QUINCLORAC AND AMINOCYCLOPYRACHLOR MOVEMENT IN SANDY SOILS OF THE SHEYENNE NATIONAL GRASSLAND, AND CONTROL OF YELLOW TOADFLAX WITH AMINOCYCLOPYRACHLOR

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ABSTRACT

Quinclorac and aminocyclopyrachlor leaching potential was evaluated in replicated field conditions in soil from five ecological sites of the Sheyenne National Grassland (SNG). Herbicide concentration was estimated using bioassays. Quinclorac did not leach past approximately 45 cm following 51 cm of precipitation applied over 9 wk and 15 cm of precipitation applied over 48 h. Aminocyclopyrachlor leaching was greater than quinclorac and moved through all soil types following both precipitation events. Quinclorac is suitable for use at the SNG to control leafy spurge; however, aminocyclopyrachlor will not be recommended. Control of yellow toadflax with aminocyclopyrachlor was evaluated at four growth stages. Control averaged 98% 1 YAT when aminocyclopyrachlor was applied before flowering but only 50% when the herbicide was applied to the fall vegetative stage. Yellow toadflax control with picloram plus dicamba plus diflufenzopyr averaged 92% 1 YAT and was not affected by growth stage.

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INTRODUCTION

The Sheyenne National Grassland (SNG) is a native tall grass and mixed grass prairie located in southeastern North Dakota (Nelson 1986). The SNG covers 28,400 ha and consists of soils which are predominantly sandy, loamy sand, and silt loams. Approximately half of the SNG has been invaded by leafy spurge (*Euphorbia esula* L.), which continues to spread and threaten sustainability and productivity of the grassland (Pieper 2007). Leafy spurge is a deep-rooted perennial weed that degrades rangeland condition by reducing forage, crowding out native vegetation, and can be toxic to cattle that graze the plant (Messersmith et al. 1985).

Leafy spurge control methods at the SNG have been limited due to soil type and presence of the western prairie fringed orchid (*Platanthera praeclara* Sheviak and Bowles), a federally listed threatened plant (USFWS 1996). Many herbicides cannot be utilized at the SNG due to sandy soils and shallow groundwater, nor can they be applied on or near the western prairie fringed orchid (Erickson et al. 2006). Picloram, a widely used herbicide for leafy spurge control, cannot be used at the SNG due to high soil mobility characteristics and potential for groundwater contamination (Lym and Messersmith 1988). Chemical control has been limited to 2,4-D, which only reduces the top-growth for a short time (Lym and Messersmith 1990). Biological control of leafy spurge has been successful with the use of *Aphthona* spp. flea beetles in many environments (Lym 1998). However, *Aphthona* spp. have not established well in areas with sandy soils, such as found at the SNG.

The U.S. Forest Service has proposed the identification and implementation of new integrated control programs for invasive weeds at the SNG (Pieper 2007). Quinclorac and aminocyclopyrachlor have been considered for leafy spurge control as part of the new program. Both herbicides have reduced leafy spurge in previous trials (Kuehl and Lym 1997; Lym 2010);

however, potential for movement of quinclorac and aminocyclopyrachlor through the sandy soils of the SNG into groundwater is a concern.

Yellow toadflax (*Linaria vulgaris* Mill.) is a perennial weed that has invaded areas near the SNG. Invasion of yellow toadflax has potential to crowd out native vegetation at the SNG and is mildly toxic to cattle (Mitich 1993). Aminocyclopyrachlor has provided inconsistent control of yellow toadflax, ranging from 30 to near 100% control 1 year after treatment (YAT) (Alms et al. 2012; Conklin and Lym 2012; Jenks 2012; Sebastian and Beck 2010b; Wallace and Prather 2012). The difference in control may have been due to the yellow toadflax growth stage at application. For example, aminocyclopyrachlor applied to flowering yellow toadflax resulted in near 100% control 14 months after treatment (MAT) compared to a fall vegetative application which resulted in 0% control 12 MAT (Conklin and Lym 2012).

The objectives of this research were to evaluate: 1) the effects of precipitation on quinclorac and aminocyclopyrachlor movement in the sandy soils of the SNG; and 2) yellow toadflax control using aminocyclopyrachlor applied at four growth stages. The long range goal is to improve chemical control of both leafy spurge and yellow toadflax with limited impacts on the environment.

LITERATURE REVIEW

Sheyenne National Grassland

Land use of the area known as the SNG was similar to many other areas in the Midwest prior to being designated as a National Grassland in 1960 (Olson 1997). Under the Homestead Act of 1862, qualified individuals could settle 65 ha of federal land to help facilitate settlement of the Great Plains. Many individuals homesteaded the area of the SNG; however, not all areas within the SNG boundaries were settled. Low average annual precipitation in many places and unprofitable farming conditions led Congress to amend the Homestead Act in 1909 to double the allowed acreage to 130 ha. Individuals who moved to and homesteaded the area near the SNG began farming and primarily grew wheat (*Triticum aestivum* L.) (Ely et al. 1907), which was difficult due to sandy soils found throughout the area.

Despite the hardships of farming in the Midwest, many people left the cities and moved to rural lands during the Great Depression of the 1930s (Olson 1997). The large influx of new people caused problems for farmers already in the area, which was further compounded by natural disasters. The drought of the 1930s (dust bowl) was the most severe and sustained drought since the mid-1850s (Burnette and Stahle 2013). For example, parts of Kansas and Missouri recorded 40 cm less precipitation over the growing season, combined with the highest ever recorded temperatures. The hot temperatures and low precipitation led to widespread soil erosion and crop loss. The combination of farming conditions compounded with the drought could not be overcome and farms began to fail (Olson 1997).

To alleviate the agricultural problems of the region, the federal government began purchasing farmland through the land utilization program in 1934 (Olson 1997). Land Utilization Projects (LUP) were implemented to transfer sub-marginal cropland affected by the drought to a suitable use and emphasize proper grassland resource management such as flood and erosion control, grass and tree planting, and improved water access. The program gained permanent status in 1937 with the passage of the Bankhead-Jones Farm Tenant Act.

The goal of converting sub-marginal cropland back to natural grasslands failed in many cases (Cunfer 2001). For example, the Little Missouri LUP in western North Dakota was comprised of 303,520 ha of land of which only 20% had ever been plowed. The unplowed land purchased was native grassland and had been used as rangeland for common access cattle grazing. The introduction of LUP changed who had access to the rangeland rather than meeting the goal of reclaiming sub-marginal cropland. The LUP first focused on restoring degraded lands, then emphasized proper rangeland management. By the mid-1940s, local grazing associations were created to help promote grassland management. Three requirements were implemented to join a grazing association: 1) ranchers must be dependent on the reserved land, 2) ranchers must have grazed cattle in the area prior to September 1934, and 3) ranchers must have commensurability, which was the ability of the rancher to provide adequate feed over winter. These requirements eliminated many small ranchers from access to lands in the LUP.

Financial constraints also impacted many areas which surrounded LUPs (Hurt 1985). Appraisals of land prices were much lower during the drought compared to previous years when supplemental land purchases were approved. Land owners incurred financial setbacks when payment for the land placed into LUPs was delayed by the government for over a year. Additionally, the displacement of many landowners changed the tax base of an area surrounding a LUP. In some instances there was a reduction of up to 50% of the tax base when families relocated from an area. This problem was partially addressed in Title III of the Bankhead-Jones Farm Tenant Act which required 25% of revenue earned on project lands to be returned to the affected counties.

Following World War II the economy boomed, normal weather patterns returned, and popularity of the LUP decreased (Cunfer 2001). The Secretary of Agriculture transferred management of the LUP's to the U.S. Forest Service in 1954 from the Soil Conservation Service, followed by the re-classification of over 1.5 million ha into several national grasslands in 1960 (Cunfer 2001; Olson 1997). Since then, the SNG has been managed for outdoor recreation, watershed health, and wildlife and fish habitat. In addition, cattle grazing, utility rights of way, and other special activities were permitted on the SNG.

In order to manage the National Grassland system for multiple uses, several laws were passed by Congress to guide the U.S. Forest Service in the decision process. The Multiple Use - Sustained Yield Act of 1960 conveyed the management philosophy of the U.S. Forest Service to meet multiple demands of forest land use (Culhane and Friesma 1979). Then from 1969 to 1974 Congress passed three acts that now govern the management actions of the U.S. Forest Service on the SNG. The National Environmental Policy Act of 1969 required evaluation of environmental impacts of all major management actions (Olson 1997). Any actions that risk the survival of endangered or threatened species, such as the western prairie fringed orchid, were prohibited by the Endangered Species Act of 1973. Finally, in 1974 the Forest and Rangeland Renewable Resources Planning Act required the Forest Service to prepare a plan to ensure a renewable resource management strategy.

The SNG is located in southeast North Dakota in the Sheyenne River Delta (Figure 1) and consists of choppy sand dune topography, and sandy soils (Nelson 1986). The SNG soils developed from wind eroded deltaic or lacustrine parent material, and were deposited by the Sheyenne River along the margin of the glacial Lake Agassiz (Nelson 1986; Pieper 2007). The vadose zone here generally consists of 80 to 95% medium to fine sand, and the groundwater is

4.5 m or less below the soil surface (Pieper 2007). Water infiltration is rated from well drained to poorly drained as the topography flattens.

Source: U.S. Forest Service

Figure 1. Map of the Dakota Prairie Grassland system with the Sheyenne National Grassland located in southeast North Dakota near Lisbon.

The U.S. Forest service has classified the SNG land using ecological site descriptions (ESD) reports prepared by the Natural Resource Conservation Service (NRCS) (Caudle et al. 2013). An ESD report contains four major sections: site characteristics, plant communities, site interpretations, and supporting information. Ecological sites are defined by characterizing “a distinctive kind of land based on recurring soil, landform, geological, and climate characteristics that differs from other kinds of land in its ability to produce distinctive kinds and amounts of vegetation and in its ability to respond similarly to management actions and natural disturbances.” The five major ecological sites located at the SNG are choppy sands, limy sub-irrigated, sands, sub-irrigated sands, and wet meadow. The delineation among sites has been mainly due to differences in soil type. For example, choppy sands soil is fine sand while wet meadow soils are a loamy sand (NRCS 2012). The dominant vegetation also has been used to further delineate among ecological sites, such as the presence of a mixed grass, tall grass prairie, or sedge meadow vegetative communities. Delineating between different ecological sites can be difficult because the sites typically are close in proximity and can overlap.

The SNG vegetation is a mixture of tall grass and mixed grass communities (Pieper 2007). The specific vegetation community found within the SNG has been associated with various landforms. For example, hummocky areas and choppy sand dunes are associated with a mixed grass prairie, while tall grass prairies have typically been located on level areas of the SNG. Swales and depressions in localized areas support wetland vegetative communities. Areas with tall grass prairie have included grasses such as big bluestem (*Andropogon gerardii* Vitman) and little bluestem (*Schizachyrium scoparium* Michx.). Mixed grass prairies include blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths), needle and thread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth], and prairie sandreed (*Calamovilfa longifolia* Hook). Other grasses located throughout the SNG include sand bluestem (*Andropogon hallii* Hack.), Indiangrass (*Sorghatrum nutans* Nash), and Kentucky bluegrass (*Poa pratensis* L.). Wetland vegetation and lowland sedge areas include reed grasses (*Calamogrostis* spp.), sedges (*Carex* spp.), and cattail (*Typha latifolia* L.). The SNG also includes 30 plant species listed as sensitive by the U.S. Forest Service.

The SNG contains one of three metapopulations of the federally listed endangered western prairie fringed orchid in North America (Pieper 2007). The western prairie fringed orchid generally has been associated with sedge meadows at the SNG. Approximately 1600 ha have been occupied by the western prairie fringed orchid across 31 allotments. Perhaps the largest threat for western prairie fringed orchid survival at the SNG is intrusion from leafy spurge

(USFWS 1996). The U.S. Forest Service estimated approximately 650 ha of leafy spurge directly overlapped with known western prairie fringed orchid habitat (Pieper 2007). Therefore, leafy spurge control options must be weighed with non-target effects on the western prairie fringed orchid.

Cattle ranchers depend on grazing federal lands, such as the SNG, for their livelihood (Pieper 2007). Currently, the SNG has 55 grazing allotments with one grazing permit issued to the Sheyenne Valley Grazing Association (Bernadette Braun, personal communication, 2013). The Sheyenne Valley Grazing Association has managed the grazing permit on the SNG for approximately 59,000 animal unit months (AUM). One concern at the SNG in relation to cattle grazing has been the continued spread of leafy spurge (Pieper 2007). The U.S. Forest Service predicted that if leafy spurge was left untreated, the grazing capacity of the SNG would be reduced up to 50%.

Leafy Spurge

Leafy spurge is a deep-rooted, perennial weed of the Euphorbiaceae family (Selleck et al. 1962). Stems are pale green, tough, woody, and grow up to 1 m high. Vegetative stems emerge from a woody crown early in the spring. Leaves are linear-lanceolate shaped up to 5 cm long, and have a bluish-green color. Yellow-green bracts form on a terminal cyathium early in the growing season, followed by the development of small true flowers (Messersmith et al. 1985; Selleck et al. 1962). Seeds develop in three-chambered capsules which disperse the seeds by dehiscing explosively (Hanson and Rudd 1933; Selleck et al. 1962). Leafy spurge seeds are gray-brown and 2.5 mm long by 1 mm wide. Leafy spurge produces an average of 2500 seeds m^{-2}, which can remain viable for up to 8 yr (Messersmith et al. 1985; Selleck et al. 1962). Leafy spurge root systems can be very extensive, growing 5 m deep (Bakke 1936). Latex is present throughout leafy spurge plants. The latex is an irritant, emetic, and purgative to most species that ingest the plant.

Leafy spurge has successfully invaded a wide variety of habitats due to several morphological traits (Messersmith et al. 1985). Each year, infestations can spread nearly 5 m through underground vegetative growth while above ground radial movement averaged 1 m of spread (Selleck et al. 1962). New infestations generally begin from seed which has 60 to 80% viability (Hanson and Rudd 1933; Messersmith et al. 1985). Additionally, leafy spurge grows in dense patches that exclude native plants and may have allelopathic properties that reduce the growth of other species (Messersmith et al. 1985).

Control methods for leafy spurge have been well characterized and evaluated. Several herbicides including 2,4-D, dicamba, glyphosate, picloram (Lym 1998), imazapic (Lym 2002), and quinclorac (Kuehl and Lym 1997) will control leafy spurge. Treating leafy spurge using 2,4-D alone is not effective, and averaged <50% control 12 MAT (Lym and Messersmith 1985). Imazapic has provided adequate leafy spurge control at the SNG and averaged 88% 12 MAT when applied in the spring (Lym 2002). However, imazapic may cause grass injury, especially to cool season grasses when applied in fall. The most commonly used treatment in North Dakota has been spring-applied picloram plus imazapic plus 2,4-D applied at 280 + 70 + 1100 g ai ha^{-1} (Lym 2011), which can provide nearly 100% control up to 24 MAT (Lym 2002). The wide spread use of picloram for leafy spurge control has led to the contamination of wells in North Dakota (Lym and Messersmith 1988), including one on the SNG. Thus, picloram is no longer allowed to be used on the SNG which has severely limited control options.

Quinclorac controlled leafy spurge without injury to the western prairie fringed orchid when applied in the fall (Erickson et al. 2006). In one North Dakota study, leafy spurge control using fall-applied quinclorac ranged from 72 to 99% 9 MAT (Kuehl and Lym 1997). At the SNG, fall-applied quinclorac reduced leafy spurge density 93 to 100% 10 MAT (Kirby et al. 2003). Leafy spurge control using quinclorac has been improved when applied with diflufenzopyr (Lym 2001). For example, leafy spurge control increased from 49 to 71% 12 MAT when diflufenzopyr was applied with quinclorac compared to quinclorac alone.

Leafy spurge has been controlled using aminocyclopyrachlor in North Dakota. For example, aminocyclopyrachlor applied to leafy spurge at 140 g ai ha^{-1} in June 2007 and reapplied in June 2009 provided 98% control 36 months after the first treatment (Lym 2011), which was better than the standard treatment of picloram plus imazapic plus 2,4-D. Similarly, aminocyclopyrachlor at 140 g ha^{-1} applied once in September averaged 97 and 82% control 12 and 36 MAT, respectively. However, the effects of aminocyclopyrachlor on the western prairie fringed orchid are unknown.

Biological control insects were introduced to control leafy spurge in the 1980s (Lym 1998). To date, twelve species of biological control insects have been released in the U.S. (Lym 2005). The most successful agents in North Dakota have been *Aphthona* spp. flea beetles, which feed on the root system of leafy spurge in the larval stage. The release of *Aphthona* spp. at one site in North Dakota reduced leafy spurge cover 6- to 7-fold within 7 yr (Kirby et al. 2000). Effective *Aphthona* spp. establishment has been dependent on physical features of the site (Lym 1998). For instance, the sandy soils and shallow groundwater at the SNG has limited *Aphthona* spp. establishment which has reduced leafy spurge control.

Leafy spurge is not consumed by cattle; however, goats and sheep will graze the plant (Lym et al. 1997). Cattle avoid leafy spurge infestations because internal and external contact with the latex causes sores (Lym and Kirby 1987). Several studies have evaluated leafy spurge control using goats. In North Dakota, angora goats alone did not reduce leafy spurge density after 3 yr in a rotational grazing system at the SNG (Lym et al. 1997). However, season-long grazing reduced leafy spurge density at Camp Grafton South near Devils Lake, ND. The reduction of leafy spurge cover was sufficient to improve forage quality for cattle grazing. While leafy spurge reduction can be achieved using goats alone, the reduction only lasts for the duration of grazing. Control of leafy spurge can be increased when grazing is combined with fall application of picloram plus 2,4-D.

Cultural methods such as properly timed cultivation and planting competitive grass species have been used to reduce leafy spurge density (Lym 1998). Mowing and fire have controlled leafy spurge top growth and could be used at the SNG. Spring prescribed burning at the SNG combined with or without grazing did not affect the density of the western prairie fringed orchid (Sieg and King 1995). Cultural control methods combined with herbicide treatments have been more successful at controlling leafy spurge than cultural methods alone.

Integration of multiple methods to control leafy spurge designed for a specific site has provided more effective, long-term control than individual methods applied alone (Lym 1998). For example, *Aphthona* spp. integrated with fall applied picloram plus 2,4-D reduced stem density 95% 1 YAT in North Dakota (Lym and Nelson 2002), which is similar to initial control obtained with herbicide treatments alone. However, the reduced leafy spurge density was maintained for at least 7 yr after the herbicide treatment, which is much longer than residual control from herbicide treatments. Other integrated practices for leafy spurge control include cultural methods integrated with herbicide treatments and grazing with goats combined with herbicide treatments (Lym 1998).

Yellow Toadflax

The sandy soils of the SNG may also facilitate an invasion of yellow toadflax, which is a perennial weed native to Eurasia that was introduced to the United States as an ornamental plant (Saner et al. 1995). In 2012, yellow toadflax was reported on over 5600 ha in North Dakota and continues to spread (Anonymous 2012). Yellow toadflax grows 30 to 80 cm tall and can be found in pasture, rangeland, rights-of-way, and other disturbed areas (Mitich 1993). Leaves are linear lanceolate and arranged alternately on the stem. From June to September, bright yellow flowers with five petals and orange throats grow on a raceme. Yellow toadflax reproduces by seed or vegetatively, which allows the rapid colonization of an area (Saner et al. 1995), similar to leafy spurge. The spread of an existing patch is largely due to vegetative reproduction, while new patches establish from seed germination. Seed production can vary from 10 to 165 seeds per stem; however, seed germination is often below 10%. Plants can regrow from root segments, which limit the benefit of cultural control methods (Nadeau et al. 1992).

Yellow toadflax control options are limited and generally less successful than those for leafy spurge. Intense cultivation of yellow toadflax 8 to 10 times the first year followed by 4 to 5 times the next year provided control (Morishita 1991). However, tillage is not practical in rangeland and pasture settings. Mowing can be used to reduce seed production, but does not reduce yellow toadflax density (Lajeunesse 1999; Saner et al. 1995).

Long-term control of yellow toadflax using herbicides such as dicamba, diflufenzopyr, and picloram is limited and variable (Sebastian and Beck 2010a). In Colorado, control ranged from 29% with dicamba, to 70% with picloram, and up to 97% with picloram plus dicamba plus diflufenzopyr 24 MAT. Conversely, picloram plus dicamba plus diflufenzopyr provided only 39% control in North Dakota (Conklin 2012). Picloram applied alone or with dicamba plus diflufenzopyr in midsummer has been recommended for yellow toadflax control in North Dakota (Zollinger et al. 2014).

Yellow toadflax control using aminocyclopyrachlor has varied based on application rate and growth stage of the weed. Yellow toadflax control averaged 90 to 100% regardless of rate and plant growth stage in some studies (Alms et al. 2012; Jenks 2012), while aminocyclopyrachlor applied to flowering or late-flowering plants averaged 70% (Conklin 2012; Sebastian and Beck 2010b.). Aminocyclopyrachlor applied at the vegetative regrowth stage provided 33 to 46% control 10 MAT, but declined to 0% 12 MAT (Conklin 2012). The effect growth stage has on yellow toadflax control using aminocyclopyrachlor is unclear.

Biological control of yellow toadflax has had minimal success (Sing et al. 2005). Eight insect species which feed on yellow toadflax have been introduced either accidentally or intentionally into the U.S. *Mecinus janthinus* (Germar) is the most established biological control agent in the country but has not reduced yellow toadflax. In one North Dakota evaluation, *M. janthinus* did not establish for at least 2 yr after release (Almquist 2008). No other biological control agent has established in the state (Nowierski 2004).

Quinclorac

Quinclorac is a substituted quinolinecarboxylic acid, a highly selective auxin herbicide (Grossmann 1998). In sensitive plants, quinclorac is readily absorbed through leaves, roots, and germinating seeds then translocated throughout the plant. When the herbicide is absorbed, a phytohormonal system response causes growth inhibition, stimulates senescence, and finally causes necrosis. Grassy and broadleaf weeds can be controlled using quinclorac in turf, agricultural fallow, idleland, agricultural right-of-way, grass sown for seed, rice (*Oryza sativa*

L.), sorghum [*Sorghum bicolor* (L.) Moench], and wheat (*Triticum* spp.) (Grossmann 1998; Grossmann and Kwiatkowski 2000; Street and Mueller 1993).

Chemical properties of quinclorac may reduce leaching potential in the soils of the SNG compared to other auxin herbicides. Water solubility for quinclorac is lower at only 62 mg L^{-1} compared to 430 and 2480 mg L^{-1} for picloram and aminopyralid, respectively (Senseman 2007a; Senseman 2007b; Senseman 2007c). Quinclorac can be persistent in soil due to a higher sorption coefficient (K_{oc}) of 446 and soil half-life of 210 days (Hill et al. 2000) compared to a sorption value of 10.8 and average 35 d half-life for aminopyralid (Senseman 2007a). Quinclorac is a weak acid with a pKa of 4.34 (Senseman 2007c) compared to 2.56 for aminopyralid (Senseman 2007a) and 2.30 for picloram (Senseman 2007b).

Aminocyclopyrachlor

Aminocyclopyrachlor is a pyrimidinecarboxylic acid herbicide that has both foliar and residual activity and has been developed for broadleaf weed control in range and pasture (Rick et al. 2011). Aminocyclopyrachlor is structurally similar to picloram, a pyridinecarboxylic acid used for broadleaf weed control in rangeland, pasture, and non-crop areas (Oliveira et al. 2013). However, physical and chemical properties differ from picloram. Aminocyclopyrachlor water solubility is 4200 mg L^{-1} (Anonymous 2009) compared to 430 mg L^{-1} for picloram (Senseman 2007b). Soil sorption (K_{oc}) differs at 28 (Anonymous 2009) compared to 16 (Senseman 2007b) for aminocyclopyrachlor and picloram, respectively. Aminocyclopyrachlor has favorable environmental characteristics including low use rates and low mammalian toxicity (Rick et al. 2011). Additionally, aminocyclopyrachlor soil half-life in Lamoure loamy sand, which is similar to SNG soils, averaged 40 d (Conklin and Lym 2013) compared to an average half-life of 90 d for picloram (Senseman 2007b).

Aminocyclopyrachlor has been evaluated for control of many noxious and invasive weeds found in North Dakota. Adequate to excellent control of Canada thistle (*Cirsium arvense* L.), perennial sowthistle (*Sonchus arvensis* L.), leafy spurge (Lym 2010), absinth wormwood (*Artemisia absinthium* L.), houndstongue (*Cynoglossum officinale* L.), yellow toadflax (Conklin and Lym 2012), Russian knapweed (*Centaurea repens* L.), and saltceder (*Tamarix ramosissima* Ledeb.) (Lindenmayer et al. 2010) can be achieved using aminocyclopyrachlor. Aminocyclopyrachlor has potential for use in the turf, vegetation management, rangeland, and pasture markets because of the wide range of activity (Oliveira et al. 2013).

Herbicide Mobility

Environmental fate of quinclorac and aminocyclopyrachlor at the SNG may be largely affected by the sorption characteristics and, thus, the leaching potential of each herbicide (Oliveira et al. 2001; Xu et al. 2009). The connection between sorption and mobility is typically an inverse relationship, where a higher sorption value may predict lower leaching potential. Sorption and mobility are affected by soil physicochemical properties such as cation exchange capacity (CEC), soil texture, ion concentration, organic matter content, and soil pH (Oliveira et al. 2001; Oliveira et al. 2011; Xu et al. 2009).

Soil properties affect herbicides differently depending on the chemical structure of the herbicide (Xu et al. 2009). Weak acid herbicides, such as aminocyclopyrachlor and quinclorac, typically have a positive adsorption correlation to clay content, which may reduce the risk of herbicide leaching (Hill et al. 2000; Hill et al. 1998; Oliveira et al. 2011). For example, aminocyclopyrachlor sorption was positively correlated to clay content in two different studies (Oliveira et al. 2011; Oliveira et al. 2013). Sorption characteristics of other auxin herbicides, such as picloram, have also increased as clay content in the soil increased (Fast et al. 2010). However, the type of clay mineral and not just clay content can affect herbicide sorption.

Sorption values for picloram increased from 0.25 to 1016 mg L^{-1} on kaolinite and montmorillonite clay minerals, respectively.

Auxin herbicides also have a positive adsorption correlation to organic matter content (Xu et al. 2009). For example, quinclorac sorption in loamy soils increased as organic matter content increased from 2.1 to 5.9%, which reduced leaching depth of the herbicide (Hill et al. 2000). Aminocyclopyrachlor sorption was positively correlated to organic matter along with clay content (Oliveira et al. 2011). However, in a separate study aminocyclopyrachlor adsorption was correlated only to clay content (Oliveira et al. 2013).

Soil pH can also affect sorption and leaching for weak acid herbicides (Oliveira et al. 2001), such as quinclorac and aminocyclopyrachlor. If the soil pH value is higher than the pKa value of a weak acid herbicide, molecules will be deprotonated into the anionic form. In the negatively charged anionic form, a herbicide may be repelled from binding to clay minerals which are also negatively charged. For example, quinclorac soil adsorption decreased from 39 to 34% when pH increased from of 5.7 to 6.7, respectively (Williams et al. 2004). Aminocyclopyrachlor adsorption also tended to have a negative correlation with increased soil pH levels (Oliveira et al. 2011).

MATERIALS AND METHODS

Herbicide Movement

Movement of quinclorac and aminocyclopyrachlor in sandy soils of the SNG was determined using soil columns to replicate field soil conditions (Weber and Whitacre 1982). Soil was collected from the five dominant ecological sites found at the SNG during the summers of 2012 and 2013. The ecological sites included choppy sands (Mixed, frigid Typic Udipsamments) (Soil Survey Staff 2011), sands (Sandy, mixed, frigid Entic Hapludolls), sub-irrigated sands (Mixed, frigid Aquic Upidsamments), limy sub-irrigated (Sandy, mixed, frigid Aeric Calciaquolls), and wet meadow (Sandy, mixed, frigid Typic Endoaquolls). The topsoil was collected from 0 to 25 cm at all sites, except at the choppy sands site, where the sandy subsoil was collected. After collection, the soil was screened through a 6 mm sieve, mixed thoroughly, air dried, and stored at 21 C (Samuel 2007).

Table 1. Physical and chemical characteristics of soils from various ecological sites on the Sheyenne National Grassland, near Lisbon, ND. Analysis performed by NDSU soil testing lab.

Ecological site	Soil series	Sand	Silt	Clay	Organic matter	pH
		%				
Choppy sands	Serden	94	3	3	1.0	6.3
Sands	Maddock	91	6	3	1.6	6.2
Sub-irrigated sands	Aylmer	90	8	2	1.5	6.0
Limy sub-irrigated	Ulen	80	14	6	3.7	8.0
Wet meadow	Hamar	84	14	2	2.4	6.7

Soil columns were constructed from polyvinylchloride (PVC) pipe measuring 70 cm long with a 7.6 cm inside diameter (Samuel 2007). The PVC pipe was cut longitudinally along the central axis and silicon applied to the inside perpendicular to the cut at 10 cm increments to reduce water boundary flow (Weber and Whitacre 1982). Columns were re-sealed with silicon, secured together using metal clamps, and capped with a fiberglass mesh screen attached to the bottom to retain soil (Samuel 2007). Soil was added to the columns and packed using a mechanical soil packer to a depth of 65 cm (Samuel 2007; Weber and Whitacre 1982). The columns were saturated top to bottom with distilled water over a 48 h period, and then placed on dry soil from the same site for 48 h to equilibrate gravimetric water content.

Treatments included one of two herbicides and precipitation events. Herbicide was applied to the soil surface equivalent to labeled field use rates of quinclorac at 420 g ha^{-1} or aminocyclopyrachlor at 140 g ha^{-1} in 10 mL of water in a serpentine pattern. The herbicide was allowed to equilibrate for 24 h before precipitation was applied to the soil column. Precipitation events included either the average annual precipitation of 51 cm applied over 9 wk or the largest recorded heavy rain event of 15 cm water over 48 h. Water was applied using 1500 ml bags with water flow regulated by metal clamps. Glass wool was placed on the soil surface to ensure even distribution of the water (Samuel 2007). Each herbicide/precipitation event was applied to all soil types, with 4 columns in each run, and repeated a second time. Leachate from the column was collected using 14.5 cm inside diameter by 9 cm deep plastic containers. Following each treatment, columns were allowed to stand for 48 to 72 h. Then column halves were separated and the soil was divided into 5 cm segments. Soil from each segment was placed into 7.5 cm deep by 10 cm inside diameter plastic pots with five holes drilled in the bottom and lined with filter paper[1]. The soil was allowed to dry to approximately 45% moisture content prior to analysis. Plastic pots were placed in 13 by 13 by 3.5 cm deep foam trays to prevent water loss.

Preliminary trials were conducted to evaluate alfalfa (*Medicago sativa* L.), peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and tomato (*Solanum lycopersicum* L.) as indicator species for quinclorac. Sunflower was sensitive with the

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[1] VWR Filter Paper 415, Size: 9 cm, VWR International Inc., 800 E Fabyan, Batavia, IL 60510.

most reliable response to quinclorac concentration and was used. Aminocyclopyrachlor concentration was determined by a soybean bioassay as previously described by Conklin and Lym (2013). A standard curve was prepared for each soil type, and bioassayed concurrently with the soil column bioassay. For the standard curve, 300 g of soil was placed into pots as previously described, treated with herbicide, mixed, and moistened to approximately 45% field capacity. Aminocyclopyrachlor was applied at 0, 4.5, 9, 18, and 36 µg kg^{-1}, and quinclorac at 0, 31.25, 62.5, 125, 250, and 500 µg kg^{-1} with 4 replicates for each herbicide rate. Eight sunflower or soybean seeds were sown, then plants were thinned to four per pot after emergence. Water soluble fertilizer[2] was applied at 85 kg nitrogen ha^{-1} to each pot. Soil was moistened by adding distilled water alternately to the surface and sub-surface throughout the bioassay as needed. Pots were re-randomized twice weekly to reduce environmental variability. The greenhouse environment was maintained at 21 C with natural light supplemented by metal halide lamps at 450 µE m^{-2} s^{-1} for 16 h per day. Sunflower and soybean plants were harvested approximately 21 and 14 d after planting, respectively. Height of sunflower and soybean plants was measured from soil surface to apical meristem. Height was compared to a standard curve to estimate herbicide concentration for all soil types, except the limy sub-irrigated ecological site when sunflower and soybean dry weight was used.

Aminocyclopyrachlor Efficacy

Aminocyclopyrachlor efficacy on yellow toadflax was evaluated in a field trial established at the Knudtson Waterfowl Production Area (WPA) near Jamestown, ND in 2012 and repeated in 2013. The WPA was purchased by the U.S. Fish and Wildlife Service to preserve wetland and grassland habitat needed for waterfowl and other wildlife (USFWS 2007) and had been infested

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[2] Jack’s Classic All Purpose Water Soluble Plant Food, Analysis: 20-20-20, J. R. Peters, Inc., 6656 Grant Way, Allentown, PA 18106.

by yellow toadflax from contaminated grass seed. The primary vegetation at the WPA was Kentucky bluegrass and smooth brome (*Bromus inermis* Leyss). Initial yellow toadflax stem density averaged 8 stems m^{-2}. Other weeds established at the site included absinth wormwood and Canada thistle. The soil was a Hamerly-Tonka complex (Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls; Fine, smectitic, frigid Argiaquic Argialbolls) which is a loam-silt loam complex and rated as poorly drained (Soil Survey Staff 2011). Average annual precipitation for the WPA is 51 cm (NDAWN 2013). In 2012 the WPA received approximately half the precipitation of only 25 cm, while in 2013 above normal precipitation of 61 cm was recorded.

Aminocyclopyrachlor at 70, 105, and 140 g ha^{-1} was compared to the standard treatment of picloram plus dicamba plus diflufenzopyr at 1120 + 210 + 84 g ha^{-1}. Treatments were each applied to yellow toadflax approximately the 15th of the month in June, July, August, or September. There was one untreated control for comparison. All treatments were applied with a non-ionic surfactant at 0.25% v/v. Yellow toadflax growth stage and height varied across the four application dates from vegetative in June to flowering and seed set in September (Table 2). Herbicide treatments were applied using a hand boom sprayer with four 8002 nozzles[3] that delivered 160 L ha^{-1} at 241 kPa. Treatments were assigned to 3- by 9-m plots using a randomized complete block design (RCBD) with four replicates. Yellow toadflax density was evaluated by counting the number of stems in four 0.5- by 0.5-m quadrats per plot before treatment, 1 MAT, and approximately 12 MAT.

Table 2. Yellow toadflax height and growth stage at herbicide application at the Knudtson Waterfowl Production Area near Jamestown, ND.

Yellow toadflax	June	July	August	September
Height (cm)	10 to 30	25 to 45	25 to 45	25 to 45
Growth stage	Vegetative	Pre-bud	Flower initiation	Flower/seed set

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[3] TeeJet, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189-7900.

Statistical Analysis

Movement of herbicides in the different soil types was determined by regression analysis. A linear equation was calculated from the plant measurements of the standard curve soils. Plant height or weight from each column segment was compared to the linear equation to estimate herbicide concentration. Estimated herbicide concentration was analyzed using the GLM procedure in SAS[4].

Efficacy of aminocyclopyrachlor on yellow toadflax was analyzed using the GLM procedure of SAS. Yellow toadflax control was determined by comparing stem density of each treatment to the untreated control. Control was analyzed as a 4 by 4 factorial with timing, treatment, and timing by treatment as factors (Kyser and DiTomaso 2013). F-test results were considered significant at $P \leq 0.05$, and separation of means calculated with an F-protected least significant difference test at $\alpha = 0.05$.

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[4] Statistical Analysis Software 2003, version 9.1, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513.

RESULTS AND DISCUSSION

Herbicide Movement

Aminocyclopyrachlor leached farther in soil columns compared to quinclorac in all five soils types collected from the SNG (Figures 2 – 5). Aminocyclopyrachlor leached through the entire soil profile following the heavy rainfall event of 15 cm precipitation applied over 48 h and the seasonal average of 51 cm precipitation applied over 9 wk, but quinclorac stayed within the soil column.

Quinclorac and aminocyclopyrachlor movement in the limy sub-irrigated, sands, sub-irrigated sands, and wet meadow soils was similar for each herbicide and was different than the choppy sands soil. Therefore, data from the four similar soils were combined by herbicide and hereafter will be referred to as the four combined soils (FCS). Detection limits of 50 and 5 $\mu g\ kg^{-1}$ were identified for quinclorac and aminocyclopyrachlor, respectively.

Quinclorac leached farther following the heavy rainfall event of 15 cm precipitation applied over 48 h compared to 51 cm precipitation applied over 9 wk in all soil types (Figures 2 and 3). Quinclorac concentrations dropped below detection limits at a depth of 40 to 45 cm following 15 cm precipitation applied over 48 h in the FCS. Quinclorac appeared to move in a pulse with the highest concentration found at 25 cm. Movement was greater in the choppy sands soil compared to the FCS and leached to a depth of 60 to 65 cm following both precipitation events. Quinclorac leached only to a depth of 20 to 25 cm in the FCS following 51 cm precipitation applied over 9 wk.

Soil texture and organic matter content may have affected quinclorac movement. Quinclorac movement was less in the FCS which had a higher organic matter content compared to the choppy sands soil (Table 1), and is similar to reported leaching rates in loamy soils (Hill et al.

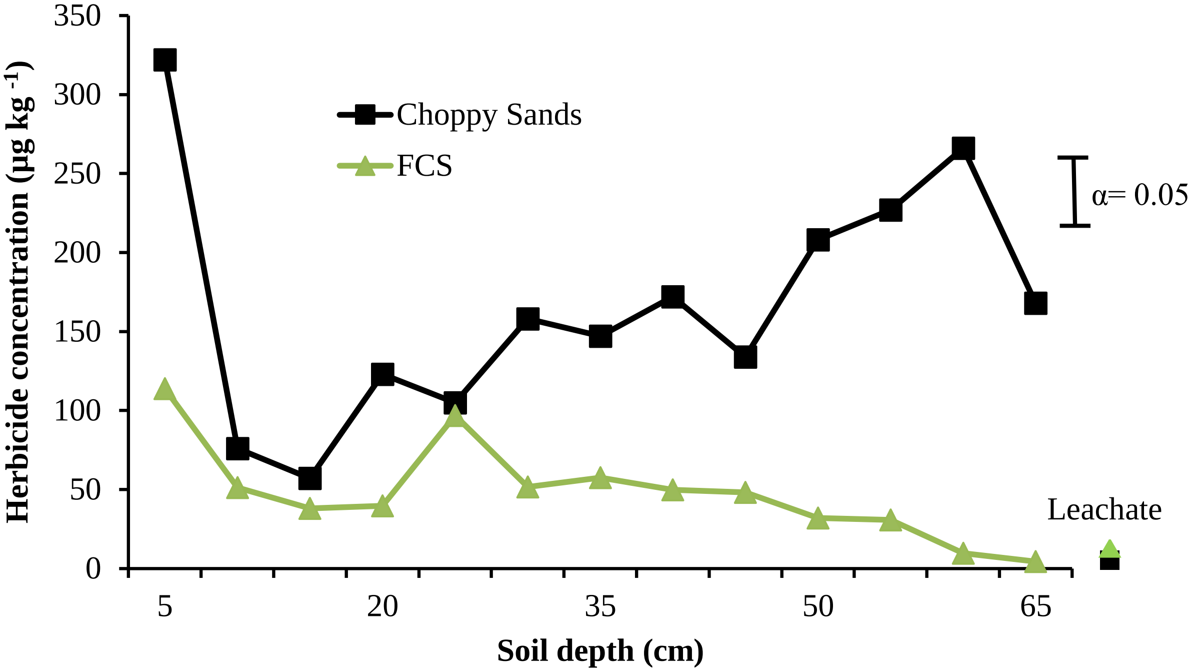

Figure 2. Quinclorac concentration following 15 cm of precipitation applied over 48 h in soils collected from the Sheyenne National Grassland near Lisbon, ND to a depth of 65 cm and in the collected leachate. The results from four separate soils were combined (FCS) for presentation.

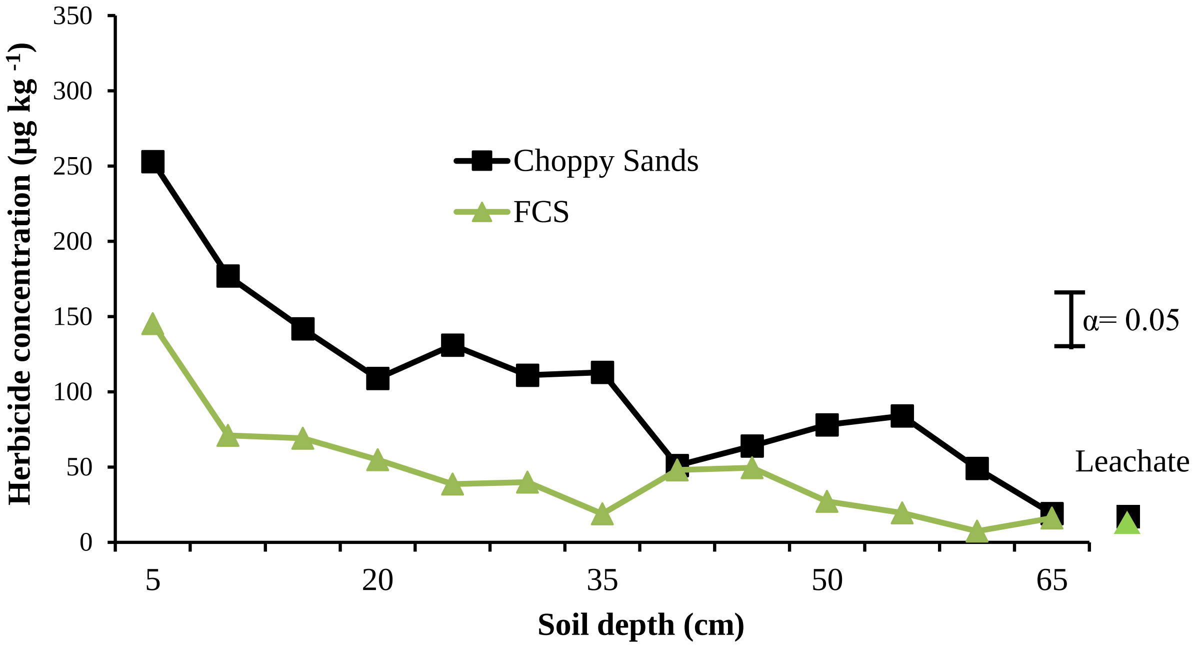

Figure 3. Quinclorac concentration following 51 cm of precipitation applied over 9 wk in soils collected from the Sheyenne National Grassland near Lisbon, ND to a depth of 65 cm and in the collected leachate. The results from four separate soils were combined (FCS) for presentation.

2000). Aminopyralid and clopyralid, two auxin herbicides with similar properties to quinclorac, also had significant adsorption correlation to changes in soil organic matter, sand, silt, and clay content (Bukun et al. 2010).

Aminocyclopyrachlor leached through the entire column, regardless of soil type following both precipitation events (Figures 4 and 5). In contrast to quinclorac, higher aminocyclopyrachlor concentrations moved through the soil profile following the seasonal rainfall event of 51 cm precipitation applied over 9 wk compared to the heavy rainfall event of 15 cm precipitation applied over 48 h. Aminocyclopyrachlor moved in a pulse similar to quinclorac in the FCS following 15 cm precipitation applied over 48 h, with the greatest concentration at the 35 cm depth of the soil column (Figure 4). Overall, aminocyclopyrachlor leaching was greater in the choppy sands soil compared to the FCS and moved completely through the column following 15 cm precipitation applied over 48 h.

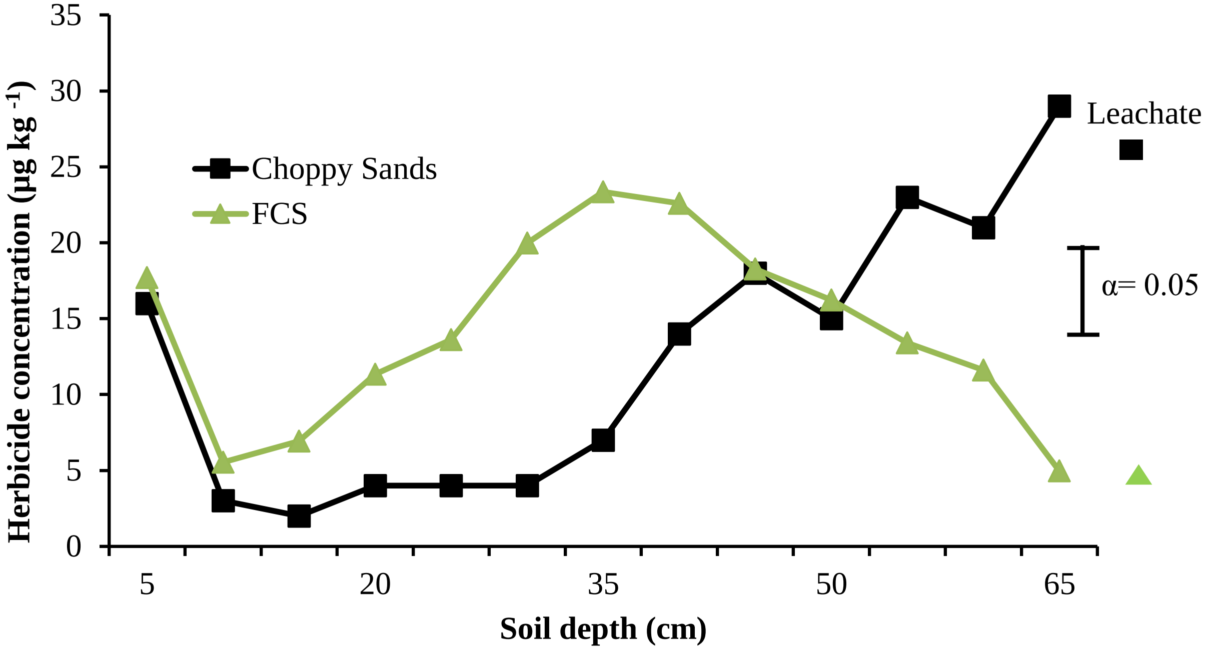

Figure 4. Aminocyclopyrachlor concentration following 15 cm of precipitation applied over 48 h in soils collected from the Sheyenne National Grassland near Lisbon, ND to a depth of 65 cm and in the collected leachate. The results from four separate soils were combined (FCS) for presentation.

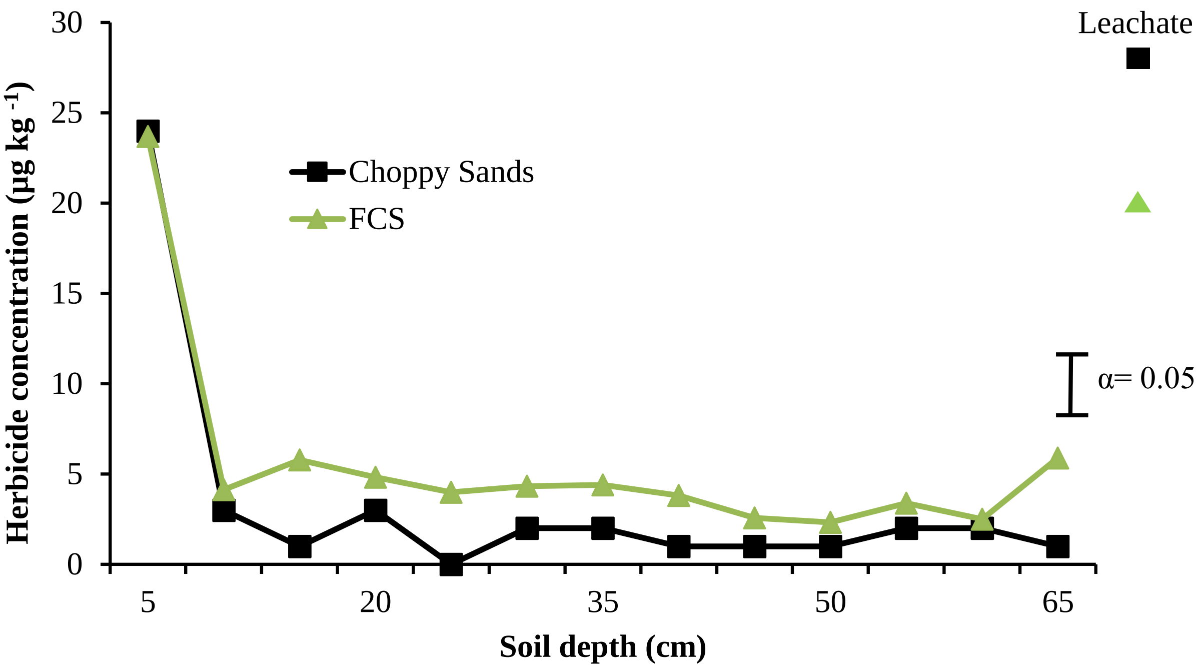

Figure 5. Aminocyclopyrachlor concentration following 51 cm of precipitation applied over 9 wk in soils collected from the Sheyenne National Grassland near Lisbon, ND to a depth of 65 cm and in the collected leachate. The results from four separate soils were combined (FCS) for presentation.

Aminocyclopyrachlor readily leached through the soil collected from the SNG, which varied in soil particle and organic matter content. This is similar to the ranking of “leacher,” which aminocyclopyrachlor was referred to in a study of three Brazilian soils (Oliveira et al. 2013). Aminocyclopyrachlor had similar leaching characteristics to picloram, which may allow land managers to use picloram as a leaching model for this herbicide. For example, Lym and Messersmith (1988) detected picloram in several groundwater samples across North Dakota, including one at the SNG. In addition, picloram was detected in 22 samples from 10 wells at the SNG from 1993 to 1994 (Pieper 2007).

Although aminocyclopyrachlor and picloram have similar leaching characteristics in soil, aminocyclopyrachlor may have a lower impact compared to picloram on the environment. Aminocyclopyrachlor application rates which are half compared to picloram combined with shorter soil half-life may reduce environmental fate concerns while using aminocyclopyrachlor.

For example, application rates for leafy spurge control have been 280 and 140 g ha^{-1} for picloram and aminocyclopyrachlor, respectively (Zollinger et al. 2014). Soil half-life differs from 35 d for aminocyclopyrachlor (Conklin and Lym 2013) to 90 d for picloram (Senseman 2007b).

Aminocyclopyrachlor and quinclorac leaching was hysteretic following both precipitation events. Hysteresis is defined as once a herbicide is adsorbed to the soil particle surface it does not readily desorb (Oliveira et al. 2013). An average aminocyclopyrachlor concentration of 20 µg kg^{-1} was retained in the top 5 cm across all soil types (Figures 4 and 5). This is similar to aminocyclopyrachlor hysteresis observed in 17 different soil types which ranged from sandy to clay textures (Oliveira et al. 2011; Oliveira et al. 2013). Approximately 208 µg kg^{-1} of quinclorac was retained in the top 5 cm across all soil types (Figures 2 and 3). Other auxin herbicides, such as picloram and aminopyralid, have also displayed hysteretic movement (Oliveira et al. 2013; Samuel 2007).

Quinclorac leaching was greater following 15 cm of precipitation applied over 48 h which contrasts to greater aminocyclopyrachlor movement following 51 cm of precipitation applied over 9 wk (Figures 2 and 5). Aminocyclopyrachlor is more weakly adsorbed to soil surfaces and has a higher leaching potential (Oliveira et al. 2011; Oliveira et al. 2013) compared to quinclorac which may have accounted for this difference. Herbicide sorption coefficient (K_{oc}) values of 446 and 28 for quinclorac and aminocyclopyrachlor, respectively (Anonymous 2009; Hill et al. 2000) also support this hypothesis. An alternative explanation could be due to the difference in the water solubility of each herbicide. Quinclorac water solubility is 62 mg L^{-1} (Senseman 2007c) compared to 4.2 g L^{-1} for aminocyclopyrachlor (Anonymous 2009). To dispense the prescribed quantity of water over 9 wk, approximately 5.6 cm precipitation was delivered weekly. Due to the lower water solubility of quinclorac, the heavy rain event of 15 cm precipitation applied over

48 h may have caused more quinclorac to be leached compared to greater amounts of precipitation applied over a longer period of time. This explanation is supported by Hill et al. (1998) which reported quinclorac movement increased as precipitation increased. Conversely, aminocyclopyrachlor leached farther following the higher total amount of 51 cm precipitation applied over 9 wk due to higher water solubility, even though dispensed in smaller amounts.

Quinclorac and aminocyclopyrachlor movement may be affected by individual soil characteristics at the SNG. Several interacting factors often influence herbicide sorption and mobility (Fast et al. 2010; Oliveira et al. 2011). For instance, Cecil sandy loam soil collected in Florida with 6% more clay, 0.47% more organic matter, and 1.4 units lower pH than an Arredondo fine sand soil would be predicted to have a higher sorption value for picloram. However, the opposite occurred and sorption values were 0.12 and 0.81 mg kg^{-1} for the Cecil sandy loam and Arredondo fine sand, respectively. The type of clay particles in the Arredondo fine sand soil may have outweighed the other factors. Predictions of quinclorac and aminocyclopyrachlor leaching in the SNG soils may be complicated due to interacting characteristics within each soil type.

Aminocyclopyrachlor Efficacy

Yellow toadflax control with aminocyclopyrachlor varied by growth stage. Control averaged 98% 1 YAT when aminocyclopyrachlor was applied prior to flowering, but only averaged 50% when the herbicide was applied to the fall vegetative stage (Figure 6). This supports a previous North Dakota study when aminocyclopyrachlor applied to flowering plants in July averaged 96% control compared to 0% when applied to the vegetative regrowth stage in September (Conklin and Lym 2012). Picloram plus dicamba plus diflufenzopyr averaged 92% 1 YAT yellow toadflax control regardless of application date (Figure 6). There was no interaction between any herbicide treatment with growth stage at application.

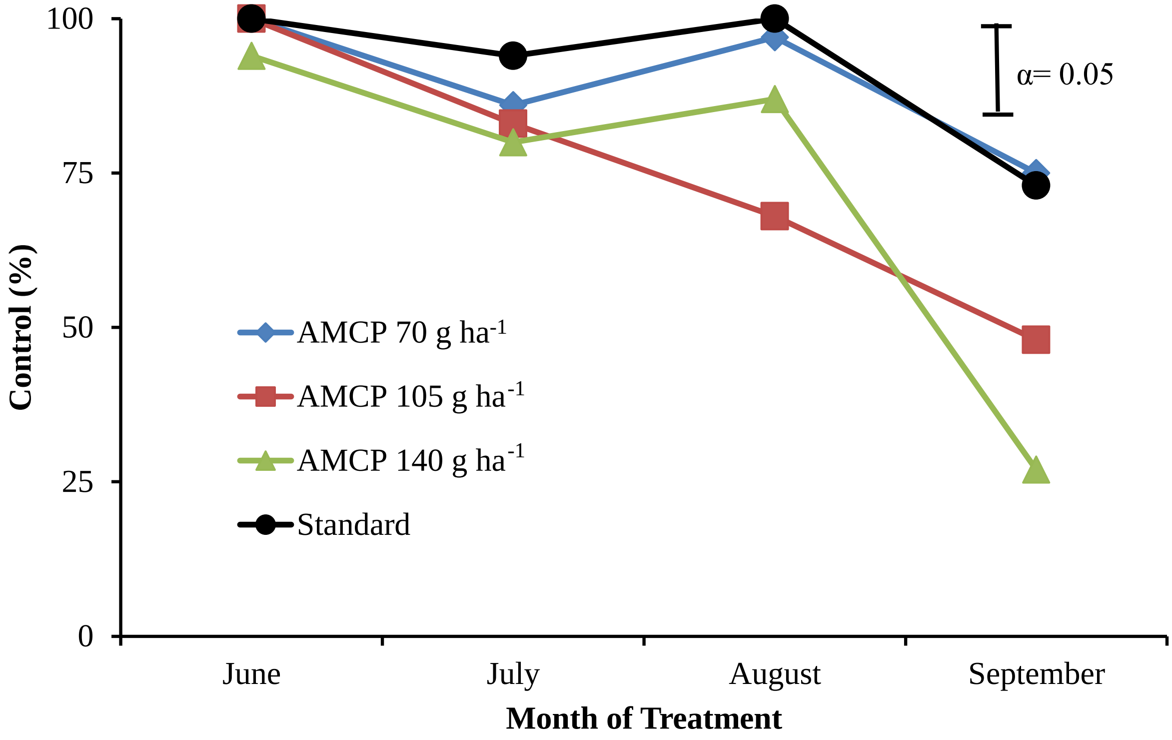

Figure 6. Yellow toadflax control 1 yr after treatment in June, July, August, or September at the Knudtson Waterfowl Production Area near Jamestown, ND. The standard treatment was picloram plus dicamba plus diflufenzopyr at 1120 + 210 + 84 g ha^{-1}.

Aminocyclopyrachlor applied at 70, 105, and 140 g ha^{-1} averaged 89, 75, and 72% control, respectively, 1 YAT (Figure 6). This contrasts with previous reports that as aminocyclopyrachlor application rates increased weed control also increased (Conklin and Lym 2012; Jenks 2012; Sebastian and Beck 2010b). In addition, this contradicts previous reports that found aminocyclopyrachlor applied to yellow toadflax generally provided better or similar control to the standard treatment of picloram plus dicamba plus diflufenzopyr.

The hot and dry field conditions during the 2012 growing season may have caused reduced aminocyclopyrachlor efficacy on yellow toadflax. Although the growing season average maximum temperature was only 1 C warmer than the long-term average (NDAWN 2013), many days were 6 to 11 C higher than the average daily maximum temperatures. In addition, precipitation from June to October was approximately 18 cm less than the long-term average. Aminocyclopyrachlor efficacy was reduced when applied in dry conditions in North Carolina (Lewis et al. 2013). For example, bermudagrass (*Cynodon dactylon* L.) injury was reduced from 28 to 19% when aminocyclopyrachlor was applied in wet and dry conditions, respectively.

Herbicide translocation to the roots has influenced perennial weed control (Lym and Moxness 1989). In yellow toadflax, only 2% of applied ^{14}C-aminocyclopyrachlor was translocated to the roots compared to 12% in leafy spurge (Lym 2014). The low level of aminocyclopyrachlor translocation may have influenced the variable level of control observed in this study as well as other evaluations (Alms et al. 2012; Conklin and Lym 2012; Jenks 2012; Sebastian and Beck 2010b). In addition, increased top growth necrosis from higher aminocyclopyrachlor application rates may have further reduced herbicide translocation to the roots.

Large amounts of genetic diversity found within and among U.S. populations of yellow toadflax (Ward et al. 2008) may have affected control. Variable yellow toadflax response to herbicide treatments may be observed even within the same pasture, which could be due to variation in biotype susceptibility. Newly established yellow toadflax patches are introduced from seed and likely differ from established populations, which spread mainly through vegetative reproduction (Saner et al 1995; Ward et al. 2008).

CONCLUSION

The environmental fate of a herbicide is important in the determination of use rate and location. Quinclorac did not leach through the soil profile of any soil type from the SNG. Movement was reduced in the soil as organic matter and clay content increased. Therefore, quinclorac is suitable for use at the SNG for leafy spurge control. Aminocyclopyrachlor readily leached through all soil types. Due to high leaching potential and similarity to picloram, aminocyclopyrachlor is not recommended for use at the SNG.

Yellow toadflax control using aminocyclopyrachlor varied by growth stage. The current recommendation of treating yellow toadflax from mid-summer to fall with aminocyclopyrachlor (Zollinger et al. 2014) should be revised to include earlier application dates. Also, the standard treatment of picloram plus dicamba plus diflufenzopyr provided more consistent yellow toadflax control over the growing season than aminocyclopyrachlor in this study. Thus aminocyclopyrachlor use for yellow toadflax control may be limited to areas where picloram cannot be used.

LITERATURE CITED

Almquist TL (2008) Effect of aminopyralid on Canada thistle and the native plant community in a restored tallgrass prairie. M.S. thesis. North Dakota State University, Fargo, ND. 59 p

Alms JK, Moechnig MJ, Vos DA, Deneke DL (2012) Yellow toadflax control with fall herbicide applications. Proc West Soc Weed Sci 65:23-24

Anonymous (2009) DuPont: DPX-MAT28 Technical Bulletin. E.I. du Pont de Nemours and Company. Available at https://lists.alaska.edu/pipermail/cnipml/attachments/20090310/-f10dfb94/MAT28TechBulletin.pdf

Anonymous (2012) 2012 Annual weed board report. Bismark, ND: North Dakota Department of Agriculture. 1 p Available at: http://www.nd.gov/ndda/program/noxious-weeds

Bakke AL (1936) Leafy spurge, *Euphorbia esula* L. Iowa Agr Expt Sta Res Bull 198:209-245

Bukun B, Shaner DL, Nissen SJ, Westra P, Brunk G (2010) Comparison of the interactions of aminopyralid vs. clopyralid with soil. Weed Sci 58:473-477

Burnette DJ, Stahle DW (2013) Historical perspective on the dust bowl drought in the central United States. Climatic Change 116:479-494

Caudle D, DiBenedetto J, Karl M., Sanchez H, Talbot C (2013) Interagency ecological site handbook for rangelands. Available at: http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=33151.wba. 109 p

Culhane PJ, Friesema HP (1979) Land use planning for the public lands. Nat Res J 19:43-74

Conklin KL (2012) Aminocyclopyrachlor: weed control, soil dissipation, and efficacy to seedling grasses. M.S. Thesis. Fargo, ND: North Dakota State University. 83 p

Conklin KL, Lym RG (2012) Absinth wormwood (*Artemisia absinthium* L.), houndstongue (*Cynoglossum officinale* L.), and yellow toadflax (*Linaria vulgaris* Mill.) control with aminocyclopyrachlor. Proc Weed Sci Soc Amer Pp 77

Conklin KL, Lym RG (2013) Effect of temperature and moisture on aminocyclopyrachlor soil half-life. Weed Technol 27:552-556

Cunfer G (2001) The new deal's land utilization program in the great plains. Great Plains Quarterly 21:193-210

Ely CW, Willard RE, Weaver JT (1907) Soil survey of Ransom County, North Dakota. Washington, DC: U.S. Department of Agriculture

Erickson AM, Lym RG, Kirby D (2006) Effect of herbicides for leafy spurge control on the western prairie fringed orchid. Rangeland Ecol Manage 59:462-467

Fast BJ, Ferrell JA, MacDonald GE, Krutz LJ, Kline WN (2010) Picloram and aminopyralid sorption to soil and clay minerals. Weed Sci 58:484-489

Grossmann K (1998) Quinclorac belongs to a new class of highly selective auxin herbicides. Weed Sci 46:707-716

Grossmann K, Kwiatkowski J (2000) The mechanism of quinclorac selectivity in grasses. Pestic Biochem Physiol 66:83-91

Hanson HC, Rudd VE (1933) Leafy spurge life history and habits. North Dakota Agric Exp Stn Bull 266. 24 pp

Hill BD, Miller JJ, Harker KN, Byers SD, Inaba DJ, Zhang C (2000) Estimating the relative leaching potential of herbicides in Alberta soils. Water Qual Res J Can 35:693-710

Hill BD, Moyer JR, Inaba DJ, Doram R (1998) Effect of moisture on quinclorac dissipation in Lethbridge soil. Can J Plant Sci 78:697-702

Hurt D (1985) The National Grasslands: origin and development in the dust bowl. Agric History 59:246-259

Jenks BM (2012) Yellow toadflax control in rangeland with DPX-MAT 28. Proc West Soc Weed Sci 65:4

Kirby DR, Carlson RB, Krabbenhoft KD, Mundal D, Kirby MM (2000) Biological control of leafy spurge with introduced flea beetles (*Aphthona* spp.). J Range Manage 53:305-308

Kirby DR, Lym RG, Sterling JJ, Sieg CH (2003) Leafy spurge control in western prairie fringed orchid habitat. J Range Manage 56:466-473

Kuehl BD, Lym RG (1997) Leafy spurge (*Euphorbia esula*) control with quinclorac. Weed Technol 11:265-269

Kyser GB, DiTomaso JM (2013) Effect of timing on chemical control of dalmatian toadflax (*Linaria dalmatica*) in California. Invasive Plant Sci Manag 6:362-370

Lajeunesse S (1999) Dalmatian and yellow toadflax. Pages 202-216 In R. L. Sheley and J. K. Petroff, ed. Biology and Management of Noxious Rangeland Weeds. Corvallis: Oregon State University Press

Lewis DF, Jeffries MD, Stek HJ, Richardson RJ, Yelverton FH. (2013) Effect of ambient moisture on aminocyclopyrachlor efficacy. Weed Technol 27:317-322

Lindenmayer B, Westra P, Brunk G, Nissen S, Shaner D (2010) Field and laboratory studies with aminocyclopyrachlor (DPX-MAT28). Proc Weed Sci Soc Am Abstr 281

Lym RG (1998) The biology and integrated management of leafy spurge (*Euphorbia esula*) on North Dakota rangeland. Weed Technol 12:367-373

Lym RG (2001) Evaluation of diflufenzopyr with auxin herbicides for leafy spurge control. Res Prog Rep West Soc Weed Sci p 9-11

Lym RG (2002) Leafy spurge control with imazapic combined or alternated with picloram plus 2,4-D or quinclorac and dicamba. Res Prog Rep West Soc Weed Sci p 13-16

Lym RG (2005) Integration of biological control agents with other weed management technologies: successes from the leafy spurge (*Euphorbia esula*) IPM program. Biol Control 35:266-375

Lym RG (2010) Control of invasive and troublesome weeds with aminocyclopyrachlor in North Dakota. Proc West Soc Weed Sci 63:41

Lym RG (2011) Long-term control of leafy spurge with aminocyclopyrachlor. Res Prog Rep West Soc Weed Sci p 28-29

Lym RG (2014) Comparison of aminocyclopyrachlor absorption and translocation in leafy spurge (*Euphorbia esula*) and yellow toadflax (*Linaria vulgaris*). Weed Sci In press

Lym RG, Kirby DR (1987) Cattle foraging behavior in leafy spurge (*Euphorbia esula*)-infested rangeland. Weed Technol 1:314-318

Lym RG, Messersmith CG (1985) Leafy spurge control with herbicides in North Dakota: 20-year summary. J Range Manage 38:149-154

Lym RG, Messersmith CG (1988) Survey for picloram in North Dakota groundwater. Weed Technol 2:217-222

Lym RG, Messersmith CG (1990) Cost-effective long-term leafy spurge (*Euphorbia esula*) control with herbicides. Weed Technol 4:635-641

Lym RG, Moxness KD (1989) Absorption, translocation, and metabolism of picloram and 2,4-D in leafy spurge (*Euporbia esula*). Weed Sci 37:498-502

Lym RG, Nelson JA (2002) Integration of *Aphthona* spp. flea beetles and herbicides for leafy spurge (*Euphorbia esula*) control. Weed Sci 50:812-819

Lym RG, Sedivec KK, Kirby DR (1997) Leafy spurge control with angora goats and herbicides. J Range Manage 50:123-128

Messersmith CG, Lym RG, Galitz DS (1985) Biology of leafy spurge. In A. K. Watson, ed. Leafy Spurge. Monogr. 3. Champaign, IL: Weed Sci Soc Am p. 42-56

Mitich LW (1993) Yellow toadflax. Weed Technol 7:791-793

Morishita DW (1991) Dalmatian toadflax, yellow toadflax, black henbane, and tansy mustard: importance, distribution, and control. Pages 399-402 *in* L. F. James, J. O. Evans, M. H. Ralphs, and R. D. Child, eds. Noxious Range Weeds. Boulder, San Francisco, and Oxford: Westview Press

Nadeau LB, King JR, Harker KN (1992) Comparison of growth of seedlings and plants grown from root pieces of yellow toadflax (*Linaria vulgaris*). Weed Sci 40:43-47

[NRCS] Natural Resource Conservation Service (2012) Ecological site descriptions for MLRA 56. Available at: https://esis.sc.egov.usda.gov/Welcome/pgApprovedSelect.aspx?type=ESD

Nelson WT (1986) Grassland habitat types – Sheyenne National Grasslands. M.S. Thesis. Fargo, ND: North Dakota State University. 47 p

[NDAWN] North Dakota Agricultural Weather Network (2013) Monthly Data Table. Available at http://ndawn.ndsu.nodak.edu/weather-data-monthly.html. Accessed: December 11, 2013

Nowierski RM (2004) Toadflax. Pages 379-395 in E. M. Coombs, J. K. Clark, G. L. Piper, and A. F. Cofrancesco, Jr., ed. Biological Control of Invasive Plants in the United States. Corvallis: Oregon State University Press

Oliveira RS, Alonso DG, Koskinen WC (2011) Sorption-desorption of aminocyclopyrachlor in selected Brazilian soils. J Environ Sci and Health, Part B 59:4045-4050

Oliveira RS, Alonso DG, Koskinen WC, Papiernik SK (2013) Comparative sorption, desorption and leaching potential of aminocyclopyrachlor and picloram. J Environ Sci and Health, Part B 48:1049-1057

Oliveira RS, Koskinen WC, Ferreira FA (2001) Sorption and leaching potential of herbicides on Brazilian soils. Weed Res 41:97-110

Olson E (1997) National grasslands management a primer. U.S. Department of Agriculture. 40 p Available at: http://www.fs.fed.us/grasslands/resources/documents/primer/NG_Primer.pdf

Pieper DM (2007) Final environmental impact statement: noxious weed management project, Dakota Prairie Grasslands. Bismark, ND: U.S. Forest Service. 140 p

Rick SK, Meredith JH, Claus JS, Alford C (2011) Aminocyclopyrachlor for range and pasture weed control. Proc Weed Sci Soc Am Abstr 242

Samuel LW (2007) Aminopyralid effect on Canada thistle (*Cirsium arvense*) and native plants in western North Dakota. Ph. D. Dissertation. Fargo, ND: North Dakota State University. 94 p

Saner MA, Clements DR, Hall MA, Doohan DJ, Crompton CW (1995) The biology of Canadian weeds. 105. *Linaria vulgaris* Mill. Can J Plant Sci 75:525-537

Sebastian JR, Beck KG (2010a) Yellow toadflax control in Colorado. Res Prog Rep West Soc Weed Sci p. 30-31

Sebastian JR, Beck KG (2010b) Yellow toadflax control in Colorado with aminocyclopyrachlor. Res Prog Rep West Soc Weed Sci p. 32-33

Selleck GW, Coupland RT, Franton C (1962) Leafy spurge in Saskatchewan. Ecol Monogr 32:1-29

Senseman SA ed. (2007a) Aminopyralid *in* Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp 331-332

Senseman SA ed. (2007b) Picloram *in* Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp 353-356

Senseman SA ed. (2007c) Quinclorac *in* Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. Pp 357-358

Sieg CH, King RM (1995) Influence of environmental factors and preliminary demographic analysis of a threatened orchid, *Platanthera praeclara*. Am Midl Nat 134:307-323

Sing SE, Peterson RKD, Weaver DK, Hansen RW, Markin GP (2005) A retrospective analysis of known and potential risks associated with exotic toadflax-feeding insects. Biol Control 35:276-287

Soil Survey Staff (2011) Natural Resources Conservation Service, U.S. Department of Agriculture. Web Soil Survey. Available at http://websoilsurvey.nrcs.usda.gov/

Street JE, Mueller TC (1993) Rice (*Oryza sativa*) weed control with soil applications of quinclorac. Weed Technol 7:600-604

[USFWS] U.S. Fish and Wildlife Service (1996) *Platanthera praeclara* (western prairie fringed orchid) recovery plan. U.S. Fish and Wildlife Service, Ft. Snelling, Minnesota. 101 p

[USFWS] U.S. Fish and Wildlife Service (2007) Waterfowl production areas: Prairie jewels of the National Wildlife Refuge System. Arlington, VA: U.S. Department of the Interior. 2 p

Wallace J, Prather T (2012) Yellow toadflax control with combinations of aminocyclopyrachlor and sulfonylureas at two application timings. Res Prog Rep West Soc Weed Sci p. 14

Ward SM, Reid SD, Harrington J, Sutton J, Beck KG (2008) Genetic variation in invasive populations of yellow toadflax (*Linaria vulgaris*) in the western United States. Weed Sci 56:394-399

Weber JB, Whitacre DM (1982) Mobility of herbicides in soil columns under saturated- and unsaturated-flow conditions. Weed Sci 30:579-584

Williams W, Wehtje G, Walker RH (2004) Quinclorac: soil behavior and foliar vs. root absorption by torpedograss (*Panicum repens*). Weed Tech 18:626-633

Xu D, Meyer S, Farenhorst A, Pennock D (2009) Land use and riparian effects on prairie wetland sediment properties and herbicide sorption coefficients. J Environ Qual 38:1757-1765

Zollinger R, Christoffers M, Endres G, Gramig G, Howatt K, Jenks B, Lym R, Ostlie M, Robinson A, Thostenson A, Valenti HH (2014) North Dakota Weed Control Guide. North Dakota State Univ. Ext Serv Publ W-253. p. 65