basal bark application of woody plants up to 20-cm diameter at breast height (Miller et al. 2010).

These data also provide alternative basal bark treatments at substantially lower herbicide concentrations than those used under the current management paradigm for *S. terebinthifolia* basal bark application with triclopyr ester. For example, in this study, the low rate of triclopyr acid was equal to a 65% reduction in herbicide active ingredient compared with the triclopyr ester treatment with no substantial change in herbicide costs. This is very noteworthy, as land managers often attempt to maximize invasive plant control with reduced herbicide concentrations where possible. However, given we did not directly compare equivalent concentrations of each formulation, it is clear that additional research should examine lower concentrations of triclopyr ester and determine whether the two formulations have equal activity at equivalent concentrations. Other research has demonstrated that triclopyr ester may be effective at lower concentrations on other species as a basal bark treatment. For example, Enloe et al. (2016) demonstrated triclopyr ester applied at 48 g L^{-1} resulted in 76% mortality of *L. sinense*. Jackson (2017) demonstrated that triclopyr applied at 24 g L^{-1} was effective for controlling five different native hardwood species the year following treatment.

Although comparable data are lacking for triclopyr acid and imazamox, recent work on basal bark applications of aminocyclopyrachlor to other difficult to control species is in agreement with our findings. Minogue and Lorentz (2021) found basal bark applications of aminocyclopyrachlor effectively controlled *Eucalyptus benthamii* Maiden et Cambage (Camden white gum) applied at a concentration comparable to the high concentration in the current study. Enloe et al. (2015) found basal bark applications of aminocyclopyrachlor at 24 g L^{-1} to *T. sebifera* resulted in significantly higher rootstock mortality than triclopyr ester at 96 g L^{-1}. The primary limitation of aminocyclopyrachlor for basal bark treatment is the low use rate of 320 g ha^{-1}. This limits the number of stems that can be treated on a per-hectare basis. Additionally, aminocyclopyrachlor is relatively water soluble, and the primary absorption path for activity is uncertain for penetration of the outer bark versus root absorption. This is also true for imazamox, which is highly water soluble as an ammonium salt formulation. Future studies should examine the absorption pathways for these two herbicides into woody plants. Additionally, we observed some incompatibility of imazamox with Impel™ Red bark oil. Treatments emerged from the single nozzle as a thick, sticky drizzle as opposed to an atomized spray. This would be unacceptable to most applicators, due to time and money spent on cleaning or replacing clogged sprayers.

The effectiveness of the triclopyr acid formulation at concentrations below the triclopyr ester standard warrants further investigation on *S. terebinthifolia* and several other woody invasive species. Future studies should seek to determine the lowest effective concentration for basal bark application and should consider efficacy at larger operational scales. This would better inform land managers on the utility of this novel triclopyr formulation in relation to the triclopyr ester formulation.

Cut Stump Study

Application time ranged from 1.7 to 2.4 s cm^{-1} of stem circumference at LMU21 and 2.3 to 3.1 s cm^{-1} of stem circumference at CX 36 and did not differ among treatments at either site (Table 3). Across treatments, application volumes averaged 0.55 to 0.71 ml cm^{-1} of stem circumference at LMU21 and CX36, respectively. These data again reflect consistency in the methodology across the range of *S. terebinthifolia* shrub sizes evaluated at each site. The application volumes are slightly lower than previous cut stump application studies on *T. sebifera* (Enloe et al. 2015) and *A. altissima* (DiTomaso and Kyser 2007). However, target application volume is frequently not specified with cut stump treatments, because the surface area of the inner bark and cambial tissue may vary across species.

At 360 DAT, most herbicide treatments had no stump sprouts at LMU21 (Table 4). The only treatments where stump sprouting occurred included aminocyclopyrachlor at 6 and 12 g L^{-1}, aminopyralid at 6 g L^{-1}, and imazamox at 30 g L^{-1}. There were no differences in stump sprouting between these four treatments, and all had significantly lower stump sprouting than the untreated control, which had the highest number of new sprouts per centimeter of stem circumference. At CX36, only the two highest concentrations of aminocyclopyrachlor resulted in no new stump sprouts. All other treatments resulted in extremely low stump sprouting, significantly lower than the nontreated control, with the exception of triclopyr acid applied at 86 g L^{-1}. Although sites were not compared directly, the larger stumps at CX36 tended to result in more resprouts across most herbicide treatments than smaller-diameter stumps at LMU21. This is in general agreement with other studies that have shown larger stumps tend to resprout more than smaller stumps following herbicide treatment for multi-stemmed shrubs (Enloe et al. 2018).

Stump mortality was in general agreement with stump sprouting data. At LMU21, the same treatments with no stump sprouting resulted in 100% mortality, while the two lowest concentrations of aminocyclopyrachlor, the lowest concentration of aminopyralid, and imazamox all resulted in 80% to 90% mortality. While none of these were statistically different from the criteria of 100% mortality according to Wilson's test, all except aminocyclopyrachlor at the lowest concentration and imazamox differed from the untreated control. At CX36, a similar pattern was

Table 3. *Schinus terebinthifolia* pretreatment and application time data for the cut stump application study at Cape Canaveral Air Force Station, FL.[a]

		Stem count		Mean RCD[b]		Circumference		Application time	
		no. plant^{-1}		cm		s cm^{-1}			
	g L^{-1}	LMU21	CX36	LMU21	CX36	LMU21	CX36	LMU21	CX36
Aminocyclopyrachlor	6	5.6	1	2.2 a	21.3 a	40.8 a	67.0 a	1.7 a	2.4 a
	12	5.1	1	3.5 a	20.6 a	41.5 a	64.6 a	1.8 a	2.2 a
	24	3.5	1	3.1 a	20.9 a	30.6 a	65.8 a	2.1 a	3.1 a
Aminopyralid	6	3.6	1.1	2.3 a	20.2 a	25.4 a	66.0 a	2.4 a	2.3 a
	12	3.9	1	3.1 a	20.6 a	33.9 a	64.8 a	2.1 a	2.5 a
	24	3.2	1	2.7 a	21.0 a	24.5 a	66.1 a	2.0 a	2.8 a
Imazamox	30	7.6	1	2.4 a	21.5 a	52.3 a	67.5 a	1.8 a	3.2 a
Triclopyr acid	86	3.5	1	3.8 a	20.1 a	32.8 a	65.6 a	2.0 a	2.3 a
	172	4.2	1	3.6 a	21.3 a	34.9 a	66.8 a	2.2 a	2.5 a
Triclopyr amine	90	4.9	1	2.6 a	20.2 a	40.1 a	63.5 a	2.0 a	2.7 a
	180	3.2	1.1	3.1 a	20.8 a	26.9 a	69.3 a	2.3 a	2.5 a
Non-treated, oil only	—-	3.8	1	3.3 a	20.3 a	32.4 a	63.9	1.6	2.1 a

[a]Means within columns followed by the same letter are not different using Tukey's adjustment.
[b]RCD, root collar diameter.

Table 4. *Schinus terebinthifolia* response to cut stump herbicide treatments at 360 d after treatment (DAT) at Cape Canaveral Air Force Station, FL.

		Stump sprouts[ab] no. cm^{-1}		Stump mortality[c] cm	
	g L^{-1}	LMU21	CX36	LMU21	CX36
Aminocyclopyrachlor	6	0.02 b	0.003 b	80 b	89 a
	12	0.02 b	0	90 a	100
	24	0	0	100	100
Aminopyralid	6	0.2 b	0.02 b	90 a	56 a*
	12	0	0.02 b	100	78 a
	24	0	0.01 b	100	89 a
Imazamox	30	0.02 b	0.01 b	80 ab	78 a
Triclopyr acid	86	0	0.04 ab	100	56 a*
	172	0	0.02 b	100	89 a
Triclopyr amine	90	0	0.02 b	100	89 a
	180	0	0.01 b	100	78 a
Nontreated, oil only	—	0.5 a	0.4 a	10 b*	22 a*

[a]No. cm^{-1} of stem circumference
[b]Means within columns used in the analysis (followed by letters) are not significantly different if followed by the same letter using Tukey's adjustment.
[c]Rootstock mortality means within columns followed by an asterisk (*) are significantly less than 100% based on the Wilson score 85% confidence limit for 100% mortality.

evident, as only the two highest concentrations of aminocyclopyrachlor resulted in 100% mortality. All other herbicide treatments resulted in 56% to 89% mortality and were not different from one another. However, the lowest concentration of aminopyralid, imazamox, and the lowest concentration of triclopyr acid all resulted in mortality significantly lower than 100% (Table 4).

Overall, these cut stump data indicate that aminocyclopyrachlor applied at 24 g L^{-1} provided 100% mortality across both sites, while 12 g L^{-1} was 90% and 100% effective at LMU21 and CX36, respectively. We observed efficacy break points where mortality was significantly less than 100% for aminopyralid (6 g L^{-1}) and triclopyr acid (86 g L^{-1}) on the larger trees at CX36. However, these studies also indicate most herbicides and concentrations tested performed comparably to the commercial standard of triclopyr amine at 90 and 180 g L^{-1}. Additionally, aminocyclopyrachlor and aminopyralid could be applied at much lower use rates, with both reducing herbicide use by at least 73% without substantially altering herbicide costs.

Again, comparable data on this and other species are lacking for triclopyr acid. However, recent studies indicated cut stump applications with aminocyclopyrachlor were highly effective on Russian olive (*Elaeagnus angustifolia* L.) (Edwards 2011). Enloe et al. (2015) found cut stump application of imazamox at 30 and 60 g L^{-1} to *T. sebifera* resulted in 30% or lower mortality, while aminopyralid at 24 g L^{-1} resulted in 68% mortality with December applications.

One important sidebar we observed in our cut stump studies was the phenomenon of fallen trunks rooting and resprouting. At CX36, we observed rooting from the cut stems that were in contact with soil in 8 out of the 108 trees (7.4%). Although not quantified further, we suspect this rooting may be a response to higher surface soil moisture (Puri and Thompson 2003) under the canopy of the larger trees. While relatively low, this equates to significant retreatment on a per-hectare basis. While this has been observed for many herbaceous species and vines, reports of large woody stems possessing this type of meristematic activity are more limited for invasive species in Florida.

Finally, one question we did not address in the current research was whether cut stump or basal bark treatments provided better control of *S. terebinthifolia* than the other in general. These studies were independently conducted and were temporally separated by approximately 1 mo for each experimental run. Additionally, application volume per experimental unit was approximately 3.6 times greater for basal bark compared with cut stump treatment, and this limits our ability to directly compare techniques even within herbicides applied at the same concentration. However, our data indicate both techniques were generally effective for most herbicides tested.

Here, we show adequate performance of new herbicide active ingredients, expanding potential options for controlling *S. terebinthifolia* with conventional IPT techniques. We also demonstrate these new active ingredients can be effective at lower concentrations than commercial standards, potentially reducing herbicide load in the environment.

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