Using the Wet-Blade to Control Invasive Species along Roadway Corridors.

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Using the Wet-Blade to Control Invasive Species along Roadway Corridors

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March 2014

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Final Report

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EXECUTIVE SUMMARY

Experiments were conducted to test the feasibility of using the Diamond Wet-Blade mower along roadside rights-of-way. The research conducted compared Canada thistle control, herbicide drift, and operational costs of the Wet-Blade versus broadcast spray application using the herbicide aminopyralid. It was determined that there were no differences between the Wet-Blade and broadcast spraying in terms of Canada thistle control. Herbicide treatments conducted in the spring using at least 88 g ha^{-1} aminopyralid provided greater than 70% control that lasted for two years after treatment. Broadcast spraying produced detectable drift up to 3 m into non-target areas. Operation of the Wet-Blade is approximately 2 times the cost of broadcast application. The combination of effective Canada thistle control combined with almost no herbicide drift make the Wet-Blade an excellent tool for herbicide application in areas where herbicide contamination is of concern.

CHAPTER 1: INTRODUCTION

1.1. General background

Non-native invasive species are those that have prevalent populations outside their native habitats with ecological or economic ramifications (Murphy et al. 2006). Invasion by these species is one of the most important threats to biodiversity, second only to habitat loss (Vitousek et al. 1996, Wilcove et al. 1998). Eighty percent of all endangered organisms are threatened by non-native species (Armstrong 1995), while 57% of the endangered plant species are threatened by non-native plants (Wilcove et al. 1998). Endangered plants are not the only plants affected. Most of the established non-native species in America have displaced or reduced populations of native plants (Morse et al. 1995). Norway maple, *Acer platanoides* (Wyckoff and Webb 1996, Martin 1999), kudzu, *Pueraria montana* (Forseth and Innis 2004), and common reed, *Phragmites australis* (Warren et al. 2001) are among the myriad invasive species that threaten biodiversity in native plant communities. As a consequence, the reduction of native plants has also resulted in the loss of wildlife dependent on native plants for food or habitat (Pimentel et al. 2005). This is especially important concerning endangered or threatened animals, such as the bog turtle (Kiviat 1978) and many wetland birds (Benoit and Askins 1999). Non-native invasive plants also affect abiotic attributes of ecosystems. They can affect soil chemistry and nutrient cycling (Ehrenfeld 2004), fire disturbance regimes (D'Antonio and Vitousek 1992), and hydrology (Gordon 1998).

1.2. Invasive species and roadside rights-of-way

1.2.1. Roadsides as habitat for invasive species

There are over 6.2 million kilometers of public roads in the United States (National Research Council 1997), and a major characteristic of these roadways is the high incidence of invasive species found growing along the roadsides and medians. These areas serve as ideal habitats for invasive species to thrive. When surveyed, both paved and unpaved roadsides had higher non-native species richness and abundance than undisturbed natural areas (Christen and Matlack 2009). The highest richness and abundance of non-natives was next to paved roads, which had higher traffic and more disturbed roadside area (Gelbard and Belnap 2003).

Roadsides are continuously disturbed habitats that provide opportunities for non-native invasive plants to establish populations (Forman and Alexander 1998). Even poor competitors can successfully establish populations in highly disturbed habitats (Rejmanek 1989) regardless of disturbance type (Rentch et al. 2005). Disturbances, such as excavation and vehicle accidents, expose soil on which invasive species may germinate.

Roadsides are also ideal habitat for invasive species because of the open canopies and moist soil. The open canopy of roads promotes the establishment of non-native species intolerant of shade such as *P. australis* (Haslam 1972) and Canada thistle, *Cirsium arvense* (Holm et al. 1977). In addition to the open canopy, roads are sloped to direct water to the roadsides where it is then held or distributed (Johnson et al. 1975, McNabb and Batterson 1991), providing a moist substrate on which non-native plants thrive. In California, plant communities growing on moist soils next to roads contained more exotic species than the drier soils a distance from roadsides (Gelbard and Harrison 2003). In some locations, roadside ditches are essentially man-made interconnected linear wetlands (Maheu-Giroux and de Blois 2007, Jodoin et al. 2008).

Northern roadside soil also tends to be saline due to winter salt application (Richburg et al. 2001). In England, up to 34 g m^{-2} of salt (KCl and NaCl) may be applied to a road in any given winter (Davison 1971). In Massachusetts, road crews apply between 17,700 and 22,500 kg of salt per kilometer on major highways (Mattson and Godfrey 1994). In Canada, sodium concentrations can remain elevated up to 9 m perpendicular from the roads (DiTommaso 2004). Native plants may not tolerate these conditions, but many invasive plants, including *C. arvense*, are highly salt tolerant (Wilson 1979) and can grow well along roadsides. *Phragmites australis*, particularly the non-native haplotype (Vasquez et al. 2005), thrives in ditches contaminated with salt deicers because it is more tolerant of saline soils than associated native plants (McNabb and Batterson 1991).

1.2.2. Roads contributing to the spread of invasive species

Because non-native populations can be extensive along roadsides there is greater potential for reproduction and dispersal (Tyser and Worley 1992, Harrison et al. 2002). Roadways serve as corridors through which non-native plants disperse (Christen and Matlack 2009, Mortensen et al. 2009), especially paved roads with heavy traffic (Gelbard and Belnap 2003, Mortensen et al. 2009). The spread of invasive plants along roadsides is most likely due to vehicles. In one study, mud collected on a single car was shown to have transported approximately 4,000 viable seeds, which represented 124 plant species, a distance of 15,000 km (Schmidt 1989). Vehicles have also been shown to transport non-natives through the movement of contaminated soil (Mortensen et al. 2009). In Quebec, Canada, the dispersal of *P. australis* has been attributed to the movement of rhizome fragments (Delisle et al. 2003) as a result of ditch digging and cleaning (Jodoin et al. 2008).

Though the spread of invasive species occurs more readily along road systems (Almasi 2000), established populations of invasive plants on roadsides can invade the natural areas bordering the road (Tyser and Worley 1992, Harrison et al. 2002, Gelbard and Harrison 2003). Non-native plants can also spread into croplands from roadside populations. For example, roads act as refuges from which *C. arvense* had been shown to invade croplands (Foote et al. 1970).

Roadsides are ideal for the growth and spread of invasive species. Farmlands and natural areas are not isolated from each other— they are connected by roads. Control of invasive species along roads will reduce the spread of these plants into adjacent natural areas and farmlands. Because of this, control of invasive species needs to be a joint effort between farmers, land managers, and state and federal agencies. A great deal of research is conducted on agricultural weed control and control of invasive species in natural areas, but research needs to focus on roads as well, or weeds will continue to be harbored and spread from roadsides. Two invasive species, *P. australis* and *C. arvense*, are persistent, problematic weeds along roadsides (Foote et al. 1970, Delisle et al. 2003).

1.3. Description of the invasive species, Phragmites australis and Cirsium arvense

1.3.1 Phragmites australis

Phragmites australis (Cav.) Trin. ex Steud., common reed, was a rare native plant in North America prior to the early 1900s, but a non-native haplotype—introduced to North America from Eurasia—began to spread after 1910 (Saltonstall 2002). Since introduction, common reed has become invasive and is now found throughout North America and the world from the tropics to the arctic (Haslam 1972); however, local climates have a large influence on its distribution and rate of spread (Jodoin et al. 2008). It is found in freshwater wetlands (Saltonstall 2002), brackish tidal wetlands, and coastal marshes (Marks et al. 1994, Chambers et al. 1999). Populations of this plant tend to be monotypic clones (Amsberry et al. 2000), with locally widespread distributions of colonies. Jodoin et al. (2008) determined that 24% of 1359 km of roads surveyed in Quebec, Canada were dominated with *P. australis*. High densities of this plant occur along old (Jodoin et al. 2008) and new roadsides (McNabb and Batterson 1991). This plant continues to spread and dominate wet roadside habitats in southern Michigan but has not yet become dominate in northern Michigan (McNabb and Batterson 1991).

Phragmites australis is shade intolerant and produces tall (>4 m), annual culms that emerge from an extensive network of perennial rhizomes (Ekstam 1995). *Phragmites australis* culms are physiologically connected through the rhizomes and share resources until they can sustain themselves (Hara et al. 1993, Amsberry et al. 2000). The connection between culms minimizes competition between stems allowing the colonies of clones to thrive (Hara et al. 1993), especially when the density of culms can be over 100 stems m^{-2} (League et al. 2006). The connection between shoots also allows this species to spread into less favorable habitat from nearby established populations (Amsberry et al. 2000). Amsberry et al. (2000) determined that plants in suitable, high marsh habitats were providing plants in low marsh habitats with the resources necessary for survival. When their common rhizomes were severed, the plants in the unsuitable low marsh habitats had lower photosynthetic rates and survivorship than the plants with connected rhizomes (Amsberry et al. 2000). Rhizomes typically live 3-6 years (Haslam 1969). During the winter, 30% of a population's rhizomes die (Granéli et al. 1992).

Phragmites australis reproduces poorly by seed, especially in high latitudes (Tucker 1990, Small and Catling 2001). In North America, genetic factors may make clonal populations poor sexual reproducers (Alvarez et al. 2005); however, sexual reproduction is important and does occur along roadsides (Brisson et al. 2008). Initial spread by seeds may be important to establish small populations that then grow and spread aggressively through rhizomes (Ailstock et al. 2001, Mal and Narine 2004, Alvarez et al. 2005). Rhizomes can grow up to 2 m per year (Haslam 1969) and to depths >1 m in the soil (Haslam 1972, Granéli et al. 1992, Burdick et al. 2001).

Rhizomes store nutrients and carbon throughout the winter (Granéli et al. 1992). In the spring, the stored resources are allocated to shoot and aboveground tissue growth (Fiala 1976). The shoots develop annually from axillary buds found at the rhizome nodes (Mal and Narine 2004). After the shoots are established, new rhizomes and roots are grown from the buds

(Haslam 1972), and rhizomal resource stores are replenished (Fiala 1976, Granéli et al. 1992, Klimeš et al. 1999). The non-native haplotype can quickly activate dormant rhizomal buds and efficiently utilize the resources stored in the rhizomes when aboveground stems are damaged (League et al. 2006). Quick bud activation allows populations of *P. australis* to grow and spread rapidly, especially if rhizome fragments are transported.

Evidence suggests rhizome fragments as short as 10-20 cm can produce a plant (Haslam 1969, Ailstock et al. 2001). It is also known that rhizomes sequester nutrients in the fall to be used for spring growth (Fiala 1976, Granéli et al. 1992), but research suggest that there is only enough carbohydrate in a rhizome to support growth for 2-4 days (Best and Dassen 1987). On the other hand, Granéli et al. (1992) stated that the rhizomes have a lot of underutilized carbon and can theoretically support three times the observed spring growth.

1.3.2. Cirsium arvense

Cirsium arvense (L.) Scop., Canada thistle, is native to Europe, Western Asia, and North Africa, and was introduced to North America in the 17th century (Moore 1975). It likely arrived to North America as a contaminant in agricultural seed and packing straw (Hansen 1918, King 1925). It then spread throughout the midwestern United States during the early 20th century (Hayden 1934). It is now naturalized throughout the world (Brooks 1986). In North America, it is a serious weed along roadsides (Foote et al. 1970) and in agricultural regions (Gibson et al. 2006). It is a noxious weed in most Canadian provinces and all but the southeastern states of the United States (USDA, NRCS 2010). There are four varieties of this species worldwide, but the variety *horridum* is most common in North America (Moore 1975). *Cirsium arvense* can grow as far north as 59ºN latitude in Canada and 68ºN latitude in Scandinavia and Siberia where it can tolerate winter temperatures less than -25ºC (Hayden 1934, Moore 1975). Its southern limit of 25ºN (Hayden 1934) is most likely limited by daylight—it requires 14-16 hours of light to flower (Hunter and Smith 1972)—and climate. *Cirsium arvense*, a C_3 plant, is not adapted to hot, arid climates (Håkansson 2003, Bickler 2009). Its optimum growth occurs when day temperatures are at 25ºC and night temperatures are at 15ºC (Haderlie et al. 1987). It grows poorly in saturated soils and cannot tolerate drought (Wilson 1979). This species is highly tolerant of salt and can withstand NaCl concentrations in soils up to 20,000 ppm (Wilson 1979).

Mature *C. arvense* range between 30-150 cm tall and are shade intolerant, perennial forbs (Moore 1975, Holm et al. 1977) with high phenological and morphological variation (Hodgson 1964). This species is a vigorous weed because it is able to reproduce asexually by stem and root fragments and sexually by seeds (Hamdoun 1972, Nadeau and Born 1989). The seeds are viable shortly after one week (Derscheid and Schultz 1960) and a single female plant can produce up to 40,000 seeds a year (Royer and Dickinson 1999), which can remain dormant in the soil for 20 years (Hutchison 1992). *Cirsium arvense* achenes have plumes, but they are loosely attached so wind dispersal is minimal (Bakker 1960, Bostock and Benton 1979).

Though *C. arvense* reproduces well by seeds, its greatest regenerative capacity is through vegetative propagation (Bostock and Benton 1979). Established populations have been shown to spread primarily by vegetative propagation (Holm et al. 1977). Population expansion can occur at a rate of about 2 m per year (Amor and Harris 1974). Roots grow deeper than 1.5 m but only those less than 1 m deep are capable of producing shoots (Hayden 1934). A meter segment of *C. arvense* root can have up to 25 buds from which stems can grow (Donald 1994). These buds are primarily produced in the fall and elongate the next summer when the days are warm (McAllister 1982). The roots are easily fragmented by frost (Dexter 1937), animals, or other environmental disruptions (Bostock and Benton 1979). Each root fragment has the potential to develop into a reproductive plant. Root fragments as short as 0.5 cm with a single bud can produce a shoot, but those greater than 2.4 cm had near 100% shoot growth in greenhouse experiments (Hamdoun 1972). Hamdoun (1972) also showed that fewer shoots were produced from uncut roots than roots with the same length but cut into a number of fragments. Longer root fragments do, however, develop into plants that have more biomass than short root fragments (Gustavsson 1997).

Cirsium arvense stores carbohydrates in the roots. In late spring and summer, stored carbohydrates make up 3% of the root biomass (McAllister and Haderlie 1985) with the lowest amounts in May through August (Wilson et al. 2006). In the fall, resources are reallocated back to the roots, reaching up to 26% of the root biomass (McAllister and Haderlie 1985). The plant reallocates the carbohydrates for new growth in April (Wilson et al. 2006).

1.4. Control of Phragmites australis and Cirsium arvense

1.4.1. Control of Phragmites australis

Eradication of *P. australis* from wetlands, marshes, and roadsides is unrealistic (Warren et al. 2001), but management is feasible. Herbicides have been the primary means of control. The herbicide Rodeo® (Dow AgroScience), which contains the active ingredient glyphosate, was shown to be effective in controlling populations, but a few years after treatment, *P. australis* returned as a dominant species (Marks et al. 1994, Ailstock et al. 2001). Treatment with imazapyr has shown better control of *P. australis* and with greater efficacy than glyphosate, however this pesticide, like glyphosate, negatively affected non-target species (Kay 1995, Mozdzer et al. 2008).

Mowing does little to control *P. australis* dominance, and has been shown to double stem density (Warren et al. 2001). Burning is also ineffective because it does not destroy rhizomes or roots (Marks et al. 1994), though it does reduce the population’s growing season (Hocking 1989). It was shown that burning did, however, remove the mat of dead culms, which exposed the soil and allowed a diverse plant community to grow rapidly. But after a few years, *P. australis* had returned as a dominant species (Ailstock et al. 2001). Management for *P. australis* tends to focus on culms, though land managers must keep rhizomes in mind as they are driving force behind population expansion (League et al. 2006).

There are few options for controlling *P. australis,* and they are often costly and only effective in the short term. A cut-stem herbicide application that allows the herbicide to translocate to below ground tissue (Wahlers et al. 1997b, a) may provide longer control of *P. australis*, especially with herbicides that show moderate efficacy as a foliar application.

The original intent of the research was to test control methods for both *P. australis* and *C. arvense*; however, due to the inability of the available equipment to operate within *P. australis* infested areas, this aspect of the research had to be abandoned. It should be noted that due to the saturated soils associated with *P. australis* infestations, land managers wanting to use the wet-blade would need to test the use of low compaction equipment, or utilize a long boom to ensure that the tractor remains on firm ground at all times. No further information or results will be presented with regard to *P. australis*.

1.4.2. Control of Cirsium arvense

Control of *C. arvense* had been attempted with many herbicides, although most displayed little to intermediate efficacy (Moore 1975). 2,4-D, a synthetic auxin, was the primary herbicide used in the 1960s-70s to control *C. arvense*, but it did not provide the desired control (Foote et al. 1970). Picloram had been shown to control populations more effectively with the highest efficacy during late summer (Foote et al. 1970, Moore 1975, Beck and Sebastian 2000). Milestone® (Dow AgroSciences), a new herbicide with the active ingredient aminopyralid, had been shown to control *C. arvense* with the same efficacy as picloram (Enloe et al. 2007), but aminopyralid did not translocate well out of the tissue on which it was applied (Bukun et al. 2009). This may have been because the leaves and stems died and desiccated before the chemical had time to move to new tissue (Bukun et al. 2009). Spring and fall applications were shown to be equally effective at controlling 89 to 97% of the population (Enloe et al. 2007).

Mowing an area had little effect on the percent cover of *C. arvense*, and mowing prior to herbicide application only weakly improved control (Beck and Sebastian 2000). The combination of mowing and herbicide treatment was not recommended because the costs of repeated mowing outweighed the control improvement (Beck and Sebastian 2000). Because *C. arvense* is able to propagate from stem fragments, mowing without herbicide may also increase the number of propagules in an area and increase the probability of its spread. Biocontrols have been examined for use to control *C. arvense*, but none have been shown to work. A preliminary study using the fungus *Phomopsis cirsii* has shown it to be a strong candidate for use, but it has not yet been commercially developed (Leth et al. 2008). There have been mixed results when using fire as a means to control *C. arvense*. Areas burned have shown more resistance to *C. arvense* in Colorado (Reever-Morghan et al. 2000), but roots can survive fire, and seeds in the seed bank can quickly establish (Rowe 1983) resulting in immediately higher stem densities (Travnicek et al. 2005).

Similar to *P. australis*, there are few effective control methods available for *C. arvense* and repeated treatments can be costly. Aminopyralid appears promising and works effectively at killing aboveground biomass, but this herbicide does not translocate well when applied to stems and foliage.

1.5. Wet-Blade technology

1.5.1. Efficacy of Wet-Blade technology

The Diamond Wet-Blade (Diamond Mowers Inc., Sioux Falls, SD) system is a combination mowing system that applies herbicide to stems as it cuts. The mower blades are designed to wipe herbicide onto the cut stems. Applying herbicides to cut stems allows the plants to absorb the herbicide directly into xylem and phloem and translocate the chemical to belowground tissue. It was shown in a laboratory study that up to 90% of a radiolabeled herbicide was taken in by cut *Eupatorium capillifolium*, dogfennel, stems after 60 minutes. After 48 hours, 7% had translocated to the roots (Wahlers et al. 1997b). Wahlers et al. (1997a) showed a reduction in biomass and plant regrowth after cutting stems with sheers coated with herbicide to simulate the Wet-Blade system. Using a Burch Wet-Blade (Burch Company, Charlotte NC), a system that preceded the Diamond Wet-Blade, Henson et al. (2003) showed control of weeds over a span of two years. The system does not work well for all plants. For example, it provided little control of southern wax myrtle, *Myrica cerifera* (Sellers and Mullahey 2008), and *Digitaria sanguinalis*, crabgrass (Barker et al. 2005) when compared to broadcast spray application. Application of plant growth inhibitors using the Wet-Blade did not suppress seed-head production or provide better control of *Andropogon virginicus* and *Trifolium repens*, white clover, than broadcast sprays (Hixson et al. 2007).

1.5.2. Herbicide drift created by the Wet-Blade system

Herbicides are considered the most economic and effective weed control tool for agricultural and non-agricultural areas (Sylwester 1951, DiTomaso 1997). Despite the benefits of herbicides, there are risks associated with their use. Until recently, much of the risk assessments have been focused on people with direct contact with the herbicides, i.e. those who manufacture, mix, and apply the chemicals, but recent attention has shifted to non-occupational exposures due to drift (Ames 2002). Drift occurs when a chemical is transported by air currents out of a targeted area during application (De Schampheleire et al. 2009). People are at risk of herbicide exposure in non-target areas, which include schools and neighborhoods adjacent to areas in which herbicides are applied (Ames 2002, Alarcon et al. 2005). Pesticides have been shown to induce acute (Alarcon et al. 2005) and chronic illnesses (Alavanja et al. 2003), and herbicides have off target effects on neighboring plant communities by reducing species diversity (De Snoo and Van der Poll 1999).

Drift is influenced by factors including application technique, physical properties of the product, and weather (De Schampheleire et al. 2009). The amount of drift also depends on the application method. All sprayers are prone to some amount of drift (Kleijn and Snoeijing 1997), some over 50 m (Smith 1989, Fox et al. 1993). Other technologies have little to none. One of these technologies is the Diamond Wet-Blade system which contains the herbicide within the mowing deck. A study on a prototype mower has shown that the Wet-Blade system had significantly less drift than broadcast sprays when tested on a well maintained lawn (Askew 2007).

1.5.3. Costs to control invasive plants with the Wet-Blade system

Weed control is expensive. Control of invasive plants in croplands costs approximately $3 billion per year (Pimentel et al. 2005). Though not as high as agriculture, the cost of weed control on United States roadsides was $276 million per year in the 1990s (Westbrooks 1998), which included herbicide purchases and application expenses. Mowing adds to the cost of roadside maintenance. Mowing pasture can range between $35-100 per ha (Beck and Sebastian 2000), and the costs of mowing the roadside may be approximately the same if similar equipment is used. Currently, when a mowing and herbicide application is utilized, the roadside will be mowed and the worker will return at a later date to apply herbicide, which can essentially double the costs because twice the labor time is needed along with the additional fuel costs. It has been stated that the Wet-Blade reduces weed management costs by half (Anonymous n.d.)

1.6. Objectives

Objective # 1: Improve weed control:

We hope our research will provide land managers with another tool in their ‘toolbox’ of treatments options. A healthy roadside environment reduces maintenance costs, aids in preserving the roadside surface, provides safety for vehicles and travelers, limits liability for the governing agency, and improves the overall driving experience (Mn/DOT 2000-19).

Objective # 2: Reduce herbicide use through integrated weed management:

Rather than a broadcast application of herbicide, the Wet-Blade System applies herbicide only to the cut surface of the vegetation. This technique greatly reduces the amount of herbicide used. Less herbicide will result in reduced environmental pollution, improved environmental stewardship and clean water practices.

Objective #3: Reduce worker and environmental exposure:

The application of herbicide to the cut surface results in reduced herbicide drift. Less drift translated into reduced water pollution, off target damage, and applicator exposure. The result of which is a sustainable weed control program within MnDOT’s managed areas.

** All three objectives dovetail into the 2008 MnDOT strategic direction for research: Green roads: in construction/maintenance, environmental stewardship, and clean water practices.

1.7. Report organization

This report begins with an introductory chapter discussing the role roadside rights-of-way play as habitat for invasive species and their role contributing to the spread of invasive species. The introduction also describes the biology and current management practices for the two species looked at during this study, *Phragmites australis* and *Cirsium arvense*. The introduction concludes by describing Wet-Blade technology and its current use as a weed management tool. Chapter 2 is a literature review on *Cirsium arvense* management and the potential for the Wet-

Blade to improve the control of *Cirsium arvense*. Chapter 3 describes the experimental design and methods of this study, Chapter 4 reports the results, and conclusions are discussed in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

There are over 6.2 million km of public roads in the United States (National Research Council 1997). A major attribute of these roadways is their high incidence of invasive species. Roadsides serve as ideal habitats for invasive species to thrive because they are routinely mowed to maintain an open canopy, have consistently moist soils, and in northern latitudes, have high soil salinity due to deicer applications throughout the winters (DiTommaso 2004; Richburg et al. 2001). Because populations of invasive plants can be large along roadsides there is great potential for reproduction and dispersal (Harrison et al. 2002; Tyser and Worley 1992). Therefore, control of invasive species along roadsides is critical, particularly of Canada thistle [*Cirsium arvense* (L.) Scop.], a serious weed in these areas (Foote et al. 1970).

Canada thistle was introduced to Quebec and Ontario, Canada by early colonizers through contaminated crop seeds (Hodgson 1964) and has since spread throughout North America. Canada thistle now infests 5.1 billion ha in the U.S. (Duncan et al. 2004). It has proven to be a severe invader of natural areas and agricultural fields (Donald 1994), and thus has become one of the most costly invasive species due to crop losses and management (Pimentel et al. 2000). Canada thistle heights range between 30 and 150 cm tall, with wide ranging phenological and morphological plasticity (Hodgson 1964). Canada thistle grows exceptionally well along roadsides because it is a shade intolerant (Holm et al. 1977), highly salt tolerant (Wilson 1979), perennial forb (Moore 1975) that is able to reproduce sexually by seeds and asexually by stem and root fragments (Bostock and Benton 1979; Hamdoun 1972). Population expansion can occur at a rate of about 2 m per year (Amor and Harris 1974).

Control of Canada thistle has been attempted with many herbicide formulations. Late summer applications of picloram have been shown to control populations most effectively (Beck and Sebastian 2000; Foote et al. 1970; Moore 1975). Aminopyralid, a pyridine carboxylic acid herbicide (Hare et al. 2005), controls Canada thistle with the same efficacy as picloram, with both spring and fall applications controlling 89 to 97% (Enloe et al. 2007). Aminopyralid has a low absorption and translocation rate in Canada thistle, but it has been shown to be more affective at control at lower rates than the similar clopyralid (Bukun et al. 2009; Enloe et al. 2007). Only approximately 60% of foliar applied aminopyralid was absorbed into Canada thistle, and less than 10% translocated to the roots (Bukun et al. 2009); however, this herbicide has been shown to provide over 90% control even at low rates of 80 g a.i. ha^{-1} (Enloe et al. 2007). Mowing alone has had little effect on Canada thistle, and mowing prior to herbicide application only weakly improved control; therefore, mowing alone has not been recommended as a control measure (Beck and Sebastian 2000).

The Diamond Wet-Blade (Diamond Mowers Inc., Sioux Falls, SD) system is a combination mowing herbicide system that simultaneously applies herbicide to cut stem surfaces, and ideally results in translocation of the chemical to belowground tissue. Using sheers coated with herbicide, Wahlers et al. (1997a) recorded that up to 90% of the herbicides clopyralid and triclopyr was absorbed by cut dogfennel [*Eupatorium capillifolium* (Lam.) Small] stems, of which 7% was translocated to root tissue. Cut stem applications of herbicide to dogfennel resulted in > 67% reduction in biomass and plant regrowth for all herbicide concentrations tested (Wahlers et al. 1997b). The Wet-Blade system has been shown to provide control of dogfennel, annual lespedeza [Kummerowia striata (Thunb.) Schindl.], and red and white clovers (*Trifolium pratense* L. and *T. repens* L., respectively) (Henson et al. 2003; Jester et al. 2009). The Wet-Blade has also been shown to effectively inoculate tropical soda apple (*Solanum viarum* Dunal) with bacterial and viral biological control agents (Charudattan et al. 2001). The system does not improve control for all plants. For example, when compared to similar rates of broadcast spray applications, the Wet-Blade provided unsatisfactory control of southern wax myrtle [*Myrica cerifera* (L.) Small] (Sellers and Mullahey 2008) and crabgrass [*Digitaria sanguinalis* (L.) Scop.] (Barker et al. 2005). Application of plant growth inhibitors using the Wet-Blade did not suppress seedhead production or provide better control of broomsedge (*Andropogon virginicus* L.), white clover, tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.], or bahiagrass (*Paspalum notatum* Flueggé) than broadcast sprays (Gannon and Yelverton 2011; Hixson et al. 2007).

Although the control of invasive species using the Wet-Blade is comparable to broadcast spray treatment, its use may have implications for reducing environmental contamination through herbicide drift. Drift occurs when a chemical is transported out of a targeted area during application (De Schampheleire et al. 2009). In addition to the equipment operator, people are at risk of herbicide exposure in non-target areas, which include schools and neighborhoods adjacent to areas where herbicides are applied (Alarcon et al. 2005; Ames 2002). Drift is influenced by factors including application equipment, physical properties of the product, and weather (De Schampheleire et al. 2009). All sprayers are prone to some amount of drift (Kleijn and Snoeijing 1997), with some sprayers producing drift over 50 m (Fox et al. 1993; Smith 1989); however, the Wet-Blade has been shown to greatly reduce herbicide drift when used on turf. Askew (2007) had shown that a Wet-Blade system affixed to a riding lawnmower resulted in no detectable drift when treating a maintained lawn. Conversely, herbicide drift from pump sprayer, spray gun, and rear mounted boom sprayer was detected up to 2 m from the application site (Askew 2007).

There have been few papers published regarding herbaceous weed control using the commercially available Wet-Blade technology; however, no literature could be found that evaluated the efficacy of the Wet-Blade system when seasonal timing and rate of herbicide application is considered. Additionally, there was no literature that discussed the drift produced and the costs to maintain and operate a Wet-Blade system versus broadcast herbicide applications and mowing along roadside right-of ways. Land managers must use the best tools that increase weed control and reduce any risks associated with pesticide drift. This study aimed to integrate not only the weed control aspect of the technology but also assess environmental contamination and operational costs. The objectives of this study were to: 1) evaluate the efficacy of the Wet-Blade system to control Canada thistle along roadside rights-of-way across seasons and application rates in comparison to broadcast spraying and mowing; 2) assess the potential for herbicide drift by both methods of application, and 3) estimate the operational costs of the Wet-Blade versus broadcast and mow only treatment options.

CHAPTER 3: EXPERIMENTAL DESIGN AND MATERIALS

3.1. Cirsium arvense control

Two sites along interstate highway rights-of-way were selected in the greater Minneapolis/St. Paul, MN area ("St. Paul" site: 44°57'3.78"N, 93° 1'17.33"W and "Blaine site": 45° 8'35.38"N, 93°11'8.59"W). Vegetation in ten 0.25 m^2 quadrats was sampled at each site prior to the experimental treatments. Both the St. Paul and the Blaine sites were dominated primarily by Canada thistle [73.2 ± 7.3 % and 51.1 ± 10.7 %, respectively (mean ± 1 SE)], reed canary grass (Phalaris arundinacea L.)(17.4 ± 7.5 % and 2.4± 2.4 %), and Kentucky bluegrass (Poa pratensis L.)(9.3 ± 5.7 % and 40.0 ± 9.1 %), with intermittent populations (< 7 % total at each site) of smooth brome (Bromus inermis Leyss.), yellow rocket (Barbarea vulgaris W.T. Aiton), tall nettle (Urtica procera Muhl. ex Willd.), and willow (Salix spp). The experiment was a split-block design with blocks representing one of three seasonal timing treatments (timing): spring-only application (Sp), fall-only application (Fa), and fall-spring (FS) applications. Each block was divided into 4.6 m × 7 m subplots in which application rate (low, medium, or high) and application equipment (Wet-Blade or broadcast spray) was randomly assigned. Sp applications occurred between 24 and 27 May 2010, Fa application between 28 and 30 September 2010, and the FS treatment had the first application between 28 and 30 September 2010 and a second application between 23 and 26 May 2011. These dates were chosen because applications of aminopyralid during both these seasons were previously shown to be highly effective (Enloe et al. 2007). The herbicide Milestone (Dow AgrioSciences LLC., Indianapolis, IN.), with the active ingredient (a.i.) aminopyralid, was used at 88 g a.i. ha^{-1}(low), 105 g a.i. ha^{-1} (medium) and 123 g a.i. ha^{-1} (high). Both the Wet-Blade and broadcast spray herbicide applications were conducted by a certified applicator with a 60 horsepower tractor equipped with a side-mounted Wet-Blade mower deck and a side-mounted boomless sprayer. The systems were computer operated to adjust the flow rate of the herbicide accordingly with the speed of the tractor. Although the wind speed was less than 1 km h^{-1}during all treatments, tarps were used to cover adjacent plots to prevent herbicide drift from affecting non-target treatments. Three untreated control plots were included in each block and were used to calculate the effect size of the treatments as a percent difference using the equation:

$$\text{Difference (\%)} = [(T_{in}-C_i)/C_i)]*100 \qquad [3.1]$$

Where C_i is the control mean of block i, T_{in} is the measurement of plot n in block i. Mow-only plots were included for comparison. There were three replications of each treatment at each location, for a combined total of 144 plots.

To evaluate control Canada thistle density was determined by counting the stems in three to five randomly placed 0.25 m^2 quadrats in each plot once a year for two years after treatments. Sampling was conducted between 21 and 25 September of each year when there was no evidence of aboveground growth at the end of the two growing seasons immediately after treatment. All plants within each quadrat were harvested, separated by species, dried at 65°C to a constant weight, and then weighed using a PN-2100B precision balance (American Weigh Scales, Inc. Norcross, Georgia). The subsamples within each plot were averaged to serve as a single measurement.

The treatment effect on Canada thistle density and biomass was examined using a mixed-effects analysis of variance (ANOVA) (Montgomery 2009) with site location treated as a random effect and timing, equipment, and herbicide rate treated as main effects. The biomass of all other species was combined and analyzed using mixed effects ANOVA to determine the treatment effect on the growth of non-target species. The mow-only treatments were not included in the ANOVA analyses; however, mow-only was compared to the control treatments using a student's t-test to determine if there was a mowing effect. Each growing season was analyzed separately. All post-hoc comparisons were performed using Tukey's HSD (α of 0.05). All analyses were performed using JMP 9.0 (SAS Institute Inc., Cary, NC; SAS Institute 2010).

3.2. Herbicide drift

A second pair of sites along roadside rights-of-way were selected in the greater Minneapolis/St. Paul, MN area (45º08'37.3"N, 093º10'58.2"W and 45º04'15.5"N, 093º10'05.7"W). The two sites were dominated by Canada thistle and reed canary grass. At each site, six 3.0 m x 1.5 m plots were established. One Whatman #2 filter paper (5.5 cm diameter) was placed on the ground in the center of each plot. Fourteen additional filter papers were placed in a straight line on the ground 0.25 m, 0.5 m, 0.75 m, 1 m, 1.5 m, 2.0 m, 3.0 m, 4.0 m, 5.0 m, 6.0 m, 7.0 m, 8.0 m, 9.0 m, and 10.0 m downwind from each plot edge. Prior to treatment, blazon dye (Milliken Chemical, Spartanburg, SC) was mixed into the herbicide tank to form a 1 % solution. Three of the plots at each site were treated with the Wet-Blade system and the other three were treated with a broadcast application. Aminopyralid was used at a rate of 123 g a.i. ha^{-1} for both treatments. The wind speed was monitored with a Mini Environmental Quality Meter (SPER Scientific, Scottsdale, AZ) and varied between 3.22 and 12.6 km hr^{-1} during treatments. Herbicide drift was measured using methods modified from Askew (2007). After treatment, each filter paper was immediately placed into a 6 dram glass vial. Dye was extracted from the filter papers by soaking them in 15 ml distilled water for 24 hr. The light absorbency of 200 µl of each solution was analyzed using a Multiskan microplate spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA) at a wavelength of 629 nm (Askew 2007). The absorbency of the 1 % tank solution served as the baseline. Drift was calculated as a percentage of the baseline absorbency.

Light absorbency data were analyzed using MANOVA to test the effects application equipment had on drift throughout the 10 m distance. Subsequent t-tests were used to compare treatment effects at each distance. Nonlinear regression was used to model herbicide deposition across distance (Rautmann et al. 2001). All analyses were performed using JMP 9.0 (SAS Institute Inc., Cary, NC; SAS Institute 2010) at an α of 0.05.

3.3. Cost analysis

For practical application purposes the cost analysis is presented in US customary units of measurement rather than metric. The costs of Canada thistle control using both the Wet-Blade and broadcast herbicide were estimated using operational costs of the equipment for a tractor equipped with a side and rear mounted Wet-Blade system, one with a side mounted boomless broadcast sprayer, and a truck with a boomless sprayer. Cost analyses consisted of expenditures for labor, maintenance, repairs, fuel, and herbicide costs. Depreciation of the equipment was also accounted for. Though mowing is not used as a means of weed control in Minnesota, roadside rights-of-way are mowed partially (approximately 8 feet from the road) multiple times a year, and entirely (from the road to the fence) every 5 years for routine maintenance purposes such as maintaining a sightline and preventing snow from drifting onto the road. Because broadcast herbicide applications could be followed by a scheduled maintenance mowing, the cost of broadcast with a subsequent mowing of the entire right-of-way was also calculated to compare to Wet-Blade application. The Wet-Blade application would serve as both a concurrent herbicide application and maintenance mowing.

CHAPTER 4: RESULTS

The Blaine site received a large amount of precipitation during the spring months in 2011, which resulted in soft, water saturated soil. Therefore, the spring application of the FS treatment at the Blaine site was unable to be conducted because the equipment could not be operated safely. The fall portion of the application, however, was conducted in that block, so those plots were included in the analyses as Fa treatments. Additionally, a large willow tree fell into three plots in the Sp treatment at the Blaine site, and two FS plots at the St. Paul site were over grown with staghorn sumac (*Rhus typhina* L.). These five plots were not included in the analyses.

4.1. Cirsium arvense control

Thistle density

Year 1: Mowing alone did not reduce the density of thistle stems at the end of year 1 compared to the untreated control plots (P = 0.21). There was also no equipment effect at the end of the first growing season (P = 0.83)—the Wet Blade effect was equivalent to broadcast herbicide application and did not enhance control of Canada thistle. Because there was no significant difference between the equipment used, data were combined across equipment for further analyses. There was a significant timing by rate interaction at the end of the first growing season (P = 0.01). Treatments at the high rate resulted in density reductions ranging from 77.0 ± 11.9% (Mean ± 1SE) following the Fa treatment to 100 ± 0% following the FS treatment (Figure 4.1). Treatments at the low rate showed greater variability of Canada thistle control, ranging from 4.7 ± 25.3% for the FS treatments to an 84.7 ± 8.7% decrease in density during the Fa application. Both the low rate applied in the FS treatment and the Fa application of medium rate did not provide a significant decrease in Canada thistle density after the first growing season (10.9 ± 47.4% decrease).

Year 2: Mowing alone also did not reduce the density of thistle stems at the end of year 2 compared to the untreated control plots (P = 0.72). There were neither equipment effects (P = 0.81), nor any significant treatment effects on density at the end of the second growing season (P = 0.98). All timings and rates did, however, result in significant decreases in Canada thistle density ($P \leq 0.05$) except for the low rate applied in the Fa and FS timing, and the Fa high rate ($P > 0.05$) (Figure 4.1). Though not statistically different than any of the other treatments, Sp applications of the high and medium rates and the Fa high rate each provided greater than 90% control after the second growing season.

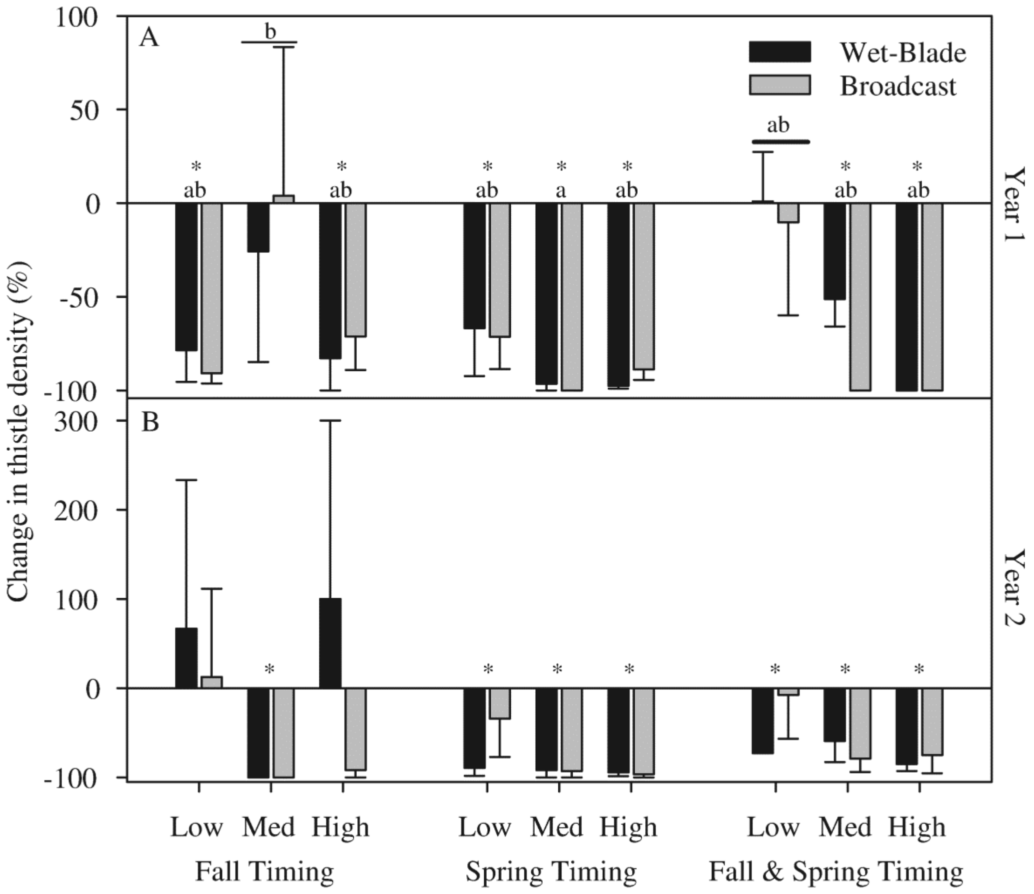

Figure 1. Change in thistle density when compared to the control as an effect of timing and herbicide application rate at the end of the A) first growing season and B) second growing season after treatment. Different letters indicate significant differences between treatments (timing × rate) ($P \leq 0.05$). Treatments with an asterisk (*) indicate a significant difference between treatments (timing × rate) and control group ($P \leq 0.05$). Error bars indicate 1 SE.

Thistle biomass per m^2

Year 1: Timing had no effect on the mowing efficacy ($P = 0.44$); however, mowing alone did decrease the aboveground biomass of Canada thistle during the first growing season ($P = 0.03$). The control plots had 94.0 ± 22.3 g m^{-2} Canada thistle biomass compared to the mowed plots that had 57.4 ± 20.6 g m^{-2}, a 38.9% difference. Similar to density, the application equipment had no effect on thistle biomass (both seasons $P = 0.75$). Data were combined across equipment for further analyses. At the end of the first growing season, there was a significant timing by rate interaction ($P = 0.02$)(Figure 4.2). High application rates resulted in a reduction of biomass between 79.7 ± 10.2% after the Fa treatment and 100 ± 0% after the FS treatment. When a medium rate of herbicide was used, Canada thistle biomass was reduced 96.8 ± 2.1% and 99.5 ± 0.5% in the FS and Sp timing treatments, respectively. The medium rate applied in the Fa treatment did not result in a reduction of Canada thistle biomass at the end of the first growing season ($P > 0.05$). The Sp treatments resulted in the smallest range of biomass reduction between herbicide rates. The Sp low treatment decreased Canada thistle biomass by 70.6 ± 16.1% and the medium rate decreased the biomass by 99.5 ± 0.5% (Figure 4.2a).

Year 2: There was no difference between mowing and the control treatments ($P = 0.31$), and timing had no effect on the mowing efficacy after the second growing season ($P = 0.97$). Additionally, the application equipment had no effect on thistle biomass ($P = 0.62$). At the end of the second growing season, there were no differences between any treatments ($P > 0.05$)(Figure 4.2b); however, most of the treatments did significantly reduce Canada thistle biomass. When compared to the control, only the Sp timing resulted in decreases of biomass for all rates ($P < 0.05$). Fa and FS low and Fa high treatments resulted in mean increases in biomass, although these increases were not significant. The Fa medium treatment had a 100 ± 0% reduction in biomass, and both Sp medium and high treatments provided reductions of 94.9 ± 3.4% and 97.2 ± 2.1%, respectively. Similar to the first growing season, the Sp timing resulted in consistently large reductions in biomass that ranged from 71.2 ± 25.0% when a low herbicide rate was used to 97.2 ± 2.1% for high rates.

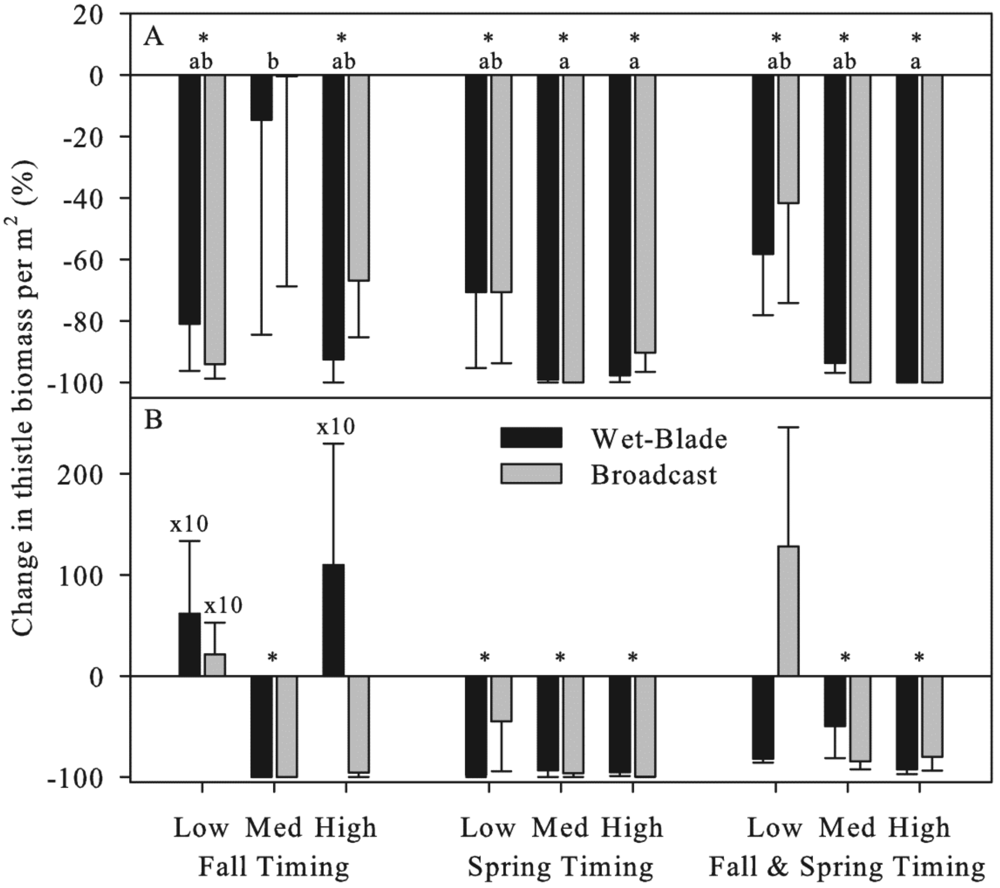

Figure 2. Change in thistle biomass m^{-2} when compared to the control as an effect of timing and herbicide application rate A) one growing season and B) two growing seasons after treatment. Different letters indicate significant differences between treatments (timing × rate) ($P \leq 0.05$). Treatments with an asterisk (*) indicate a significant difference between treatments (timing × rate) and control group ($P \leq 0.05$). Note that the Fall low Wet-Blade and broadcast and high Wet-Blade treatments are 10 times greater than what is displayed in the figure. Error bars indicate 1 SE.

Biomass per individual thistle plant

Year 1: At the end of year one, the mean biomass of individual Canada thistle plants in the mowing treatments were slightly smaller (1.8 ± 0.5 g) than those in the control group (2.4 ± 0.5 g); however, these differences were not significant ($P = 0.41$). There were no equipment effects ($P = 0.56$), the Wet-Blade and broadcast application equipment affected individual plant biomass equally, so data were combined for further analyses. There was a timing by rate interaction after the first growing season ($P = 0.03$) (Figure 4.3). During the first growing season, all treatments resulted in significant decreases in the size of plants compared to the control group ($P \leq 0.05$). The FS high rate killed all of the plants in this treatment, so there was a 100% ± 0% decrease in plant size. There were thistle plants present in all the other treatments. The Sp and FS timings at the medium rate reduced the biomass per plant 99.4 ± 0.6% and 96.5 ± 1.8%, respectively. The Fa medium rate resulted in the smallest decrease in the biomass per plant, 52.9 ± 19.8 %. The Sp treatments consistently reduced plant size by over 80% across all herbicide rates.

Year 2: After the second growing seasons, mowing had no effect on the mean biomass of individual Canada thistle plants ($P = 0.12$). There were no differences between any treatments the second year ($P > 0.05$) (Figure 4.3). The Canada thistle plants in all the low rate treatments rebounded, and showed no significant decrease in their biomass ($P > 0.05$), though the Fa and FS in that rate had mean increases in size. The plants in the Fa high treatment surprisingly rebounded and had a mean increase in biomass, though not significant. The Fa medium rate, on the other hand, killed all the thistles in the treatment after two growing seasons. The Sp high treatment had the best lasting effect—plants in that treatment were reduced by 85.8 ± 7.1% during the first year and by 82.2 ± 11.5% the second year (Figure 4.3).

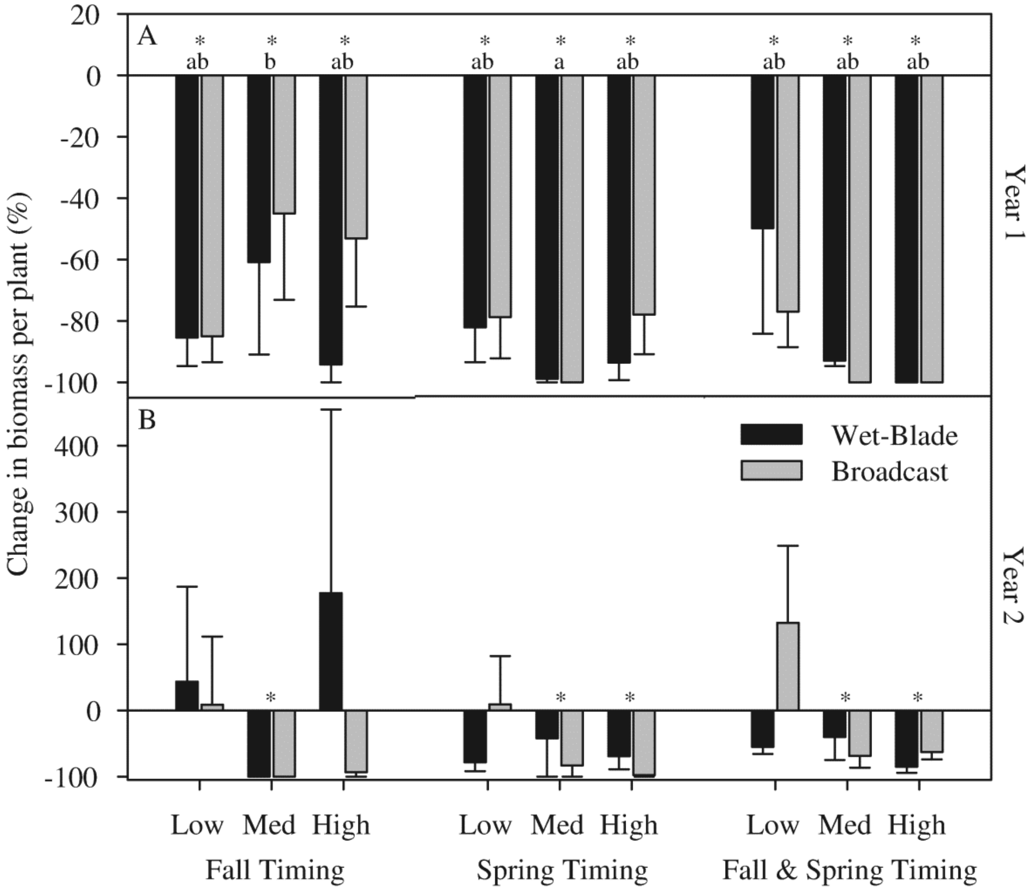

Figure 3. Change in thistle biomass plant^{-1} when compared to the control as an effect of timing and herbicide application rate A) one growing season and B) two growing season after treatment. Different letters indicate significant differences ($P \leq 0.05$). Treatments with an asterisk (*) indicate a significant difference between treatments (timing × rate) and control group ($P \leq 0.05$). Error bars indicate 1 SE.

Non-target plant biomass

Year 1: There were no mowing effects on non-target plant biomass at the end of year one ($P = 0.13$). The non-thistle plants consisted mostly of reed canary grass, smooth brome, and Kentucky bluegrass. There was a significant timing by rate effect on non-thistle biomass after the first growing season ($P = 0.03$)(Figure 4.4). The FS treatments had the largest increases in non-thistle biomass ranging from increases of 66.8 ± 27.9% in the low treatment to 141 ± 33% and 253.5 ± 70.6% in the high and medium treatments, respectively. The Fa low treatment had the smallest increase in biomass, 27.3 ± 12.7%.

Year 2: There were no mowing effects on non-thistle plant biomass at the end of year two ($P = 0.15$). During the second year, only the timing effect was significant ($P < 0.0001$)(Figure 4.4b). The Sp treatments resulted in the largest overall increase in biomass, while the Fa timing was the smallest.

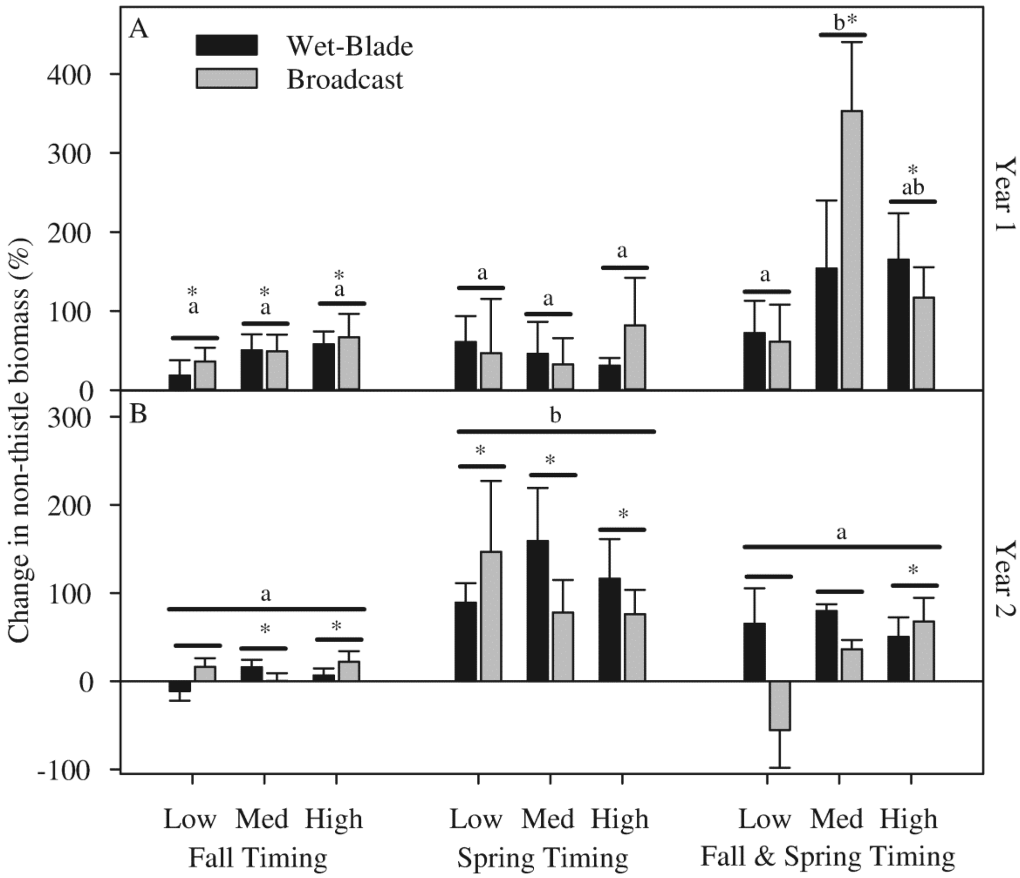

Figure 4. Change in non-thistle biomass m^{-2} when compared to the control as an effect of timing and herbicide application rate A) one growing season and B) two growing season after treatment. In graph A, different letters indicate significant differences between treatments (timing × rate) ($P \leq 0.05$). In graph B, different letters indicate significant differences between timing ($P \leq 0.05$). Treatments with an asterisk (*) indicate a significant difference between treatments (timing × rate) and control group ($P \leq 0.05$). Error bars indicate 1 SE.

4.2. Herbicide drift

Application equipment had an effect on herbicide drift. The broadcast treatments resulted in more drift over a greater distance than the Wet-Blade system ($P = 0.005$; Figure 4.5). An average of 44.3 ± 12.3 % (mean ± 1 SE) of the tank mix reached the soil surface in broadcast plots. Though not statistically significant, broadcast spray treatments produced detectable drift at levels that averaged between 2% and 10% of the tank mix up to a distance of 3 m from plots. The Wet-Blade system did not produce significant drift at any distance, including directly below the equipment which resulted in an average of 0.76 ± 0.39% of the tank mix ($P > 0.11$ for all distances)(Figure 4.5). Drift deposition for the broadcast spray equipment was best explained by the nonlinear equation:

$$y = 3.657x^{-0.774} \qquad [4.2]$$

Where y represents spray deposition and x is the distance from the treated area ($P < 0.001$, $r^2 = 0.59$). Drift as a function of distance did not result in a significant model for the Wet-Blade system.

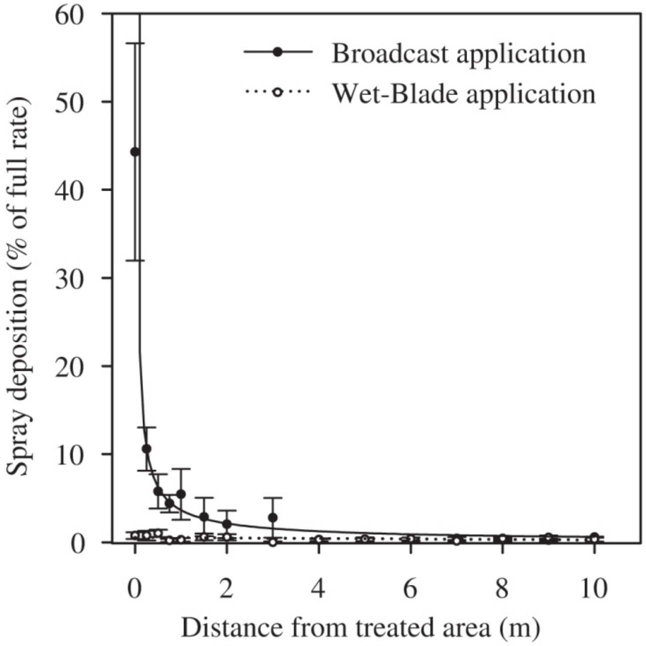

Figure.5. The amount of spray deposition detected as a function of distance after a Wet-Blade or broadcast spray herbicide application. The solid line depicts the broadcast spray drift deposition explained by equation 4.2.

4.3. Cost analysis

The cost of the Wet-Blade operation was greater than that of the broadcast-only treatments (Table 1). Wet-Blade operations cost \$46.68 per acre while broadcast-only treatments cost \$22.87 per acre with the tractor and \$18.57 using the truck. The greater cost of the Wet-Blade operation is attributed to the increased labor and tractor operation costs. Technicians operate the Wet-Blade system at lower speeds (2.5-3 mph) than broadcast treatments (4 -5 mph) and trucks (10-15 mph). The Wet-Blade can only treat a 10 to 15 foot wide swath in a single pass, while the broadcast system can treat up to 35 feet perpendicular to the equipment. Because of the slower travel speeds and less area treated in a single pass, the Wet-Blade system requires 5 times the time to treat the same area as the broadcast sprayer mounted to a tractor, 18 minutes per acre and 3.6 minutes per acre, respectively. The truck is able to travel at a higher speed; therefore, it is able to treat an acre in 1.8 minutes at a lower cost.

In addition to the time spent treating the rights-of-way, there is also time associated with filling up the water tank as the Wet-Blade tractor uses a 25 gallon water tank. The Wet-Blade system uses only 1 gallon of water per acre; therefore, the tank does not need to be refilled throughout the workday and is able to treat 3 acres per hour. The broadcast spraying equipment mounted on the tractor uses a larger tank, 250 gallons, and expends more water per acre at 25 gallons per acre. It requires a refill every 10 acres. It takes approximately 30 minutes to fill the water tank and drive back to the area to be treated. When refill time is factored in, the amount of area treated by a broadcast tractor would be reduced from 16.67 to 11.11 acres per hour.

The truck is equipped with a 750 gallon water tank, so it is able to treat 30 acres at 25 gallons of water per acre before needing to refill; therefore, it would need to be refilled approximately every hour. Depending on where the nearest refilling station is, the truck can take about 30 minutes to fill and return to the site. Factoring in refill time, the truck is able to apply herbicides at a rate of 20 acres per hour.

If the broadcast herbicide treatment is followed by a subsequent maintenance mowing at a later date, then the cost of mowing adds substantially to the treatment costs. The cost of a broadcast treatment with a truck followed by mowing is $48.02 per acre; whereas, the Wet-Blade requires no follow-up mowing. The simultaneous application of herbicide and mowing with the Wet-Blade system is 2.79% less costly per acre than a broadcast treatment of herbicide followed by a subsequent mowing. The cost difference between Wet-Blade treatment and mow only treatment is about 37%, due to the high cost of herbicides used; however, it would be reasonable to rotate the Wet-Blade treatment in with the routine mowing. This practice would prevent an additional broadcast treatment.

Table 1. Operational costs in US dollars associated with the Wet-Blade herbicide application system and broadcast herbicide application. All information was provided by the Minnesota Department of Transportation.

Method	Time (h ac^{-1})	Cost ac^{-1}				
		Labor[b]	Vehicle[c]	Equipment[d]	Herbicide[e]	Total
Tractor Mow	0.30	8.74	20.36	0.35	0.00	29.45
Tractor Wet-Blade	0.30	8.74	20.36	0.58	17.00	46.68
Tractor Broadcast	0.06	1.75	4.07	0.05	17.00	22.87
Truck Broadcast	0.03	0.87	0.68	0.02	17.00	18.57
Tractor Broadcast & subsequent mow	0.36	10.48	24.44	0.39	17.00	52.31
Truck Broadcast & subsequent mow	0.33	9.61	21.04	0.37	17.00	48.02

[a] Does not include time to refill water tank

[b] Costs based on 2012 technician labor costs at $29.12 h^{-1}

[c] Includes maintenance, repairs, fuel, and depreciation

[d] Includes maintenance, repairs, and depreciation

[e] Treatments at an herbicide rate of 7 oz ac^{-1} with surfactant

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Cirsium arvense control

Based on the decreases in thistle density, thistle biomass, and plant size, we conclude that both the Wet-Blade and broadcast applications of aminopyralid along roadside rights-of-way were equally effective at controlling Canada thistle. This agrees with previous research that shows the Wet-Blade is equally effective as broadcast spraying for controlling unwanted species such as dogfennel (Henson et al. 2003), bahiagrass (Gannon and Yelverton 2011), and white clover (Jester et al. 2009). The herbicide aminopyralid works very well at rates greater than 88 g a.i ha^{-1}, regardless of application method. We choose to use the suggested rates listed on the label for this study to determine if there would be an equipment × rate interaction, which there were none. The rates used in this study may have been too high to show an equipment effect; therefore, future studies should look at lower herbicide rates in order to determine if the Wet-Blade application system can better control Canada thistle at rates lower than suggested. Beck and Sebastian (2007) showed that mowing alone did not control Canada thistle, and our results support their finding. A single mowing, or in the case of the FS treatment, two mowings, did not disrupt the plants ability to grow. Early season mowing can prevent the plants from flowering (Bicksler and Masiunas 2009), and thus reduce the potential for sexual reproduction; however, Canada thistle primarily reproduces asexually, so mowing alone would have little effect on controlling thistle reproduction.

An immediate reduction in the Canada thistle density is important for successful, long term management. A goal of management is to reduce the number of reproducing individuals in a population. The high herbicide rates decreased the thistle population by greater than 77%, while the medium rate was only effective when applied during the Sp and FS treatments. If immediate control of Canada thistle is necessary, spring treatments at medium and high rates are sufficient and would not require a second herbicide application as in the FS treatment. During the spring timing, all rates provided sufficient control of Canada thistle; however, the medium and high rates provided the most control over the longest period of time. Enloe et al. (2007) showed that rates between 80 and 100 g a.i. ha^{-1} resulted in 88 to 93% decreases in percent cover of the Canada thistle after one year when herbicide was applied in the spring. These are slightly better results using comparable rates than our results. The discrepancy between studies may be the different methods used to assess control. We counted thistle stems and weighed biomass, while Enloe et al. (2007) gauged percent cover subjectively though visual estimates.

Unlike Enloe et al. (2007), who showed that a fall timing of aminopyralid effectively controlled over 90% of the Canada thistle, we had highly variable thistle control during the fall timing. Herbicide treatments conducted in the fall are speculated to provide improved Canada thistle control due to a disruption of carbohydrate concentrations in the roots (Wilson et al. 2006), thus resulting in the best effects after first frost (Wilson and Michiels 2003). The Fa treatments in our study, though, were variable and interestingly the medium rate had very poor control the first season and 100% control the second. The low and high rates resulted in an opposite trend. One Fa broadcast plot at the medium rate at the St. Paul site had 102.8 thistle stems m^{-2} at the end of the first growing season and a Wet-blade plot treated in the same timing and rate had 74.64 stems m^{-2}. The thistle densities in the same plots were reduced to 2.8 and 0 thistle stems m^{-2}, respectively at the end of the second growing season. The other Fa medium rate plots did, however, have thistle densities comparable to the other rates after the first season (between 0 and 17.2 thistle stems m^{-2}). It appears perhaps that the initial thistle populations in those two plots were so dense and established that there was a lag in thistle control, thus resulting in the large variation shown in these treatments within and between years. If the two outlying plots are disregarded, the fall treatments would show comparable control in the first season. The second season, however, had unexpected reductions in Canada thistle density the Fa timing control plots at both sites. The Fa control plots had densities of 20.8 and 39.2 thistle stems m^{-2} at the St. Paul and Blaine sites, respectively, at the end of the first growing season. The control plot densities decreased to 0.04 and 0.36 thistle stems m^{-2}, respectively during the second growing season. We suspect that our fall treatments appear to have failed after the second growing season because the Fa blocks at both sites, including the control subplots, had low Canada thistle infestation relative to the Sp and FS blocks during second growing season not related to our treatments. Thistle densities in the control plots of the Sp and FS blocks were similar (24 and 29.2 thistle stems m^{-2}, respectively). The low thistle infestation in the untreated plots of the Fa block may have artificially amplified small effect sizes when calculated as a percent difference from the control. Previous studies have found that fall herbicide treatments work well, if not better, on Canada thistle, than early season treatments, particularly when herbicides are applied during the bolting stage (Hunter 1995; Miller and Lym 1998) due to the herbicide's effect on root carbohydrate levels (Wilson et al. 2006).

A major aim of invasive species management is to decrease the target species while concurrently increasing the dominance of the desirable non-target species, consequently changing the plant community (Krueger-Mangold et al. 2006) to the desired composition to meet management needs. The non-target species would fill any niches or consume resources that become available due to the removal of the invasive species (Samuel and Lym 2008). Introducing or maintaining allelopathic species would also aid in Canada thistle resistance (Bicksler and Masiunas 2009). Treating Canada thistle infested plant communities with aminopyralid had been shown to reduce the Canada thistle density, while simultaneously increasing the dominance of forbs and monocots (Samuel and Lym 2008). In our study, mowing alone had no effect on the biomass of non-target species; however, in the herbicide treatments, regardless of the application equipment used, there was an increase in non-target plants. The Sp treatment would achieve management goals of increasing non-target plant biomass by stimulating the growth of non-thistle species and having a lasting effect into the second year. Mowing has been shown to have no effect on reed canary grass (Kilbride and Paveglio 1999) and smooth brome (Willson and Stubbendieck 1996), so if aminopyralid is applied using the Wet-Blade system, there would be no effect due to the mowing disturbance on these grasses.

5.2. Herbicide drift

Drift deposition produced by the broadcast equipment used in this study behaved similar to drift deposition as described by Askew (2007) and Rautmann et al. (2001). The Wet-Blade system produced negligible herbicide drift, whereas the broadcast spray resulted in detectable, albeit not significant, drift on the soil surface three meters off target. At 1 m and beyond, there were no differences between the two systems; however, the greater variability in drift associated with the broadcast spray equipment introduces a source of error for applicators and an increased likelihood of drift. It is likely that wind speed played a role in broadcast application drift; therefore, applicators should ensure that wind speeds are low to ensure no greater drift than was measured in this study. Increasing the droplet size by reducing spray pressures or increasing the size of the orifice will reduce the herbicide drift created by broadcast spraying equipment (Bode et al. 1976). Drift can also be mitigated during broadcast spraying by lowering boom height (Combellack et al. 1996) or installing a boom shroud (Wolf et al. 1993).

The Wet-Blade system contains all herbicide in the mowing deck and delivers the herbicide directly to the plant, rather than spraying the herbicide through the air prior to it reaching the plant. Where herbicide drift is a concern, such as in urban areas, near sensitive habitats, or near agricultural crops, the Wet-Blade system should be used to minimize drift. The Wet-Blade also discretely applies herbicide, thus minimizing its visual impact (Jester et al. 2009), which is an attribute especially valuable in areas where public perception is a concern, particularly where all herbicides are viewed as hazardous (Sparks and Shepherd 2006).

5.3. Cost analysis

Broadcast herbicide application with the truck is 60.21% less costly than Wet-Blade herbicide application alone; however, incorporating the Wet-Blade into the routine mowing cycle could lead to a 2.79% savings per acre if conducted once during the 5 year right-of-way mowing cycle. MnDOT maintains approximately 12,000 miles of roads and 185,000 acres of unpaved rights-of-way, 9% (16,650) of which is treated. The cost to conduct a broadcast herbicide treatment with the truck would cost \$309,190.50 (\$18.57 per acre × 16,650 acres) per year while using the Wet-Blade throughout the same area would cost \$777,222 (\$46.68 × 16,650) per year. The cost of using a broadcast herbicide followed by a routine mowing would increase that cost to \$799,533 (\$48.02/acre × 16,650 acres) over a treatment cycle, a 2.79% difference.

The Wet-Blade equipment is significantly more costly than broadcast spraying; however, there would be slight cost savings if a Wet-Blade herbicide treatment is conducted simultaneously with a maintenance mowing. However, due to the wear on the more expensive Wet-Blade equipment, judicious use of the Wet-Blade as an integrated weed management tool would be warranted along roadside rights-of-way, especially near sensitive areas where the risks of herbicide drift are greater than the cost of the Wet-Blade operation.

5.4. Recommendations

This study showed that the Wet-Blade system worked equally as well broadcast spraying in the control of Canada thistle. When using either the Wet-Blade or broadcast spray, fast and lasting control of Canada thistle is important for continued management. Quickly decreasing the dominance of Canada thistle in a managed area prior to seedhead production will reduce the ability of this species to sexually reproduce while long-term suppression will allow other species in the community to increase in population size and fill the niches previously occupied by Canada thistle. Factoring in fast and lasting effects, herbicide treatments of aminopyralid conducted in the spring are the best option for Canada thistle management. Although variability in efficacy depends on many factors (Gannon and Yelverton 2011), the spring treatments resulted in reductions in Canada thistle density, biomass, and size of individual plants across all rates with comparatively low variability within and between rates, while also increasing the biomass of non-target species. Similar to Beck and Sebastian (2000), we determined that mowing is not an option for Canada thistle management along roadside rights-of-way.

The Wet-Blade equipment is significantly more costly than broadcast spraying; however, there would be cost savings if a Wet-Blade herbicide treatment were conducted simultaneously with a maintenance mowing. The Wet-Blade system controls Canada thistle as well as broadcast spraying; therefore, use of the Wet-Blade as a low-risk, integrated weed management tool is recommended along roadside rights-of-way near sensitive areas where the risks of herbicide drift outweigh the cost of the Wet-Blade operation.

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