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Minimizing off-target herbicide movement using novel application technology

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Drift is a point of contention with pesticide applications, causing the need to research application methods that provide consistent efficacy while minimizing off-target movement. Experiments were conducted to evaluate eight undiluted herbicides on invasive woody plants, Chinese tallow (*Triadica sebifera*) and Callery pear (*Pyrus calleryana*), when applied individual plant treatment (IPT) via hack-and-squirt. Applications of undiluted aminocyclopyrachlor or imazapyr at 1 ml per 7.6 cm of tree diameter at breast height (DBH) made in the spring provided superior control over other herbicides or application timings. CamelBak® hydration reservoirs were evaluated for storage durability with eight undiluted herbicides. A third study was conducted to assess droplet size and distribution of Roadside Inc.'s new sprayer head for driftable fines. All nozzles were evaluated in a wind tunnel and produced droplet sizes above the benchmark for driftable fines (≤150 µm). The spray head also distributed droplets effectively from 2-30 feet from spray origin.

DEDICATION

I would like to dedicate this thesis to my grandfather, Robert G. Quick. You not only pushed me to chase my dreams, but always had faith that I would be able to achieve them. Your influence on my life was greater than you could have ever known. I only wish you were here today to see this dream become reality.

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TAKING A HACK AT CHINESE TALLOW (*TRIADICA SEBIFERA*) AND CALLERY PEAR (*PYRUS CALLERYANA*): AN INDIVIDUAL PLANT TREATMENT (IPT) APPROACH FOR INVASIVE TREE SPECIES

Abstract

Chinese tallow (*Triadica sebifera*) and Callery pear (*Pyrus calleryana*) are invasive trees that pose a significant threat to pasture and rangeland throughout Mississippi. These trees quickly overtake pastures, natural areas, and rights of way and inhibit native trees from thriving in these ecosystems. The objectives of this study were to evaluate control from eight undiluted herbicides applied by hack-and-squirt to individual trees and assess impact to nearby native species to determine if selective control could be achieved with individual plant treatment (IPT) application method without injury to desirable native species.

Burden's Creek ATV Park (BCAP) (Collins, MS) and Andy Berry Farms (ABF) (Mendenhall, MS) provided site locations used to evaluate control of Chinese tallow and collateral damage on surrounding native species. TVA's Customer Service facility (TVA) (Starkville, MS) and roadside along Highway 45 (HWY45) (Verona, MS) were site locations used to assess control of Callery pear and respective native species injury. According to site land managers neither site was under a vegetation management plan and, therefore, all locations had overgrowth of the specific invasive tree species located at that site. Applications were made in winter, spring, summer, and fall by hack-and-squirt. A hatchet was used to make an incision

through the bark into the cambium layer of the tree at a rate of one hack per 7.6 cm of tree trunk diameter at breast height (DBH). Following this hack, either 0.5 or 1 ml of undiluted herbicide was applied into each incision via a Neogen Prima Tech® (Neogen Prima Tech, 277 Faison W McGowan Road, Kenansville, North Carolina, U.S.) 1-2 ml Adjustable Veterinary Dose Gun attached to a CamelBak® (CamelBak, 2000 South McDowell Suite 200 Petaluma, California, U.S.) hydration pack (Figure 1.1) designed by Dr. John D. Byrd.

Initial visual injury ratings were taken one month after treatment (MAT) for all seasons and locations. For Chinese tallow, aminocyclopyrachlor was the most efficacious treatment at an average of 95% visual control. However, at BCAP herbicides applied in winter, imazapyr provided superior control at 90% compared to aminocyclopyrachlor at 85%. For Callery pear, aminocyclopyrachlor applied in winter and summer provided the highest control at an average of 68%. For applications made in spring, imazapyr provided the highest control but was economically unacceptable due to a lot control level of ~36%.

Final ratings were taken the following fall prior to leaf abscission. For Chinese tallow, imazapyr and aminocyclopyrachlor provided the best control throughout seasons at >99% and 95% control, respectively, with spring the best application season to apply treatments. Final ratings of Callery pear showed varied results across seasons and locations, but the triethylamine salt of triclopyr showed acceptable results throughout all seasons at 70.9% control on average.

Introduction

Background

Pastures and rangeland make up over 27% of the world's land use with over 528 million of those acres within the United States borders alone (NRCS 2019). Grazing land constitutes the largest private lands category in the United States and is crucial to our national economy and industries. Within Mississippi, hay production is the fourth highest valued crop produced and has a $120 million dollar production value (NASS 2019). Areas such as these are essential to our country and state, making them important zones to preserve and keep in proper operating condition. For these reasons, many weed scientists have made it their life's work to protect these areas from invasive species, erosion, and other threats.

Invasive Species

Invasive species pose a serious threat to water quality, biodiversity, animal habitat, tree cover, and fire risk of natural ecosystems (Anonymous 2019). Biodiversity is negatively affected by invasive species because they often create a monoculture, whereas a healthy ecosystem typically consists of diverse herbs, shrubs, and trees. The invasion of non-native species cost the U.S. economy an estimated $120 billion annually through control efforts, loss in crop and livestock production, property value damage, and lowered export potentials (Pimentel et al. 2005). In addition to staggering economic statistics, invasive species have also contributed to the decline of an estimated 42% of U.S. endangered and threatened plant species (Anonymous 2016). Invasive species are frequently found along major travel corridors due to transportation from outside ecosystems via vehicle[1]. Meunier and Lavoie (2012) proved there is an increase in invasive species along roadsides as they observed increased smooth bedstraw (*Galium mollugo*) populations within 125 m of a paved road. Rauschert, et al. (2010) also showed this was true when researchers witnessed increased expansion and reproduction of Japanese stiltgrass (*Microstegium vimineum*) along roadsides when compared to disturbed and intact forests. These researchers verified Darlington's observation that *Plantago major* spread along European

[1] Personal communication with Gary Ervin, BIO 8990 (2018)

settlers' footpaths and around settlements; hence, Native Americans called the plant "the white man's foot" (Darlington 1847). The introduction of invasive plants into ecosystems of native species means control methods must be selective; weedy invasive plants should be removed without damage to adjacent native species. This is exemplified in a forest ecosystem infested with the woody invasive Chinese tallow (*Triadica sebifera*) and Callery pear (*Pyrus calleryana*). Many control methods for tallow or Callery pear adjacent desirable species such as oak (*Quercus* spp.) or hickory (*Carya* spp.) would result in negative overall effect. Due to the invasiveness of certain species, many states have cost-share or landowner programs to assist landowners with the control. Such programs exist in Mississippi for the grassy invasive cogongrass (*Imperata cylindrica*) and for the woody invasive Chinese tallow tree[2].

Chinese tallow (Triadica sebifera)

Chinese tallow (*Triadica sebifera*) was introduced to the United States in 1772 by Benjamin Franklin (founders.archive.gov letter to John Bartram) as a seed oil crop (Randall et al. 1996). Elliott (1824) stated this deciduous tree was completely naturalized along the coasts of South Carolina and Georgia. If the initial introduction occurred in 1772 as indicated by the letter from Franklin to Bartram, it took only 52 years for Chinese tallow tree to be widely distributed along the coasts of these two states. Today, you will commonly find it called "popcorn tree" and see it planted for its aesthetic properties, primarily bright fall foliage with contrasting white fruits and more recently as a nectar source for honey production.

Chinese tallow can reach 6 to 12 m in height and has smooth, simple leaves that grow in an alternate pattern (Elliott 1824). Yellow flowers are produced in the spring followed by the

[2] Personal communication with John D. Byrd

classic “popcorn” looking fruit in fall (Byrd 2018b). Chinese tallow is known to have extreme reproductive potential and the ability to produce upwards of 100,000 seed per mature tree annually (Peterson 2018). This plant causes significant ecosystem disturbance, readily displacing native species thus creating a monoculture that has negative effects on other plant and wildlife in the area (Peterson 2018). Toxic compounds primarily occur in foliage as both seed coating and seed oil is nontoxic (Burrows and Tyre 2013). Fruits are commonly spread by birds (Renne et al. 2000) but are toxic to ruminant animals (Russell et al. 1969). The fruit is also disseminated by water (Byrd 2018b), as shown by the ability of this plant to germinate in floodplains and other wet areas. If Chinese tallow becomes established, it is a very difficult plant to remove by known control methods, both mechanical and chemical (Jubinsky & Anderson 1996). For this reason, Chinese tallow has been labeled as a noxious weed in many southeastern states, including Mississippi. Cost share programs are in place in Mississippi to assist landowners with the control of this persistent and resilient tree.

Callery pear (Pyrus calleryana)

Callery pear (*Pyrus calleryana*) was introduced to the United States in 1917 by Frank N. Meyer in an attempt to control fire blight that was ravaging the common pear (*Pyrus communis*) throughout the western United States (Vincent 2005). This tree was selected by Meyer because it was found to be “nearly totally immune” to the fire blight in the United States and the hope was to use it to genetically modify the susceptible trees in the States (Meyer 1918). Even then, Meyer (1918) saw the tenacity of this species when he said,

> “One finds it growing under all sorts of conditions; one time on dry, sterile mountain slopes; then again with its roots in standing water at the edge of a pond; sometimes in

open pine forest, then again among scrub on blue-stone ledges in the burning sun (p. 41)."

Even with a plethora of samples, gathering seed proved to be a difficult and slow process due to samples being small and producing little individual fruit.

Once introduced to the United States in 1917, work began immediately both in Oregon at a research station and Maryland at the USDA Plant Introduction Station to analyze fire blight resistance and scion-rootstock compatibility (Culley & Hardiman 2007). During these studies, *Pyrus calleryana* was again found to be tolerant of many adverse growing conditions. This hardiness trait was later utilized in more rootstocks than just the original fire blight cases.

Callery pear grows upwards of 15 m in height and can cover an area of 12 m in diameter. This species experiences rapid growth, and some variants have upright branches that can easily split and break in strong rains or winds (Byrd 2019). *Pyrus calleryana* also produces sharp thorns that can be upwards of five inches in length. These thorns are difficult to remove and pose a serious threat to people and equipment. Flowering occurs in the early spring and leaves the tree covered in beautiful white flowers that are approximately 2.5 cm diameter. Seeds require stratification, but after that requirement is fulfilled will germinate in many environmental conditions. This tree is not currently listed as a noxious weed in Mississippi but remains quick to spread and difficult to control.

Hack-and-Squirt

Hack-and-squirt, or frill herbicide application have been utilized for many decades to selectively control undesirable woody species. Whitten (1941) used a chemical application method initially reported by Lantz (1938) and published by Craighead and St. George (1938) to introduce chemicals directly into sapwood to kill elm (*Ulmus* spp.) trees in an attempt to stop the spread of Dutch elm disease (*Ceratostomella ulmi*) vectors. Hack-and-squirt application is a modification of that technique as well utilizing different herbicides as compared to Whitten's work.

In contrast to broadcast and other foliar spray applications, hack-and-squirt (frill) applications have minimal potential for drift onto adjacent sites. Herbicide is directly injected into the tree so it never breaks into droplets and only has a short distance to travel, both of which are important parameters when mitigating off-target movement (McWhorter & Gebhardt 1987). This application method is commonly used on forestry and rights-of-way applications to control individual woody plants because it allows for precise placement of active ingredients with minimal potential to impact desirable woody plants within close proximity. Cuts are made through the bark around the circumference of the plant to expose the cambium layer, then herbicides are applied directly into the cut. Since the volume of applied herbicide is small, typically 0.5 to 1 ml per incision, and distance between herbicide release and the target is a few centimeters, physical off-target movement of herbicide is almost impossible. While this application method is more environmentally friendly than foliar sprays, it is also more labor intensive and is usually impractical for herbaceous plant applications.

Other benefits of hack-and-squirt application methods compared to other application methods include reduced herbicide costs compared to basal bark, foliar, or other treatments. Many herbicides are applied at 0.5 to 1 ml of undiluted product or as a 1:1 v/v ratio of herbicide and water per incision with incisions made continuously or up to every 10 cm of stem diameter at breast height (DBH), depending on label instructions (Albritton 2011; Byrd 2018). Hack-and-squirt applications require a hatchet or similar device to make an incision, herbicide, and tool to apply the herbicide in the opening. While Kochenderfer et al. (2012) considered hack-and-squirt to be one of the cheapest manual application methods, labor costs can be high if target stem density is high. Contractor costs can range from $60 to $150 acre (Self 2016). A second benefit that is difficult to document is the monetary value of reduced environmental impact by precise herbicide placement. Properly made incisions into the bark produce a cup that hold the herbicide and prevent movement onto the ground (Jackson and Finley 2011). This minimizes the potential to damage desirable species and keeps the herbicide applied on the targeted woody plant. Herbicide retention in the cut allows full absorption and prevents contamination on the ground that could have an adverse impact on other species in the area allowing for a more environmentally friendly application than basal bark or foliar applications.

Technology

There has been an increase in the use of technology for hack-and-squirt over the last few decades. Not only have the herbicides used for hack-and-squirt improved, but methods of application have also improved. One of these improvements is the HypoHatchet® Tree Injector (Forestry Suppliers Inc., 205 W Rankin St., Jackson, MS). This hatchet is designed to dispense herbicide simultaneously as the incision is made. Downsides to the HypoHatchet® are the price (~$450) and the frequency of cleaning required for proper operation (Byrd 2018; Forestry Suppliers 2008). A second improvement involves the device used to carry the herbicide during application. For years, herbicide was put into inexpensive plastic squirt bottles or applied with syringes. Squirt bottles may become inoperable quickly when used with the solvents found in certain herbicide formulations. Syringes are messy to fill and cumbersome to carry into the field. An alternative concept to transport herbicide evaluated as part of this research is the hydration backpack. A line-fill livestock vaccinator will be attached to dispense herbicide into incisions (Byrd 2018; Enloe 2016b). This combination facilitates transportation, is readily available through online retail outlets, convenient to use and low cost-while also accurate. This method should increase efficiency of the hack-and-squirt applications.

Research

Studies to document effectiveness of frill herbicide application are not as prevalent as other application method studies and most of the existing frill studies focus on the effectiveness of frill application as compared to basal bark treatment. The second most common types of studies focus on effectiveness of active ingredients on specific noxious species. This section of the literature review will show and discuss different studies that have been conducted looking at some of the parameters listed above.

Hack-and-Squirt vs. other Application Methods

Other methods of woody vegetation control such as basal bark treatment and tree injection are commonly compared to frill to examine effectiveness for selective control of non-desirable species. These studies utilize different methods of application on the same species of woody vegetation to accurately show how each affects the ability of an active ingredient to control the woody vegetation. In one study, Bowker and Stringer (2011) looked at three methods of herbicide application to control tree of heaven (*Ailanthus altissima*). The three application methods evaluated were tree injection (EZ-Ject lance and Jim-Gem tree injector), basal bark spray, and hack-and-squirt. Bowker and Stringer (2011) hoped to determine the method of application best suited for control. They also paired different active ingredients to specific application methods depending on which were most effective for that active ingredient. Several treatment combinations were evaluated in the study: (1) EZ-Ject system with glyphosate capsules, (2) full basal bark application of 25% triclopyr ester with 75% non-polar carrier mixture, (3) hack-and-squirt 1 ml undiluted Pathway (premix 20.9% amine salt of triclopyr + 5.4% amine salt of picloram), (4) tree injector with 1 ml undiluted Accord (isopropylamine salt of glyphosate 53.6%), and (5) hack-and-squirt 1 ml undiluted Accord (Bowker and Stringer 2011). Ratings were taken 12 months after application of visual percent top dieback. Results showed that, on average, hack-and-squirt worked equal to or greater than the other treatment methods tested. This study supports research published by Piirto et al. (1996) that evaluated efficacy of triclopyr on tanoak (*Notholithocarpus densiflorus*) by cut-stump, frill, and basal-bark applications until one year after treatment. At the end of the research period, they concluded hack-and-squirt applications were superior to basal bark. On average, approximately 92% of trees treated by hack-and-squirt experienced some form of crown dieback, whereas trees treated with the basal bark method averaged approximately 35% control (Piirto et al. 1996). Studies by Lastinger and Enloe (2017) and Buddenhagen et al. (2004) compared application methods much like those referenced above. Results from these studies compare closely with Bowker and Stringer (2011) and Piirto et al. (1996). All four plant species evaluated in Lastinger and Enloe's (2017) experiment exhibited 100% defoliation when treated by hack-and-squirt, whereas only certain species resulted in 100% defoliation when treated by basal bark. After conducting their experiment, Lastinger and Enloe (2017) concluded hack-and-squirt applications are a viable alternative to both basal bark and cut stump application. Buddenhagen et al. (2004) found similar results when hack-and-squirt was compared to basal bark application methods on red quinine (*Cinchoma pubescens*). In their study, they found the most effective control was obtained with a mixture of picloram and metsulfuron applied by hack-and-squirt (Buddenhagen et al. 2004). Overall, all studies that compare the percent control of different application methods show that hack-and-squirt is one of, if not the best method of herbicide application for selective woody vegetation control.

Herbicide Studies

A different approach to hack-and-squirt evaluation is an examination of the effects of different herbicides applied by the same method to the same species. Gresham (2005) evaluated percent defoliation of triclopyr, glyphosate, and imazapyr on Chinese tallow tree in Georgetown County, South Carolina through one year after application He concluded imazapyr was the most effective herbicide for defoliation of Chinese tallow (Gresham 2005).

Application Timing Studies

A third approach to hack-and-squirt evaluation involves time of application. Currently, hack-and-squirt applications are recommended for late fall or early winter treatments for woody species (Self 2016). In 2003, Bruhn et al. looked at multiple hack-and-squirt application factors, one of which was time of year (season) of application for efficacy of white (*Quercus alba*), northern red (*Q. rubra*), and black (*Q. velutina*) oaks. For this study, application timings were autumn, winter, and summer. Bruhn et al. (2003) looked at how timings of the application affected control of the three species of oaks. Authors of this study reported application date had little effect on the percentage of crown dieback or foliage transparency. They did find slight differences in the percentage of live roots depending on application timing (Bruhn et al. 2003). Overall, there have been few published studies that evaluated the hack-and-squirt application. As more hack-and-squirt research published, individuals will continue to find it is a viable alternative to methods such as cut stump and basal bark — providing better control while remaining more environmentally friendly.

Materials and Methods

Chinese tallow (*Triadica sebifera*)

An environmentally safe approach to control Chinese tallow was established at two locations in southern Mississippi during the winter of 2019. The first experimental site was located approximately three miles north of Collins, Mississippi at the Burden's Creek ATV Park (BCAP) (31.684801, -89.596778) while the second was located in a pasture at Andy Berry Farms (ABF) (31.752059, -89.859570) roughly sixteen miles south of Mendenhall, Mississippi. BCAP consisted of both Boswell and Savannah soils along with a heavy Myatt Silt Loam, whereas ABF had a Bibbs and Mantachie soil, all of which were prone to frequent flooding and consistently wet conditions. Both areas contained profuse stands of Chinese tallow ranging in size from seedling to mature tree. Areas for treatment were selected based off an average tree size of 4-5" diameter at breast height (DBH) and a dense enough population to allow for a full study to be contained within an area of approximately .1 hectares (Figure 1.2).

Each treatment was applied to blocks of ten trees, and this was replicated four times in a randomized complete block (RCB) design, providing a total of forty trees for each of the nine treatments (eight herbicide treatments plus untreated control, described below) and 360 trees total per seasonal application. Trees were marked with alternating paint colors to allow for quick differentiation between herbicide treatments. Application was done to both locations at the same time per season to keep all control ratings on the same date. Throughout the study, it took approximately two- and one-half hours to treat a total of 360 trees for each season.

Callery pear (*Pyrus calleryana*)

Field studies were conducted at two locations to evaluate herbicides on control of Callery pear (*Pyrus calleryana*). The initial site was located on the property of the Tennessee Valley

Association Customer Service Center (TVA) (33.468550, -88.795488) adjacent the Mississippi State University Thad Cochran Research, Technology, and Economic Development Park. The second site was located approximately ten miles south of Tupelo on the east side of highway 45 (HWY45) (34.142115, -88.701674) along the Mississippi Department Of Transportation (MDOT) managed right-of-way. The TVA site had both Kipling silty clay loam and Oktibbeha soils, whereas HWY45 consisted of Ora and Prentiss fine sandy loams. Neither location saw flooding nor excessively wet conditions. Both locations had an abundant number of Callery pear that were easily accessible for treatment. Since Callery pear frequently develops multiple trunks rather than one straight trunk, diameter at breast height was determined as the cumulative sum of diameters of all stems at breast height and the number of hacks applied to each stem based on its diameter. For this reason, Callery pear specimens were significantly larger than Chinese tallow and required, on average, more hacks per specimen.

Each treatment was applied to blocks of one tree and was replicated four times in a randomized complete block (RCB) design providing for a total of four trees per treatment and 36 trees per seasonal study. Trees were marked with both paint and metal tree tags (Forestry Suppliers Inc., 205 W Rankin St., Jackson, MS). The paint allowed for seasonal applications to be differentiated whereas tags marked the herbicide treatment and seasonal application timing for each respective tree.

Treatments

Peer reviewed published research focused on control of Chinese tallow and Callery pear is sparce. Eight herbicides and a no herbicide control were evaluated in these studies designed to be applied over four seasons and evaluated for two years. Treatments included (i) isopropylamine salt of imazapyr (Polaris AC Complete, .48 kg l^{-1} ae) at 1 ml per hack, (ii) isopropylamine salt of glyphosate (Roundup PRO, .44 kg l^{-1} ae) at 1 ml per hack, (iii) dimethylamine salt of glyphosate (Accord XRT II, .48 kg l^{-1} ae) at 1 ml per hack, (iv) triethylamine salt of triclopyr (Garlon 3A, .36 kg l^{-1} ae) at 1 ml per hack, (v) butoxyethyl ester of triclopyr (Garlon 4, .48 kg l^{-1} ae) at 1 ml per hack, (vi) choline salt of triclopyr (Vastlan, .48 kg l^{-1} ae) at 0.5 ml per hack, (vii) acid of triclopyr (Trycera, .34 kg l^{-1} ae) at 0.5 ml per hack, (viii) potassium salt of aminocyclopyrachlor (Method 240SL, .24 kg l^{-1} ae) at 1 ml per hack, and (ix) hack alone with no herbicide as a negative control (Table 1.1).

A 30.5 cm long hatchet was used to expose the cambium layer for herbicide exposure at a rate of one hack per 7.6 cm DBH. Herbicides were dispensed from a CamelBak® (CamelBak, 2000 South McDowell Suite 200 Petaluma, California, U.S.) Hydration Backpack plumbed with a Neogen Primo Tech (Neogen Corporation, 944 Nandino Blvd, Lexington, KY 40511) 1-2 ml adjustable line-fill vaccine dose gun which was developed to dispense livestock medicine[3]. This system was used to dispense accurate rates of herbicide quickly and directly to the cambium layer after the hack was made. One application of herbicide was made per hack

Both locations were treated at the same time each season to allow for consistent rating dates. Application timings for both species were made winter (3/1/19-3/18/19), spring (5/8/19-5/24/19), summer (7/9/19-7/26/19), and fall (11/25/19-12/18/19) based off the calendar dates for each season. Visual control ratings were taken at one, six, and twelve months after treatment when leaves were present. Twig break was evaluated for Callery pear during the winter but proved to be an inaccurate method to rate tree injury as data did not correspond with fall or spring visual injury ratings. The final visual rating was taken fall of 2020 before leaf abscission.

[3] John D. Byrd, Mississippi State University Extension Publication 3276

SAS 9.4 (2008) was used to analyze for variance, then determine if there were significant differences between locations, seasons, treatments, or two- and three-way interactions. Significant differences were detected for three-way interaction of location by treatment by season, therefore, data were separated by location and season for analysis of monthly rating timing with PROC GLM to present each treatment and season independently. Means were separated with Fisher's LSD test with an observed significance level of P=0.05.

Results and Discussion

Chinese tallow (*Triadica sebifera*)

Analysis of Chinese tallow injury by PROC GLM revealed differences ($P < 0.0383$) between study locations for the first-year control practices with BCAP averaging 7% more control when compared to ABF; for this reason, data are presented by location. This difference in control could be explained by a smaller average diameter at BCAP (Table 1.2). Herbicide treatments visually evaluated one month after treatment revealed spring herbicide application increased Chinese tallow injury an average of 21% more than other seasonal applications. This contradicts with general guidelines found in the Weed Control Guidelines for Mississippi (2020) and previous hack-and-squirt research (Self 2016) which both state that late summer through early winter is the ideal time period for individual woody plant frill or hack and squirt applications. This contrast could be at least partly explained by the species of tree being treated. However, when evaluated at 12 MAT, spring herbicide application still provided a significant ($P < 0.0230$) increase in overall injury to Chinese tallow across all herbicides when compared with other seasons. These data would show that Chinese tallow is more susceptible to spring applications regardless of average tree diameter (Table 1.3). While control from treatments applied in spring was greatest, the order of overall treatment efficacy was followed by summer, winter, and fall, respectively (Table 1.4). These data could potentially show that Chinese tallow is most susceptible to herbicidal injury via hack-and-squirt when the tree is in the initial leaf expansion stage following winter dormancy.

Chinese tallow at Burden's Creek ATV Park

One Month after Treatment

Observations 1 MAT indicated aminocyclopyrachlor provided rapid and effective control of Chinese tallow at 94% when averaged across all application timings. Injury ratings in the study varied 1 MAT with herbicide control appearing somewhat sporadic. This was likely caused by certain herbicides working faster than others. Effective herbicide treatments for winter included: imazapyr and dimethylamine salt of glyphosate both with 90% control, aminocyclopyrachlor 85% control, and isopropylamine salt of glyphosate 80% control. All other herbicides provided 5% control or less. Spring applications of aminocyclopyrachlor provided 100% control, triethylamine and choline salts of triclopyr both gave 93% control while dimethylamine salt of glyphosate only provided 23% control. Summertime applications revealed that only aminocyclopyrachlor provided adequate (98%) control of Chinese tallow 1 MAT. Surprisingly, imazapyr offered the least control during summertime applications at 5% control. (Table 1.5). Fall crown dieback ratings were not able to be analyzed 1 MAT due to no foliage bring present on the tree at the rating timing.

Twelve Months after Treatment

Data from 12 MAT showed no significant ($P < 0.3932$) relationship between season and treatment, meaning that herbicide rankings remained mostly consistent across all seasons although level of control varied. This would show that application timing effects level of control seen by herbicides but does not change the order of effectiveness of the herbicides examined. Imazapyr provided the best overall control of Chinese tallow 12 MAT with an average seasonal control of 99% (Table 1.6). Other herbicides that provided sufficient control were aminocyclopyrachlor with 93% control and the choline salt of triclopyr with 87% control. The dimethylamine salt of glyphosate provided insufficient control through all seasons 12MAT with an average of 45% control.

Chinese tallow at Andy Berry Farms

One Month after Treatment

Data from Any Berry Farms also showed that the best overall herbicide at 1 MAT was aminocyclopyrachlor with 93% control when averaged across all seasons. This remains consistent with the Burden Creek's ATV Park (BCAP) data. Generally, herbicides at ABF were much slower to control Chinese tallow when compared with BCAP. This could be caused by a slight visual increase in tree DBH at ABF versus BCAP. For the winter application timing, aminocyclopyrachlor and the dimethylamine salt of glyphosate provided 78% and 77% control, respectively. Aminocyclopyrachlor provided 100% control and the choline salt of triclopyr provided 83% control one month after spring treatment. Only aminocyclopyrachlor provided sufficient control for the summer application timing at 100% control. The butoxyethyl ester of triclopyr consistently provided insufficient control throughout all seasons 1MAT (Table 1.7). Once again, fall crown dieback ratings were not possible due to no foliage being present at rating time.

Twelve Months after Treatment

At twelve months after treatment, no interaction (P = 0.4020) was found between season and treatment. This again means that herbicide rankings remained somewhat consistent throughout all seasonal application timings. For this reason, the herbicides with the most control will not be broken down by season as in the 1 MAT results but will be given on an overall basis across all seasons. Imazapyr and aminocyclopyrachlor both provided 100% control across all seasons. The dimethylamine salt of glyphosate was a weak herbicide throughout all seasons providing minimal control of Chinese tallow. For fall applications, the isopropylamine salt of glyphosate only provided 10% control (Table 1.8).

Callery pear (*Pyrus calleryana*)

Overall, control results on Callery pear (*Pyrus calleryana*) varied greatly when compared to Chinese tallow. Lower control numbers were seen, and herbicide activity was somewhat sporadic. This could be due to the differences in physiology between the two species, but also is more than likely due to size differences between the species treated (Table 1.2). Most treated Chinese tallow consisted of one main stem with an average diameter of three inches, whereas most Callery pear divided into several main stems by eighteen inches from ground level. For this reason, the number of main stems at breast height was recorded, then these stems were measured and added together to form a cumulative DBH for the tree. This DBH was then used to calculate amount of herbicide applied.

Differences (P = .0126) between study locations were found when an analysis of Callery pear injury was conducted with PROC GLM (Table 1.2). Because of this, locations were then analyzed individually and will be discussed separately. Analysis of application timing indicated that a fall application provided the highest level of control for both locations with an average of

23% more control than the second highest seasonal application timing (Table 1.9). This could likely be caused by statistically smaller trees being treated during the fall application timing (Table 1.3). However, superior fall control is also seen in an application timing study conducted by Self (2016). The differences between Chinese tallow and Callery pear susceptibility to herbicide application could be explained by differences in physiology and growth rates between the two species.

Callery pear at Tennessee Valley Authority

One Month after Treatment

Observations from the TVA location show that there was no "best" overall herbicide throughout the seasons 1 MAT. For the winter application timing, herbicides that showed statistically higher control included aminocyclopyrachlor, isopropylamine salt of glyphosate, triethylamine salt of triclopyr, imazapyr, dimethylamine salt of glyphosate, and choline salt of triclopyr. Although there was no statistical separation between these herbicides, aminocyclopyrachlor had the highest numerical control at 80%. Herbicides that provided higher control for spring application were imazapyr, isopropylamine salt of glyphosate, triethylamine salt of triclopyr, acid of triclopyr, and choline salt of triclopyr. Imazapyr had the highest percentage of control at 34%. Aminocyclopyrachlor, butoxyethyl ester of triclopyr, and dimethylamine salt of glyphosate all offered <15% control 1 month after spring treatment. Summer application timing showed that aminocyclopyrachlor and triethylamine salt of triclopyr provided the best control at 49% and 45%, respectively while both glyphosate formulations provided 5% or less control (Table 1.10). Overall, at the TVA location the fall application timing saw an average herbicide control of 71% compared to winter, spring, and summer with 47%, 45%, and 37% overall control, respectively.

Twelve Months after Treatment

Control data from 12 MAT showed an interaction (P = 0.0002) between season and treatment confirming the inconsistent control data for Callery pear mentioned previously. For this reason, each application timing will be discussed individually to show herbicides that provided better control. For the winter timing, aminocyclopyrachlor and choline salt of triclopyr provided the best control with 100% and 87% control, respectively. The acid of triclopyr, imazapyr, butoxyethyl ester of triclopyr, and aminocyclopyrachlor provided better control than other herbicides and the untreated following the spring application timing. The summer application timing showed triethylamine salt of triclopyr, aminocyclopyrachlor, and imazapyr provide the highest control with an average of 68% control. For the fall application timing, it was found that all herbicides except for butoxyethyl ester of triclopyr and the untreated provided sufficient control results with aminocyclopyrachlor providing the highest numerical control at 95%. Both glyphosate formulations provided insufficient control throughout the winter, spring, and summer application timings (Table 1.11).

Callery pear on Highway 45N

One Month after Treatment

No herbicide could be labeled “best” for all seasons 1 MAT at the HWY45 location. The winter application timing showed that aminocyclopyrachlor, triethylamine salt of triclopyr and imazapyr were the more effective herbicides with a control of 76%, 71%, and 70% control, respectively. Imazapyr, aminocyclopyrachlor, and choline salt of triclopyr provided the highest numerical control of Callery pear following a spring application timing yet only averaged 38% control. Potassium salt of aminocyclopyrachlor provided the best control for the summer application timing with 65% control 1 MAT, whereas imazapyr only offered 9% control (Table

1.12). No ratings were taken 1 MAT for the fall application timing due to no foliage being present.

Twelve Months after Treatment

An interaction (P = 0.0314) existed between season and treatment for the 12 MAT data from the HWY45 location. Because of this, herbicide control percentages for application timings will be discussed individually. Triethylamine salt of triclopyr provided the best results for the winter application timing with an overall control of 90%. Both the dimethylamine and isopropylamine salts of glyphosate provided <15% control. Aminocyclopyrachlor, triethylamine salt of triclopyr, and imazapyr provided the highest numerical control for the spring application timing with 75%, 68%, and 61% control, respectively. The summer application timing revealed three herbicides that provided numerically higher control: aminocyclopyrachlor (85%), triethylamine salt of triclopyr (83%), and butoxyethyl ester of triclopyr (88%). As stated earlier, the fall application timing yielded the highest overall control when compared to other treatment timings. This was shown when all herbicides were found to provide sufficient control when compared to the negative control (Table 1.13). The three herbicides that provided the highest numerical control were imazapyr, aminocyclopyrachlor, and butoxyethyl ester of triclopyr all with 98% control.

For those who seek control methods for both species, these data suggest that, overall, imazapyr and aminocyclopyrachlor provide sufficient control throughout most seasonal application timings. Chinese tallow is more susceptible to applied herbicides when applications are made during the spring. Overall, Callery pear remains the more difficult species to control, and efficacy of applied herbicides varied by application timing with the fall application providing the highest overall control. Herbicides applied to Callery pear also provided slower control when compared to the same treatments on Chinese tallow. Both these control variations are likely due to physiological differences between the two species and the increased size of the Callery pear trees compared to Chinese tallow. Applied herbicides were found to cause no damage to adjacent hardwood species, allowing for a control method that can be utilized by growers that are struggling with controlling invasive species intermixed with desirable native hardwoods. These data show that hack-and-squirt is a feasible application method that provides sufficient selective control of invasive species, while allowing for an economical and environmentally friendly application process.

Table 1.1 Herbicide manufacturer, rates, and formulations applied in field experiments on Chinese tallow and Callery pear.

Postemergence Herbicides				
Common name	**Trade name**	**Product Rate**	**Manufacturer**	**City, State**
isopropylamine salt of imazapyr	Polaris AC Complete	1 ml/incision	NuFarm	Melbourne, Australia
isopropylamine salt of glyphosate	Roundup PRO	1 ml/incision	Monsanto	St. Louis, MO
dimethylamine salt of glyphosate	Accord XRT II	1 ml/incision	Dow AgroSciences	Indianapolis, IN
triethylamine salt of triclopyr	Garlon 3A	1 ml/incision	Dow AgroSciences	Indianapolis, IN
butoxyethyl ester of triclopyr	Garlon 4	1 ml/incision	Dow AgroSciences	Indianapolis, IN
choline salt of triclopyr	Vastlan	0.5 ml/incision	Dow AgroSciences	Indianapolis, IN
potassium salt of aminocyclopyrachlor	Method 240SL	1 ml/incision	Bayer	Leverkusen, Germany
acid of triclopyr	Trycera	0.5 ml/incision	Helena	Collierville, TN

Table 1.2 Average diameter and visual control by location for Chinese tallow (*Triadica sebifera*) and Callery pear (*Pyrus calleryana*). Due to location by treatment interaction data presented by location for each species.

Species	Location	Average diameter[1]	Average control[1]
Chinese tallow	BCAP	3.31 b	69.03 a
Chinese tallow	ABF	3.63 a	61.04 b
Callery pear	TVA	9.2 a	50.26 b
Callery pear	HWY45	8.8 a	57.61 a

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.3 Average diameter of treated trees by species and season. Each species is compared individually. Fall season had statistically smaller trees for each species.

Species	Season	Average diameter
Chinese tallow	Winter	3.59 a
Chinese tallow	Spring	3.49 a
Chinese tallow	Summer	3.52 a
Chinese tallow	Fall	3.29 b
Callery pear	Winter	10.36 a
Callery pear	Spring	11.25 a
Callery pear	Summer	10.34 a
Callery pear	Fall	4.04 b

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.4 Seasonal visual response to herbicide application for Chinese tallow (*Triadica sebifera*) at 12 months after treatment (MAT) averaged across treatments.

Season	% Overall Chinese tallow control 12 MAT[1]
spring	81 a
summer	68 b
winter	56 c
fall	55 c

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.5 Chinese tallow (*Triadica sebifera*) visual response 1 month after treatment to herbicides applied seasonally at Burden's Creek ATV Park in Collins, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer
		----% Chinese tallow control[1]----		
isopropylamine salt of imazapyr	1	90 a	45 bc	5 d
isopropylamine salt of glyphosate	1	80 a	33 cd	13 d
dimethylamine salt of glyphosate	1	90 a	23 d	10 d
triethylamine salt of triclopyr	1	2.5 b	93 a	55 bc
butoxyethyl ester of triclopyr	1	2.5 b	33 cd	43 c
choline salt of triclopyr	0.5	0 b	93 a	68 b
potassium salt of aminocyclopyrachlor	1	85 a	100 a	98 a
acid of triclopyr	0.5	5 b	65 b	60 b
negative control	hack only	0 b	0 e	0 d

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.6 Chinese tallow (*Triadica sebifera*) visual response 12 months after treatment to herbicides applied seasonally at Burden's Creek ATV Park in Collins, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer	Fall
		----------% Chinese tallow control[1]----------			
isopropylamine salt of imazapyr	1	100 a	100 a	100 a	95 a
isopropylamine salt of glyphosate	1	78 a	85 ab	63 bc	65 a
dimethylamine salt of glyphosate	1	30 b	60 b	43 c	48 ab
triethylamine salt of triclopyr	1	53 ab	88 ab	90 ab	58 ab
butoxyethyl ester of triclopyr	1	43 ab	98 a	93 ab	80 a
choline salt of triclopyr	0.5	75 ab	100 a	95 ab	78 a
potassium salt of aminocyclopyrachlor	1	60 ab	100 a	100 a	100 a
acid of triclopyr	0.5	25 b	90 ab	100 a	48 ab
negative control	hack only	50 ab	0 c	0 d	0 b

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.7 Chinese tallow (*Triadica sebifera*) visual response 1 month after treatment to herbicides applied seasonally at Andy Berry Farms near Mendenhall, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer
		------% Chinese tallow control[1]------		
isopropylamine salt of imazapyr	1	53 c	50 c	23 c
isopropylamine salt of glyphosate	1	58 bc	28 d	5 d
dimethylamine salt of glyphosate	1	77 ab	20 d	5 d
triethylamine salt of triclopyr	1	2.5 d	78 b	60 b
butoxyethyl ester of triclopyr	1	10 d	30 d	23 c
choline salt of triclopyr	0.5	11 d	83 ab	30 c
potassium salt of aminocyclopyrachlor	1	78 a	100 a	100 a
acid of triclopyr	0.5	5 d	33 cd	25 c
negative control	hack only	8 d	0 e	5 d

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.8 Chinese tallow (*Triadica* sebifera) visual response to herbicides 12 months after treatment applied seasonally at Andy Berry Farms near Mendenhall, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer	Fall
		----------% Chinese tallow control[1]----------			
isopropylamine salt of imazapyr	1	100 a	100 a	100 a	100 a
isopropylamine salt of glyphosate	1	63 ab	100 a	40 bc	20 de
dimethylamine salt of glyphosate	1	60 ab	75 a	38 bc	25 cd
triethylamine salt of triclopyr	1	35 bc	93 a	73 ab	55 b
butoxyethyl ester of triclopyr	1	30 bc	90 a	63 ab	35 bc
choline salt of triclopyr	0.5	55 abc	100 a	73 ab	53 b
potassium salt of aminocyclopyrachlor	1	100 a	100 a	100 a	100 a
acid of triclopyr	0.5	60 ab	78 a	53 abc	50 b
negative control	hack only	0 c	0 b	0 c	0 e

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.9 Seasonal visual response to herbicide application for Callery pear (*Pyrus calleryana*) 12 months after treatment (MAT).

Season	% Overall Callery pear control 12MAT[1]
spring	46 b
summer	48 b
winter	43 b
fall	76 a

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.10 Callery pear (*Pyrus calleryana*) visual response 1 month after treatment to herbicides applied seasonally at TVA customer service center in Starkville, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer
		--------% Callery pear control[1]--------		
isopropylamine salt of imazapyr	1	68 a	34 a	15 cde
isopropylamine salt of glyphosate	1	73 a	21 abc	5 de
dimethylamine salt of glyphosate	1	59 ab	6 cd	3 e
triethylamine salt of triclopyr	1	73 a	20 abc	45 ab
butoxyethyl ester of triclopyr	1	33 c	11 bcd	21 cd
choline salt of triclopyr	0.5	70 a	24 ab	24 c
potassium salt of aminocyclopyrachlor	1	80 a	14 bcd	49 a
acid of triclopyr	0.5	36 bc	19 abc	31 bc
negative control	hack only	0 d	0 d	0 e

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.11 Callery pear (*Pyrus calleryana*) visual response 12 months after treatment to herbicides applied seasonally at TVA customer service center in Starkville, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer	Fall
		----------% Callery pear control[1]----------			
isopropylamine salt of imazapyr	1	50 bc	70 ab	61 ab	94 a
isopropylamine salt of glyphosate	1	28 cd	40 bcd	13 cd	69 ab
dimethylamine salt of glyphosate	1	42 c	23 de	16 cd	83 a
triethylamine salt of triclopyr	1	44 c	31 cde	81 a	89 a
butoxyethyl ester of triclopyr	1	60 bc	64 ab	31 c	49 b
choline salt of triclopyr	0.5	87 ab	43 bcd	35 bc	71 ab
potassium salt of aminocyclopyrachlor	1	100 a	59 abc	63 ab	95 a
acid of triclopyr	0.5	37 cd	75 a	34 bc	89 a
negative control	hack only	3 d	1 e	0 d	0 c

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.12 Callery pear (*Pyrus calleryana*) visual response 1 month after treatment to herbicides applied seasonally along highway 45 rights-of-ways near Verona, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer
		------% Callery pear control[1]------		
isopropylamine salt of imazapyr	1	70 a	40 a	9 cd
isopropylamine salt of glyphosate	1	48 ab	15 bcde	10 cd
dimethylamine salt of glyphosate	1	14 bc	23 abcd	44 ab
triethylamine salt of triclopyr	1	71 a	30 abc	46 ab
butoxyethyl ester of triclopyr	1	36 abc	14 cde	33 bc
choline salt of triclopyr	0.5	46 ab	38 a	50 ab
potassium salt of aminocyclopyrachlor	1	76 a	35 ab	65 a
acid of triclopyr	0.5	26 bc	6 de	54 ab
negative control	hack only	0 c	0 e	0 d

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Table 1.13 Callery pear (*Pyrus calleryana*) visual response 12 months after treatment to herbicides applied seasonally along highway 45 rights-of-ways near Verona, MS.

Herbicide	Product Rate (ml/incision)	Winter	Spring	Summer	Fall
		----------% Callery pear Control[1]----------			
isopropylamine salt of imazapyr	1	85 a	70 ab	61 ab	94 a
isopropylamine salt of glyphosate	1	76 a	40 bcd	13 cd	69 ab
dimethylamine salt of glyphosate	1	38 b	23 de	16 cd	83 a
triethylamine salt of triclopyr	1	81 a	31 cde	81 a	89 a
butoxyethyl ester of triclopyr	1	65 ab	64 ab	31 c	49 b
choline salt of triclopyr	0.5	80 a	43 bcd	35 bc	71 ab
potassium salt of aminocyclopyrachlor	1	86 a	59 abc	63 ab	95 a
acid of triclopyr	0.5	66 ab	75 a	34 bc	89 a
negative control	hack only	0 c	1 e	0 d	0 c

[1] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test at $P \leq 0.05$.

Figure 1.1	Camelbak® hydration reservoir paired with Neogen Prima Tech® 1-2 ml adjustable dose gun.

Camelbak® hydration pack designed by John D. Byrd and used for application of undiluted herbicides into the cambium layer of treated species. Picture from Mississippi State Extension publication P3276.

Figure 1.2 Winter treatment area at BCAP.

Winter treatment area at Burden’s Creek ATV Park showing density and size of Chinese tallow (*Triadica sebifera*) species.

Literature Cited

Albritton T (2011) A Poor Man's Way to Improve His Forest. Alabama's Treasured Forests Fall/Winter 2011: 1-2.

Anonymous (2016) Invasive Plants. USDA Forest Service. https://www.fs.fed.us/wildflowers/invasives/index.shtml. Accessed on March 29, 2019

Anonymous (2019) The Problem with Invasive Plants. City of Portland Environ Serv. https://www.portlandoregon.gov/bes/article/330681. Accessed: March 29, 2019

Bowker D, Stringer J (2011) Efficacy of Herbicide Treatments for Controlling Residual Sprouting of Tree-of-heaven. Proceedings from the 17th Central Hardwood Forest Conference: 128-133.

Bruhn JN, Wetteroff JJ, Haugen L (2003) Survival of Oak Root Systems Following Frill Girdle Herbicide Treatment for Oak Wilt Control. Proceedings from the 13th Central Hardwood Forest Conference: 544-550.

Buddenhagen CE, Renteria JL, Gardener M, Wilkinson SR, Soria M, Yánez P, Tye A, Valle R (2004) The Control of a Highly Invasive Tree Cinchona pubescens in Galapagos [1]. Weed Technol 18: 1194–1202.

Byrd, JD (2018a) Applying Herbicides with the Hack-and-Squirt Method. Mississippi State University Extension. Ext Pub P3276.

Byrd, JD (2018b) Chinese Tallowtree. Mississippi State University Extension. Ext Pub P3189.

Byrd, JD (2019) Callery pear. Mississippi State University Extension. Ext Pub P3316.

Craighead FC St. George RA (1938) Experimental work with the introduction of chemicals into the sap stream of trees for the control of insects. J Forestry 36:26-34.

Culley, TM, Hardiman, NA (2007) The Beginning of a New Invasive Plant: A History of the Ornamental Callery Pear in the United States. BioScience, 57(11), 956–964.

Elliott S (1824) A Sketch of the Botany of South-Carolina and Georgia in Two volumes. Volume 2. Charleston, SC: J.R. Schenck.

Enloe SF (2016) Let's Take a Hack at Hack and Squirt IPT. https://conference.ifas.ufl.edu/aw17/presentations/3%20Thurs%209B%20850am%20Enloe.pdf. Accessed: March 26, 2019

Gresham CA (2005) Efficacy of 'Hack and Squirt' Application of Imazapyr, Triclopyr, and Glyphosate to Control the Invasive Tree Species Chinese Tallowtree. Proceedings of the 14th Biennial South Silvicultural Res Conf: pp. 121-122.

Jackson D, & Finley JC (2019) Using Hack-and-Squirt Herbicide Applications to Control Unwanted Trees. PennState Extension Service. Ext Pub EE0262.

Jubinsky G, Anderson LC (1996) The Invasive Potential of Chinese Tallow-Tree (Sapium sebiferum Roxb.) in the Southeast. Castanea, 61(3), 226–231.

Kochenderfer JD, Kochenderfer JN, Miller GW (2012) Manual herbicide application methods for managing vegetation in Appalachian hardwood forests US DA Forest Service Northern Research Station. Gen Tech Rep NRS-96: 6-21.

Lantz AE (1938) An efficient method for introducing liquid chemicals into living trees. USDA Bur Ent and Quar E-434 4 p.

Lastinger CA, Enloe SF (2017) Changing the "Hack and Squirt" paradigm for woody invasive plant control. https://bugwoodcloud.org/CDN/fleppc/Symposia/2017/6-Lastinger_FLEPPC_PP_2017.pdf. Accessed: March 26, 2019

McWhorter CG, Gebhardt MR (1987) Methods of Applying Herbicides. Monograph series. Champaign, IL: Weed Science Society of America. Pp 305-306.

Meunier G and Lavoie C (2012) Roads as Corridors for Invasive Plant Species: New Evidence from Smooth Bedstraw (*Galium mollugo*). Inv Plant Sci and Manag 5: 92-100.

Meyer FN (1918) South China explorations: Typescript, July 25, 1916-September 21, 1918. http://archive.org/details/CAT10662165MeyerSouthChinaExplorations. Accessed: June 24, 2021.

Michael Vincent (2005). On the spread and current distribution of Pyrus Calleryana in the United States. Castanea, *70*(1), 20–31.

NASS (2019). Mississippi Crop Values. United Stated Department of Agriculture National Agricultural Statistics Service. Release Date: April 12, 2019.

NRCS (2019) Range and Pastureland Overview. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/landuse/rangepasture/?cid=nrcsdev11_001074 Accessed on July 15, 2021.

Piirto DD, Smith B, Huff EK, Robinson ST (1996) Efficacy of Herbicide Application Methods Used to Control Tanoak (*Lithocarpus densiflorus*) in an Uneven-Aged Coast Redwood Management Context. USDA For Ser Gen Tech Rep 160: 199-208.

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 53: 273-288.

Randall JM, Marinelli J, Garden BB (1996) Invasive Plants: Weeds of the Global Garden. Brooklyn, NY: Brooklyn Botanic Garden. Pp 24-45.

Rauschert E, Mortensen D, Bjornstad O, Nord A, Peskin N (2010) Slow Spread of the Aggressive Invader, *Microstegium vimineum* (Japanese stiltgrass). Bio Inv 12:563-579.

Self B. (2016) Tree Injection for Timber Stand Improvement. Mississippi State University Extension. Ext Pub 2942.

Whitten RR (1941) The Internal Application of Chemicals to Kill Elm Trees and Prevent Bark-Beetle Attack. USDA Cir 605. P 12.

CHAPTER II

LONG-TERM CAMELBAK® HYDRATION RESERVOIR DURABILITY WHEN EXPOSED TO UNDILUTED HERBICIDE AND THE ELEMENTS

Abstract

A nonheated, noncooled enclosed metal building at the R.R. Foil Plant Science Research Center (33.471008, -88.782063, Starkville, MS) was used to evaluate storage of herbicides in CamelBak® (CamelBak, 2000 South McDowell Suite 200 Petaluma, California, U.S.) hydration reservoirs. Four hundred seventy-three (473) ml of isopropylamine salt of imazapyr, isopropylamine and dimethylamine salts glyphosate, triethylamine and choline salts, butoxyethyl ester, and acid of triclopyr, and potassium salt of aminocyclopyrachlor were poured into separate reservoirs. Four replicated reservoirs were hung over 1.2 L Rubbermaid® (Rubbermaid, 1402 Adams Farm Pkwy Greensboro, North Carolina, U.S.) plastic storage containers.

Reservoirs were evaluated visually each month for the first six months, then again at 12 and 24 months after storage (MAS). At one month after storage some of the acid of triclopyr leaked from the reservoir into the Rubbermaid storage container. By 24 MAS, both the acid and butoxyethyl ester of triclopyr leaked into the Rubbermaid storage container from the CamelBak® hydration reservoir.

Introduction

To ensure ease of use and effectiveness of herbicide treatments, application equipment must be chosen based on the treatment site, weed species to be treated, and method of application

(Motooka et al. 1999). In the past, much research has focused on application equipment that ensured increased control while also providing ease of usage to the applicator. This focus, in many ways, has shifted in recent years to increased precision of herbicide placement so injury to surrounding desirable species in the environment is minimized (Ess et al. 2001). Herbicide application via hack-and-squirt (frill) allows for all three parameters to be met: effective control of targeted plants, ease of usage, and increased control of herbicide placement. Hack-and-squirt is a longstanding application method that is used to selectively control stems and undesirable woody species within an ecosystem, which has typically been woodlands (McWhorter & Gebhardt 1987), but has much broader sites of application.

There are many strengths to the use of hack-and-squirt as an application method. One of the most noted strengths would be the cost of treatments. Hack-and-squirt is known to be one of the least expensive manual application methods available for individual plant treatment (Jackson & Finley 2019). Researchers have calculated that hack-and-squirt enables trees to be treated at a cost of less than $0.02 of chemical per tree (Albritton 2011). A second strength is the ability to selectively control undesirable tree species that may be growing near desirable species of woody plants. When considering concern for off-target damage to nontarget vegetation, the enhanced ability to control herbicide placement is a strong positive (Fellers 2020). Thirdly, treatments can be applied at any time during the year although, treatment effectiveness can vary depending on the species treated (Ferrell et al. 2006).

Not all aspects of hack and squirt applications are positive, application of undiluted herbicides can be detrimental to the functionality of application equipment. Solvents in the herbicide formulations can deteriorate dispersal equipment that results in failure to function properly. Application tools such as the Hypo-Hatchet® (Forestry Suppliers, Inc., 205 West

Rankin Street Jackson, MS 39201) must be cleaned frequently to continue to function properly (Byrd 2018a). Secondly, hack-and-squirt requires a lot of time and/or manpower compared to other individual plant treatment methods. The time requirement is directly proportional to the number of stems per unit of area. Lastly, depending on the target tree species, certain seasons do not allow effective control when using this application method and rain events can flush the herbicide out of the hacks (Ferrell et al. 2006).

Other potential users of hack and squirt applications include livestock producers or any individual with property bounded by fencing. Unwanted vegetation often emerges along these fence lines by birds and mammals that deposit seed of these woody species. Therefore, inexpensive and effective equipment to hack and squirt sapling woody plants has much appeal to livestock producers that often need to store unused herbicide for continued workdays later.

This study was devised to create and test application tools to counter some of the disadvantages of hack-and-squirt. Readily available components were combined to create a device that facilitates precise applications made by hack-and-squirt that are less susceptible to malfunction of herbicide storage over time. A CamelBak® hydration reservoir was paired with a Neogen Prima Tech® (Neogen Corporation, 944 Nandino Blvd, Lexington, KY 40511) (Figure 1.1) 1-2 ml adjustable line fill vaccinator. This simple tool allowed for precise amounts of herbicide to be injected into each hack while also allowing the applicator to easily carry the undiluted herbicide on his back. The study objectives were to analyze the CamelBak® hydration reservoir for durability over time when filled with undiluted herbicides commonly used in hack-and-squirt applications to control woody vegetation.

Materials and Methods

In June 2019, four replications of nine Camelbak® hydration reservoirs were filled with 473 ml undiluted herbicide or water. A nonclimate controlled metal sided building at the R.R. Foil Plant Science Research Center provided space to conduct the long-term study. Reservoirs were supported by string directly above a er, 17.8 cm diameter plastic container (Rubbermaid) to catch leakage (Figure 2.1). The herbicides included in this study were: isopropylamine salts of imazapyr or glyphosate; dimethylamine salt of glyphosate; triethylamine or choline salts, butoxyethyl ester, and acid of triclopyr; and potassium salt of aminocyclopyrachlor (Table 2.1). A Fisher Scientific® (Fisher Scientific, 168 Third Avenue, Waltham, MA, U.S.) accumet pH meter 25 was used to measure all undiluted herbicides' pH.

Rubbermaid containers were examined for leakage monthly for the first six months, then at 12 and 24 months after filling. Containers that contained any leaked herbicide were ranked from most to least depending on the visual amount of herbicide that had leaked into the container.

Results and Discussion

Results were ranked visually from most leaked herbicide to least or no leaked herbicide. Of the herbicides evaluated, the butoxyethyl ester and acid formulations of triclopyr leaked out of the Camelbak® hydration reservoirs. The acid of triclopyr leaked sooner than the butoxyethyl ester with leakage initially observed one month after treatment. The butoxyethyl ester of triclopyr did not leak any herbicide at the 12 month after filling evaluation, but by 24 months after filling had leaked (Table 2.2). The acid of triclopyr also visually leaked more herbicide than the butoxyethyl ester. This leakage could be caused by the acidic pH of both the acid (2.33) and butoxyethyl ester (3.48) formulation of triclopyr. No leakage was visible in containers under reservoirs that contained other undiluted herbicides. The hydration reservoirs filled with the butoxyethyl ester of triclopyr appeared damaged and had a white crust that had developed on the exterior of the bag up to the herbicide fill line. None of the salt formulations of herbicides leaked in the study, only ester and acid formulations.

With this data, it can be concluded that long-term storage of undiluted herbicides in Camelbak® hydration reservoirs is feasible depending on herbicide formulation. This will allow growers to have an easily accessed application method that allows for easy application while also allowing for quick starts and stops to the application process.

Table 2.1 Herbicides used in the Camelbak® hydration pack study. Undiluted herbicide pH measured using Fisher Scientific® accumet pH meter 25.

Herbicide List				
Common name	**Trade name**	**pH**	**Manufacturer**	**City, State**
isopropylamine salt of imazapyr	Polaris AC Complete	6.93	NuFarm	Melbourne, Australia
isopropylamine salt of glyphosate	Roundup PRO	4.89	Monsanto	St. Louis, MO
dimethylamine salt of glyphosate	Accord XRT II	4.93	Dow AgroSciences	Indianapolis, IN
triethylamine salt of triclopyr	Garlon 3A	8.72	Dow AgroSciences	Indianapolis, IN
butoxyethyl ester of triclopyr	Garlon 4	3.48	Dow AgroSciences	Indianapolis, IN
choline salt of triclopyr	Vastlan	6.60	Dow Agrosciences	Indianapolis, IN
potassium salt of aminocyclopyrachlor	Method 240SL	7.15	Bayer	Leverkusen, Germany
acid of triclopyr	Trycera	2.33	Helena	Collierville, TN

Table 2.2 Visual leakage of Camelbak® hydration reservoirs filled with undiluted herbicide or water.

	Visual Leaking of Herbicide at Different Rating Timings[1]						
Herbicide	1 MAT	2 MAT	3 MAT	4 MAT	6 MAT	12 MAT	24 MAT
isopropylamine salt of imazapyr	no	no	no	no	no	no	no
isopropylamine salt of glyphosate	no	no	no	no	no	no	no
dimethylamine salt of glyphosate	no	no	no	no	no	no	no
triethylamine salt of triclopyr	no	no	no	no	no	no	no
butoxyethyl ester of triclopyr	no	no	no	no	no	no	**yes**
choline salt of triclopyr	no	no	no	no	no	no	no
potassium salt of aminocyclopyrachlor	no	no	no	no	no	no	no
acid of triclopyr	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**	**yes**
negative control	no	no	no	no	no	no	no

[1] All treatments marked with a **yes** had visual herbicide leakage at that specific rating timing.

Figure 2.1 Camelbak® hydration pack study.

Layout of the Camelbak® hydration reservoir durability test located at Mississippi State University's R.R. Foil Plant Science Research Center.

Literature Cited

Albritton T (2011) A Poor Man's Way to Improve His Forest. Alabama's Treasured Forests Fall/Winter 2011:1-2.

Byrd JD (2018a) Applying Herbicides with the Hack-and-Squirt Method. Mississippi State University Extension. Ext Pub P3276.

Ess DR, Parsons SD, Medlin CR (2001) Implementing Site-Specific Management: Sprayer Technology – Controlling Application Rate and Droplet Size Distribution On The Go. Purdue University. Pub SSM-5-W.

Fellers J (2020) Using hack-and-squirt method to control undesirable vegetation. CU in the Woods: Winter 2020 Edition. Clemson Cooperative Extension.

Ferrell J, Langeland K, Sellers B. (2006) Herbicide Application Techniques for Woody Plant Control. University of Florida Extension. Ext Pub SS-AGR-260.

Jackson D, & Finley JC (2019) Using Hack-and-Squirt Herbicide Applications to Control Unwanted Trees. PennState Extension Service. Ext Pub EE0262.

McWhorter CG, Gebhardt MR (1987) Methods of Applying Herbicides. Monograph series. Champaign, IL: Weed Science Society of America. Pp 305-306.

Motooka P, Nagai G, Ching L, Powley J, Teves G, Arakaki A (1999) Woody plant control for the home, pasture, and forest. University of Hawaii at Manoa. Weed Control Oct. 1999. WC-4.

CHAPTER III

EVALUATING ROADSIDE INC. SPRAY HEAD FOR DRIFT POTENTIAL BY ASSESSING DROPLET SIZE AND DISTRIBUTION

Abstract

Spray pattern distribution of the Roadside, Inc. (Roadside Inc., 1168 US-431 Abbeville, Alabama, U.S.) spray head was evaluated with FD&C blue dye (Flavors and Colors, 20653 Lycoming St. A-9 Diamond Bar, CA 91789) mixed in water at the Mississippi Horse Park (Starkville, MS) (33.406929, -88.795635) on photo paper sheets (Hewlett Packard Enterprise, 10300 Energy Drive, Spring, Texas, U.S.) linearly placed at 30.5 cm intervals to 9 m perpendicular to the line of vehicle travel. Truck speed was the recommended spray application speed of 17.7 km h^{-1}. After blue spray droplets dried, coverage was analyzed by ImageJ software. Results showed consistent coverage from 0.61-8.53 m from the sprayer head.

Droplet sizes of the seven nozzles used to construct the Roadside, Inc spray head were measured at the University of Nebraska West Central Research and Extension Center (41.084718, -100.771318) in North Platte, NE wind tunnel and laser diffraction system (Sympatec GmbH System, Clausthal-Zellerfeld, Germany). Each of the seven nozzles present on the spray head were evaluated individually. The flat fan nozzle was tested under normal agricultural test parameters with 30 cm from the laser diffraction system and wind speed of 24 km h^{-1}. All straight stream nozzles were tested under new parameters of 2.4, 4.8, and 7.3 m from the laser diffraction system and a wind speed of 13.7 km h^{-1}. Analysis indicated all tips at the

recommended operation pressure of the new spray head design produced droplets well above the benchmark for driftable fines (<150 microns).

Introduction

Roadside Vegetation Management

Weedy vegetation on land beside roadways has been viewed as a source of contaminants to infest adjacent agricultural lands since the early 1800's (Anonymous 1895; Sinclair 1826; Upham 1910). Management of weedy vegetation adjacent roadsides has been important to avoid conflict between agricultural landowners and community development. In the early 1800's, when travel speeds were slow, most transportation corridors were soil, and the traffic consisted primarily of pedestrian or animal, maintenance needs for adjacent vegetation was very different than today. As transportation technology evolved and transportation speed increased, the need for increased motorist safety also increased (Brandt et al. 2015).

The American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Vegetation Management (Anonymous 2011) described the characteristics of highway right-of-way vegetation as plant material that contribute to motorist safety, economical to establish and maintain, stabilize soil, and prevent erosion, promote environmental stewardship, create positive public relations, aesthetic, legally compliant, and contribute to transportation sustainability. Therefore, any vegetation on the right-of-way that compromises these characteristics is considered a weed.

There have been many different methods of roadside maintenance depending on the road location and use. In some areas, animals such as goats and sheep are grazed along the roadsides to control the growth of unwanted grasses and brush (Porter 2013; Brandt et al. 2015). While this biological approach to weed control may be viewed as a positive approach for both farmer and municipalities, because it provides pasture for livestock and may reduce right-of-way maintenance expense, animal rights groups, such as People for the Ethical Treatment of Animals (PETA), and drivers may not view the practice favorably as animal-vehicle collisions become more frequent.

Newer and safer methods of roadside vegetation management have been developed, such as mowing and herbicide application. These methods help preserve roadsides while maintaining as safe environment as possible for both motorists and roadside workers alike.

In roadside vegetation management, rights-of-way are often divided into three maintenance zones, and each zone requires a different level of vegetation management. The zone closest to the road is, by most sources, considered "zone 1" or vegetation-free zones (Anonymous 2011; Anonymous 2017). Zone 1 should be maintained as bare ground with no vegetation (Anonymous 2011) to facilitate water movement off the driving surface during rainfall events. "Zone 2" or the recovery zones extends from zone 1 away from the driving surface typically to the right-of-way drainage feature and should be covered with desirable plant material that meet the criteria of aesthetics, economics, soil stabilization, etc., but should provide adequate space to move a vehicle safely out of the flow of traffic (Anonymous 2011; Anonymous 2000). The final area of roadside right-of-way is "Zone 3" or the natural area, extends from the right-of-way drainage feature to the edge of the right-of-way (Anonymous 2011). Vegetation management in Zone 3 or the natural area should blend the right-of-way and land adjacent the right-of-way.

An integrated approach to roadside vegetation management is ideal and should be encouraged. Integrated pest management is a concept that implies all management tactics are incorporated in the process: cultural, mechanical, biological, chemical, and preventative.

Robbins et al. (1942) listed mowing, burning, disking, blading, hand pulling, hoeing, and herbicide application as suitable methods for roadside vegetation management. Once the right-of-way is established, the primary practical approaches are preventative, mechanical, and chemical; however, biological control may be used in some locations. Mechanical vegetation management is known to be a more expensive method of the listed management tactics. The Mississippi Department of Transportation (MDOT) reported tractor mowing costs ranged from \$75.90 ha^{-1} for contracted rural areas to \$86.45 ha^{-1} for MDOT equipment and personnel mowed rural areas, and up to \$260.00 ha^{-1} in metropolitan areas where equipment had to be transported via semi-trucks due to traffic loads[4]. Alabama Department of Transportation (ALDOT) reported[5] string trimming costs around cable barrier and guard rail at \$1187.50 ha^{-1}. Rotary mowers operating on rights-of-way can be dangerous to equipment operators as well as motorists[6]. Development of selective herbicides and equipment specifically designed for roadside applications has made herbicide treatments one of the most cost-effective forms of vegetation management (Anonymous 2018).

Herbicide use in the United States increased by 130% between the years of 2002 and 2010 (Alves et al. 2017). Increased herbicide use has several benefits, but also creates new problems. One potential issue faced by roadside vegetation management applicators is off-target movement. Off-target movement can damage surrounding crops, landscapes, and ecosystems; the regulatory consequences of off-target damage may not be limited to monetary fines but may also result in additional regulations that are intended to minimize future issues. Off-target movement can occur either by physical movement of the spray droplet particle during the

[4] Mississippi Department of Transportation Maintenance Summary Fiscal Year 2020
[5] Personal communication with Howard Peavey, ALDOT Agronomist
[6] Clarion-Ledger, August 5, 1998, Jackson, MS

application or as movement of chemical vapors after the application (McWhorter and Gebhardt 1987). This physical movement of the spray droplet during an application is known as primary movement (Bish et al. 2021; Carlsen et al. 2006; Jones et al. 2019). Some factors that affect physical off-target movement are droplet size, boom height, air temperature, wind speed, and wind direction (Bode et al. 1976; Felsot et al. 2010) although there is no agreement on which factors are most important. Applicators can mitigate a certain number of these factors by adjusting boom heights, operating speeds, application timings, etc.

Droplet size influences the amount of expected off-target movement when spraying pesticides. As early as the late 1940s, Brooks (1947) calculated a water droplet 100 µm in diameter would drift 15 m falling 3 m in a 4.8 km h^{-1} wind while under the same parameters, a 3 µm diameter droplet would travel almost 13 km. The Spray Drift Task Force (1997) concluded droplet size spectrum is the variable most likely to significantly influence off-target movement of herbicides. The droplet size spectrum is the range of droplet sizes produced by a spray tip. The ability to control the size of droplets is critical to optimize herbicide efficacy yet minimize damage to the surrounding vegetation due to off-target movement. Some factors that impact droplet size are nozzle tip, orifice size, operating pressure, and the viscosity of the spray solution (Womac et al. 1997). Variation in any one of these factors can alter droplet size, and therefore, the drift potential.

Another factor that influences off-target drift of herbicides is wind speed and direction. While applicators have no control over wind speed nor direction, these environmental factors should be closely monitored. Nordby and Skuterud (1974), found that as wind speed increased from 1 to 4 m s^{-1} (3.6 to 14.4 km h^{-1}) drift increased from 1-4% to 2-9%. To reduce off-target drift, many herbicide labels prohibit applications when wind speed exceeds 16 to 19 km h^{-1} or drop below 3 km h^{-1}.

Each herbicide follows a different set of regulations, so it is important to read and follow the label instructions of the herbicide to ensure those regulations are followed. These regulations are designed to keep that herbicide on the desired target and out of the surrounding environment. Regulations on the label can include buffer zones, rate of applications, specific nozzles, and specific droplet size requirements for proper herbicide function.

Droplet size can influence whether the herbicide contacts the intended target. Droplet size is measured in microns (micrometers) (ASABE 2009), which are exactly one-thousandth of a millimeter. The American Society of Agricultural and Biological Engineers categorize spray droplet size into eight size ranges (Figure 3.1). These eight ranges were formed to determine droplet size best suited for different applications. The ASABE figure also shows drift potential for specific droplet range. In general, as droplet size increases the potential for that droplet to move off-target decreases. The downside to large droplet sizes, is that as droplet sizes increase herbicide efficacy may decrease or coverage on very small vegetation decreases, so fewer target weeds are controlled. A balance between large and small droplet sizes and therefore, effective control and target deposition is a crucial management decision for most applicators (Hanna et al. 2009).

Droplet sizes can be measured with different methods. Accurate measurement of spray droplet size is an important performance evaluation of various spray technologies (Fritz et al. 2014). In a 2015 study, twenty-two nozzle types were measured in the CPAS Wind Tunnel Research Facility at the University of Queensland. In this study, droplet sizes were measured using laser diffraction (Sympatec Helos Sympatec Inc., Clausthal, Germany) (Ferguson et al.

2015). Laser diffraction allowed researchers to replicate a real-world application measurement of average droplet size per nozzle type. Although laser diffraction is a common method used to measure droplet size, it is not the only one used. In 1987, Dodge et al. compared laser diffraction (LD) with phase/Doppler (PD) method of droplet size measurement. They concluded PD measurements were better suited for detailed spray modeling that required both drop velocity as well as size, whereas LD was best for overall droplet size behavior within a nozzle pattern and best for comparing nozzle types (Dodge et al. 1987).

Application pressure and droplet velocity are closely related variables that play a large role in the potential for pesticide drift. Generally, as application pressure is increased, drift potential also increases, primarily because droplet size decreases as pressure increases. In contrast, when velocity of liquid movement is increased it decreases time that liquid remains in the air and therefore reduces the potential for movement off-target.

Positive correlation of drift potential and application pressure was confirmed in a 2015 study that examined application pressure as a parameter for drift potential. This study concluded droplet size diameter of every combination of other parameters (nozzle type, nozzle flow rate, herbicide, and carrier volume) was reduced when the pressure of that combination increased (Creech et al. 2015). These researchers found that a pressure increase from 138 to 276 kPa with AIXR, TT, TTI, and XR nozzles or from 276 to 414 kPa with the AI nozzle decreased Dv0.5 (median droplet size where 50% of droplets are smaller and 50% are larger[7]) by 25% over specific nozzles tested (475 to 380 μm). They also found that as application pressure increased from 138 to 414 kPa in AIXR, TT, TTI, and XR nozzles or from 276 to 552 kPa for the AI nozzle the volume fraction of fine droplets produced almost tripled (Creech et al. 2015). This

[7] Pesticide Environmental Stewardship, Understanding Droplet Size

reduction in droplet size diameter would increase drift potential of that solution. Another study found that when all other parameters remained constant, drift increased from 1-4% to 2-9% when the pressure of the application was raised from 2-5 to 10 bar (Nordby & Skuterud 1974). Reduced application pressure of the spray liquid is critical to reduce drift potential.

The speed at which a spray droplet falls after the aerodynamic drag and gravitational forces are in balance is known as the sedimentation velocity (Bache & Johnstone 1992). Sedimentation velocity is directly related to droplet diameter (Nuyttens et al. 2009). When sedimentation velocity of the solution is increased, the distance of off-target drift is generally reduced (Ozkan et al., 1998). Ozkan et al. (1998) found this was true for droplets that were 75 microns or larger. In a study conducted with a phase/Doppler particle analyzer (PDPA 100-1D, Aerometrics In., Sunnyvale, Calif.) it was found that velocity remains constant with various droplet sizes until sizes are smaller than 70 microns (Sidahmed et al. 1999). Droplets smaller than 70 microns continue to lose sedimentation velocity as droplet size decreases. Increasing droplet size and sedimentation velocity reduces your drift potential when making applications.

Nozzle type and flow rate are important parameters when considering drift potential of a pesticide application. Usually, nozzle types vary between the kinds of applications, but in certain applications, there are various nozzle types that can be selected. When this is the case, it is important to pick the nozzle type and flow rate that allows for the best herbicide efficacy with the least potential to drift.

In 2009, a study was conducted in a wind tunnel at the Silsoe Research Institute in Bedford, UK (Nuyttens et al. 2009). These wind tunnel dimensions (3.0 m wide 2.0 m high, and 7.0 m long) are large enough that airflow would not be disturbed by internal walls or other factors. In this study, nozzles were placed 0.5 m above horizontal collectors. Drift was assessed with a fluorescent tracer dye. This tracer measured the amount of spray deposited down the wind tunnel onto polythene lines perpendicular to wind direction (Nuyttens et al. 2009). These scientists concluded air-inclusion type nozzles resulted in the lowest drift potential. In a separate study, tests were performed to determine the effect of nozzle type on drift potential and droplet size (Creech et al. 2015). This study was conducted at the Pesticide Application Technology Laboratory at the West Central Research Center in North Platte, NE using a static spray chamber and Sympatec laser diffraction system (Sympatec Inc., Clausthal, Germany). Six nozzle types were tested (AI, AIXR, TT, TTI, XR, and HSD), then placed on an actuator that ran through the laser diffraction system at a speed of 0.2 m s^{-1}(Creech et al. 2015). These authors concluded nozzles with droplet size-increasing technology were best for reducing drift potential of herbicide. This also shows that nozzle selection plays an important role in the control of off-target spray drift.

When selecting spray nozzles, it is important to account for the flow rate of the nozzle in addition to nozzle type. Nuyttens et al. (2009) studied four nozzle flow rates (Internal Orifice Sizes [IOS] of 02, 03, 04, and 06) in a wind tunnel to investigate the impact of nozzle size on droplet size and drift potential. Nozzle flow rate was a more important variable in their model for regular flat-fan nozzles sized between a 02 and 04. Between 04 and 06 flow rates there was no significant change in the droplet size nor drift potential of the herbicide sprayed (Nuyttens et al. 2009). For air-inclusion or other low-drift design nozzles, drift potential between flow rates were not different. In a second study, there was an 8% increase in Dv0.1, Dv0.5, and Dv0.9 values when nozzle flow rate increased from 03 to 05 (Creech et al. 2015).

Overall, nozzle type and flow rate have an influential effect on the spray droplet spectrum of an herbicide application. Large nozzles produce larger droplets that have a decreased chance for off-target movement. Low flow rate nozzles produce smaller droplets that increase the chance for off-target movement to nontargets adjacent to the target site.

The speed of the spray vehicle can also impact drift potential. Robbins et al. (1952) stated one of the primary requirements of any spray equipment is uniform application. To help ensure uniformity, application equipment speed should be kept constant as speed and application volume are inversely correlated (Anderson 1983). Studies have shown that an increase in vehicle speed will increase the chances of off-target pesticide drift by decreasing droplet size to smaller than the recommended range (Eubank 2011). This is due to the vertical air jet being bent and distorted, leading to much finer droplet sizes being released from the sprayer nozzles (Nuyttens et al. 2007).

A study conducted in 1992, consisted of three separate experiments in which vehicle speed was one of the variables being tested. The study was performed using tap water that contained (50 mg sodium fluorescein l^{-1}) sprayed onto artificial targets representing pre-crop emergent stands of monocot and dicot plants (Nordbo 1992). Filter paper and vertical cotton pipe-cleaners were placed on a plywood sheet to create a layout of approximately 100 objects m^{-2}, average nozzle height was 50 cm, and travel speeds tested were 2.5, 5.0, and 7.5 km h^{-1} for the first two tests and 3.5, 5.0, and 8.0 km h^{-1} for the third (Nordbo 1992). Their study showed that droplets influenced by greater turbulence from increased sprayer speeds had a positive net gain in kinetic energy and therefore, greater deviation in all directions from the nozzle. This turbulence would have a greater effect on smaller droplets since they would move with less energy.

The results from Nordbo's study agree with a later study by Arvidsson et al. (2011). In this study, researchers evaluated drift potential in a grazed pasture with a tractor sprayer outfitted with a 12 m wide spray boom. The tractor was driven five times down a 27.4 m long path spraying a water and fluorescent dye (Uvitex LV concentrate) mixture. Airborne drift was collected with dynamic samplers (Isokinetischen Sonde model TU, Berlin, Germany), each of which contained two separate sample ducts with filter paper. Collectors were immediately moved into darkness for storage until fluorescence could be measured and analyzed. Results showed travel speed and drift potential were directly related. They determined under constant pressure, for every 1 m s^{-1} increase in forward travel speed, drift deposition increased by 1.0% (Arvidsson et al. 2011). Their explanation for this relationship is the increase in airflow created by faster forward motion of the sprayer, which causes a detrainment of small drops, and therefore, negatively influences spray drift (Arvidsson et al. 2011).

Studies have shown that increased forward travel speed of a sprayer has a negative impact on the potential for off-target movement of the product being sprayed. Although many new technologies such as (drift retardant surfactants, adjuvants, air-induction nozzles, low-drift nozzles, etc.), have been developed to combat drift, they are not always adequate to counter the effect of sprayer travel speed. The introduction of low-drift nozzles in particular, did not sufficiently compensate for the increase in vehicle speed (Zande et al. 2004). Because of the negative relationship held by travel speed and drift potential, following the label requirements for application speed is crucial when applying pesticides.

Weather conditions play a large role in the potential for a spray solution to move off-target. Wind speed and direction are the most common weather parameters linking weather to drift potential. Other parameters include temporal period, relative humidity, temperature, and vertical air movement (Sumner 1997). Managing applications around these weather conditions is paramount to ensuring optimum herbicide efficacy and minimal off-target movement.

Wind is the most common weather parameter considered when preparing a field application. Wind is a function of speed and directional parameters. Herbicide lost from the target and the distance that herbicide move both are directly correlated to wind speed. Severe drift can even occur under low wind speeds, especially when temperature is inverted. A temperature inversion occurs when the air nearest the ground is cooler than the air above it. Then, as elevation rises, temperature increases to a certain point then starts to decrease again. When spraying, wind direction must be considered as well. An application should never be made when the wind is blowing in the direction of a desirable target. Wind's effects on drift can be reduced by up to 70% with the use of shielded booms and lowered boom heights (Smith et al. 1982; Kruger and Ogg 2013). However, neither of these modifications are applicable to boomless sprayer designs typically used for roadside applications. For this reason, extreme attention must be paid to wind speed and directions when applications are made in this environment.

In 2017, Alves et al. (2017) examined the effect of wind speeds (0.9, 2.2, 3.6, and 4.9 m s^{-1}) on dicamba (Clarity^{R}, BASF, Research Triangle Park, NC) applications (Alves et al., 2017). Main plots and subplots of the experiment included four nozzle types (XR, TT, AIXR, and TTI) and downwind distances from 2 to 12 m from release. Conclusions from this study state that as wind speed increased, drift potential increased across all nozzle types. Alves et al. (2017) also stated "the smaller the droplet size, the greater the drift potential".

These results agree with an earlier study by Phillips and Miller (1999) who evaluated a field and wind tunnel study to evaluate the effect of wind on drift, but with differing methods. For the field experiment, a passive line collector array in a semi-circle pattern downwind of the static spray nozzle was used. A 0-1% tracer dye (Orange G, BDH Ltd.) solution with an addition of 0-1% surfactant (Agral, Zeneca Plc.) was used for tests. Tests were conducted under approximately neutral conditions, characterized by dense cloud cover and wind speeds greater than 1.5 m s^{-1}. Results from these studies show the amount of solution detected downwind of the nozzles increased for both nozzle flow rates. Also, the rate of increase in the movement of off-target spray increased for the nozzle which produced finer droplets (Phillips & Miller 1999). Their experiments also showed that wind tunnel experiments can adequately replace field measurements of off-target spray volume, especially for wind speeds of approximately 2 m s^{-1}, which is typically recommended for agricultural herbicide applications (Phillips & Miller 1999).

Both studies show the importance of attention to wind speed and direction when herbicides are applied. Since off-target movement of herbicide increases as wind speed increases, it is essential to make applications when wind speeds are below 16.1 km h^{-1} (Kruger & Ogg 2013). Some researchers have stated that cross wind affects drift potential more than parallel winds. This information could be used to the advantage of the applicator (Nordby & Skuterud 1974). However, it is still paramount to spray within the legal restraints on chemical labels. Also, never apply an herbicide when wind direction is toward a desirable target. Although these recommendations seem obvious, wind remains one of the largest weather conditions affecting herbicide drift.

There are other conditions to consider when calculating the potential for off-target movement of herbicides. Wind and vehicle speed, nozzle type, and flow rate are all important parameters that directly affect physical drift or primary movement. Less noticed parameters such as temporal period, temperature, and humidity can also affect off-target movement by secondary movement. Secondary movement is the traveling of herbicide particles after the application is made (Bish et al. 2021; Mueller 2015). Although these conditions are much more difficult to keep track of during applications, they are no less important than factors influencing physical drift or primary movement.

Temporal period is a component of pesticide drift. Although this variable may not play as clear of role in drift potential as wind speed, it can still have a negative effect on the chemicals applied. Smith et al. (1974) concluded bimonthly periods of “May-June” and “July-August” produced statistically equal results for reduced drift potential spraying. They also found differences in night versus day sprays. Through their study they found that nighttime (7 pm – 6 am) applications reduced drift more than day-time (7 am – 6 pm) applications (Smith et al., 1974). They specifically found the worst time to spray is between 2 pm and 6 pm, the hottest part of the day. This data shows time of day influences the ability of that application to drift. Although it is not feasible for all applications to be made at night, one can use this study to help determine when not to make an application.

Many other weather conditions must be considered when pesticides are applied, such as relative humidity and temperature. Temperature and humidity are not usually the first parameters considered with respect to pesticide application, but both can have a negative impact on the pesticide as these parameters impact droplet evaporation, which also reduces droplet diameter and mass. Temperature also influences atmosphere stability during applications and causes temperature inversions. This condition occurs during very calm conditions that might otherwise appear ideal to spray. A temperature inversion occurs when the air nearest the ground is cooler than the air above it. Then, as elevation rises, temperature increases to a certain point then starts to decrease again. This condition allows for increased suspension of droplet particles. Increased duration in the air coincides with more time to move laterally off-target (Hofman & Solseng 2001).

Overall, weather conditions play a large role in the ability to move pesticides off-target. Since these conditions cannot be controlled by human intervention, they must be closely monitored to minimize drift potential.

Vegetation along roadways is known for being highly variable in both species and maintainability. Outside of challenges posed by the various species present and weather conditions, roadside applications themselves present a plethora of other obstacles that an applicator must navigate when making an application. One of these obstacles is the different regulations that are relevant to roadside applications. These regulations include buffer zones for waterways, crops, and residential areas. Buffer zones are decided partially due to herbicide in use and the drift potential of the application system used. For this reason, the objectives of this study were to evaluate the droplet distribution and droplet sizing of Roadside Inc.'s new roadside spray head design to evaluate the potential efficacy and off-target movement of the application system. With new data on the drift potential, or lack thereof, of modern roadside spray heads it is hoped that certain regulations can be updated to match the advances in technology.

Materials and Methods

Droplet Distribution Study

In spring of 2018, the Mississippi State University Horse Park (Starkville, MS) (33.406929, -88.795635) was used as a site to test droplet distribution of the Roadside, Inc. (Roadside Inc., 1168 US-431 Abbeville, Alabama, U.S.) spray head (Figure 3.2). This indoor arena was chosen so that measurement of sprayer droplet distribution could be analyzed with negligible effects from wind. Wind speed in the arena was measured at 2.1 km h^{-1} using a Kestrel 3000 (Kestrel Meters, 21 Creek Circle Boothwyn, PA 19061).

A line of 25 labeled sheets (21.6 by 27.9 mm) of Hewlett Packard (Hewlett Packard Enterprise, 10300 Energy Drive, Spring, Texas, U.S.) inkjet photo paper spaced 3.1 cm apart for a total length of 9.1 m perpendicular to the line of truck travel was placed to catch spray droplets. The line of photo paper was repeated six times with a 3.7 m space between rows for a total length of 18.5 m parallel to truck travel. FD&C blue powdered dye #1 (Flavors and Colors, 20653 Lycoming St. A-9 Diamond Bar, CA 91789) was measured to 0.45 kg and slurred in 19 L of water then added to 1135 L in the 6435 L tank on the spray truck. The spray truck, equipped with the Roadside Inc. broadcast spray head, was driven perpendicular to the rows of photo paper at the recommended operation speed of 18 km h^{-1}. After spraying and time for droplets to dry, photo paper was collected and taken to Mississippi State University's Agricultural and Biological Engineering department where it was analyzed using ImageJ software. Results were plotted on a 3D graph to map percent coverage on each sheet.

Droplet Size Study

In fall of 2018, droplet sizes of all 7 nozzle types on the Roadside, Inc. spray head were measured with a laser diffraction system (Sympatec GmbH System, Clausthal-Zellerfeld, Germany) in collaboration with the University of Nebraska-Lincoln West Central Research and Extension Center (41.084718, -100.771318). The spray head consists of four Vee-Jet (TeeJet Technologies, P.O. Box 832, Tifton, Georgia, U.S.) H1/4U-0020/4040 nozzles, one H1/8U-0004 nozzle, two H1/8U-0005 nozzles, one H1/4U-0008, two H1/4U-0010 nozzles, three H1/8U-0015 nozzles, and two H1/8U-0020 nozzles. Each nozzle was removed from the spray head and tested individually for droplet sizing using water.

The only flat fan nozzle in the spray head configuration, the Vee-Jet H1/4U-4040 was tested using set standard agricultural testing procedures. The nozzle was attached to a nozzle fitting that was placed in the center of the wind tunnel 30 cm from the laser diffraction system with an air speed of 24 km h^{-1} blowing from behind the nozzle fan in the spray direction. The spray pattern produced by the nozzles was then sprayed across the laser diffracting system three times allowing for three replications.

All other nozzles were straight stream Vee-Jets and had to be tested using new parameters to allow for proper droplet separation of the water stream. The H1/8U-0004, H1/8U-0005, H1/8U-0008, H1/8U-0010, H1/8U-0015, and H1/8U-0020 nozzles were placed on the same nozzle fitting as the flat fan and all tested at 2.4, 4.8, and 7.3 m from the laser diffraction system (Figure 3.3). Wind speed was set at 13.7 km h^{-1}. These changes allowed for the stream of water to break into droplets before crossing through the laser of the diffraction system. Each nozzle was tested three times to allow for replications.

Data was collected using the laser diffraction system and was recorded in Microsoft Office Excel with all parameters listed for each nozzle and replication. Dv_{10}, Dv_{50}, and Dv_{90} were recorded along with the percentage of droplets sized under certain size benchmarks.

Results and Discussion

Droplet Distribution Study

Droplet distribution testing of the Roadside Inc. spray head resulted in ineffective droplet coverage at less than 0.61 m from the spray head and distances greater than 7.62 m from the spray head (Figure 3.4). The spray head was stated to provide effective coverage out to 9.1 m when all nozzles were operated at the proper pressure.

The ineffective droplet distribution at less than 0.61 m from the spray head is detrimental to effective roadside applications. A distance of 0.61 m would fall into zone 1 or the “clear zone” of highway vegetation management (Lail et al. 2016). This bare ground area is important to vegetation management and passenger safety because it allows the water to rapidly flow off the paved surface in a rainfall event (Shields 2020). The reduction in droplet distribution at 0.62 m could be caused by lack of a transition nozzle between the H1/4U-0020/4040 flat fan nozzles and the H1/8U-0004 straight stream nozzle. This gap in sprayer coverage might could be remedied by nozzle adjustment or by adding other nozzles between the flat fan and straight stream to increase coverage in that area.

Lack of droplet distribution beyond the 7.62 m distance could be explained by an improper nozzle setup. Since droplet distribution stopped abruptly at 7.62 m from the spray head it would be more likely that the spray head does not provide coverage to the full 9.1 m as originally stated. This would leave the outer edge of highway vegetation management zone 2 untreated in certain applications[8]. This could potentially shorten the safety clear zone, therefore reducing the amount of open area on the roadside for passengers to safely spot a hazard on the roadside.

Droplet Size Study

Wind tunnel evaluation of the H1/4U-0020/4040 flat fan nozzle showed that 0% of droplets were below the 150-micron benchmark for driftable fines. Replication one, two, and three showed an average DV_{50} of 1599, 1598, and 1585 microns, respectively (Table 3.1). The largest droplets Brooks (1947) reported were 1000 µm or 1 mm which he described as moderate rain were calculated to drift less than 1.5 m in a 3 m fall with slight breeze. Droplets produced by this nozzle were 1.5 times the diameter of those he reported. These data show that the likelihood of particle drift is much lower with roadside applications using this spray head when compared

[8] PennState Roadside Vegetation Management Factsheet 1

to standard agricultural applications which commonly have average droplet sizes ranging from 200 to 500 microns (Ferguson, O'Donnell, Chauhan, Adkins, Kruger, Wang, Ferreira, et al. 2015).

Analysis of the six straight stream nozzles revealed a similar conclusion as with the flat fan nozzle. The H1/8U-0004 straight stream nozzle had an average DV_{50} of 990, 1022, and 958 microns at 2.4, 4.8, and 7.3 meters, respectively. H1/8U-0005 nozzles averaged 906 microns at 2.4 meters, 962 microns at 4.8 meters, and 711 microns at 7.3 meters. H1/8U-0008 nozzles provided the largest overall droplets at 1217, 1206, and 1106 microns at 2.4, 4.8, and 7.3 meters, respectively. The H1/8U-0010 nozzle produced an average DV_{50} droplet size of 1089, 1076, and 1060 microns at 2.4, 4.8, and 7.3 meters, respectively. A DV_{50} of 870, 854, and 804 microns was recorded at 2.4, 4.8, and 7.3 meters, respectively, by the H1/8U-0015 nozzle. The H1/8U-0020 nozzle produced an average droplet size with a DV_{50} of 961 microns at 2.4 meters, 957 microns at 4.8 meters, and 1135 microns at 7.3 meters. As with the flat fan nozzle, all droplet sizes are well above the benchmark of 150 microns for driftable fines.

The smallest DV_{10} recorded by the laser diffraction system was 360.01 microns produced by the H1/8U-0015 nozzle at 7.3 meters from the nozzle. When data from all three replications were averaged, it was found that 97.8% of all droplets produced by the six straight stream nozzles were above the 150-micron drift standard. With only 2.2% of droplets falling below the benchmark for driftable fines, it could be said that the Roadside Inc. sprayer head is very unlikely to have off-target particle movement during normal application scenarios.

These data suggest that the Roadside Inc. sprayer head is unlikely to cause a significant off-target movement of droplets during applications, allowing for more droplets to hit the desired target area. With more droplets hitting the target area, damage to adjacent row crops, pastures, gardens, and native ecosystems can be kept at a minimum. More droplets hitting the target rights-of-ways also means that drivers using the roadways will have a better field of view allowing for a safer driving experience. These, and other adjustments made to modern spray heads such as these should be considered as more regulatory legislation is being passed creating an increasingly difficult application environment for rights-of-way applicators who are tasked with the safety of interstate and highway drivers.

Table 3.1 TeeJet nozzle droplet sizes.

Nozzle	Solution	Pressure (PSI)	Airspeed (mph)	Distance (ft)	Avg. Dv10	Avg. Dv50	Avg. Dv90	% below 150 microns
H14U4040	water	51	15	1	---	1594	---	---
H18U0004	water	29	8.5	8	489	990	1125	0
H18U0005	water	29	8.5	8	533	906	1212	0
H18U0008	water	29	8.5	8	641	1217	1392	0
H18U0010	water	29	8.5	8	608	1089	1388	0
H18U0015	water	29	8.5	8	586	870	1375	0
H18U0020	water	29	8.5	8	545	961	1347	0.003
H18U0004	water	29	8.5	16	876	1022	1573	0.07
H18U0005	water	29	8.5	16	652	962	1390	0.04
H18U0008	water	29	8.5	16	1028	1206	1424	0
H18U0010	water	29	8.5	16	539	1076	1356	0
H18U0015	water	29	8.5	16	500	854	1311	0.15
H18U0020	water	29	8.5	16	375	957	1108	0.93
H18U0004	water	29	8.5	24	512	958	1145	0
H18U0005	water	29	8.5	24	437	711	905	0
H18U0008	water	29	8.5	24	1039	1106	1424	0
H18U0010	water	29	8.5	24	789	1060	1414	0
H18U0015	water	29	8.5	24	369	804	828	0.8
H18U0020	water	29	8.5	24	638	1135	1396	0.24

Spray Quality*	Size of Droplets	VMD Range (Microns**)	Color Code	Retention on Difficult to Wet Leaves	Used for	Drift Potential
Extremely Fine	Small	<60	Purple	Excellent	Exceptions	High
Very Fine		61-105	Red	Excellent	Exceptions	
Fine		106-235	Orange	Very Good	Good Cover	
Medium		236-340	Yellow	Good	Most Products	
Coarse		341-403	Blue	Moderate	Systemic Herbicides	
Very Coarse		404-502	Green	Poor	Soil Herbicides	
Extremely Coarse		503-665	White	Very Poor	Liquid Fertilizer	
Ultra Coarse	Large	>665	Black	Very Poor	Liquid Fertilizer	Low

Figure 3.1 ASAE droplet size classification.

Size ranges in microns of different droplets, suggested applications of size ranges, and drift potential of size ranges (ASAE, 2009).

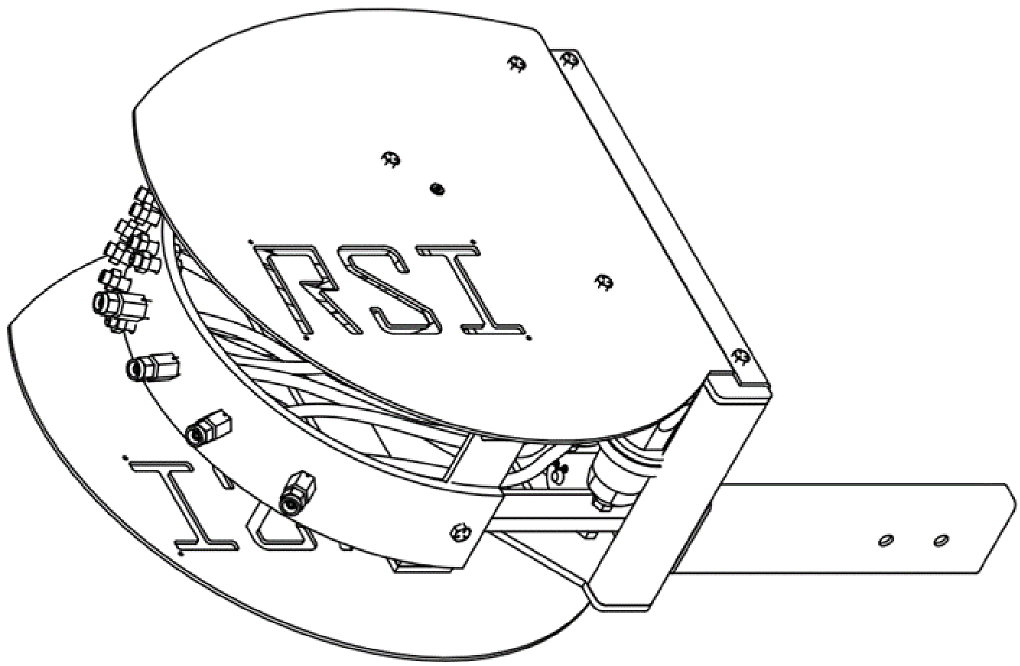

Figure 3.2 Roadside Inc. sprayer head tested during droplet size and distribution studies.

Figure 3.3 Straight stream nozzle from Roadside Inc. sprayer head being tested under new parameters.

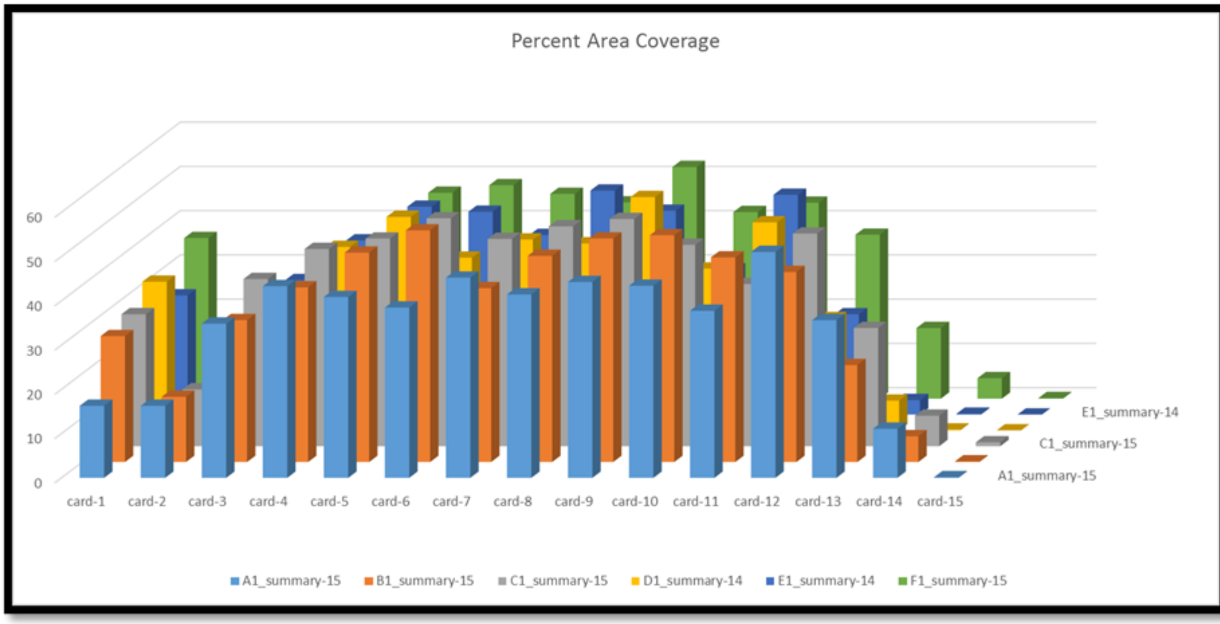

Figure 3.4 Droplet distribution data from distribution testing. Analyzed by MSU's Agricultural and Biological Eng. department using ImageJ software. (Card 1 is closest to spray truck).

Literature Cited

Alves SG, Kruger GR, da Cunha JPAR, de Santana DG, Pinto LAT, Guimarães F, Zaric M (2017b) Dicamba Spray Drift as Influenced by Wind Speed and Nozzle Type. Weed Technology 31:724–731.

Anonymous (1896) Two Hundred Weeds: How to Know Them and How to Kill Them Pages 592-611 in CW Dabney (ed) Yearbook of the United States Department of Agriculture 1895. Government Printing Office Washington DC.

Anonymous (2000) Implementing Integrated Vegetation Management on Pennsylvania's Roadsides. Peen State Roadside Vegetation Fact Sheet. https://plantscience.psu.edu/research/projects/vegetative-management/publications/roadside-vegetative-mangement-factsheets/1implementing-ivm-on-roadsides. Accessed: March 27, 2019

Anonymous (2011) Guidelines for Vegetation Management. American Association of State Highway and Transportation Officials. Washington, DC.

Anonymous (2017) Roadside Manual. Washington State Department of Transportation. https://www.wsdot.wa.gov/publications/manuals/fulltext/M25-30/Roadside.pdf. Accessed: March 28, 2019.

Anonymous (2018) Roadside Vegetation Management. Min Dep of Trans. https://www.dot.state.mn.us/roadsides/vegetation/pesticide.html. Accessed: March 27, 2019

Arvidsson T, Bergström L, and Kreuger J (2011) Spray drift as influenced by meteorological and technical factors. Pest Manage Sci 67: 586–598.

Anderson WP (1983) Sprayer Calibration and Herbicide Dosage Calculation pages 341-364 in Weed Science Principles West Publishing Co St. Paul.

[ASAE] The American Society of Agricultural and Biological Engineers (2009) S572.1. https://cdn2.hubspot.net/hub/95784/file-32015844-pdf/docs/asabe_s572.1_droplet_size_classification.pdf. Accessed: March 26, 2019

Bache DH, Johnstone DR (1992) Microclimate and Spray Dispersion. New York: E. Horwood, 1992.

Bish M, Oseland E, Bradley K (2021) Off-target pesticide movement: a review of our current understanding of drift due to inversions and secondary movement. Weed Technol. 35:345-356.

Bode LE, Butler BJ, Goering CE (1976) Spray drift and recovery as affected by spray thickener, nozzle type and nozzle pressure. Transactions ASAE 19(2):213-218.

Brandt J, Henderson K, Uthe J, Urice M (2015) Integrated Roadside Vegetation Management Technical Manual. Faculty Book Gallery: 116. https://scholarworks.uni.edu/facbook/116. Accessed: March 27, 2019

Brooks FA (1947) The Drifting of Poisonous Dusts Applied by Airplanes and Land Rigs. Agric. Engineering 28:6.

Carlsen SCK, Spliid NH, Svensmark B (2006) Drift of 10 herbicides after tractor spray application. 2. Primary drift (droplet drift). Chemosphere 64: 778-786.

Creech CF, Henry RS, Fritz BK, Kruger GR (2015) Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. Weed Technology 29: 298–310.

Dodge LG, Rhodes DJ, Reitz RD (1987) Drop-size measurement techniques for sprays: comparison of Malvern laser-diffraction and Aerometrics phase/Doppler. Applied Optics 26: 2144.

Eubank T (2011) Ground Speed Affects Spray Droplet Deposition. file:///C:/Users/hbq2/Zotero/storage/BW688NQV/ground-speed-affects-spray-droplet-deposition.html. Accessed: March 26, 2019

Felsot AS, Unsworth JB, Linders JBHJ, Roberts G, Rautman D, Harris C, Carazo E (2010) Agrochemical spray drift; assessment and mitigation—A review*. J Environ Sci Health, Part B 46: 1–23.

Ferguson JC, O'Donnell CC, Chauhan BS, Adkins SW, Kruger GR, Wang R, Urach Ferreira PH, Hewitt AJ (2015) Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. Crop Protection 76: 1–6.

Fritz BK, Hoffmann WC, Bagley WE, Kruger GR, Czaczyk Z, Henry RS (2014) Measuring Droplet Size of Agricultural Spray Nozzles-Measurement Distance and Airspeed Effects. Atomization and Sprays 24: 747–760.

Hanna M, Kruckeberg J, Darr M, Steward B (2009) Nozzle and droplet size effects on pesticide performance and drift. Proceedings of the 21st Annual Integrated Crop Management Conference: Pp 49-52.

Hofman V, Solseng E (2001) Reducing Spray Drift. Agric Eng 1210: 1-7.

Jones GT, Norsworthy JK, Barber T (2019) Off-target movement of diglycolamine dicamba to non-dicamba soybean using practices to minimize physical drift. Weed Technol 33:24-40.

Kruger GR, Ogg CL (2013) Spray Drift of Pesticides. Univ Neb-Lin Ext Public G1773.

Lail E, Janow L, Weddle V, Bright P, Hopper J, Tucker S, Conatser EB, Perry R, Hampton K (2016) TDOT Integrated Vegetation Management Program Guidelines. https://www.tn.gov/content/dam/tn/tdot/environmental/redesign/hbo-pollinator-program/pdfs/ref_tdot_pollinator_ivmp_spray_guidelines_rev03142016.pdf. Accessed: June 22, 2021.

Mueller TC (2015) Methods to measure herbicide volatility. Weed Sci 63: 116-120.

Nordbo E (1992) Effects of nozzle size, travel speed and air assistance on deposition on artificial vertical and horizontal targets in laboratory experiments. Crop Protection 11: 272–278.

Nordby A, Skuterud R (1974) The effects of boom height, working pressure and wind speed on spray drift. Weed Res 14: 385–395.

Nuyttens D, De Schampheleire M, Baetens K, Sonck B (2007) The Influence of Operator-Controlled Variables on Spray Drift from Field Crop Sprayers. Trans ASAE 50:1129–1140.

Ozkan HE, Zhu H (1998). Effect of Major Variables on Drift Distances of Spray Droplets.Ohio St Univ Ext Public FABE-525.

Phillips JC, Miller PCH (1999) Field and Wind Tunnel Measurements of the Airborne Spray Volume Downwind of Single Flat-Fan Nozzles. J Agric Engi Res 72: 161–170.

Porter M (2013) The Right Way to Vegetation Management in Pesticides and You 33:3. www.beyondpesticides.org/weeds. Accessed: March 26, 2019.

Robbins WW, Crafts AS, Raynor RN (1952) Equipment for Applying Herbicides. New York: Weed Control McGraw-Hill Book Co. Pp 319-345.

Shields K (2020) Chapter 6: Roadside Management. WSDOT Maintenance Manual. https://wsdot.wa.gov/publications/manuals/fulltext/M51-01/Chapter6.pdf. Accessed: June 24, 2021.

Sidahmed MM, Brown RB, Darvishvand M (1999) Drop-Size/Velocity Correlations at Formation of Sprays from Fan Nozzles. Trans ASAE 42: 1557–1564.

Sinclair G (1826) Hortus Gramineus Woburnensis: or An Account of the Results of Experiments on the Produce and Nutritive Qualities of Grasses and Other Plants used as the Food of More Productive Domestic Animals. London.

Smith DB, Harris FD, Butler BJ (1982) Shielded Sprayer Boom to Reduce Drift. Trans ASAE 25: 1136–1140.

Spray Drift Task Force (1997). A Summary of Ground Application Studies.

Sumner PE (1997) Reducing Spray Drift. Coop Ext Ser The Univ Geo.Public ENG97-005.

Upham AA (1910) An Introduction to Agriculture. New York: D Appleton and Company. P 296.

Womac AR, Goodwin JC, Hart WE (1997) Tip Selection for Precision Application of Herbicides. Univ Tenn Agric Exp Stat. Bull. http://trace.tennessee.edu/utk_agbulletin/430. Accessed: March 26, 2019

Zande JC, Stallinga H, Michielsen JMGP, Velde P (2004). Effect of sprayer speed on sprayer drift. Ann Rev Agric Eng 4.