PRAIRIE RESPONSE TO CANADA THISTLE INFESTATION, AND NATIVE FORB RESPONSE TO AMINOCYCLOPYRACHLOR

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Prairie response to Canada thistle invasion was evaluated by comparison of forage yield between aminopyralid treated and non-treated infestations in North Dakota. In general, forage production was unaffected by Canada thistle in both grazed and wildland locations. The economic threshold was 37 stems m^{-2} for a treatment to be cost-effective. Canada thistle should still be controlled to improve overall flora quality. The susceptibility of 10 prairie forbs to aminocyclopyrachlor at 0, 35, 70, and 105 g ha^{-1} was evaluated in the greenhouse. Blue flag iris was tolerant and harebell was moderately tolerant to aminocyclopyrachlor. American licorice, prairie rose, purple prairie clover, and wild bergamot were moderately susceptible; however, plants may regrow in the field as some survived at 105 g ha^{-1}. Azure aster, Canada goldenrod, great blue lobelia, and purple coneflower were very susceptible to aminocyclopyrachlor and likely would be eliminated in the field.

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INTRODUCTION

Canada thistle [*Cirsium arvense* (L.) Scop.] is one of several noxious weeds that threatens the sustainability of many remaining natural grasslands (Mullin et al. 2000). Canada thistle has a long-standing history as a troublesome weed and was likely introduced to North America in the early 17th century as a hay or crop contaminate (Dewey 1901; Hansen 1918). By 1900, all states on or north of the 37th parallel had reported the weed present (Dewey 1901). The plant is now considered a noxious weed in 33 states (NRCS 2015a).

Canada thistle has been categorized as a competitive, ruderal perennial, which had infested over 5 million ha of range, pasture, and wildland in the United States by 2003 (Grime 2001; Lym and Duncan 2005). The plant can also be found in natural wetlands, cultivated cropland, roadways, and will thrive in disturbed, natural communities with open vegetation (Tiley 2010). Prairie restoration sites are especially susceptible to noxious weeds, such as Canada thistle (Gurevitch et al. 2006). Once established, the weed can spread relatively quickly by both seed and root (Hayden 1934).

Invasive plants, such as Canada thistle or leafy spurge (*Euphorbia esula* L.), cause extreme economic losses in the United States by a reduction in habitat, biodiversity, and grass production (Keane and Crawley 2002). Often, many desirable non-target species are injured as a result of chemical treatment, which may leave an area susceptible to further noxious weed establishment (Obrigawitch et al. 1997). The control of problem weeds at the expense of desirable, native plants is not an appropriate method for a weed management program. Once remediation is achieved, native plants need to remain for a healthy and sustainable plant community to reestablish (Crone et al. 2009).

Aminocyclopyrachlor is a new herbicide developed for broadleaf weed control in turf, rangeland, pastureland, and other non-crop areas (Anonymous 2009; Oliveira et al. 2013). Aminocyclopyrachlor has controlled many perennial weeds such as Canada thistle and leafy spurge (Lindenmayer et al. 2010; Lym 2010), but has caused damage to some native grasses (Conklin 2012; Hergert et al. 2015). Little information about the impact of aminocyclopyrachlor on desirable forb species is available. The objectives of this study were to determine: 1) the effect of Canada thistle density on forage production and 2) the efficacy of aminocyclopyrachlor on native forbs in a controlled environment. Two studies were conducted to determine the effect of Canada thistle on forage production. The first study compared production following Canada thistle control with aminopyralid while the second compared yield of infested to non-infested, side-by-side sites.

LITERATURE REVIEW

Prairie Response to Canada Thistle Infestation

Canada Thistle Biology and Ecology. Canada thistle has been categorized as a competitive, ruderal perennial, as the weed is often found in roadside ditches, rangeland, pastureland, cropland, and disturbed areas (Grime 2001; Tiley 2010). The ability to quickly spread and form dense colonies is due to the reproductive methods of the plant (Hoefer 1981). Canada thistle is dioecious with all flowers of an individual plant being either male or female (Moore 1975). The plant can produce upwards of 5300 seeds per stem under favorable conditions with the majority of seed production occurring in female plants (Hay 1937); however, seeds are occasionally found on male plants (Hodgson 1968). Due to competition from nearby grasses and forbs, very few seedlings are able to become established. Canada thistle primarily relies on an extensive root system that allows reproduction to occur vertically and laterally from randomly occurring root buds (Hayden 1934).

Canada thistle requires a 14 to 16 h photoperiod to bolt and flower from the rosette growth stage (Miller and Lym 1998). The current geological extent of the weed is primarily limited by temperature, moisture, and altitude. Mountain ranges in England, Scotland, and Wales, for example, are absent of Canada thistle in higher altitudes due to reduced temperatures and moisture compared to lower altitude areas (Halliday 1997; Tiley 2010). Canada thistle can be found in regions of India and Iceland, otherwise thought to be uninhabitable to the plant due to local climatic conditions (Guggisberg et al. 2012). Micro climates and tempered air from warm ocean currents likely allow these small populations to exist. Canada thistle thrives in conditions most favorable to many crop plants such as wheat or corn (Detmers 1927; Moore 1975). Open, sunny, clay soils with temperatures from 0 to 32 C and 30.5 to 101.5 cm of annual precipitation are ideal for the plant (Detmers 1927; Hodgson 1968). During optimum growing conditions, Canada thistle can produce dense infestations relatively quickly. The dense colonies can then displace native grasses and forbs by over-shading, competition for nutrients, and allelopathic tendencies, ultimately causing plant diversity to decrease (Hutchison 1992).

Canada Thistle Distribution and Genetic Diversity. Canada thistle is likely native to Eastern Europe and has spread globally through human migration and agricultural activity (Moore 1975; Tiley 2010). The herbaceous plant can be found across Europe and into the temperate areas of Asia, Japan, North America, Northern Africa, South Africa, Australia, and Chile (Figure 1). The distribution of Canada thistle generally follows latitudes associated with agriculture. In Eurasia, the weed can be found as far north as 68 N in Siberia, but thrives to ~58 N, and extends south to 30 N in Northern Africa (Moore 1975). In North America, the southern limit is 37 N and reaches northward to 58 to 59 N. In the southern hemisphere, 25 S is the northern edge in South America, Africa, Australia, and New Zealand (Holm et al. 1991). Predictive climate models suggest the reach of Canada thistle has yet to climax, with millions of hectares of habitable rangeland not yet colonized (Guggisberg et al. 2012).

There are three *Cirsium arvense* gene pools found in Europe geographically separated into Eastern Europe, Western Europe, and south of the Alps in Italy/Bosnia Herzegovina (Guggisberg et al. 2012). The east-west populations are genetically different, likely due to isolation-by-distance. Samples found at the junctions of these geographically separated gene pools tend to be an admixture of genes, creating a genetic gradient. Gene mixtures also may be found in areas not at these junctions. For example, in Scotland, Canada thistle gene pools are

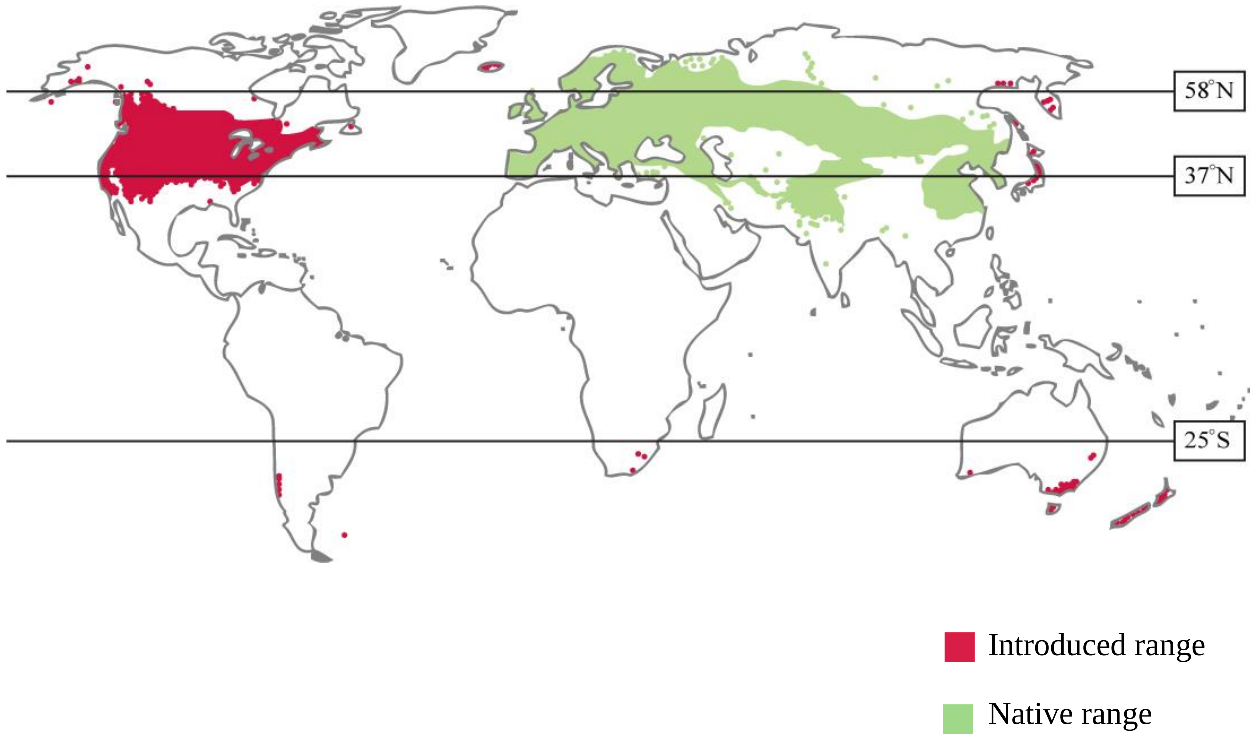

Figure 1. Current distributional range of Canada thistle based on Guggisberg et al. (2012).

generally comprised from plants found in Italy and Bosnia Herzegovina. Also, in Eastern Europe, a population almost completely consisting of genotypes of Western European origin exist within an area predominantly comprised of genotypes descended from Eastern Europe. The cause for these genetic anomalies are likely due to the movement of Canada thistle seed through human migration (Guggisberg et al. 2012; Hansen 1918).

Eastern Europe is thought to be the center of diversity of Canada thistle due to population samples exhibiting higher levels of allelic richness and private alleles than any other samples taken from Europe (Guggisberg et al. 2012). However, the high levels of genetic diversity may be partially due to the amount of hybridization that occurred in the region. The genus *Cirsium* includes roughly 350 species, many of which can be found in Southern Europe (Moore and Frankton 1974). Central Europe has the highest hybridization intensity with nearly 70 hybrids observed among 17 different local species, Canada thistle included (Bureš et al. 2010). An alternate explanation suggests high genetic diversity to be a result of a temperate refugia during the last ice age in Southern and Eastern Europe (Stewart and Lister 2001). Flora and fauna in these areas, during the end of the Pleistocene, were sheltered and sustained in stable microclimates, which could explain the high genetic diversity of Canada thistle and diversity within the genus *Cirsium.*

North America Colonization. Hansen (1918) speculated *Cirsium arvense* was introduced into Canada by French settlers, and later on by English and Dutch settlers in present day United States. Early settlers observed this weed in Canada, and shortly after, the plant was discovered in the New England states. Therefore, the introduction of *Cirsium arvense* was blamed on French settlers from Canada and the plant was referred to as "Canada thistle" (Dewey 1901). The first official recognition of the weed in the New England states was simultaneous with the discovery of plants in New York state, which suggests separate introductions (Hansen 1918). Canada thistle was then transported south and west, likely via straw packing material or small grain contaminates. By 1896, the weed had been declared noxious in 22 of the 25 states which had weed legislation (Evans 2002). By 1899, the noxious pest had occupied nearly every herbaceous community in North America north of the 37th parallel up to 58/59° N (Figure 1) (Dewey 1901). As of 2003, Canada thistle had infested over 5 million ha of range, pasture, and wildland in the United States (Lym and Duncan 2005) and currently is considered a noxious weed in 33 states (NRCS 2015a).

A newly introduced plant species depends heavily on a strong starting population and high genetic diversity to become successfully established (Holt et al. 2005). A large starting population will reduce the risk of early eradication, and genetic diversity allows natural selection to occur without elimination of an entire homogeneous population. Canada thistle likely underwent a genetic bottleneck upon introduction to North America, which is common among newly established alien species (Guggisberg et al. 2012; Novak and Mack 2005). However, current populations have very high genetic diversity (Guggisberg et al. 2012). The cause for high heterozygosity can be attributed to multiple introductions from Eastern and Western Europe on a recurrent basis (Marrs et al. 2008). North American Canada thistle population samples exhibit genes strongly associated with Western Europe or a mixture of Western and Eastern gene pools (Guggisberg et al. 2012). The former supports the theory of introduction by French, English, and Dutch settlers. The Eastern European Canada thistle alleles, found primarily in the Midwest, may be a result of a large number of Ukraine and Crimea settlers in 1874, who had transported the seed by contaminated packing material or seed stock (Krahn 1949). Guggisberg et al. (2012) supported this theory of Russian *Cirsium arvense* seed brought over, but as a contaminate on large cereal shipments to the Midwest in the late 1800s. The soil in the Midwest is similar to that of areas of Russia, which may have led to the transportation of contaminated cereal seed to be planted in the fertile soils of North America (Carleton 1900).

The Western European genotypes observed in North America differ greatly from the actual Western European samples (Guggisberg et al. 2012). Eastern European samples, conversely, exhibit fewer changes in genotype, suggesting the Western European plants have been in North America longer, allowing for evolution to occur. This affirms the theory of multiple introductions of Canada thistle from both Eastern and Western Europe, with the first introductions by French, Dutch, and English settlers.

Canada thistle populations in Eastern, Western, and Italy/Bosnia have slight adaptations to their respective environments (Guggisberg et al. 2012). The climate in eastern North

America, where Canada thistle first invaded the continent, resembles that of Russia, Ukraine, Belarus, and Central European mountain ranges (Carleton 1900). Canada thistle genotypes from this area would have been most adapted to eastern North America; however, historical data and genetic testing suggest the noxious weed was introduced from Western Europe (Dewey 1901; Guggisberg et al. 2012; Hansen 1918). The new, less fit, populations from Western Europe likely had to evolve and adapt prior to subsequent westward spread. Successive introductions from Central and Eastern Europe increased Canada thistle fitness and expansion into North America. Guggisberg et al. (2012) believed this scenario explained the time lag between the introduction of the weed in the early 17th century and the first eradication laws in the late 18th century, the assumed time when the weed spread throughout the New England States (Hansen 1918). However, the delayed noxious weed laws may simply be due to a low priority for weed regulations in the newly established governments of North America.

Canada Thistle Control. Canada thistle control has been both difficult and expensive to achieve in part because the plant vigorously reproduces by both seed and root (Hodgson 1964). Control efforts should concentrate on the reduction of vegetative growth, but not overlook seed production. Prevention of the dispersal of Canada thistle seed should inhibit the formation of new colonies and genetic diversity of the plant (Bodo Slotta et al. 2006). There are multiple methods to control Canada thistle, such as mechanical, biological, cultural, and chemical. Implementing two or more of these methods is often the best strategy to control noxious weeds (Masters and Nissen 1998; Hatcher & Melander 2003; Lym 2005).

Mechanical control, or cultivation, targets the new shoots and leaves. Cutting the top growth periodically prevents nutrient flow to the roots and reduces regrowth (Hodgson 1968). Mechanical control requires both time and fuel, and if not continually managed, the plant will rapidly re-establish. Also, mechanical methods spread the weed because Canada thistle can form shoots with sections of root as small as 1 cm long and 0.1 cm in diameter (Hamdoun 1972; Ziska et al. 2004). The incorporation of herbicides with tillage (i.e. rosette technique) has improved control of Canada thistle in crops from increased herbicide translocation to the roots (Miller and Lym 1998). The rosette technique also reduced the amount of herbicide required to adequately control Canada thistle.

Insect biological control agents have been effective in reducing some noxious weeds, such as leafy spurge (Cruttwell McFadyen 1998; Lym 2005). However, insect biological control for Canada thistle is rarely successful, and has negative effects on the native plant community. For example, the Canada thistle gall fly (*Urophora cardui* L.) only slightly reduced plant height (Peschken et al. 1982). The Canada thistle stem weevil (*Ceutorhynchus litura* F.) also has been unsuccessful in controlling the plant (Reed et al. 2006). Areas with dense populations of Canada thistle stem weevil have had up to 40% of stems damaged but weed density did not change. The larvae of the European weevil (*Larinus planus* F.) feeds on the flowers of Canada thistle and was believed to have been an effective biocontrol agent (McClay 1988); however, Louda and O'Brien (2002) report the European weevil has harmful, non-target effects on native thistle plants and minimal impact on Canada thistle.

The bacterial agent, *Pseudomonas syringae* pv. *tagetis* (PST), is a potential option for biological control of Canada thistle (Bailey et al. 2000). Tichich and Doll (2006) collected sap from plants naturally infected with PST and applied the bacteria in water with an organosilicone surfactant to healthy Canada thistle plants. A single application of PST resulted in apical chlorosis, and disease symptomology increased with multiple applications; however, Canada thistle was not adequately suppressed. Higher toxin levels of PST were likely required to translocate to the roots to improve control. *Puccinia punctiformis* (F. Strauss) Rohl. is another pathogen with potential use for controlling Canada thistle (Demers et al. 2006). *P. punctiformis* is a rust fungus which limits Canada thistle growth by reducing seed production and vegetative growth (French and Lightfield 1990). The rust fungus has been mostly unsuccessful in controlling Canada thistle; however, Berner et al. (2013) suggest mimicking the disease cycle of *P. punctiformis* to improve control. Collecting leaves bearing telia in mid-summer and re-distributing to healthy rosettes in the fall has increased disease incidence and improved control of Canada thistle.

Livestock management as a cultural control method has a large impact on weed control (Popay and Field 1996). De Bruijn and Bork (2006) found that rotational grazing at high intensity-low frequency was the best method for reducing Canada thistle density and biomass, and also increased forage quality. Short duration grazing methods did not effectively decrease Canada thistle stem density, and continuous grazing resulted in more severe infestations. Canada thistle density decreased the greatest in high intensity-low frequency grazing, likely due to season-long competition from forage regrowth. Defoliation and trampling by cattle also helped reduce Canada thistle density.

The use of mechanical, biological, and cultural methods to control Canada thistle can be effective; however, chemical is arguably the most effective method of weed control when used alone. Herbicides vary in target weed efficacy and chemical and environmental properties. Some herbicides, such as picloram, are effective for weed control yet injure many non-target species (Donald 1990). Picloram is used for deep rooted, woody and herbaceous weed control in non-crop areas, and was the first chemical found to provide long-term Canada thistle control (Donald 1990; EPA 1995). Dicamba (Shaner 2014d) and clopyralid (Shaner 2014c) will control

Canada thistle, and are both used in crop and non-crop areas (Miller and Lym 1998). Aminopyralid will control Canada thistle and, unlike picloram, has a low impact on non-target, desirable grass and forb species (Wilson et al. 2005).

Aminopyralid is applied at lower rates for weed control than other commercial products, such as picloram and clopyralid, which is environmentally beneficial in many ways (Enloe et al. 2007). Aminopyralid soil sorption is higher than other herbicides, such as picloram, which reduces soil mobility and the risk of leeching into groundwater (Fast et al. 2010). The herbicide is somewhat persistent in the soil and foliage (Rhodes and Phillips 2012). Remnant aminopyralid on consumed forage can be passed through the digestive system of animals and cause injury to broadleaf plants in the pasture and to crops or home gardens if used as fertilizer.

Aminopyralid has extremely low toxicity to mammals and is considered non-toxic to organisms such as birds, fish, and aquatic and terrestrial invertebrates (Jachetta et al. 2005). Plant species richness and diversity can be reduced by aminopyralid, but is countered by broadleaf weed control (Samuel and Lym 2008; Almquist and Lym 2010). Native grass coverage is often increased and resource competition decreased for remaining native broadleaf species. Increased grass coverage should lead towards a healthier rangeland community and improved resilience against future noxious weed establishment. The short-term loss in diversity will be outweighed by the long-term benefits of a more natural, sustainable ecosystem.

Canada Thistle Influence on Grazing. The monetary benefit associated with Canada thistle control is quite difficult to determine for a ranching enterprise (Grekul and Bork 2004). A rancher will have to discern how much more forage will grow post-treatment to decide if the effort and investment is economically worthwhile. A decrease in weed species density and cover will likely allow desirable prairie species to increase (Blumenthal et al. 2003). In Alberta, Canada, a direct correlation between Canada thistle density and change in grass yield was occasionally observed (Grekul and Bork 2004). A large increase in grass yield occurred after removal of high density Canada thistle. However, the herbage did not always increase after every treatment, possibly due to moisture availability, disturbance history, and site specific vegetation composition. Grekul and Bork (2004) suggest annual growing conditions and location characteristics may be as or more important than Canada thistle density when predicting herbage yield.

Canada thistle can harm livestock directly (e.g., scabby mouth disease, decrease animal weight and condition) and reduce crop quality and yield (Gourlay 2004; Popay and Field 1996). Revenue loss caused by Canada thistle is relatively unknown (Norland et al. 2013); however, studies of other noxious weeds such as leafy spurge (Lym and Kirby 1987; Lym and Messersmith 1985), velvet mesquite (*Prosopis velutina* Woot.) (Cable and Tschirley 1961), and big sagebrush (*Artemisia tridentata* Nutt.) (Robertson 1969) often indicate severe losses are possible.

Leafy spurge presence has reduced the carrying capacity of rangeland by direct competition with forage plants and also by influencing cattle foraging behavior by the partial or complete avoidance of infested areas (Lym and Kirby 1987; Leitch et al. 1996). Unequal grazing could result in decreased production of desirable species and allow further invasion of weed species. In North Dakota, nearly 5.5% of available grazing land was infested by leafy spurge in 1993, which caused a loss of 459,000 animal unit months (AUMs), equating to 6.8 million dollars in lost revenue (Leitch et al. 1996). In lands that were 50 to 100% infested, herbage was decreased by 16.5 to 33%, respectively (Lym and Kirby 1987). Foraging behavior response to leafy spurge infestation could ultimately result in a complete loss to a ranching enterprise.

Perennial grass production increased three-fold per ha in southwestern Arizona just 1 yr after velvet mesquite was controlled with 2,4,5-T (Cable and Tschirley 1961). Similarly, the removal of Canada thistle may result in an increase in herbage (Grekul and Bork 2004), but not to the extent of velvet mesquite. The increase of forage would allow the rangeland to support more livestock per ha, increasing the value of the land.

The control of an undesirable species may not immediately result in increased herbage yield. The removal of big sagebrush did not increase desert wheatgrass [*Agropyron desertorum* (Fisch. Ex Link) Schult] production until three yr after treatment (Robertson 1969). Despite the delayed increase of desert wheatgrass production, control of big sagebrush was still considered economically worthwhile. The eradication of an invasive plant, such as velvet mesquite, can take multiple years and multiple herbicide treatments, but once control is reached, increased forage production can last up to 20 yr (Cable 1976).

When determining the optimal time to control a pest species, there are many variables to consider such as cost of control, value of the crop, damages caused by the pest, potential damage caused by pesticide, and the effectiveness of the pesticide (Carlson and Wetzstein 1993; Sinden et al. 2011). A survey of 459 ranchers in the upper Midwest found that 60% believe the use of herbicides, biocontrol, and/or grazing animals to control leafy spurge was economical (Hodur et al. 2002). The choice of whether or not to control leafy spurge was often decided based on the feasibility of control. Infested areas were often uncontrolled due to environmental restrictions and the overall large size of the infestations. Cost was usually not the limiting factor as ranchers believed controlling leafy spurge would provide a positive economic return, which was supported by Lym and Kirby (1987).

An economic threshold model can be used to determine when to control a pest (Carlson and Wetzstein 1993). The economic threshold determines the acceptable pest density before control efforts are cost-efficient. A simple model should account for the cost of treatment, price of forage, damage caused per unit of pest, and efficacy of the pesticide. The complexity of the model can vary depending on the situation and should be flexible enough to account for uncertain variables, such as weather. However, economic threshold models are not necessarily the most helpful in determining the value of preventing an infestation (Kompas and Chu 2010). Most ranchers believe the biggest problems relating to the spread and development of leafy spurge is due to uncontrolled infestations on adjoining land, and the recognition of the problem too late to be contained (Hodur et al. 2002).

Native Forb Response to Aminocyclopyrachlor

Aminocyclopyrachlor Properties. Aminocyclopyrachlor is the first of a new class of chemistry known as a pyrimidinecarboxylic acid developed for broadleaf weed control (Anonymous 2009). The new herbicide has potential for use in noxious weed management, turf management, rangeland, and pastureland (Oliveira et al. 2013). Aminocyclopyrachlor is structurally similar to the pyridinecarboxylic acid herbicides aminopyralid and picloram, which also control broadleaf weeds in rangeland and other non-crop areas, but differs in physical and chemical properties. The water solubility of aminocyclopyrachlor is 4200 mg L^{-1} (Shaner 2014a) which is nearly twice the solubility of aminopyralid (2480 mg L^{-1}) (Shaner 2014b) and 10x that of picloram (430 mg L^{-1}) (Shaner 2014e).

Soil sorption of aminocyclopyrachlor is variable depending on soil type. The soil coefficient (K_{oc}) ranges from 2 to 26 in sand and clay soils, respectively (Shaner 2014a). On average, aminocyclopyrachlor has a higher K_{oc} than similar herbicides, such as aminopyralid and picloram which are 10.8 and 16, respectively (Shaner 2014b, 2014e). Across multiple sandy soil types, aminocyclopyrachlor soil sorption was lower than that of picloram; however, leaching potential was comparable between the two herbicides (Hall et al. 2015; Oliveira et al. 2013). Only 10% of aminocyclopyrachlor remained in the top 5 cm of the soil profile following a simulated, 15-cm rainfall event over 48 h and, 51-cm event over 9 wk, regardless of soil type (Adams and Lym 2015). Sorption of aminocyclopyrachlor was positively correlated to the organic and clay content of the soil. However, pH did not appear to affect sorption of aminocyclopyrachlor unlike other auxin-mimic herbicides such as picloram, dicamba, 2,4-D, and quinclorac (Adams and Lym 2015; Cabrera et al. 2014; Oliveira et al. 2011). The 50% dissipation time (DT_{50}) of the herbicide was also affected by soil structure (Conklin and Lym 2013). Dissipation was most rapid in soils with high clay and organic matter content where DT_{50} averaged < 20 d, compared to 44 d in sandy soil; however, DT_{50} of aminocyclopyrachlor was difficult to predict as many soil characteristics affected dissipation (Oliveira et al. 2011; Conklin and Lym 2013). Areas with sensitive rangeland species or areas of high risk for ground water contamination are not suitable for the use of aminocyclopyrachlor, especially in soil types with low organic matter and clay content as the herbicide has potential for long persistence (Adams and Lym 2015; Conklin and Lym 2013; Hall et al. 2015).

The foliar and soil activity of aminocyclopyrachlor is important for long-lasting perennial weed control (Lindenmayer et al. 2010). Aminocyclopyrachlor absorption and translocation in Canada thistle was evaluated by treating soil above or below root segments. When soil was treated with aminocyclopyrachlor below the root segments, Canada thistle shoot production and biomass were reduced; however, root biomass was not affected, suggesting the herbicide was absorbed through the roots and translocated to the shoots to inhibit growth (Lindenmayer et al. 2011).

Aminocyclopyrachlor is more effective at lower use rates than many other auxinic herbicides such as 2,4-D, which reduces risk to many aquatic and terrestrial organisms (Oliveria et al. 2013; Rupp et al. 2011). The mammalian LD_{50} (lethal dose, 50%) of aminocyclopyrachlor is >5000 mg ae kg^{-1} (USDA 2012), whereas 2,4-D can be as low as 639 mg ae kg^{-1} (NPIC 2008). Mammals exposed to aminocyclopyrachlor at concentrations up to 18,000 ppm daily, for 13 wk had slightly decreased body mass and food consumption, but no neurological affects were observed (USDA 2012). The LC_{50} (lethal concentration, 50%) was 80 mg ae L^{-1} with 2,4-D in fish (NPIC 2008), compared to 120 mg ae L^{-1} with aminocyclopyrachlor (USDA 2012).

Weeds Controlled. Many noxious and invasive broadleaf weeds in North Dakota can be controlled with aminocyclopyrachlor. The herbicide controlled Canada thistle, Russian knapweed [*Acroptilon repens* (L.) DC.] (Lindenmayer et al. 2010), leafy spurge, perennial sowthistle (*Sonchus arvensis* L.) (Lym 2010), prickly lettuce (*Lactuca serriola* L.) (Bell et al. 2011), houndstongue (*Cynoglossum officinale* L.), absinth wormwood (*Artemisia absinthium* L.), and yellow toadflax (*Linaria vulgaris* Mill.) (Conklin and Lym 2012). However, yellow toadflax control was often variable with aminocyclopyrachlor, likely due to application timing (Johnson et al. 2014; Lym 2014). Almquist et al. (2015) reported aminocyclopyrachlor was best applied in June for yellow toadflax control.

Plants highly susceptible to aminocyclopyrachlor require less herbicide to be absorbed and translocated than tolerant species; however, insufficient translocation can reduce herbicide efficacy (Bell et al. 2011). Yellow toadflax absorbed 63% of applied ^{14}C-aminocycloprachlor, but only 2% of the applied ^{14}C was recovered in the roots 24 hours after treatment (HAT) and 0.15% 192 HAT (Lym 2014). The variability of yellow toadflax susceptibility may be due to insufficient translocation of aminocyclopyrachlor to the roots. In comparison, 8.6 and 12% of applied ^{14}C-aminocyclopyrachlor was recovered 24 HAT in Canada thistle (Bukun et al. 2010) and leafy spurge roots (Lym 2014), respectively.

Noxious woody species such as Russian olive (*Elaeagnus angustifolia* L.) and salt cedar (*Tamarix ramosissima* Ledeb.) are also susceptible to aminocyclopyrachlor (Lindenmayer et al. 2010; Lym 2010). Unfortunately, vegetation near treated Russian olive stumps also died even though the herbicide was not directly applied to the plants (Lym 2010). Desirable trees near target plants may also be damaged (Edwards 2011). Non-target effects may reduce the use of aminocyclopyrachlor in rangeland restoration projects.

Impact on Grasses and Desirable Species. Plant tolerance of desirable species is important to determine prior to any herbicide treatment, especially in native sites. Removal of problem species at the expense of native species is not a desirable outcome for a weed management program. Conservation land managers, obligated by law to control noxious weeds, must consider herbicide effects on non-target species as the overall goal is to achieve a healthy, native plant community (Lym and Duncan 2005). Aminocyclopyrachlor has a wide spectrum of weed control as previously mentioned, and as with many herbicides, non-target species are also affected (Hergert et al. 2015). Although aminocyclopyrachlor is a broadleaf weed herbicide, some grass species have been injured (Conklin 2012).

Aminocyclopyrachlor caused minimal injury to buffalo grass [*Bouteloua dactyloides* (Nutt.) J.T. Columbus] (Harmoney et al. 2012), tall fescue [*Schedonorus arundinaceus* (Schreb.)

Dumort., nom. cons.] (Parker et al. 2015), intermediate wheat grass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.], and switchgrass (*Panicum virgatum* L.), whereas western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve] was severely injured following aminocyclopyrachlor applied at 112 g ai ha^{-1} (Conklin 2012). The introduced grass generas *Agropyron*, *Bromus*, *Poa*, and *Psathyrostachys* were more tolerant than native grasses, such as western wheatgrass. Grass injury was minimal to most tested species when aminocyclopyrachlor was applied at an early post-emergence growth stage (Hergert et al. 2015). Downy brome (*Bromus tectorum* L.) was the most tolerant to aminocyclopyrachlor of the species evaluated. The variable susceptibility to aminocyclopyrachlor was due to the translocation of the herbicide away from the meristematic regions (Parker et al. 2015). Tolerant plants, such as tall fescue, translocated the least amount of herbicide to the growing points of the plant. The movement of the herbicide that did occur was to the leaf tips, away from the growing points of the plant.

Aminocyclopyrachlor has controlled susceptible, broadleaf plants when applied at 140 and 280 g ha^{-1} (Harmoney et al. 2012). The extreme decrease in forb cover often caused an increase in warm season grass production (Sebastian et al. 2012; Wallace and Prather 2012). Aminocyclopyrachlor reduced most of the 16 forbs observed by Sebastian et al. (2012) in density and richness, with Porter's aster [*Symphyotrichum porter* (A. Gray) G.L. Nesom] and heath aster [*Symphyotrichum ericoides* (L.) G.L. Nesom] completely eliminated. Sagebrush (*Artemisia* spp.) and flax (*Linum* spp.) species density was reduced by 74% (Hergert et al. 2015). Aminocyclopyrachlor applied with metsulfuron decreased species richness by 57% compared to the control (Sebastian et al. 2012). Shrub density was decreased 45 to 76% and richness by 20 to 50%, depending on application rate.

Some rangeland shrubs such as western snowberry [*Symphoricarpos albus* (L.) S.F. Blake] and Woods' rose (*Rosa woodsia* Lindl.) are minimally affected by aminocyclopyrachlor (Wallace and Prather 2012). A few rangeland forbs (e.g. wild onion (*Allium textile* A. Nelson & J.F. Macbr.), fleabane (*Erigeron flagellaris* A. Gray), and spiderwort [*Tradescantia occidentalis* (Britton) Smyth]) actually increased in density and richness after aminocyclopyrachlor application, likely due to decreased competition from susceptible species (Sebastian et al. 2012). Improved high-seral forb and monocot density and richness should decrease the likelihood of future noxious weed establishment (Samuel and Lym 2008).

While the susceptibility of some rangeland forbs has been determined, many commonly found throughout North Dakota and Minnesota have yet to be evaluated. Depending on the species present, aminocyclopyrachlor has the potential to be a desirable, selective herbicide in range and pastureland for noxious weed control.

MATERIALS AND METHODS

Prairie Response to Canada Thistle Infestation

Treated Prairie Response. Change in forage yield following herbicide treatment was evaluated at two locations, the Sheyenne National Grassland (SNG) near Leonard, ND, and in Fargo, ND. Both sites were located in the southeast portion of the state but differ in soil type (Table 1) and flora attributes. The SNG site was a former homestead with loamy fine sands (Sandy, mixed, frigid Oxyaquic Hapludolls) (NRCS 2015b). Smooth brome (*Bromus inermis* Leyss.) and Kentucky bluegrass (*Poa pratensis* L.) were the primary vegetation present, along with foxtail barley (*Hordeum jubatum* L.), prairie junegrass [*Koeleria macrantha* (Ledeb.) Schult.], woolly sedge (*Carex lasiocarpa* Ehrh. Var. *americana* Fernald), meadow anemone (*Anemone canadensis* L.), and stinging nettle (*Urtica dioica* L.). The Fargo site was located on undisturbed ground within city limits with silty clay soil (Fine, smectitic, frigid Typic Epiaquerts). Kentucky bluegrass, porcupine grass [*Hesperostipa spartea* (Trin.) Barkworth], and meadow fescue [*Schedonorus pratensis* (Huds.) P. Beauv.] were the primary grass species found, along with prairie rose (*Rosa arkansana* Porter), western snowberry, American licorice

Table 1. Physical and chemical properties of soils from experiment locations in the Sheyenne National Grassland (SNG) near Leonard, ND and in Fargo, ND. Analysis performed by NDSU soil testing lab.

Site	Location	Soil series	Texture	Sand	Silt	Clay	Organic matter	pH
						%		
SNG	46°34'18.5"N, 97°18'48.0"W	Hecla	Sandy loam	72	22	6	3.9	6.8
Fargo, ND	46°55'03.8"N, 96°48'06.4"W	Fargo	Silty clay	5	45	50	7.0	7.2

(*Glycyrrhiza lepidota* Pursh), common milkweed (*Asclepias syriaca* L.), and various species of goldenrod (*Solidago* spp).

The experimental design was a randomized complete-block with 12 replicates at each location. The whole blocks measured 9 m by 6 m and were divided into two subplots, 9 m by 3 m. Canada thistle density was determined on June 18, 2014 by four stem count samples recorded for each subplot using a 0.25-m^2 quadrat. Mean density was assessed to assure at a 95% level of confidence, the density of both plots within each block were statistically similar prior to herbicide application.

The plots within each block were randomly selected as treated or non-treated (control). Aminopyralid at 120 g ai ha^{-1} plus a non-ionic surfactant (NIS) (Activator 90. Loveland Products, Inc., PO Box 1286, Greeley, CO 80632) at 0.25% v v^{-1} was applied on June 25, 2014 to control Canada thistle at both locations. Quinclorac at 420 g ai ha^{-1} plus a methylated seed oil (MSO) (Upland MSO. West Central, Inc., 2700 Trott Ave SW, Willmar, MN 56201) at 2.3 L ha^{-1} was applied to control leafy spurge in both treated and control plots at both locations on September 11, 2014. The herbicides were delivered by a CO_2-pressurized hand-held boom sprayer with four 8002 flat-fan nozzles (TeeJet, Spaying Systems Co. 200 W. North Ave, Glendale Heights, IL 60139) applied at 160 L ha^{-1} and 240 kPa.

Herbage yield was estimated 1 and 13 months after treatment (MAT) from three 0.25-m^2 quadrats harvested in each plot, cut 5 cm above the soil surface with hand clippers. The harvested vegetation was divided into four groups: Canada thistle, grasses, forbs, and woody vegetation. Samples were dried at 55 C for 96 h and weighed. Canada thistle stand counts were recorded in mid-June, prior to harvest, and mid-September, after harvest, in 2014 and 2015.

The variation in biomass of harvested material was analyzed between the treated and non-treated plots across varying Canada thistle densities using the PROC ANOVA procedure of SAS (Statistical Analysis Software, version 9.3. SAS Institute, Inc., 100 SAS Campus Dr., Cary, NC 27513). Location and replicate were considered random effects, and treatment was considered a fixed effect. Fischer's protected LSD (P=0.05) was used for mean separation. Homogeneity of variance was assessed using error mean squares from each location. A combined analysis was performed when error mean squares differed by less than a factor of 10.

The threshold pest population equation

$$N^*=r/pab$$

was used to determine Canada thistle density required so that marginal cost of treatment was equal to marginal value of forage (Carlson and Wetzstein 1993). Material and application costs (r), forage price (p), damage caused per Canada thistle stem (a), and the average percent reduction of Canada thistle upon treatment (b) were used to calculate the action threshold (N*). Herbicide application cost was based on the price of applied aminopyralid in 2015 (Zollinger et al. 2015). Forage price was determined by the average price of hay in North Dakota in 2015 (NASS 2015). The damage caused was based on the average difference in forage production and Canada thistle density between the treated and non-treated plots. Average percent reduction of Canada thistle following treatment was based on the observed herbicide efficacy 12 MAT. To determine actual forage loss, a linear regression analysis was performed. The threshold determined the minimum Canada thistle density required for a treatment of aminopyralid at 120 g ha^{-1} to be economical.

Wildland Response. Canada thistle effect on ungrazed wildland herbage production was determined at multiple sites within federal and state-operated wildlife management areas in

North Dakota. Ten similar sites, not grazed or sprayed, were selected within each of the two largest Major Land Resource Areas (MLRA) in North Dakota, the Rolling Soft Shale Plains (RSSP) and the Central Black Glaciated Plains (CBGP), for a total of 20 sites (Figure 2) (Sedivec and Printz 2012). The MLRAs differ in flora and soil composition (Table 2). The grass community at sites in the RSSP were heavily comprised of crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] and smooth brome. Many of the forage species found in central North

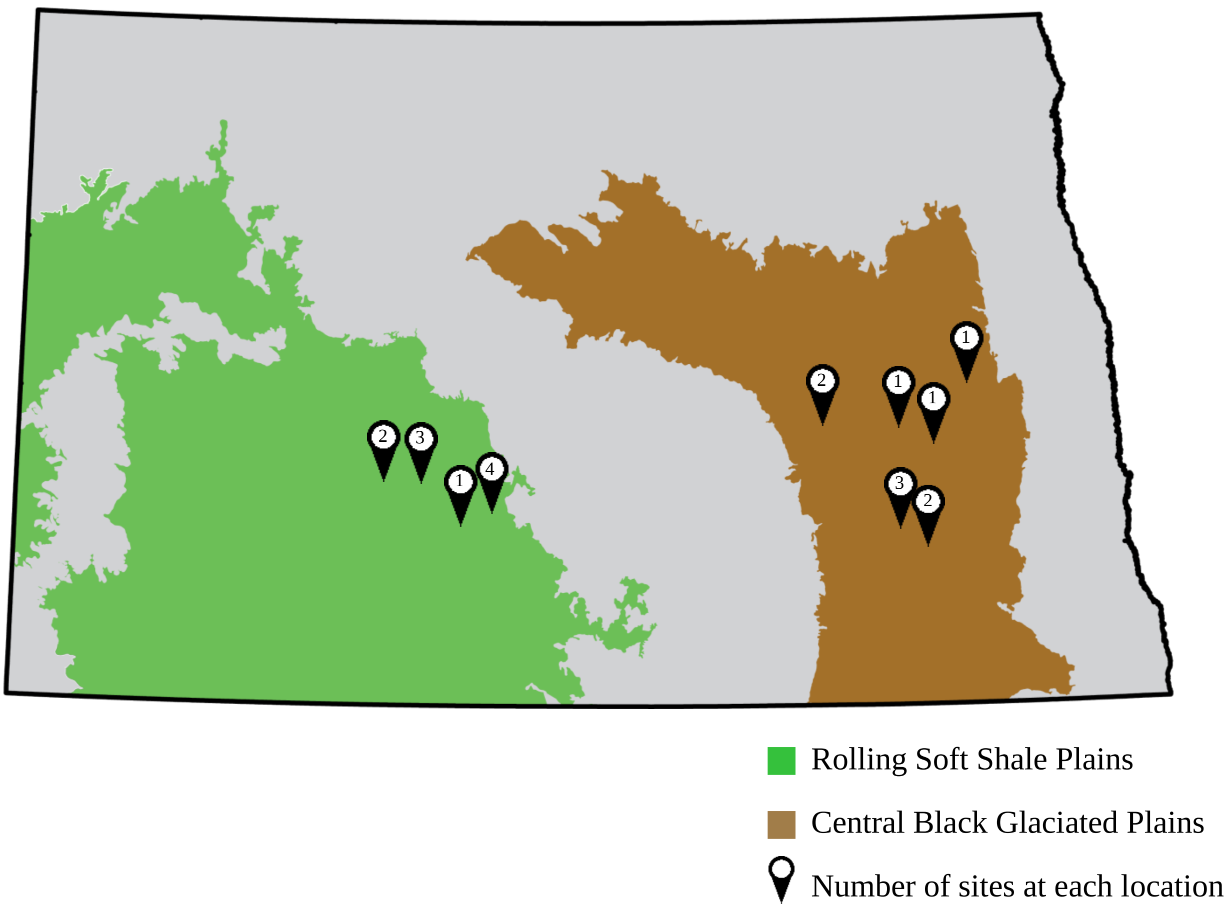

Figure 2. Location of Canada thistle infested and non-infested sites within the two largest Major Land Resource Areas (MLRAs) in North Dakota. Based on NRCS (2010) MLRAs in North Dakota map.

Table 2. Location and soil series of wildland sites within Major Land Resource Areas (MLRA).

Site[a]	Location	MLRA[b]	Soil series
Clausen Springs 1	46° 40' 52.7658" N, 98° 2' 22.7904" W	CBGP	Renshaw
Clausen Springs 2	46° 40' 55.671" N, 98° 1' 53.6088" W	CBGP	Barnes-Buse
Alton, Orris & Orvin Olson	46° 39' 35.2974" N, 98° 4' 13.9908" W	CBGP	Barnes-Buse-Langhei
Fort Ransom 1	46° 31' 12.774" N, 97° 56' 34.4322" W	CBGP	Sioux-Renshaw
Fort Ransom 2	46° 31' 16.7232" N, 97° 56' 34.4322" W	CBGP	Sioux-Renshaw
Arrowwood 1	47° 9' 18.0822" N, 98° 45' 49.2186" W	CBGP	Barnes-Svea
Arrowwood 2	47° 9' 43.8444" N, 98° 46' 54.8832" W	CBGP	Barns-Svea
Ray Holland Marsh	47° 7' 21.072" N, 98° 15' 19.2456" W	CBGP	Balaton-Wyard
Valley City	47° 0' 4.9062" N, 97° 57' 34.8978" W	CBGP	Gardena-Glyndon
Otto Spies	47° 17' 20.958" N, 97° 34' 45.9696" W	CBGP	Esmond-Heimdal-Darnen
Sweetbriar Lake 1	46° 52' 29.3376" N, 101° 16' 40.3674" W	RSSP	Farland
Sweetbriar Lake 2	46° 52' 23.754" N, 101° 16' 52.0782" W	RSSP	Lawther
Sweetbriar Lake 3	46° 52' 8.7234" N, 101° 16' 50.4516" W	RSSP	Williams-Reeder
Storm Creek 1	46° 53' 39.4584" N, 101° 36' 19.4034" W	RSSP	Daglum-Rhoades
Storm Creek 2	46° 53' 35.4222" N, 101° 36' 16.992" W	RSSP	Morton-Farland
Morton County	46° 39' 42.3894" N, 100° 53' 55.8342" W	RSSP	Cabba-Chama-Sen
Oahe Bottoms 1	46° 41' 29.0754" N, 100° 48' 14.3418" W	RSSP	Straw
Oahe Bottoms 2	46° 41' 31.4982" N, 100° 48' 20.5626" W	RSSP	Straw
Schmidt Bottoms 1	46° 41' 8.5482" N 100° 47' 40.7616" W	RSSP	Havrelon
Schmidt Bottoms 2	46° 40' 54.1452" N, 100° 46' 13.3782" W	RSSP	Havrelon

[a] Sites located on state or federally operated wildlife management areas not sprayed or grazed.
[b] Abbreviations: CBGP = Central Black Glaciated Plains; RSSP = Rolling Soft Shale Plains.

Dakota also are found on the eastern side of the state in the CBGP; however, the grass community in the CBGP is comprised predominantly of smooth brome and, occasionally, Kentucky bluegrass. The precipitation near plots in central North Dakota (Mandan NDAWN Station) was 30 cm and 31 cm in eastern North Dakota (Fingal NDAWN Station) from April 1 to July 31, 2015 (NDAWN 2015). Precipitation in the 2015 growing season was slightly higher than the previous 10 yr average of 28 cm and 27 cm in central and eastern North Dakota, respectively.

Two plots were established in close proximity at each of the 20 sites on either June 16 or June 23, 2015 (paired-plot); one in a Canada thistle infested area and one in a nearby, non-infested area. Canada thistle density was determined by counting the number of stems in three 0.25-m^2 subplots within each plot. Herbage was harvested on July 20 or July 22, 2015 from the same three 0.25-m^2 subplots. The vegetation was clipped, then dried and weighed as previously described.

The paired-plot experimental design consisted of ten replicated sites in each MLRA. The variation in biomass of harvested material was compared to determine Canada thistle effect on herbage production and differences between MLRAs using the PROC ANOVA procedure of SAS. Density, site, and replicates were considered random effects while Canada thistle presence or absence and MLRA were considered fixed effects. Fischer's protected LSD ($P=0.1$) was used for mean separation. Species diversity and abundance varied by location which was cause for an $\alpha=0.1$ level of type 1 error to denote significant differences.

The change in herbage production in both the treated prairie response and the wildland response experiments were assumed to be due entirely to Canada thistle density. Herbicide treatment was assumed to have minimal effect on herbage production and only used to reduce

Canada thistle density in the prairie response experiment. Furthermore, due to the maximum Canada thistle density at all locations being less than the economic threshold, the relationship between forage production and Canada thistle density was assumed to be able to be estimated using a linear regression. A bioeconomic weed management model was used in assessing the relationship between Canada thistle density and forage production. The parameters of the model included Canada thistle density, slope coefficient, and y-intercept to estimate forage production. The regression analysis tool in Microsoft Excel was used to perform a simple linear regression for both experiments (Tables 3 and 4). Based on a Canada thistle density of 20 stems m^{-2} and the linear regression equation for Fargo, ND in 2015 ($y=-36.867x + 2405.4$), forage production would be approximately 1670 kg ha^{-1}.

Table 3. Regression statistics to predict forage production based on Canada thistle density in Fargo, ND in 2015.

Variable	Coefficient[a]	Standard error	t-statistic
Intercept	2405.4*	119.8	20.1
Canada thistle density	-36.9*	10.1	-3.7

[a] * denotes significant at $P<0.05$. N=24, $R^2=0.38$.

Table 4. Regression statistics to predict forage production based on Canada thistle density in the Rolling Soft Shale Plains in North Dakota in 2015.

Variable	Coefficient[a]	Standard error	t-statistic
Intercept	3532.8*	636.7	5.5
Canada thistle density	-36.2	28.2	-1.3

[a] * denotes significant at $P<0.05$. N=20, $R^2=0.15$.

Native Forb Response to Aminocyclopyrachlor

Eleven native forb species were evaluated for susceptibility to aminocyclopyrachlor in greenhouse trials. Species included were American licorice, azure aster [*Symphyotrichum oolentangiense* (Riddell) G.L. Nesom], blue flag iris (*Iris versicolor* L.), Canada goldenrod (*Solidago canadensis* L.), great blue lobelia (*Lobelia siphilitica* L.), harebell (*Campanula rotundifolia* L.), prairie rose, purple coneflower (*Echinacea angustifolia* DC.), purple prairie clover (*Dalea purpurea* Vent.), white prairie clover (*Dalea candida* Michx. ex Willd.), and wild bergamot (*Monarda fistulosa* L.). However, due to the loss of multiple control plants, white prairie clover susceptibility could not be adequately quantified. The species were chosen to correlate with a field study of aminocyclopyrachlor and a similar greenhouse experiment using aminopyralid (Mikkelson and Lym 2013; Thilmony 2016).

Prairie forbs were either purchased from a nursery (Prairie Restorations, Inc., 31646 128th St., Princeton, MN 55371) in August 2014 or 2015 or grown from seed or root from local collections. The forbs were then transplanted into cone-tainers (6.3-cm diameter by 25-cm deep. Deepots™, Stuewe & Sons, Inc., 31933 Rolland Dr., Tangent, OR 97389) with a blend of commercial mix (Sunshine Mix No. 1, patented formulation with wetting agents. Sun Gro Horticulture, 770 Silver St., Agawam, MA 01001) and sandy loam soil (4:1 by volume). Plants were grown for 4 to 8 wk in a greenhouse at a maintained temperature of ~24 C with a 16 h photoperiod of natural and supplemented light using a halide light with an intensity of 450 $\mu E\ m^{-2}\ s^{-1}$. Plants were watered as needed and fertilized with a diluted 20-20-20 nutrient solution (Jack's All Purpose Water Soluble Plant Food. JR Peters Inc. 6656 Grant Way, Allentown, PA 18106) one to two times prior to treatment. Imidacloprid was applied at 0.005 g ai per cone-tainer once to American licorice, azure aster, great blue lobelia, harebell, and prairie rose to control mealybugs [*Pseudococcus longispinus* (Targioni Tozzetti)], aphids [*Myzus persicae* (Sulzer)], and spider mites (*Tetranychus urticae* Koch).

Aminocyclopyrachlor was applied when plants reached the late spring growth stage to simulate a spring treatment for weed control (Table 5). Plants were spaced evenly to maximize spray coverage. Aminocyclopyrachlor at 0, 35, 70, and 105 g ha^{-1} was applied with an air-pressurized cabinet-type sprayer equipped with an 80015 nozzle, delivering 160 L ha^{-1} at 240 kPa. All herbicide treatments were applied with an MSO plus silicone-based NIS blend (Dyne-

Table 5. Forb species and corresponding growth stages to simulate an application of aminocyclopyrachlor for spring weed control.

Common name	Scientific name	Family	Growth stage[a]	Height
				– cm –
American licorice	*Glycyrrhiza lepidota* Pursh	Fabaceae	VEG	10-25
Azure aster	*Symphyotrichum oolentangiense* (Riddell) G.L. Nesom	Asteraceae	VEG	10-15
Blue flag iris	*Iris versicolor* L.	Iridaceae	VEG to FLW	45-55
Canada goldenrod	*Solidago canadensis* L.	Asteraceae	VEG	15-35
Great blue lobelia	*Lobelia siphilitica* L.	Campanulaceae	VEG to FLW	10-25
Harebell	*Campanula rotundifolia* L.	Campanulaceae	FLW	15-30
Prairie rose	*Rosa arkansana* Porter	Rosaceae	VEG	15-40
Purple coneflower	*Echinacea angustifolia* DC.	Asteraceae	VEG	10-15
Purple prairie clover	*Dalea purpurea* Vent.	Fabaceae	VEG	10-20
White prairie clover	*Dalea candida* Michx. ex Willd.	Fabaceae	VEG to FLW	25-35
Wild bergamot	*Monarda fistulosa* L.	Lamiaceae	VEG	10-15

[a] Abbreviations: VEG = vegetative; FLW = flowering.

Amic. Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017) at 0.25% v v^{-1} to maximize potential injury.

Visual evaluations were recorded 1, 7, and 14 days after treatment (DAT) on a scale of 0 to 100% (0 equal to no effect and 100 equal to all visible material dead). The top growth was removed 14 DAT 3 cm above soil surface, and plants were allowed to regrow for 8 to 12 wk, dependent on plant response. After the regrowth period, injury was visually estimated and plant material was harvested, dried at 50 C for 96 h, and weighed to estimate the long-term effect of aminocyclopyrachlor on plant production.

The experiment was a randomized complete-block design with four replicates and repeated. Each species was analyzed as an individual experiment. Plant injury ratings and regrowth weights were assessed using the PROC GLM procedure of SAS to determine differences in injury among application rates and species. Mean separation was tested using F-protected LSD (P=0.05) and homogeneity of variance was assessed using error mean squares from each run. A combined analysis was performed when error mean squares differed by less than a factor of 10. Plant susceptibility to aminocyclopyrachlor was categorized as tolerant (<15% injury), moderately tolerant (15 to 50% injury), moderately susceptible (50 to 75% injury), and susceptible (>75% injury) based on plant regrowth response 10 or 14 weeks after treatment (WAT) (Mikkelson 2010).

RESULTS AND DISCUSSION

Prairie Response to Canada Thistle Infestation

Treated Prairie Response. Initial Canada thistle density at the Fargo location was nearly twice that found at the SNG (Tables 6 and 7). Additionally, woody vegetation (e.g. prairie rose and western snowberry) and plant composition was more prominent at the Fargo location. Thus, results from the two locations were analyzed and reported separately.

Canada thistle density at the Fargo location averaged 11 stems m^{-2} (Table 6) and varied from 3 to 33 stems m^{-2} when the experiment was established (data not shown). Following aminopyralid applied at 120 g ha^{-1}, Canada thistle growth was reduced from 715 to 140 kg ha^{-1} 1 MAT. However, grass, broadleaf, woody, and total herbage were not affected by the change in Canada thistle density or aminopyralid application 1 MAT. Due to the relatively short duration

Table 6. Aminopyralid efficacy on Canada thistle and herbage response 1 and 13 months after treatment (MAT) (June 25, 2014) when harvested in July in Fargo, ND.

	Density/date[a]		Canada	Forage			Total
Year/treatment	June	Sept	thistle	Grass	Broadleaf	Woody	herbage
	Stems m^{-2}		kg ha^{-1}				
2014							
Aminopyralid[b]	12	1.7	140	1310	260	760	2470
Control	10.1	9.5	715	1260	285	920	3180
LSD (0.05)	NS	5.5	315	NS	NS	NS	NS
2015							
Aminopyralid	2.9	4.8	140	2050	190	665	3035
Control	14.8	16.1	545	1685	235	770	3235
LSD (0.05)	4.4	5	265	305	NS	NS	NS

[a]Canada thistle density measured in June 2014 (0 MAT), September 2014 (2 MAT), June 2015 (12 MAT), and September 2015 (15 MAT). Initial density measured prior to aminopyralid treatment in June 2014.

[b]Aminopyralid was applied at 120 g ha^{-1} with Activator 90 at 0.25% v v^{-1}. Loveland Products. PO Box 1286, Greeley, CO 80632.

between treatment and harvest, benefit of Canada thistle control could not be determined the first year of the study, even though stem density decreased from 12 to 1.7 stems m^{-2} by 3 MAT.

Aminopyralid reduced Canada thistle regrowth to an average of 2.9 stems m^{-2} by June 2015 (12 MAT), compared to 14.8 stems m^{-2} in the control (Table 6). Similarly, Canada thistle yield 13 MAT was 545 and 140 kg ha^{-1} in the control and treated areas, respectively. Canada thistle control 12 MAT was 80%, which was lower than previous findings of 90% or higher with aminopyralid applied at the same rate in a similar rangeland study (Enloe et al. 2007). At Theodore Roosevelt National Park in Western North Dakota, aminopyralid provided 93 and 50% control 10 and 22 MAT, respectively (Samuel and Lym 2008).

Grass yield at the Fargo site increased by 365 kg ha^{-1} in the treated area, compared to the control in 2015, 13 MAT (Table 6). The increase in grass production likely was due to decreased competition from Canada thistle as broadleaf and woody vegetation production was not affected by reduced Canada thistle stem density or biomass. Broadleaf and woody plant species did not increase, possibly due to increased Kentucky bluegrass competition. Many forb species commonly found in the study area, such as western snowberry, prairie rose, and common milkweed, were relatively unaffected by aminopyralid (Almquist and Lym 2010; Samuel and Lym 2008). Leafy spurge was also unaffected by aminopyralid; however, quinclorac was applied in September 2014 to control leafy spurge. The decrease in leafy spurge contributed to the decrease in broadleaf plant production in 2015 (data not shown). Total herbage production was similar between treatments in both 2014 and 2015 and averaged 2,825 and 3,135 kg ha^{-1}, respectively. In general, the increase in grass yield replaced the reduced Canada thistle production.

Table 7. Aminopyralid efficacy on Canada thistle and herbage response 1 and 13 months after treatment (MAT) (June 25, 2014) when harvested in July at the Sheyenne National Grassland near Leonard, ND.

	Density/date[a]		Canada	Forage			Total
Year/treatment	June	Sept	thistle	Grass	Broadleaf	Woody	herbage
	— Stems m^{-2} —		kg ha^{-1}				
2014							
Aminopyralid[b]	6.5	0	55	4055	175	5	4290
Control	6.4	7.3	275	4170	410	30	4885
LSD (0.05)	NS	1.4	147	NS	172	NS	543
2015							
Aminopyralid	0.2	3.5	40	3525	45	35	3645
Control	2.4	8.6	345	3590	310	35	4280
LSD (0.05)	1.8	2.8	205	NS	NS	NS	634

[a]Canada thistle density measured in June 2014 (0 MAT), September 2014 (2 MAT), June 2015 (12 MAT), and September 2015 (15 MAT). Initial density measured prior to aminopyralid treatment in June 2014.
[b]Aminopyralid was applied at 120 g ha^{-1} with Activator 90 at 0.25% v v^{-1}. Loveland Products. PO Box 1286, Greeley, CO 80632.

Canada thistle density averaged 6.5 plants m^{-2} (Table 7) at the start of the study at the SNG and ranged from 1 to 12 stems m^{-2} (data not shown). Canada thistle yield was 220 kg ha^{-1} less 1 MAT with aminopyralid compared to the control; however, grass and woody plant production was similar, regardless of treatment. Broadleaf plant yield was 410 kg ha^{-1} in the control, compared to 175 kg ha^{-1} 1 MAT, likely due to the loss of aminopyralid susceptible plants such as stinging nettle and meadow anemone (Almquist and Lym 2010) that were found at the site. Total herbage production was higher in the control than the treated area, likely due to the short time for competing plant species to replace Canada thistle plants.

Canada thistle stem density at the SNG numerically was less throughout the study site 12 MAT and averaged only 0.2 and 2.4 plants m^{-2} in the treated and control, respectively (Table 7). The decrease in Canada thistle density likely was due to increased competition among the plant community, primarily smooth brome, since the site was not allowed to be grazed as in years past. This perhaps caused emergence to be slower. By September 2015 (15 MAT), Canada thistle stem density was 3.5 plants m^{-2} in the treated and 8.6 plants m^{-2} in the control. Canada thistle biomass decreased from 345 to 40 kg ha^{-1} in the control compared to the aminopyralid treatment. However, grass, broadleaf, and woody plant production were not affected by Canada thistle absence, consistent with findings in 2014, with the exception of broadleaf plants. Total herbage production of aminopyralid-treated areas decreased 595 and 635 kg ha^{-1} 1 and 13 MAT, respectively. Herbage production differences in 2014 and 2015 were due primarily to decreased Canada thistle density and differences in broadleaf plant biomass.

Forage production, combined biomass of grass and broadleaf plants, increased at Fargo but not the SNG in 2015 (Tables 6 and 7). The results from Fargo in 2015 were chosen to determine the economic threshold of Canada thistle control due to the slight increase in forage production observed (Table 6). Forage was 2240 kg ha^{-1} in the treated area, 320 kg ha^{-1} more than in the untreated areas. Based on North Dakota hay price for July 2015 (\$69 $tonne^{-1}$) (NASS 2015), the cost of aminopyralid application (\$54.75 ha^{-1}) (Zollinger et al. 2015), and herbicide efficacy, the economic threshold for Canada thistle control would be approximately 37 stems m^{-2} (Figure 3). Based on the linear regression equation, forage production for the threshold values of 37 stems m^{-2} was estimated to be approximately 1040 kg ha^{-1}, nearly 1400 kg ha^{-1} less than the forage production for an area with no Canada thistle present.

Cost and efficacy of a herbicide application can impact the economic threshold. For example, picloram has provided 97% control of Canada thistle across the Midwest (Enloe et al.

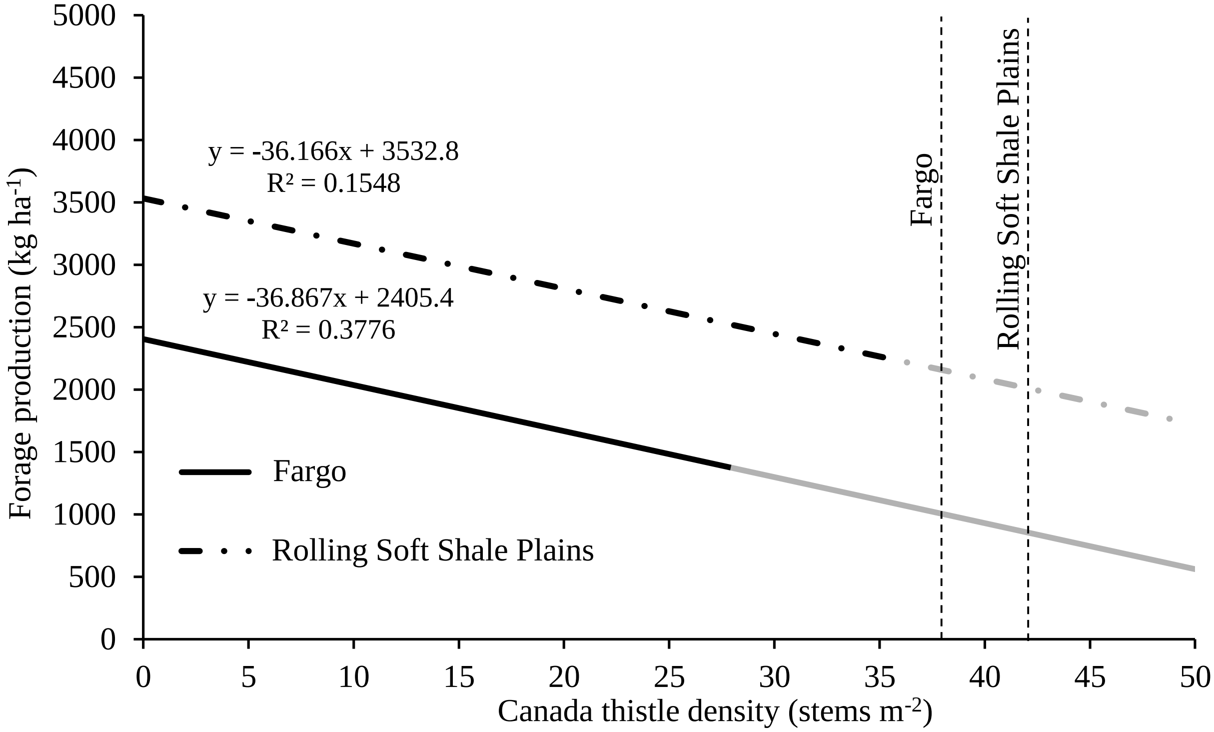

Figure 3. Economic threshold for control of Canada thistle with aminopyralid applied at 120 g ha^{-1} based on forage response at Fargo and the Rolling Soft Shale Plains in North Dakota in 2015. Maximum density was 27 stems m^{-2} in Fargo and 35 stems m^{-2} in the Rolling Soft Shale Plains. Gray segments were an extrapolation beyond observed Canada thistle densities.

2007) when applied at 420 g ai ha^{-1} (\$37 ha^{-1}) (Zollinger et al. 2015), which would result in an economic threshold of approximately 20 stems m^{-2}. Although picloram may be more cost-effective for Canada thistle control than aminopyralid, many desirable forb species would likely be reduced, which could allow other weed species to establish (Rinella et al. 2009). Clopyralid, conversely, provided 81% control of Canada thistle (Enloe et al. 2007) when applied at 420 g ai ha^{-1} (\$148 ha^{-1}) (Zollinger et al. 2015) which would result in an economic threshold of 89 stems m^{-2}. Even though the greatest increase in forage production found in the study was used for the calculation, the high density of Canada thistle required to meet cost-effective control suggested application efforts may rarely be economical, regardless of herbicide choice. However, hay quality and the health of livestock would increase with decreased Canada thistle density (Gourlay 2004; Popay and Field 1996). Biodiversity, habitat, and resilience of native plant species also will increase with Canada thistle control (Keane and Crawley 2002).

Wildland Response. Canada thistle presence did not affect grass, broadleaf, or woody plant production in the Central Black Glaciated Plains (CBGP) or Rolling Soft Shale Plains (RSSP) of North Dakota in 2015 (Tables 8 and 9). Canada thistle density in the CBGP averaged 22.1 stems m^{-2} (Table 8) and ranged from 16 to 35 stems m^{-2} (data not shown) in infested areas. Species diversity and abundance varied by location as grass biomass ranged from 1020 to 4410 kg ha^{-1} (data not shown). Total herbage production was lower in non-infested areas, with the differences in biomass entirely due to Canada thistle absence.

Herbage production in the RSSP in central North Dakota also was unaffected by Canada thistle presence (Table 9). Although Canada thistle density averaged 22.6 stems m^{-2} in the infested sites, production of grass, broadleaf, and woody species were similar to uninfested areas.

Table 8. Average herbage production of Canada thistle infested and non-infested wildlands across 10 locations in the Central Black Glaciated Plains in North Dakota.

Canada thistle	Density	Canada thistle	Forage: Grass	Forage: Broadleaf	Woody	Total
	Stems m^{-2}	kg ha^{-1}				
Infested	22.1	1320	2085	325	155	3885
Non-infested	0	0	2220	230	130	2585
LSD (0.1)	3.6	404	NS	NS	NS	335

Table 9. Average herbage production of Canada thistle infested and non-infested wildlands across 10 locations in the Rolling Soft Shale Plains in North Dakota.

Canada thistle	Density	Canada thistle	Forage Grass	Forage Broadleaf	Woody	Total
	Stems m^{-2}	kg ha^{-1}				
Infested	22.6	1200	2650	105	150	4100
Non-infested	0	0	3055	120	265	3445
LSD (0.1)	4.6	290	NS	NS	NS	535

Total herbage production was 4100 and 3445 kg ha^{-1} in the infested and non-infested areas, respectively. The herbage differences were due to the absence of Canada thistle, similar to observations in the CBGP (Table 8). Additional years of data would be required to determine if the wildland response to Canada thistle presence is consistent with the findings in 2015.

Forage production was 420 kg ha^{-1} higher in non-infested RSSP wildlands compared to Canada thistle infested areas (Table 9). The difference in stem density between infested and non-infested wildlands averaged 22.6 stems m^{-2}, which equates to a loss of 18.6 kg ha^{-1} for every one Canada thistle stem m^{-2}. The RSSP was used to determine the Canada thistle treatment economic threshold in North Dakota wildlands due to the greatest increase in forage production. Based on North Dakota hay prices in July 2015 (\$69 $tonne^{-1}$) (NASS 2015) and aminopyralid applied at 120 g ha^{-1} (\$54.75 ha^{-1}) (Zollinger et al. 2015), a wildlands herbicide treatment in the RSSP would result in an economic loss of approximately \$26 ha^{-1}, assuming 100% Canada thistle control. Canada thistle density would have to be approximately 42 stems m^{-2} for an aminopyralid treatment to be cost-effective based on return of forage alone (Figure 3). Based on the linear regression equation, forage production for the economic threshold of 42 stems m^{-2} would be 2015 kg ha^{-1}, which is over 1500 kg ha^{-1} less than an area absent of Canada thistle.

The economic threshold of 42 stems m^{-2} was slightly higher than the threshold (37 stems m^{-2}) determined for the Fargo site in 2015, likely due to differences in the plant community.

Summary. Herbage response in both the treated prairie and wildland studies suggests Canada thistle had little impact on forage production in 2015 (Tables 6 to 9). The only increase in forage production was at the Fargo location in 2015 (320 kg ha^{-1}), which was minimal (Table 6). Grekul and Bork (2004) suggested the control of Canada thistle will not provide a linear change in forage production; rather, environmental variables such as species composition, precipitation, and soil characteristics may be more important than stem density in estimating forage response to Canada thistle. In comparison, forage production increased by 500 kg ha^{-1} or more after a single treatment to control leafy spurge (Lym and Messersmith 1985). Forage production increased by 71% if treatments were continued for 3 yr.

The SNG location was heavily dominated by smooth brome which generally was not affected by Canada thistle competition. The Fargo location, conversely, had the only positive increase in forage production and was dominated by Kentucky bluegrass and meadow fescue. The findings at the Fargo location, in comparison to the SNG, are consistent with previous Canada thistle production studies (Grekul and Bork 2004; Reece and Wilson 1983). Grekul and Bork (2004) suggested sites heavily comprised of shallow-rooted, rhizomatous grasses such as Kentucky bluegrass may be more prone to initial yield reduction by Canada thistle invasion, and respond greater than species such as smooth brome when the weed is eradicated. The removal of Canada thistle and musk thistle (*Carduus nutans* L.) in Nebraska also resulted in an increase in Kentucky bluegrass production shortly after treatment (Reece and Wilson 1983). Kentucky bluegrass biomass increased as much as 4300 kg ha^{-1} following 3 yr of annual treatments.

The CBGP and RSSP were chosen for this study due to different cattle stocking rates between the two MLRAs (Sedivec and Printz 2012). The CBGP average stocking rate of 0.71 AUMs is 22% higher than the RSSP average stocking rate of 0.58 AUMs. However, average forage production observed was similar between the two MLRAs in 2015 (Tables 8 and 9), possibly due to above average rainfall (NDAWN 2015). Although no differences in MLRAs herbage production were observed, the paired-plot design of the experiment allowed for Canada thistle to be the only variable between infested and non-infested wildlands.

Canada thistle control will rarely have a positive economic return in pasture and wildlands (Figure 3). The weed density required to meet the economic threshold using aminopyralid would seldom occur naturally. In areas with higher hay prices or a plant community that responds more positively to Canada thistle removal, treatment could become more economical. Although forage yield was minimally affected by Canada thistle removal or absence, land managers in North Dakota are still legally obligated to control the plant because it is a state listed noxious weed (NDDA 2015). However, the decision to manage noxious rangeland weeds is often not to be compliant with state law, but rather, the feasibility of control since many ranchers assume a positive economic return (Hodur et al. 2002).

Native Forb Response to Aminocyclopyrachlor

The susceptibility of prairie forbs to aminocyclopyrachlor varied among species (Tables 10 to 13). Blue flag iris and harebell were the most tolerant to aminocyclopyrachlor of the 11 species evaluated, whereas azure aster, Canada goldenrod, great blue lobelia, and prairie coneflower were the most susceptible.

Blue flag iris was tolerant to aminocyclopyrachlor at all application rates (Table 10). Plant injury 2 and 10 WAT was minimal and difficult to visually discern from control plants. Regrowth weight was similar among treated and control blue flag iris plants, and averaged 1.4 g. All plants quickly regrew shortly after top growth was removed 2 WAT. Based on these results, blue flag iris likely will not be affected by aminocyclopyrachlor in the field as the herbicide was applied with an MSO plus silicone-based NIS blend surfactant to maximize potential injury in the greenhouse.

Table 10. Blue flag iris and harebell injury and regrowth response following aminocyclopyrachlor application in the greenhouse.

		Blue flag iris			Harebell		
		Injury/WAT[b]			Injury/WAT		
Treatment[a]	Rate	2	10	Wt[b]	2	10	Wt
	g ha^{-1}	—— % ——		— g —	—— % ——		— g —
AMCP[b]	35	2	0.6	1.4	21	22	1.1
AMCP	70	2	0.6	1.3	29	31	1
AMCP	105	2	0.6	1.3	40	46	0.6
Control	0	0	0	1.4	0	0	1.6
LSD (0.05)		NS	NS	NS	14	25	0.7

[a]Treatments applied with an MSO plus silicone-based NIS blend at 0.25% v v^{-1}. Dyne-Amic. Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017.
[b]Abbreviations: WAT = weeks after treatment; Wt = regrowth weight; AMCP = aminocyclopyrachlor.

Harebell was moderately tolerant to aminocyclopyrachlor (Table 10). Injury averaged approximately 30% 2 and 10 wk after aminocyclopyrachlor was applied at 35 to 105 g ha^{-1}. Regrowth of treated plants was similar to the control except when aminocyclopyrachlor was applied at the highest rate of 105 g ha^{-1}. Short-term cupping of harebell basal leaves was observed following an aminocyclopyrachlor application in the greenhouse, which would likely be short-lived in the field as well. Conversely, harebell was extremely susceptible to aminopyralid as all treated plants died, even when the herbicide was applied at 30 g ha^{-1} (Mikkelson and Lym 2013).

Prairie rose was moderately susceptible to aminocyclopyrachlor as plant regrowth declined as application rate increased (Table 11). Injury 2 WAT increased from 8 to 16% as herbicide rate increased from 35 to 105 g ha^{-1}; however, due to variability of plant response 10 WAT (data not shown) visible injury was similar regardless of application rate. Regrowth decreased from 2.1 to 1.5 g as aminocyclopyrachlor rate increased from 0 to 35 g ha^{-1}. Regrowth was reduced to 0.6 g or less when aminocyclopyrachlor was applied at 70 or 105 g ha^{-1}.

Table 11. Prairie rose, purple prairie clover, and wild bergamot injury and regrowth response following aminocyclopyrachlor application in the greenhouse.

		Prairie rose			Purple prairie clover			Wild bergamot		
		Injury/WAT[b]			Injury/WAT			Injury/WAT		
Treatment[a]	Rate	2	10	Wt[b]	2	10	Wt	2	10	Wt
	g ha^{-1}	—— % ——		- g -	—— % ——		- g -	—— % ——		- g -
AMCP[b]	35	8	9	1.5	14	22	1.2	8	4	0.4
AMCP	70	11	32	0.5	14	38	0.4	29	29	0.2
AMCP	105	16	37	0.6	22	83	0.07	26	47	0.1
Control	0	0	0	2.1	0	0	1.9	0	0	0.7
LSD (0.05)		8	NS	0.5	5	32	0.8	10	39	0.2

[a]Treatments applied with an MSO plus silicone-based NIS blend at 0.25% v v^{-1}. Dyne-Amic. Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017.
[b]Abbreviations: WAT= weeks after treatment; Wt = regrowth weight; AMCP = aminocyclopyrachlor.

Prairie rose response to aminocyclopyrachlor in the greenhouse was consistent with plant response in the field (Thilmony 2016). Prairie rose foliar cover was reduced, but not eliminated 14 MAT when aminocyclopyrachlor was applied at 170 g ha^{-1}. Other shrub species such as Woods' rose and western snowberry also responded to aminocyclopyrachlor similar to prairie rose (Wallace and Prather 2012). Woods' rose and western snowberry cover decreased slightly 13 MAT but recovered by 25 MAT. Prairie rose growth will likely be stunted the first year following aminocyclopyrachlor application, but should recover in the long-term.

Purple prairie clover was moderately susceptible to aminocyclopyrachlor at 70 g ha^{-1} (Table 11). Plant injury ranged from 22 to 83% 10 WAT as aminocyclopyrachlor application rate increased. Purple prairie clover dry weight 10 WAT was similar to the control (1.9 g) when aminocyclopyrachlor was applied at 35 g ha^{-1}. Plant regrowth weight decreased to 0.4 g or less when aminocyclopyrachlor was applied at 70 and 105 g ha^{-1}. The reduced regrowth observed in the greenhouse following herbicide application was consistent with field trials using aminocyclopyrachlor and aminopyralid on other legume species, including purple prairie clover (Miller et al. 2015; Thilmony 2016). Legume biomass was reduced by more than 71% for 3 yr following a single herbicide application at the recommended rate (Miller et al. 2015). Purple prairie clover abundance would likely decrease following an application of aminocyclopyrachlor; however, plants recovered following a field application of 170 g ha^{-1} (Thilmony 2016).

White prairie clover also appeared to be susceptible to aminocyclopyrachlor in the greenhouse; however, because most untreated plants did not regrow, an accurate assessment of white prairie clover could not be determined. The relative reduction of white prairie clover regrowth weight at low application rates suggested the plant was susceptible to aminocyclopyrachlor (data not shown). These observations are consistent with findings of similar legume species, including purple prairie clover (Miller et al. 2015; Thilmony 2016) (Table 9).

Wild bergamot was moderately susceptible to aminocyclopyrachlor in the greenhouse (Table 11). Plant injury ranged from 8 to 26% 2 WAT as aminocyclopyrachlor application rate increased from 35 to105 g ha^{-1}. Plant injury 10 WAT increased to 47% when aminocyclopyrachlor was applied at 105 g ha^{-1}. Wild bergamot regrowth decreased as aminocyclopyrachlor application rate increased and ranged from 0.1 to 0.4 g compared to 0.7 g for the control. Although wild bergamot top-growth was reduced in the greenhouse, especially at high application rates, most plants survived 10 WAT. Plant injury in the field would likely be dependent on application rate and herbicide persistence (Crone et al. 2009).

American licorice was moderately susceptible to aminocyclopyrachlor (Table 12). Injury 14 WAT was 69%, averaged over all application rates. American licorice regrowth averaged 0.4 g over aminocyclopyrachlor application rates, compared to 1.6 g for the control. Plants were grown an additional 4 wk (14 wk total) to allow maximum regrowth; however, many plants did not survive.

These findings are consistent with a field study using aminocyclopyrachlor at 170 g ha^{-1} (Thilmony 2016). American licorice was reduced from 1.8 to 0.1% foliar cover 10 MAT;

Table 12. American licorice and purple coneflower injury and regrowth response following aminocyclopyrachlor application in the greenhouse.

		American licorice			Purple coneflower		
		Injury/WAT[b]			Injury/WAT		
Treatment[a]	Rate	2	14	Wt[b]	2	14	Wt
	g ha^{-1}	—— % ——		- g -	—— % ——		- g
AMCP[b]	35	56	58	0.6	7	100	0
AMCP	70	75	57	0.4	20	81	0.1
AMCP	105	88	93	0.1	36	100	0
Control	0	0	0	1.6	0	0	0.7
LSD (0.05)		9	35	0.5	9	24	0.3

[a]Treatments applied with an MSO plus silicone-based NIS blend at 0.25% v v^{-1}. Dyne-Amic. Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017.
[b]Abbreviations: WAT = weeks after treatment; Wt = regrowth weight; AMCP = aminocyclopyrachlor.

however, by 14 MAT cover increased to 1.5% and plants exhibited minimal signs of injury. American licorice likely would be reduced following a field application of aminocyclopyrachlor, but could recover with time.

Purple coneflower was susceptible to aminocyclopyrachlor at all application rates (Table 12). Plant injury ranged from 7 to 36% as application rate increased from 35 to 105 g ha^{-1} 2 WAT; however, injury increased to an average of 93% 14 WAT, regardless of treatment. Plant regrowth weight was reduced from 0.7 g to 0.1 g or less when treated with aminocyclopyrachlor. Aminocyclopyrachlor would likely reduce purple coneflower in the field, regardless of application rate. Conversely, purple coneflower was tolerant to aminopyralid in the greenhouse up to 120 g ha^{-1} (Mikkelson and Lym 2013).

Azure aster was susceptible to aminocyclopyrachlor (Table 13). Plant injury averaged 24% 2 WAT, but increased to 100% regardless of application rate 10 WAT. Azure aster did not regrow plants died by 12 MAT (Sebastian et al. 2012). Conversely, azure aster was tolerant to

Table 13. Azure aster, Canada goldenrod, and great blue lobelia injury and regrowth response following aminocyclopyrachlor application in the greenhouse.

		Azure aster			Canada goldenrod			Great blue lobelia		
		Injury/WAT[b]			Injury/WAT			Injury/WAT		
Treatment[a]	Rate	2	10	Wt[b]	2	14	Wt	2	10	Wt
	g ha^{-1}	—— % ——		- g -	—— % ——		- g -	—— % ——		- g -
AMCP[b]	35	23	100	0	20	32	0.9	24	16	0.4
AMCP	70	15	100	0	26	89	0.1	34	69	0.02
AMCP	105	34	100	0	33	100	0	40	74	0.03
Control	0	0	0	1.5	0	0	2.6	0	0	1.1
LSD (0.05)		9	0.01	0.2	5	23	0.9	10	32	0.2

[a]Treatments applied with an MSO plus silicone-based NIS blend at 0.25% v v^{-1}. Dyne-Amic. Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017.
[b]Abbreviations: WAT = weeks after treatment; Wt = regrowth weight; AMCP = aminocyclopyrachlor.

aminopyralid, regardless of application rate (Mikkelson and Lym 2013).

Canada goldenrod was susceptible to aminocyclopyrachlor applied at 35 to 105 g ha^{-1} (Table 13). Plant injury increased as application rate increased and ranged from 20 to 33% and 32 to 100% 2 and 14 WAT, respectively. Regrowth weight decreased to 0.9 g or less when treated with aminocyclopyrachlor compared to 2.6 g regrowth in the control. Aminocyclopyrachlor likely will adversely affect Canada goldenrod in the field; however, plants may survive in the long-term if aminocyclopyrachlor is applied at 35 g ha^{-1} or less. Canada goldenrod was also susceptible to aminocyclopyrachlor applied at 170 g ha^{-1} in the field and was absent 14 MAT (Thilmony 2016). These findings are consistent with field studies of various goldenrod species using aminocyclopyrachlor (Rhodes et al. 2013; Sellers et al. 2013). Multiple species of goldenrod were susceptible to aminocyclopyrachlor in the field and some were reduced by 90% 12 MAT.

Great blue lobelia was susceptible to aminocyclopyrachlor at all application rates evaluated (Table 13). Injury 2 and 10 WAT increased from 24 to 40% and 16 to 74%, respectively, as application rate increased. Plant regrowth weight averaged only 0.4 g when treated with aminocyclopyrachlor at 35 g ha^{-1}, compared to 1.1 g in the control. Great blue lobelia regrowth was minimal (<0.1 g) 10 WAT when treated with aminocyclopyrachlor at 70 or 105 g ha^{-1}. Epinasty and leaf cupping was observed in the greenhouse and may occur shortly after a field application. Great blue lobelia will likely be reduced in density and vigor in the field if treated with aminocyclopyrachlor, regardless of application rate.

Blue flag iris and harebell were tolerant to aminocyclopyrachlor in the greenhouse and would likely not be affected following a field application. Plants such as American licorice, prairie rose, purple prairie clover, and wild bergamot were severely injured with reduced regrowth even at low application rates of aminocyclopyrachlor; however, plants may regrow in the long-term as some survived even at the high application rates used in this study. Azure aster, Canada goldenrod, great blue lobelia, and purple coneflower were all susceptible to aminocyclopyrachlor as many plants were killed at rates as low as 35 g ha^{-1}.

Aminocyclopyrachlor effectively controlled many noxious weeds such as Canada thistle and leafy spurge in rangeland and pasturelands (Lindenmayer et al. 2010; Lym 2010). However, non-target, desirable, native forbs may be injured or killed. Often, rangeland areas only have one major troublesome weed, such as Canada thistle, in which a more selective broadleaf herbicide, such as aminopyralid, would be more beneficial as fewer non-target species may be affected (Wilson et al. 2005).

The susceptibility of many species to aminocyclopyrachlor have not been evaluated in the field due to the singular growth of the plants in the wild. However, American licorice, azure aster, Canada goldenrod, prairie rose, and purple prairie clover response in the greenhouse was consistent to similar or the same species in the field when treated with aminocyclopyrachlor (Rhodes et al. 2013; Sebastian et al. 2012; Sellers et al. 2013; Thilmony 2016; Wallace and Prather 2012). Also, a similar forb tolerance study using aminopyralid in the greenhouse gave consistant results to field trials (Mikkelson and Lym 2013). Therefore, these data could be used to estimate the potential impact of aminocyclopyrachlor on desirable broadleaf species in the field and may be more cost-effective than similar field trials, especially since many of the species are relatively rare in the wild.

Herbicide selection should not only consider the efficacy on the weed being treated, but other environmental effects, including non-target plant response. Application rate is important as well, as many moderately susceptible species may survive at lower application rates; however, herbicide efficacy on noxious weeds could be reduced at lower use rates. Aminocyclopyrachlor may be a useful herbicide to control troublesome, perennial weeds, but non-target effects must be considered to improve the overall flora quality in rangeland environments.

SUMMARY

Canada thistle control is important to improve the growth and abundance of desirable rangeland species and increase hay quality. In both grazed and wildland areas, aminopyralid was used to control Canada thistle; however, the decrease in Canada thistle density rarely resulted in increased forage production and seldom would be cost-effective. The use of a less expensive herbicide treatment, such as picloram at 420 g ha^{-1}, may be more cost-effective but will likely reduce many desirable forb species. Plant community, hay price, and herbicide efficacy and cost should all be considered when designing a weed control program.

The greatest increase in forage production following control of Canada thistle was at Fargo in 2015, which was heavily comprised of Kentucky bluegrass and meadow fescue. Forage increased from 1920 to 2240 kg ha^{-1} after an average reduction of 11.9 Canada thistle stems m^{-2}. Based on the minimal increase observed at Fargo, the economic threshold for Canada thistle control was 37 stems m^{-2}. Due to the high density of Canada thistle required, control efforts would rarely have a positive economic return. The effect of Canada thistle on forage production is minimal; however, Canada thistle should still be controlled to improve the overall flora quality in rangeland environments. The prevention of the spread of Canada thistle and the protection of desirable, native plants can be more valuable than increased forage production. The early control of Canada thistle can reduce future treatment costs and damage to the native plant community.

Forage production was similar between Canada thistle infested and non-infested wildlands in the Central Black Glaciated Plains and the Rolling Soft Shale Plains of North Dakota. The slight differences in plant community observed between Major Land Resource Areas did not influence response to Canada thistle. However, rangelands heavily dominated by rhizomatous grasses, such as Kentucky bluegrass, tend to respond greater to the removal of

Canada thistle than if comprised of species such as smooth brome and crested wheatgrass. Variables such as vegetation composition or precipitation may be more indicative to rangeland response than the removal of Canada thistle.

Plant community response to an herbicide can be as important as weed control. Native forb susceptibility to aminocyclopyrachlor varied among the 11 species evaluated. Blue flag iris was the only species that was tolerant to aminocyclopyrachlor, while harebell was moderately tolerant. American licorice, prairie rose, purple prairie clover, and wild bergamot were moderately susceptible to aminocyclopyrachlor, but may regrow in the field as some plants survived application rates of 105 g ha^{-1}. Azure aster, Canada goldenrod, great blue lobelia, and purple coneflower were susceptible, even when aminocyclopyrachlor was applied at 35 g ha^{-1}. Aminocyclopyrachlor is an effective herbicide on many troublesome perennial weeds, such as Canada thistle; however, many desirable broadleaf plants could be reduced or eliminated if the herbicide is used in an invasive weed management program. In addition to herbicide efficacy to target the weed species of interest, non-target species must also be considered.

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