AMINOCYCLOPYRACHLOR: WEED CONTROL, SOIL DISSIPATION, AND EFFICACY TO SEEDLING GRASSES

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Katie Lynn Conklin

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

April 2012

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Aminocyclopyrachlor: Weed Control, Soil Dissipation, and

Efficacy to Seedling Grasses

By

Katie Lynn Conklin

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

SUPERVISORY COMMITTEE:

Dr. Rodney G. Lym
Chair

Dr. James Hammond

Dr. Richard Zollinger

Dr. Edward S. DeKeyser

Dr. Tom DeSutter

Approved:

April 4, 2012	Dr. Richard Horsley
Date	Department Chair

ABSTRACT

Aminocyclopyrachlor was developed for invasive weed control in non-cropland. Weed control, soil dissipation, and seedling grass tolerance with aminocyclopyrachlor were evaluated in field and greenhouse trials. Weed control was evaluated with aminocyclopyrachlor applied at 70 to 210 g ha^{-1}. Absinth wormwood was controlled when treated during vegetative growth, but yellow toadflax was only controlled at flowering. Aminocyclopyrachlor alone did not control houndstongue. Aminocyclopyrachlor dissipation generally increased as either soil moisture or temperature increased. The DT_{50} values ranged from 3 to > 112 d. Aminocyclopyrachlor applied to cool season grasses at 91 to 112 g ha^{-1} provided adequate weed control and was safe for use on intermediate wheatgrass, but injured western wheatgrass. Efficacy to green needlegrass could not be determined. Big bluestem, sideoats grama, and switchgrass were difficult to evaluate due to poor grass establishment, but minimal injury was observed when aminocyclopyrachlor was applied at 91 to 168 g ha^{-1}.

ACKNOWLEDGMENTS

Today I stop

I breathe deep and rest

With grateful tears I weep

Because I have come so far

~ *Kristen Jongen*

As the final exam approaches I reflect on the last two and half years. There was a great deal of excitement, frustration, and learning that went into the completion of the research that follows, and I never could have succeeded alone.

I would like to thank Dr. Rod Lym for his high expectations. Although this was the cause of some frustration, the guidance of my major advisor was never more than a phone call, email, or short walk away. Throughout this process I have had the chance to conduct field and green house research, collaborate with university and industry professionals, grow as an individual, and much more. I am truly thankful that Dr. Lym led me through this hands-on learning experience.

My thanks are also extended to Dr. Hammond, Dr. DeSutter, Dr. Zollinger, and Dr. DeKeyser. As my committee their advice to plan, analyze, and understand the research conducted was highly valued. Also, thanks to the professors and friends who helped me along the way, especially Dr. Howatt, Dr. Shaner, the Deckard’s, and my fellow graduate students.

An extra special thanks goes to my family and Andy for all the encouragement, love, and listening they have offered. My family has always told me that I can do anything, but their support and advice has been a driving force in what I have accomplished. Additionally, the faith Andy has in me and the confidence he has given me to believe in myself has been more powerful than I could imagine.

TABLE OF CONTENTS

ABSTRACT……………………………………………………………………..…………iii

ACKNOWLEDGMENTS...……………………………………………….....................iv

LIST OF TABLES ..……………………………….…………………….……………...vii

LIST OF FIGURES ....……......x

INTRODUCTION…...……………………………………………………………….....1

LITERATURE REVIEW……………………………………………………………....3

Weed Control with Aminocyclopyrachlor………………………………………….…3

Yellow Toadflax…………………………………………………………………….5

Absinth Wormwood………………………………………………………...…8

Houndstongue………………………………………………………………...…10

Aminocyclopyrachlor Soil Dissipation…….………………………………………...12

Herbicide Efficacy to Seedling Grasses……………………………………….……..15

MATERIALS AND METHODS……………………………………………………...21

Weed Control with Aminocyclopyrachlor…………………………………...…....21

Yellow Toadflax………………………………………………………...…...22

Absinth Wormwood……………………………………………………………….22

Houndstongue…………………………………………………………...……...23

Weed Control Data Analysis……………………………………………………...24

Aminocyclopyrachlor Soil Dissipation…………………………………………...…25

Moisture Study…………………………………………………………………….…26

Temperature Study…………………………………………………………………...27

Aminocyclopyrachlor Soil Dissipation Data Analysis………………………………....27

Herbicide Efficacy to Seedling Grasses……………………………………………………...28

Herbicide Efficacy to Seedling Grasses Data Analysis…………….…………………...…30

RESULTS AND DISCUSSION………………………………………………………………31

Yellow Toadflax Control………………………………………………………………….31

Absinth Wormwood Control……………………………………………………...…….34

Houndstongue Control……………………………………………………………...…….37

Aminocyclopyrachlor Soil Dissipation……………………………………………………...38

Moisture Study…………………………………………………………………………38

Temperature Study………………………………………………………………………..41

Herbicide Efficacy to Seedling Grasses…………………………………………...…..…43

Green Needlegrass………………………………………………………………………44

Intermediate Wheatgrass………………………………………………………...…49

Western Wheatgrass……………………………………………………………..…54

Big Bluestem……………………………………………………………………….…58

Sideoats Grama……………………………………………………………………..…62

Switchgrass……………………………………………………………………...…62

SUMMARY……………………………………………………………………………...….70

LITERATURE CITED……………………………………………………………...…72

LIST OF TABLES

Table Page

1. Physical and chemical characteristics of North Dakota soils included in the soil dissipation experiment……………………………………………………………...26

2. Grass species and seeding rate used for the evaluation of aminocyclopyrachlor on newly established grasses…………………………………………………………....29

3. Yellow toadflax control with aminocyclopyrachlor applied alone or with 2,4-D, chlorsulfuron, or metsulfuron during the flowering growth stage on July 19, 2010 at the Knudtson waterfowl production area near Jamestown, North Dakota……….…...32

4. Yellow toadflax control with aminocyclopyrachlor applied alone or with 2,4-D, chlorsulfuron, or metsulfuron during the fall vegetative growth stage on September 17, 2010 at the Knudtson waterfowl production area near Jamestown, North Dakota......33

5. Absinth wormwood control with aminocyclopyrachlor applied alone or with chlorsulfuron during the vegetative growth stage on May 21, 2010 at Valley City, North Dakota...…………………………………………………………………...35

6. Absinth wormwood control with aminocyclopyrachlor applied alone or with chlorsulfuron during vegetative regrowth on September 17, 2010 at Valley City, North Dakota.………………………..…………………………………….…………..36

7. Houndstongue control with aminocyclopyrachlor applied alone or with 2,4-D or chlorsulfuron to rosettes on September 8, 2010 or rosette to mature plants on June 16, 2011 near McLeod, North Dakota………………………………..………………..….37

8. Effect of moisture on aminocyclopyrachlor dissipation to 50% (DT_{50}) in four soils 56 days after treatment with 36 µg kg^{-1} and held at 16 C.………………...……………..39

9. Effect of temperature on aminocyclopyrachlor dissipation to 50% (DT_{50}) in four soils 56 days after treatment with 36 µg kg^{-1} and held at 45% field capacity..…...……..41

10. Grass stand evaluation recorded approximately 1 mo after planting in 2010 or 2011 near Fargo, North Dakota...…………………………..………..……………..43

11. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 24, 2010 to green needlegrass seedlings 4 weeks after emergence near Fargo, North Dakota...……………………………………….………………45

12. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on green needlegrass (GNG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.……………….........47

13. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2011 to green needlegrass seedlings 4 weeks after emergence near Fargo, North Dakota…..…………………………………………..…48

14. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 14, 2010 to intermediate wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota...…………………………………….……………50

15. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on intermediate wheatgrass (IWG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.………………...52

16. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2011 to intermediate wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.……………………………………..……..…..53

17. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 21, 2010 to western wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota…………………..…………………………….....55

18. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on western wheatgrass (WWG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.………………...56

19. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 18, 2011 to western wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.……………..……………………………………57

20. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2010 to big bluestem seedlings 4 weeks after emergence near Fargo, North Dakota.…………………………...……………………………..59

21. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on big bluestem (BBS), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.…………….……..….60

22. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2011 to big bluestem seedlings 4 weeks after emergence near Fargo, North Dakota……………………………...……………………...61

23. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2010 to sideoats grama seedlings 4 weeks after emergence near Fargo, North Dakota...63

24. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on sideoats grama (SOG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota…………..……...……64

25. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 18, 2011 to sideoats grama seedlings 4 weeks after emergence near Fargo, North Dakota……………………………………………………..………...65

26. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2010 to switchgrass seedlings 4 weeks after emergence near Fargo, North Dakota…………………………………………………………..66

27. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on switchgrass (SG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seding near Fargo, North Dakota……………………...…….68

28. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2011 to switchgrass seedlings 4 weeks after emergence near Fargo, North Dakota……………………………………………………………..69

LIST OF FIGURES

Figure Page

1. Chemical structure of aminocyclopyrachlor, a pyrimidine carboxylic acid herbicide, compared to aminopyralid and picloram, two pyridine carboxylic acid herbicides........…3

2. Yellow toadflax density in untreated plots from July 2010 until September 2011 at the Knudtson Waterfowl Production Area near Jamestown, North Dakota.…………….34

INTRODUCTION

Aminocyclopyrachlor (previously known as DPX-MAT28 and DPX-KJM44) is an auxin-like herbicide (Turner et al. 2009) that was developed to control invasive and troublesome weeds in non-cropland (Claus et al. 2010). Initial evaluations found that aminocyclopyrachlor controlled several, wide spread, North Dakota noxious weeds including Canada thistle [*Cirsium arvense* (L.) Scop.], leafy spurge (*Euphorbia esula* L.), knapweeds (*Centaurea* spp.), and saltcedar (*Tamarix ramosissima* Ledeb.) (Lindenmayer et al. 2010; Westra et al. 2008a; Westra et al. 2010). The spectrum of weed control and optimum application timing for aminocyclopyrachlor is still under investigation.

Aminocyclopyrachlor may provide control of yellow toadflax (*Linaria vulgaris* Mill.), absinth wormwood (*Artemisia absinthium* L.), and houndstongue (*Cynoglossum officinale* L.). Yellow toadflax and absinth wormwood are considered noxious weeds in North Dakota (NDDOA 2011). Yellow toadflax control has varied from inadequate (Lym 2009) to excellent (Sebastian and Beck 2009), while the efficacy of aminocyclopyrachlor for control of absinth wormwood has not been evaluated. Houndstongue is a weed of concern in North Dakota that is included on several county noxious weed lists (NDDOA 2011), but the efficacy of aminocyclopyrachlor on this weed is unknown.

Soil residual activity of herbicides may extend the period of weed control, but also could inhibit the establishment of crops on the treated land. Soil dissipation of herbicides may be influenced by soil texture, moisture, and temperature (Ahmad et al. 2003; Guenzi and Beard 1976; Taylor-Lovell et al. 2002). Aminocyclopyrachlor has soil residual activity (Stevens and Burke 2009; Westra et al. 2008a), but the effect of environment on aminocyclopyrachlor dissipation in North Dakota soils is unknown (Lindenmayer et al. 2010).

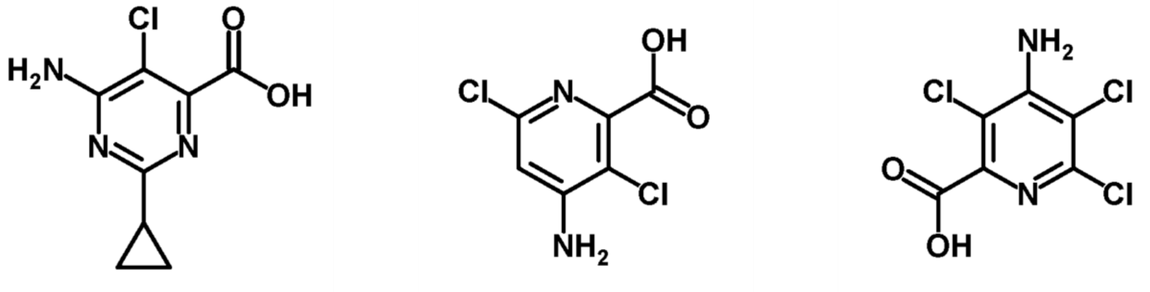
Aminocyclopyrachlor may also be useful for weed control in the establishment of grasses used for biofuel. Perennial grasses have potential to produce high biomass yield on marginal land with low production costs (Lee et al. 2009; Tilman et al. 2006), and are an alternative to corn ethanol (Borsari and Onwueme 2008; Mooney et al. 2009). Weed control has been important in the establishment of perennial grasses (Martin et al. 1982). The use of perennial grasses as a biofuel feedstock could be more widely adapted if adequate weed control was achieved with little or no injury to desired plants. Aminocyclopyrachlor may control troublesome broadleaf and grass weeds during biofuel crop establishment and thereby improve production (Vassios et al. 2010a). Cool-season grasses appear to be more sensitive to aminocyclopyrachlor than warm-season species (Douglass et al. 2009; Vassios et al. 2010b). Aminocyclopyrachlor could inhibit establishment of desirable cool-season grasses, but may be beneficial if cool season weedy grasses were controlled.

The objectives of this research were to evaluate: 1) the efficacy of aminocyclopyrachlor on yellow toadflax, absinth wormwood, and houndstongue; 2) the effect of temperature and moisture on soil dissipation of aminocyclopyrachlor in North Dakota soils; and 3) the effect of aminocyclopyrachlor alone or in combination with other herbicides on seedling grasses for biofuel production.

LITERATURE REVIEW

Weed Control with Aminocyclopyrachlor. Aminocyclopyrachlor is the first herbicide classified as a pyrimidinecarboxylic acid (Claus et al. 2010) and has both foliar and soil activity (Lindenmayer et al. 2010; Westra et al. 2010). Aminocyclopyrachlor is an auxin mimic herbicide and can be absorbed by both plant leaves and roots (Turner et al. 2009). This herbicide was initially evaluated for use in non-cropland such as pasture, rangeland, and utility and roadside right-of-ways.

Aminocyclopyrachlor is structurally similar to pyridinecarboxylic acid herbicides such as aminopyralid and picloram except it has a cyclopropyl side chain and a pyrimidine rather than a pyridine ring (Figure 1) (Bukun et al. 2010). Chemically the compounds have different properties. Aminocyclopyrachlor has a water solubility of 4.2 g L^{-1} (Anonymous 2009a; Finkelstein et al. 2008), which is approximately 10 times more water soluble than picloram (Senseman 2007c), while aminopyralid falls in between with a water solubility of 2.5 g L^{-1} (Senseman 2007a). Additionally, aminocyclopyrachlor has the highest soil binding potential with a sorption coefficient (K_{oc}) of 28 (Anonymous 2009a; Finkelstein et al. 2008) compared to 10.8 and 16 for aminopyralid and picloram, respectively (Senseman 2007a, 2007c).



Aminocyclopyrachlor **Aminopyralid** **Picloram**

Figure 1. Chemical structure of aminocyclopyrachlor, a pyrimidine carboxylic acid herbicide, compared to aminopyralid and picloram, two pyridine carboxylic acid herbicides (ChemSpider 2011).

Picloram and aminopyralid are among the top three herbicides used for weed control in North Dakota pastures (Zollinger et al. 2008), with use dependent on weed species and location. Picloram applied in the spring or fall has provided adequate long-term control of leafy spurge (Lym and Messersmith 1985) and short-term control of yellow toadflax (Almquist 2008). Aminopyralid, does not control leafy spurge (Lym and Samuel 2006; Lym 2008) or yellow toadflax (Lym 2007; Lym 2008), but was effective on absinth wormwood (Lym and Samuel 2006) and Canada thistle (Enloe et al. 2007; Lym 2008; Lym and Samuel 2006). Additionally, aminopyralid may be used to the water's edge (Anonymous 2009b) while picloram use near water is restricted due to the water solubility of the compound and high application rates (Lym and Messersmith 1988).

An ideal pasture and rangeland herbicide should be environmentally safe and have broad spectrum weed control. Aminocyclopyrachlor may be a useful alternative for land managers since the rate is often 140 g ai ha^{-1} or less and the herbicide has low mammalian toxicity (EPA 2010). Furthermore, aminocyclopyrachlor has absorption and translocation properties similar to pyridinecarboxylic acid herbicides which indicate that weed control efficacy could be equal or better than other auxin-mimic herbicides.

Maximum absorption of ^{14}C-aminocyclopyrachlor generally occurred 24 h after treatment (HAT) in both annual and perennial weeds (Bell et al. 2011; Bukun et al. 2010). Approximately 60% of applied ^{14}C-aminocyclopyrachlor was absorbed in Canada thistle (Bukun 2009) and rush skeletonweed (*Chondrilla juncea* L.) (Bell 2011). However, only an average of 10% ^{14}C-picloram was absorbed in Canada thistle 24 HAT, and ^{14}C-aminopyralid absorption in Canada thistle was slower than either ^{14}C-aminocyclopyrachlor or ^{14}C-picloram (Sharma et al.

1971). Maximum absorption of ^{14}C-aminopyralid occurred 96 HAT, and total absorption was similar to ^{14}C-aminocyclopyrachlor, about 60% (Bukun et al. 2009).

Approximately 6% of applied ^{14}C-aminocyclopyrachlor translocated to the roots of Canada thistle, while 15% moved to aboveground tissue (Bukun et al. 2010). Similar movement was reported in yellow starthistle (*Centaurea solstitialis* L.) where 1.5 and 9% of absorbed ^{14}C-aminocyclopyrachlor were found in the below-and aboveground tissue, respectively (Bell et al. 2011). Translocation of ^{14}C-aminopyralid in Canada thistle was less than ^{14}C-aminocyclopyrachlor (Bukun et al. 2009). Approximately 15% of applied ^{14}C-aminopyralid was equally directed to aboveground and belowground tissue. Much less ^{14}C-picloram translocated away from the treated leaf in Canada thistle than the either ^{14}C-aminocyclopyrachlor or ^{14}C-aminopyralid (Sharma et al. 1971). Only 2% ^{14}C-picloram moved from the treated leaf, but similar to ^{14}C-aminocyclopyrachlor the herbicide tended to be more abundant in the shoot than the roots.

Aminocyclopyrachlor controls many annual broadleaf weeds as well as several invasive and woody plants. Canada thistle (Lindenmayer et al. 2010; Vassios et al. 2010a; Westra et al. 2010), leafy spurge (Lindenmayer et al. 2010; Lym 2009; Westra et al. 2010), Russian knapweed (*Centaurea repens* L.), and saltcedar (Lindenmayer et al. 2010; Westra et al. 2010) are noxious weeds found in North Dakota that can be controlled with aminocyclopyrachlor. Yellow toadflax has been evaluated for control with aminocyclopyrachlor, but results have been inconsistent (Hoefing and Jenks 2010; Lym 2009; Sebastian and Beck 2009). Aminocyclopyrachlor has not been evaluated for control of absinth wormwood or houndstongue.

Yellow Toadflax. Yellow toadflax is a perennial forb that was introduced to North America as an ornamental that resembles snapdragons (*Antirrhinum majus* L.) (Saner et al. 1995). Yellow toadflax grows along roadsides, in disturbed areas, and in pasture and rangeland and is considered mildly poisonous to cattle (*Bos* spp.) (Mitich 1993). The plant has narrow lanceolate leaves arranged alternate on a stem 25 to 800 cm high (Saner et al. 1995). The creamy yellow flowers have five petals with a conical spur at the base that is yellow or orange. Yellow toadflax is capable of both seed and vegetative reproduction. The large, creeping root system allows the weed to form colonies and spread rapidly (Nadeau et al. 1992). The ability to reproduce by root and seed makes yellow toadflax difficult to control with cultural practices such as tillage and mowing.

Mechanical control of yellow toadflax was obtained after 2 yr of intense tillage that consisted of 8 to 10 cultivations in the first year, and 4 to 5 in the second year (Morishita 1991). However, in pasture and rangeland tillage is not practical. Mowing is more suitable, but is not recommended since it does not affect the root reserves or seed bank (Lajeunesse 1999).

Yellow toadflax may be managed with insects in some regions of the United States (US). Seven biological control agents have been released in the US and five have established in select states although, none were reported established in North Dakota (Nowierski 2004). *Brachypterolus pulicarius* L. (toadflax flower-feeding beetle) and *Gymnetron antirrhini* (Paykull) (toadflax seed capsule weevil) were accidentally introduced to North America with ornamental toadflax. Early evaluations concluded *B. pulicarius* and *G. antirrhini* effectively attacked yellow toadflax stands in Canada (Harris 1961), yet recently have been reported to have minimal impact on US populations (Sing et al. 2005). *Mecinus janthinus* Germar (toadflax stem weevil) has been released and established in North America. However, *M. janthinus* has only controlled Dalmatian toadflax [*Linaria dalmatica* (L.)] (McClay and Hughes 2007). The biological control agent was evaluated for yellow toadflax control in North Dakota (Almquist

2008), but was not present, and feeding damage was not detected 1 or 2 yr after release. *M. janthinus* had high mortality when exposed to low winter temperatures without sufficient snow cover (De Clerck-Floate and Miller 2002) which could explain why the weevil did not establish in North Dakota.

Various herbicides have been evaluated for control of yellow toadflax. Picloram, applied in midsummer, at 1120 g ai ha^{-1} provided 18 to 86% control 1 yr after treatment (YAT) and was not improved by the addition of aminopyralid, imazapic, or metsulfuron (Almquist 2008; Lym 2007; Lym 2008). However, the addition of diflufenzopyr at 448 g ai ha^{-1} increased control to 100% 1 YAT (Almquist 2008). Similarly, in Colorado, 94% yellow toadflax control was achieved 1 and 2 YAT when picloram was applied at 1120 g ha^{-1} with diflufenzopyr plus dicamba at 56 + 140 g ha^{-1} (Sebastian and Beck 2010b). Picloram applied alone or with diflufenzopyr plus dicamba was recommended for control of yellow toadflax in North Dakota (Zollinger et al. 2011). Although adequate control was achieved with picloram, it is a restricted use pesticide and must be applied by licensed applicators and cannot be used in environmentally sensitive areas where yellow toadflax has often established.

Aminocyclopyrachlor has been evaluated for yellow toadflax control with conflicting results. In a Colorado study, aminocyclopyrachlor at 21 to 840 g ha^{-1} provided 30 to 100% control of yellow toadflax 13 mo after treatment (MAT) and 19 to 100% control 2 YAT (Sebastian and Beck 2009). Similarly, aminocyclopyrachlor at 105 to 210 g ha^{-1} provided 90 to 100% control 1 YAT and 55 to 100% control 2 YAT in North Dakota (Hoefing and Jenks 2010). In a separate study, aminocyclopyrachlor was applied at 70 to 210 g ha^{-1}, and control averaged less than 30% in the year of treatment (Lym 2009). Although yellow toadflax control increased to 82% 12 MAT, by 14 MAT control declined to only 54%. Therefore, aminocyclopyrachlor applied alone may not consistently control yellow toadflax, or there may be a location, rate, or timing effect on yellow toadflax efficacy.

Yellow toadflax control with aminocyclopyrachlor may be improved if the herbicide is applied with either chlorsulfuron or metsulfuron. Aminocyclopyrachlor plus chlorsulfuron at 175 + 70 g ai ha^{-1} or metsulfuron at 56 g ai ha^{-1} controlled 100% of yellow toadflax 2.5 MAT in Idaho (Wallace and Prather 2011). Aminocyclopyrachlor plus chlorsulfuron at 140 + 53 g ha^{-1} averaged 100% control of yellow toadflax 1 YAT, and 88% control 2 YAT in North Dakota (Hoefing and Jenks 2010). The combination of aminocyclopyrachlor and chlorsulfuron or metsulfuron may allow a reduced rate of aminocyclopyrachlor for long-term control of yellow toadflax or may improve consistency of control.

Absinth Wormwood. Absinth wormwood is a silvery gray perennial sagebrush forb that was introduced to the United States from Europe (Maw et al. 1985). Absinth wormwood typically invades disturbed areas such as overgrazed pastures or re-established grasslands, but may also establish in piles of manure, thin crop stands, tree rows, and farmyards (Selleck and Coupland 1961). The plant establishes from seed and can grow over 150 cm tall (Maw et al. 1985) with a crown up to 10 cm in diameter (Selleck and Coupland 1961). Absinth wormwood has a vigorous tap root that is capable of extending lateral branches 180 cm, but it does not vegetatively reproduce. At maturity, the plant produces thousands of seeds and top growth dies back to the soil level (Maw et al. 1985). In the spring, regrowth is from the crown.

Absinth wormwood is a competitive weed that may reduce the yield of desirable plants (Selleck and Coupland 1961). The plant produces a strong sage fragrance, so if the weed is consumed through grazing or hay, milk and other dairy products may be tainted with odor and rejected for human consumption. Absinth wormwood also may impart sage odor on the grain of agronomic crops at harvest. Control of absinth wormwood is required in North Dakota since the plant is a listed noxious weed (NDDOA 2011).

Tillage, mowing, and parasites have been evaluated for control of absinth wormwood. Tillage was suitable for absinth wormwood control in crop production, but required multiple cultivations (Maw et al. 1985; Selleck 1964). Mowing is not recommended since it does not kill existing plants or prevent seed production (Maw et al. 1985). Spring-mowing, spring- and fall-mowing, and spring- and fall-mowing with either spring or fall applied nitrogen were evaluated in South Dakota; however, none of the treatments controlled absinth wormwood (Moechnig et al. 2009). Several insects and microorganisms have been observed on absinth wormwood, but most have had little effect on the plant (Maw et al. 1985). An exception was *Euzophera cinerosella* (Zell.), a stem and root boring insect. Unfortunately, native *Artemisia* spp. in Canada were also attacked, and *E. cinerosella* was deemed unsuitable for release as a biological control agent (Maw and Schroeder 1981).

Herbicides are less labor intensive and often more successful for absinth wormwood control than mowing, tillage, and biological control agents. Some of the most commonly used herbicides are auxin inhibitors such as 2,4-D, dicamba, picloram, clopyralid, and aminopyralid. A study in North Dakota evaluated absinth wormwood control with 2,4-D, dicamba, and picloram applied from May through September (Moses 1985). Picloram at 140 to 280 g ha^{-1} applied from early June through September averaged 40 to 90% absinth wormwood control, 9 to 13 MAT. Dicamba at 1120 to 2240 g ha^{-1} averaged 30 to 80% control 9 to 13 MAT, while 2,4-D at the same application rates averaged less than 10 to 82% control. In a separate study, clopyralid provided similar control as picloram and averaged 70 to 95% 14 MAT (Lym and Messersmith 1986).

Aminopyralid applied in the spring or summer provided equal or greater control of absinth wormwood than 2,4-D, dicamba, picloram, or clopyralid, but was applied at much lower rates (Lym 2010; Lym and Samuel 2006; Sebastian and Beck 2008). Aminopyralid applied at 53 g ai ha^{-1} provided 100% control of absinth wormwood 1 YAT (Lym and Samuel 2006) while 420 g ha^{-1} of either picloram or clopyralid were required to achieve the same result. Dicamba and 2,4-D at 1120 and 1680 g ai ha^{-1}, respectively, did not achieve the same level of control as aminopyralid despite a 20x to 30x greater application rate.

Control of absinth wormwood has been achieved with auxin-like herbicides, so aminocyclopyrachlor may control absinth wormwood as well. Like aminopyralid, aminocyclopyrachlor can be used at much lower rates than other growth regulator herbicides, and would be a environmentally safer alternative to currently used herbicides.

Houndstongue. Houndstongue is a biennial forb in the boraginaceae family. The weed was introduced from Europe and grows in pastures, along roadsides, and in disturbed areas (Dickerson and Fay 1982). Houndstongue will form a rosette the first year of growth and a stem up to 120 cm tall in the second year with soft pubescent leaves that are said to resemble a hound's tongue (Upadhyaya et al. 1988). More than 600 seeds may be produced on a single plant (Dickerson and Fay 1982). The seeds are prickly nuttlets that stick to animals and clothing, a feature that aids in spread of the weed (Upadhyaya and Cranston 1991). Houndstongue contains pyrrolizidine alkaloids which are most abundant in immature leaves (Pfister et al. 1992). The alkaloids are poisonous to livestock, and can be fatal if consumed in large quantities for several consecutive days (Knight et al. 1984). Houndstongue is usually avoided by grazing livestock, but is more palatable later in the season (Upadhyaya and Cranston 1991).

Since houndstongue is a biennial, control is aimed at the eradication of rosettes and prevention of seed-set by second-year plants. Flowering plants clipped 0- to 7-cm above the soil surface eliminated 60% of the second-year plants (Dickerson and Fay 1982). The remaining plants regrew and produced an average of 25 seeds per plant. Clipping could aid in management of houndstongue populations, but would not completely control houndstongue and is not a practical method in many locations.

Mogulones cruciger Hbst., a root-mining weevil, was released in Canada in 1997 for biological control of houndstongue (De Clerk-Floate and Schwarzländer 2002). One yr after release *M. curciger* had established at all release sites and had self-dispersed to houndstongue patches 150 to 330 m away from the original releases (De Clerk-Floate et al. 2005). The ability to establish and self-disperse indicate that *M. cruciger* could become a successful biological control agent, but has not been approved for release in the U.S. (USDA-APHIS 2010).

M. cruciger is an oligophagous species that feeds on plants belonging to the Boraginaceae family (De Clerck-Floate and Schwarzländer 2002). Concerns that the insect would feed on the endangered native Boaginaceae species: Terlingua Creek cryptantha (*Cryptantha crassipes* I.M. Johnston), rough popcornflower [*Plagiobothrys* hirtus (Greene) I.M. Johnston], and Calistoga popcornflower [*P. strictus* (Greene) I.M. Johnston], have prevented release approval in the US. *Cryptantha* spp. have been shown to support *M. cruciger* (Andreas et al. 2008; De Clerck-Floate and Schwarzlander 2002). In choice tests, *M. cruciger* did not accept *Plagiobothrys* spp., but in no-choice tests a single pupa, that later died, was produced on *P. hirtus* (De Clerck-Floate and Schwarzlander 2002). Houndstongue was the most attacked host in field, garden, and greenhouse choice tests.

Chemical control is the only option for houndstongue management since biological control is not available in the US, and clipping is not practical. Chlorsulfuron applied at 140 g ha^{-1} provided 97 to 100% control of second-year plants when applied from rosette to bloom stage and eliminated seed production of plants treated from rosette to 28 cm bolt stage (Dickerson and Fay 1982). Additionally, rosettes and bolted plants can be eliminated with metsulfuron applied at 21 g ai ha^{-1} or with tank mixes that include metsulfuron plus either aminopyralid or chlorsulfuron at 140 or 21 g ha^{-1}, respectively (Sebastian and Beck 2010a). Aminopyralid alone did not control either rosettes or bolted plants 1 YAT. Aminocyclopyrachlor has not been evaluated for houndstongue control.

Aminocyclopyrachlor Soil Dissipation. Soil residual of aminocyclopyrachlor could be important for long-term perennial weed control (Lindenmayer et al. 2011). Aminocyclopyrachlor applied to the soil severely limited the re-establishment of Canada thistle and provided moderate control of rush skeletonweed, which confirmed that aminocyclopyrachlor had soil activity (Lindenmayer et al. 2010; Stevens and Burke 2009). When Canada thistle roots were planted above a layer of aminocyclopyrachlor treated soil the resultant biomass was much lower compared to when planted below a treated layer of soil (Lindenmayer et al. 2011). Therefore, the herbicide was most effective when taken up by the root which is desirable for residual weed control.

Aminocyclopyrachlor remained active in the soil for at least 2 yr (Westra et al. 2008a), and the half-life was dependent on environment (EPA 2010). In turf studies the half-life ranged from 37 to 103 d, whereas in bareground the half-life was longer and ranged from 80 to 164 d (Anonymous 2009a; Finkelstein et al. 2008). Aminopyralid half-life was shorter and ranged from 25 to 35 d (Senseman 2007a). Picloram half life was longer than aminocyclopyrachlor, and with more variation ranged from 20 to 300 d, respectively (Senseman 2007c). Aminopyralid (Mikkelson 2010) and picloram (Guenzi and Beard 1976) degradation increased with increased temperature, which was attributed to increased microbial activity.

Aminocyclopyrachlor also is degraded by microbes in the soil (Anonymous 2009a; Finkelstein et al. 2008) and by photolysis (EPA 2010). Aminocyclopyrachlor was stable in anaerobic aquatic and anaerobic terrestrial environments with a half-life of 1733 and 6932 d, respectively. Aqueous photolysis was much faster than on soil, 1 to 8 d versus 129 d. Similarly, aminopyralid and picloram were rapidly photolyzed in water with half-life of 1 and 3 d, respectively (Senseman 2007a, 2007c). Volatility of aminocyclopyrachlor was very low, so both aminocyclopyrachlor and aminopyralid have a low risk of plant injury from vapor movement (Strachan et al. 2010).

High grain prices may cause land currently managed as non-cropland or enrolled in the conservation reserve program (CRP) to be converted to a cropland (Hellerstein and Malcolm 2011). Conservation reserve program land could have been treated with residual herbicides throughout enrollment, so crops planted into previous CRP land may be sensitive to herbicides; therefore the dissipation rate of the herbicide is important. Herbicide residues in soil treated with aminopyralid at 60 to 240 g ha^{-1} and picloram at 560 g ha^{-1} severely injured alfalfa (*Medicago sativa* L.), soybean (*Glycine max* (L.) Merr), and sunflower (*Helianthus annuus L.*), while corn (*Zea mays* L.) was not affected (Mikkelson and Lym 2011). Alfalfa and sunflower were tolerant to aminopyralid and picloram residue 20 MAT, yet soybean yield was reduced as much as 41%.

Agronomic crops sensitive to aminocyclopyrachlor include alfalfa (Westra et al. 2008b), spring and winter wheat (*Triticum aestivum* L.)(Kniss and Lyon 2011), soybean (Westra et al. 2008b), and sunflower. Winter wheat planted in soil previously treated with aminocyclopyrachlor resulted in yield losses, although visual estimates of injury were low (Kniss and Lyon 2011). Yield reductions of 50% were measured when the soil was treated 2, 4, and 6 mo before planting with aminocyclopyrachlor at 20, 25, and 61 g ha^{-1}, respectively. Losses were due to low seed production which was explained as the result of auxin accumulation in the ovary initiating fruit development prior to fertilization (Kniss and Lyon 2011; Gillaspy et al. 1993).

Chemical and bioassay methods can be used to determine herbicide residues in soil (Eberble and Gerber 1976). Each method has advantages and disadvantages. Chemical assays are highly sensitive and detect specific compounds in the soil; however, the assumption is made, that all residues (free and bound) are removed from the sample. Bioassays only measure the amount of active residue in the soil that causes a phytotoxic response, which is important when considering herbicide efficacy and crop response. Bioassay limitations include the narrow range of detectable concentrations and the possibility that contaminants in the soil may influence plant response.

The use of chemical assays and bioassays together can aid in the investigation of plant response, especially when herbicide residues can no longer be detected by sensitive plants (Strachan et al. 2011). Aminocyclopyrachlor residue has been detected by both mass spectrometry and bioassay (Nanita et al. 2009; Strachan et al. 2011). The chemical assay limit of detection for aminocyclopyrachlor in soil was 0.1 µg kg^{-1} (Nanita et al. 2009), while the lowest estimated concentration by bioassay was 2.0 µg kg^{-1} (Strachan et al. 2011). The chemical analysis has been directly correlated to phytotoxic responses in crops. The GR_{25} (growth reduction of 25%) in cotton, sunflower, and soybean occurred when the soil concentration of aminocyclopyrachlor was 3, 2, and 6 µg kg^{-1}, respectively.

Herbicide Efficacy to Seedling Grasses. Ethanol production has become important for energy independence in the United States due to high oil prices and limited fossil fuels (Borsari and Onwueme 2008; Sexton et al. 2009). Ethanol can be derived from any material that contains sugar (Lin and Tanaka 2006). Grain and cellulose (from plant biomass, wood, crop residue, etc.) are two of the main raw materials used for ethanol production. The starch from grain is converted into sugars and further fermented to ethanol. Cellulose conversion requires pretreatment to separate lignin (not used for ethanol) and cellulose before fermentation.

Corn is a popular feedstock for grain ethanol, but has limitations. Production of large yields on marginal land has resulted in an increased production cost (Borsari and Onwueme 2008). Also, the use of corn for energy rather than feed has increased food prices. Finally, corn ethanol conversion may use more energy than the amount produced whereas cellulosic ethanol facilities burn lignin to provide some of the energy used for production (Samson and Omielan 1992).

Legislation passed in 2007 required the US to produce 136 billion L of biofuels by the year 2022 with 45% required to be from cellulosic biomass (USDOE 2007). Perennial grasses, like switchgrass (*Panicum virgatum* L.), are moisture efficient, have low nutrient requirements, and are capable of high productivity (Samson and Omielan 1992). These characteristics make perennial grasses a potential feedstock for cellulosic ethanol. Species that have been suggested for optimum production besides switchgrass include big bluestem (*Andropogon gerardii* Vitman), and intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey) (Lee et al. 2009; Samson and Omielan 1992). In North Dakota, green needlegrass [*Nassella viridula* (Trin.) Barkworth], sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.], and western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve] may be useful for cellulosic ethanol since they are native species adapted to northern climates.

Green needlegrass (Kinch and Wiesner 1963), intermediate wheatgrass, and western wheatgrass are cool-season grasses adapted to the northern Great Plains (Asay and Knowles 1985). Green needlegrass is a native species that has a vigorous seedling, but was difficult to establish due to seed dormancy (Rogler 1960; Schaaf and Rogler 1960). The cultivar 'Lodorm' is adapted to the northern Great Plains, and was selected from a native stand near Bismarck, North Dakota. 'Lodorm' green needlegrass was so named because it has low dormancy after harvest (USDA-NRCS 2005b). The bunchgrass begins growth early in the season and can reach heights of 90 cm. The plant has narrow leaves and the seeds have long, curved awns that may be 2 to 3 cm. Green needlegrass production averaged over 7 yr was 1500 kg ha^{-1} in Montana (White and Wight 1984). In North Dakota, green needlegrass harvested once per yr averaged 3370 kg ha^{-1} and when harvested twice per yr averaged 4400 to 6670 kg ha^{-1}, over 3 yr (Larson and Carter 1970). The lower average in Montana could be due to decreased yields in the last three yr of production.

Intermediate wheatgrass was introduced to the US from Russia and Asia (Asay and Knowles 1985). Intermediate wheatgrass emerged rapidly after seeding (Lawrence 1956) and has been documented to grow to 120 cm tall (Ogle et al. 2003). The leaves are 4 to 8 mm wide and often have a blue-green hue. Seed spikes consist of $\leq$ 7spikelets enclosed in blunt-tipped glumes. In the northern Great Plains and Utah, the cultivars 'Manifest' and 'Oahe' produced the highest total dry matter, 5180 and 4950 kg ha^{-1}, respectively (Hendrickson et al. 2007). Similar results were found in South Dakota when 'Oahe' was planted on land considered marginal for crop production (Lee et al. 2009). In North Dakota 'Oahe' averaged 3840 kg ha^{-1} biomass which converted to approximately 1460 L ha^{-1} ethanol (Berti et al. 2011). Although yields were comparable to other biofuel feed stocks such as smooth bromegrass, big bluestem, and switchgrass (Lee et al. 2009), irrigation could make intermediate wheatgrass superior to these species. Irrigated intermediate wheatgrass averaged over five harvests per yr and produced 23,000 kg ha^{-1} total biomass (Robins 2010).

Western wheatgrass is native to North America and is an important component of the shortgrass and mixed-grass prairie (Painter and Detling 1981). Western wheatgrass reaches heights of 30 to 90 cm, and has coarse blue-green leaves (USDA-NRCS 2002), similar to, but narrower than intermediate wheatgrass. The single-stalked grass can be slow to establish, but had more basal cover than green needlegrass in established rangeland (Goetz 1969). Highly rhizomatous cultivars such as 'Rodan' form sod in dryland conditions (USDA-NRCS 1988). Western wheatgrass biomass yield was less than intermediate wheatgrass, 1270 versus 3840 kg ha^{-1}, respectively in North Dakota trials (Berti et al. 2011). However, the native species may be more suitable for use on marginal lands. Western wheatgrass maintained a more adequate stand on poorly drained and saline/sodic soil than intermediate wheatgrass while averaging similar yield (Lauriault et al. 2005).

Big bluestem, sideoats grama, and switchgrass are native, warm season grasses found throughout the tall- and mixed-grass prairie (Voigt and MacLauchlan 1985). Big bluestem is a dominant species of the tall-grass prairie (Moser and Vogel 2005). Big bluestem leaves are hairy on the upper surface near the nodes (USDA-NRCS 2005a), which often appear purple. This grass grows up to 180 cm and produces a branched seed head. Seeds are hairy with short twisted awns, and have a reddish tint. Big bluestem generally required 2 yr after seeding to produce maximum biomass yield (Martin et al. 1982; Propheter et al. 2010). In Kansas, biomass increased from 4400 kg ha^{-1} the year of establishment to 7700 kg ha^{-1} one year later (Propheter et al. 2010). Similarly, in Nebraska, yield increased from 4440 kg ha^{-1} to 9650 kg ha^{-1} the yr following establishment (Martin et al. 1982). Biomass yield was lower in northern climates, for example, in South Dakota established stands of big bluestem averaged approximately 2500 to 3750 kg ha^{-1} (Lee et al. 2009). In field studies the cultivar 'Bison' demonstrated tolerance to northern climates (Madakadze et al. 1998; USDA-NRCS 2005a) and produced an average biomass yield of 4040 kg ha^{-1} in North Dakota, South Dakota, and Minnesota.

Sideoats grama is a widely adapted grass that is spread throughout most of the US (Gould 1959). Sideoats grama establishes easy and will maintain a vigorous stand (Harlan 1949). Leaves of sideoats grama have stiff hairs along the edges (USDA-NRCS 1977), but vary in width from narrow to broad (Gould 1959). The distinctive characteristic of this grass is the one sided head with nodding spikelets that usually have a colorful cast of orange, purple, red, salmon, or yellow (Harlan 1949). When hand weeded, established sideoats grama produced 6770, 7800, and 9100 kg ha^{-1} dry matter at three locations in Nebraska (Martin et al. 1982). In northern states, the cultivar 'Pierre' averaged 1160 to 3890 kg ha^{-1} (USDA-NRCS 1977). 'Pierre' was developed from seed collected in South Dakota, and is adapted to semiarid regions of the northern Great Plains.

Switchgrass is a wide spread native grass that has received much attention as a biofuel crop (Madakadze et al. 1998; McLaughlin et al. 1996; Samson et al. 1992). This warm-season species can grow up to 150 cm and is identified by the tuft of dense, white hairs where the leaf blade attaches to the sheath (USDA-NRCS 1990). The seed head is an open panicle with a purple tint. Seedling establishment has limited production in North Dakota (Berti et al. 2011). Studies conducted in North Dakota, South Dakota, and Nebraska indicated that low stand frequency in the year of establishment limited biomass yields in the second year (first year of production) (Schmer et al. 2006). When stands were adequate, switchgrass yield reached 7280 kg ha^{-1}, similar to yields obtained in research throughout the region (Hall et al. 1982; Martin et al. 1982). In North Dakota, seedling establishment was more dependent on cultivar than seeding depth, and 'Dacotah' had the highest pure live seed emergence (Berti et al. 2011). 'Dacotah' is a winter hardy, drought tolerant cultivar that was developed from seed collected in south-central North Dakota (USDA-NRCS 1990).

Weed competition can interfere with perennial grass establishment and grass yield (Washburn and Barnes 2000; Martin et al. 1982). Weeds compete with desirable species for water, nutrients, space, and light. In biomass production, weeds also may lower the quality of the crop, decrease the energy recovered, or reduce production efficiency (Buhler et al. 1998). Pre- and post-emergence herbicides recommended for grass establishment in North Dakota are limited (Zollinger et al. 2011). The current recommendations are limited to 2,4-D, bromoxynil, fluroxypyr, and MCPA.

Weed control is important in the establishment of perennial grasses. Forage yield of five warm-season grasses increased when handweeded (Martin et al. 1982). Atrazine has been used pre-emergence for grass establishment and improved forage yields, although tolerance to the herbicide varied by grass species. Post-emergence herbicides such as dicamba (Canode and Robocker 1970) and bromoxynil (Peters et al. 1989) have successfully controlled broadleaf weeds in grass establishment with little crop injury. Fenoxaprop, sethoxydim, and sulfometuron control weedy grasses, but have caused injury to several perennial grasses including big bluestem, intermediate wheatgrass, and switchgrass.

The effect of aminocyclopyrachlor on grass species has been evaluated in just a few cases. Warm-season grasses were less injured by aminocyclopyrachlor than cool-season grasses (Vassios et al. 2010a). Reduced grass establishment was observed when aminocyclopyrachlor was applied at the seedling stage, yet grass biomass yield increased compared to the untreated, likely due to improved weed control. In turf, tall fescue (*Festuca arundinacea* Schreb.) was not injured by aminocyclopyrachlor applied at 53 to 79 g ha^{-1} (McCullough et al. 2011). In established native prairie, aminocyclopyrachlor at 28 g ha^{-1} reduced the diversity of native plants but increased big bluestem production and provided better weed control than aminopyralid, clopyralid, and picloram (Edwards et al. 2010).

Aminocyclopyrachlor and aminopyralid were compared as pre-plant herbicides in the establishment of two cool season grasses (Vassios et al. 2010b). Slender wheatgrass [*Elymus trachycaulus* (Link) Shinners] was more tolerant of aminopyralid while western wheatgrass was more tolerant of aminocyclopyrachlor. In a similar study, slender wheatgrass was among the most tolerant species to aminocyclopyrachlor and aminopyralid, in addition to Canada wildrye (*Elymus canadensis* L.), galleta grass (*Pleuraphis* Torr.), and sideoats grama (Douglass et al. 2011). The first study did not indicate that slender wheatgrass was intolerant of aminocyclopyrachlor, but noted that the grass was more tolerant of aminopyralid.

MATERIALS AND METHODS

Weed Control with Aminocyclopyrachlor. Aminocyclopyrachlor efficacy was evaluated on yellow toadflax, absinth wormwood, and houndstongue in spring and fall experiments for each weed. The yellow toadflax studies were conducted at the Knudtson Waterfowl Production Area (WPA) near Eckelson, North Dakota, while absinth wormwood studies were located at a reclaimed gravel pit at Valley City, North Dakota. A single houndstongue study was conducted in a pasture near Kathryn, North Dakota, while two subsequent houndstongue studies were established in a pasture near McLeod, North Dakota. The experimental design for each study was a randomized complete block with four replicates, except the houndstongue experiments at McLeod which only had three replicates. Plot size for the yellow toadflax and absinth wormwood studies were 3- by 9-m while plots at the Kathryn houndstongue location were 1.2- by 6-m, and were 3- by 6-m at the McLeod houndstongue location.

Aminocyclopyrachlor was applied alone or with chlorsulfuron, metsulfuron, or 2,4-D in all studies, and application rates varied depending on the target weed. A standard herbicide applied at the common use rate for each weed species was included for comparison in each experiment, except the houndstongue studies at McLeod where treatments were limited due to sparse weed density. The standard treatment used for comparison was picloram plus dicamba and diflufenzopyr for yellow toadflax, aminopyralid for absinth wormwood, and metsulfuron for houndstongue (Zollinger et al. 2010). A nonionic surfactant[1] was included in each herbicide treatment at 0.25% v/v. All herbicides were applied with a hand-held boom sprayer with two or four 8002 nozzles[2] that delivered 160 L ha^{-1} at 240 kPa.

---

[1] Induce, alkyl aryl polyoxylkane ethers, free fatty acids and dimethyl polysiloxane, Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

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

Yellow Toadflax. The Knudtson WPA was farmland reclaimed to attract migratory waterfowl, non-game birds, and resident wildlife. Yellow toadflax established at this site when a native grass seed mixture contaminated with invasive weed seeds was planted. Other weeds established at this site were absinth wormwood and Canada thistle. Although native grasses were planted, the dominant species present were Kentucky bluegrass (*Poa pratensis* L.) and smooth bromegrass. The soil at the WPA was a Hamerly-Tonka complex (Soil Survey Staff 2011). The Hamerly loam series is classified as Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls. The Tonka silt loam series is classified as Fine, smectitic, frigid Argiaquic Argialbolls.

Herbicide treatments were applied to yellow toadflax in the summer or fall of 2010. Summer applications were made on July 19, 2010 when plants were in the vegetative to flowering stage and were 30 to 65 cm tall. Fall applications were made on September 17, 2010 when plants were in the fall vegetative growth stage 30 to 50 cm tall. Weed density was measured by counting yellow toadflax stems in three 0.25-m^2 quadrats through the center of each plot. Weed density was evaluated 0, 12, and 14 MAT for the summer study and 0, 10, and 12 MAT for the fall experiment. Visual evaluations of yellow toadflax injury were made on a scale of 0 to 10, with 0 equal to no injury and 10 equal to complete above-ground death, while yellow toadflax control was evaluated on a scale of 0 to 100, with 0 equal to no control and 100 equal to complete stand reduction. Injury was recorded 15 and 30 d after treatment (DAT) only for the yellow toadflax treated at flowering. Additionally, percent control of the yellow toadflax treated in July was recorded approximately 60, 365, and 420 DAT, while evaluation of September treatments were recorded 300 and 365 DAT.

Absinth Wormwood. The Valley City site was a former gravel pit used by the North Dakota Department of Transportation. Following gravel collection and storage at the site, the land was re-leveled and vegetation was allowed to establish from the seedbank. Absinth wormwood, alfalfa, Kentucky bluegrass, smooth bromegrass, and yellow sweetclover [*Melilotus officinalis* (L.) Lam.] were the predominant species that established. The soil at Valley City was Renshaw-Sioux loam that is excessively drained (Soil Survey Staff 2011). The Renshaw series is classified as Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Calcic Hapludolls. The Sioux series is classified as Sandy-skeletal, mixed, frigid Entic Hapludolls.

Herbicide treatments were applied to absinth wormwood in the vegetative growth stage on May 21, 2010 or September 17, 2010. Absinth wormwood treated in May was 30 cm tall, while plants treated in September had been mowed and allowed to re-grow to approximately 40 cm. Weed density was measured by counting absinth wormwood stems in five 0.25-m^2 quadrats through the center of each plot. Weed density was evaluated 0, 3, 12, and 16 MAT for the spring study and 0, 8, and 12 MAT for the fall study. Visual evaluations of absinth wormwood injury and control were recorded on the same scale as yellow toadflax at approximately 15, 30, 60, 90, 365, 390, and 480 DAT for the spring experiment and 15, 240, and 365 DAT for the fall experiment.

Houndstongue. The Kathryn site was near the Sheyenne River in a Kentucky bluegrass pasture canopied by deciduous trees. In addition to houndstongue, dame's rocket (*Hesperis matronalis* L.), and stinging nettle (*Urtica dioica* L.) were present. The soil at Kathryn was Nutley silty clay, classified as Fine, smectitic, frigid Chromic Hapluderts (Soil Survey Staff 2011).

Herbicide treatments were applied on June 3, 2010. Houndstongue growth stage varied from 10 cm rosettes to bolted, flowering plants. Weed density was measured by counting houndstongue stems in six 0.25-m^2 quadrats down the center of each plot 0, 3, and 12 MAT.

Visual evaluations of houndstongue injury and control were conducted as previously described and recorded approximately 15, 30, 60, 90, and 365 DAT .

The two houndstongue experiments located near McLeod were in a horse pasture which had been heavily grazed prior to treatment. The remaining vegetation consisted primarily of Kentucky bluegrass and smooth bromegrass; although a variety of broadleaf weeds were present and the houndstongue density was inconsistent. The soil at this site was Hecla-Garborg loamy fine sands (Soil Survey Staff 2011). The Hecla series is classified as Sandy, mixed, frigid Oxyaquic Hapludolls. The Garborg series is classified as Sandy, mixed, frigid Typic Endoaquolls.

Herbicide treatments were applied on September 8, 2010 and June 16, 2011. Houndstongue treated in the fall was in the rosette growth stage while houndstongue treated the following spring varied from 5 cm rosettes to flowering. Houndstongue density was measured in six 0.25-m^2 quadrats per plot, three right of center and three left of center, 0 and 9 MAT for the fall 2010 experiment and 0 and 3 MAT for the spring 2011 experiment. Houndstongue injury and control were visually evaluated as previously described. Evaluations of the fall houndstongue experiment were recorded 15, 180, and 365 DAT, while the spring study was evaluated 15, 30, 60, and 90 DAT.

Weed Control Data Analysis. Density, visual injury and visual control data were analyzed with SAS[3] ANOVA using PROC GLM. *F*-test results were considered significant at $P \leq 0.05$ and treatment means were separated using an *F*-protected least significant difference at $P=0.05$. Weed control was calculated after analysis based on the stem density of each treatment as a percentage of the untreated stem density.

---

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

Aminocyclopyrachlor Soil Dissipation. The effect of moisture and temperature on the dissipation of aminocyclopyrachlor was evaluated on four North Dakota soils using a soybean bioassay. Fargo silty clay (Fine, smectitic, frigid Typic Epiaquerts) (Soil Survey Staff 2011), Svea-Barnes loam (Fine-loamy, mixed, superactive, frigid Pachic Hapludolls; Fine-loamy, mixed superactive, frigid Calcic Hapludolls), Glendive-Havre clay (Coarse-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents; Fine-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents), and Lamoure loamy sand (Fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquolls), soils were collected near Fargo, Jamestown, Medora, and Walcott, North Dakota, respectively. Soil was obtained from 0- to 15-cm depth, screened through a 6 mm sieve, air dried, and stored at 22 C.

The field capacity (FC) was determined for each soil type in a preliminary study. A 500 g air-dried sample of each soil type was placed in separate paper bags and oven dried at 75 C for 40 h. Oven-dry weight for each soil was measured and recorded. The soil was then transferred to individual plastic containers with drainage holes. Pots were placed in Styrofoam trays and 300 to 500 ml distilled water was added alternately to the surface and subsurface until water was no longer absorbed. The pots were removed from the trays and lightly covered with tinfoil. Gravitational water was allowed to drain for 48 h and the weight of each soil type was recorded. Gravimetric water content was calculated using Equation 1 (Coyne and Thompson 2006) and considered FC (Table 1).

$$\% \text{ by wt} = [(\text{wet soil} - \text{oven-dry soil}) / (\text{oven-dry soil})] \times 100 \qquad [1]$$

The amount of water required to achieve 22.5, 45, and 90% FC was determined for each soil type.

Table 1. Physical and chemical characteristics of North Dakota soils included in the soil dissipation experiment.

Location	Soil series	Sand	Silt	Clay	Organic matter	Field capacity gravimetric water content	pH
		% by wt					
Fargo	Fargo	5	45	50	7.0	55	7.2
Jamestown	Svea-Barnes	37	42	21	6.4	51	5.7
Medora	Glendive-Havre	5	35	60	1.2	38	8.1
Walcott	Lamoure	86	9	5	2.6	49	7.8

Moisture Study. Aminocyclopyrachlor was applied at 36 µg kg^{-1} in 10 ml of solution to 500 g air-dry soil in wax paper bags and allowed to dry for 24 h. Soil was mixed in the bags by overturning 20 times and poured into individual 10-cm diameter by 8-cm plastic pots with five 0.25-cm diameter holes in the bottom. Each pot was placed in a separate 13- by 13- by 4-cm deep tray to collect leachate, and soil water contents were established at 22.5, 45, or 90%. The soil was stored in dark chambers with a constant temperature of 16 ±2 C for 8 wk where moisture content was monitored to maintain the desired % FC. Upon removal the soil was frozen to reduce or eliminate microbial activity until the bioassay. Soil with water contents of 22.5% and 45% FC was warmed 5 d at 16 ±2 C. Soil with a water content of 90% FC was allowed to warm 2 d at 16 ±2 C and 3 d at 21 ±2 C to reduce water content to approximately 45% FC. All soil was taken to the greenhouse after 5 d and individually mixed prior to planting.

Aminocyclopyrachlor concentration remaining in the soil was determined by a soybean bioassay. A standard curve for each soil type was prepared with aminocyclopyrachlor concentrations of 0, 4.5, 9, 18, and 36 µg kg^{-1} soil. The soil was air dried, mixed, and placed into plastic pots as previously described. Eight 'Traill' soybean seeds were planted 1-cm deep in all soils. Each soil was moistened by adding water alternately to the surface and subsurface throughout the bioassay as needed to maintain approximately 50% FC. After emergence soybeans were thinned to 4 per pot and water soluble fertilizer[4] was applied at 85 kg nitrogen ha^{-1}. Pots were rotated every 4 d to reduce environmental variability in the greenhouse. The greenhouse was maintained at 21 C, and natural sunlight was supplemented with metal halide lights with an intensity of 450 $\mu E\ m^{-2}\ s^{-1}$ for a 16 hr photoperiod. Soybeans were cut at the soil surface 15 to 17 d after planting and stem height was measured to the apical meristem.

Temperature Study. Soil was weighed, mixed, and placed in pots as previously described, except water content was maintained at 45% FC for the duration of the temperature study. The soil was stored in dark chambers with temperature held constant at 8 ±2, 16 ±2, or 24 ±2 C. Four pots of each soil type were removed 0, 2, 4, 8, and 16 wk after treatment (WAT). Soil was frozen until the soybean bioassay was initiated. Soil was warmed at 16 ±2 C for 5 d and then placed in the greenhouse and prepared for planting. The moisture and temperature bioassays were conducted at the same time and utilized the same standard curve.

Aminocyclopyrachlor Soil Dissipation Data Analysis. The moisture and temperature studies were a randomized complete block with four replicates. Soybean stem height was analyzed with SAS[3] ANOVA using PROC GLM. Experiments were repeated and runs were homogeneous. Regression analysis was used to develop curves based on soybean stem height from standard curve soils. The equations estimated herbicide concentration in moisture and temperature treated soils based on soybean stem height.

---

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

The time to 50% dissipation (DT_{50}) of aminocyclopyrachlor was calculated individually for each replicate in every soil. The first-order rate Equation 2 was used to describe

$$\ln(A_t/A_o) = -\mathrm{k}t \qquad [2]$$

aminocyclopyrachlor dissipation (Walker 1987). A_t was the concentration of aminocyclopyrachlor in the soil at time t, A_o was the initial aminocyclopyrachlor soil concentration, and k was the dissipation rate constant. Equation 3 was used to calculate DT_{50}

$$DT_{50} = 0.693/\mathrm{k} \qquad [3]$$

where k was the rate constant from Equation 2.

When the DT_{50} value for a replicate could not be determined, i.e., was greater than 56 or 112 d for the moisture study, or temperature study, respectively, the value was considered missing and estimated. When four or more DT_{50} values were missing within one treatment 56 or 112 d were used rather than an estimated value for moisture or temperature studies, respectively. The DT_{50} values of aminocyclopyrachlor in each soil were subjected to ANOVA and compared using least squares means (LSMEANS). Treatment means were separated by probability of difference (PDIFF, $P \leq 0.05$). Treatment means calculated with more than four missing DT_{50} values are preceded with > to indicate that actual dissipation could be longer than the mean.

Herbicide Efficacy to Seedling Grasses. The effect of aminocyclopyrachlor applied alone or with 2,4-D, chlorsulfuron, or metsulfuron was evaluated on three cool-season grasses: green needlegrass, intermediate wheatgrass, and western wheatgrass and three warm-season grasses: big bluestem, sideoats grama, and switchgrass. Each species was a separate experiment, with treatments assigned to 3- by 4-m plots using a RCBD with four replicates, except western wheatgrass which had three replicates due to flooding. The studies were conducted on North

Dakota State University research land near Fargo, North Dakota. The soil at the site was Fargo-Ryan silty clay (Ryan: Fine, smectitic, frigid Typic Natraquerts) (Soil Survey Staff 2011).

Grasses[5] were planted at Natural Resource Conservation Service recommended rates (Table 2) using a 6-row grain drill[6] with 30.5-cm spacing. Cool-season species were seeded April 22, 2010 while warm-season species were seeded May 21, 2010. Weed competition in 2010 consisted primarily of Canada thistle, common ragweed (*Ambrosia artemisiifolia* L), perennial sowthistle (*Sonchus arvensis* L.), and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes]. The experiments were repeated in 2011 with a single planting date of May 26, due to

Table 2. Grass species[a] and seeding rate used for the evaluation of aminocyclopyrachlor on newly established grasses.

Grass species	Variety	Seeding rate[b]
		— kg ha^{-1} —
Cool-season grasses		
Green needlegrass	Lodorm	8
Intermediate wheatgrass	Manifest	11
Western wheatgrass	Rodan	11
Warm-season grasses		
Big bluestem	Bison	8
Sideoats grama	Pierre	8
Switchgrass	Dacotah	5

[a] Seed from United States Department of Agriculture, Natural Resources Conservation Service, Bismarck Plant Materials Center, 3308 University Drive, Bismarck, North Dakota 58504.

[b] Pure live seed.

---

[5] Seed provided by United States Department of Agriculture, Natural Resources Conservation Service, Bismarck Plant Materials Center, 3308 University Drive, Bismarck, North Dakota 58504.

[6] Almaco heavy-duty grain drill, 99M Avenue, Nevada, Iowa 50201-1558.

wet spring conditions. Common lambsquarters (*Chenopodium album* L.), lanceleaf sage (*Salvia reflexa* Hornem.), redroot pigweed (*Amaranthus retroflexus* L.), wild mustard (*Sinapis arvensis* L.), and yellow foxtail, were the most abundant weeds in 2011.

Grass establishment was determined by evaluating grass frequency and density prior to herbicide application. Frequency was estimated by counting the number of 10-cm segments with the desired grass present in 100-cm from the fourth and eighth seeded rows in the center of each plot. Density was measured by counting the number of individual plants in 100-cm of row from the same locations as the frequency measurements.

Herbicides were applied approximately 30 d after emergence with a hand-held boom sprayer as previously described. Bromoxynil was applied at 420 g ha^{-1} to control treatments to reduce broadleaf weed competition. Herbicide efficacy was estimated by visual assessment of grass response approximately 0, 2, 4, 6, and 8 WAT. Assessments were made on a scale of 0 to 10, with 0 equal to no injury and 10 equal to complete above-ground grass control. Above-ground biomass was harvested in two 0.25-m^2 quadrats from the fourth and eighth rows in each plot. Western wheatgrass, intermediate wheatgrass, and green needlegrass planted in 2010 were harvested July 7, 8, and 11, 2011, respectively. Big bluestem, sideoats grama, and switchgrass planted in 2010 were harvested August 8 and 9, 2011. Grasses seeded in 2011 have not been harvested. Plants were separated into desired grass species, grass weeds, and broadleaf weeds. Harvested plant material was dried at 50 C for at least 72 hr and weighed to estimate yield.

Herbicide Efficacy to Seedling Grasses Data Analysis. Data from 2010 and 2011 were analyzed separately. Frequency, density, injury and harvest data were analyzed with SAS[3] ANOVA using PROC GLM. All *F*-test results were considered significant at $P \leq 0.05$ and treatment means were separated using an *F*-protected least significant difference at $P=0.05$.

RESULTS AND DISCUSSION

Yellow Toadflax Control. Aminocyclopyrachlor applied at the flowering growth stage provided excellent control of yellow toadflax, but was not effective when plants were treated in the fall vegetative growth stage (Tables 3 and 4). Aminocyclopyrachlor applied in the summer at 147 to 210 g ha^{-1} provided an average of 96% yellow toadflax control 12 MAT which was similar to the current standard of picloram plus dicamba plus diflufenzopyr (Table 3). Yellow toadflax control averaged 96% 14 MAT when aminocyclopyrachlor was applied alone at all application rates. Yellow toadflax control was similar when aminocyclopyrachlor was applied with either 2,4-D, chlorsulfuron, or metsulfuron and averaged 95, 100, and 98% control, respectively, 14 MAT.

Aminocyclopyrachlor did not control yellow toadflax regardless of application rate when applied alone or with other herbicides in the vegetative regrowth stage 10 or 12 MAT (Table 4). Picloram plus dicamba plus diflufenzopyr was the only treatment that controlled yellow toadflax when applied at the vegetative regrowth stage, and averaged 81% control 10 MAT; however, control was only 39% 12 MAT. Although yellow toadflax density was reduced in herbicide treated plots, there was also a reduction of yellow toadflax in the untreated plots which may have masked any herbicide effect (Figure 2).

The decrease in yellow toadflax density could have been due to above average precipitation (USDC-NOAA 1981-2010, 2010-2011), and a resultant increase in grass competition. Kentucky bluegrass and smooth bromegrass production dramatically increased during the growing season (personal observation). Also, throughout the spring and summer of 2010 WPA officials made continuous surveys in search of bird nests which caused repeated disturbance of the vegetation. Surveys were not conducted in 2011 and disturbance was minimal (personal observation).

Table 3. Yellow toadflax control with aminocyclopyrachlor applied alone or with 2,4-D, chlorsulfuron, or metsulfuron during the flowering growth stage on July 19, 2010 at the Knudtson waterfowl production area near Jamestown, North Dakota.

		Evaluation (mo after treatment)	
Treatment[a]	Rate	12	14
	— g ai ha^{-1} —	% control	
Aminocyclopyrachlor	105	60	85
Aminocyclopyrachlor	147	91	95
Aminocyclopyrachlor	171	100	100
Aminocyclopyrachlor	175	94	98
Aminocyclopyrachlor	210	100	100
Aminocyclopyrachlor + 2,4-D	147 + 1113	87	95
Aminocyclopyrachlor + chlorsulfuron	175 + 70	97	100
Aminocyclopyrachlor + metsulfuron	171 + 26	99	98
2,4-D	1113	0	54
Chlorsulfuron	70	40	85
Metsulfuron	26	3	63
Picloram + (dicamba + diflufenzopyr)[b]	1120 + 294	99	95
Untreated	⋯	0	0
LSD (0.05)		17	21

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Dicamba + diflufenzopyr, a commercial premix, Overdrive®, by BASF Corporation, Agricultural Products, 26 Davis Drive, Research Triangle Park, NC 27709.

The decrease in yellow toadflax density was noted for the study initiated in July 2010, but was not as severe. Grass injury was observed when aminocyclopyrachlor and picloram treatments were applied in July which could have decreased grass competition in the spring of 2011 when yellow toadflax growth began. As grass injury subsided and competition increased yellow toadflax density further declined which could explain the unexpected control of yellow toadflax achieved with 2,4-D, chlorsulfuron, or metsulfuron alone 14 MAT.

Table 4. Yellow toadflax control with aminocyclopyrachlor applied alone or with 2,4-D, chlorsulfuron, or metsulfuron during the fall vegetative growth stage on September 17, 2010 at the Knudtson waterfowl production area near Jamestown, North Dakota.

		Evaluation (mo after treatment)	
Treatment[a]	Rate	10	12
	g ai ha^{-1}	% control	
Aminocyclopyrachlor	105	1	0
Aminocyclopyrachlor	147	0	0
Aminocyclopyrachlor	171	40	0
Aminocyclopyrachlor	175	46	0
Aminocyclopyrachlor	210	33	0
Aminocyclopyrachlor + 2,4-D	147 + 1113	0	0
Aminocyclopyrachlor + chlorsulfuron	175 + 70	45	0
Aminocyclopyrachlor + metsulfuron	171 + 26	15	0
2,4-D	1113	0	0
Chlorsulfuron	70	6	0
Metsulfuron	26	0	0
Picloram + (dicamba + diflufenzopyr)[b]	1120 + 294	81	39
Untreated	…	0	0
LSD (0.05)		43	NS

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Dicamba + diflufenzopyr, a commercial premix, Overdrive®, by BASF Corporation, Agricultural Products, 26 Davis Drive, Research Triangle Park, NC 27709.

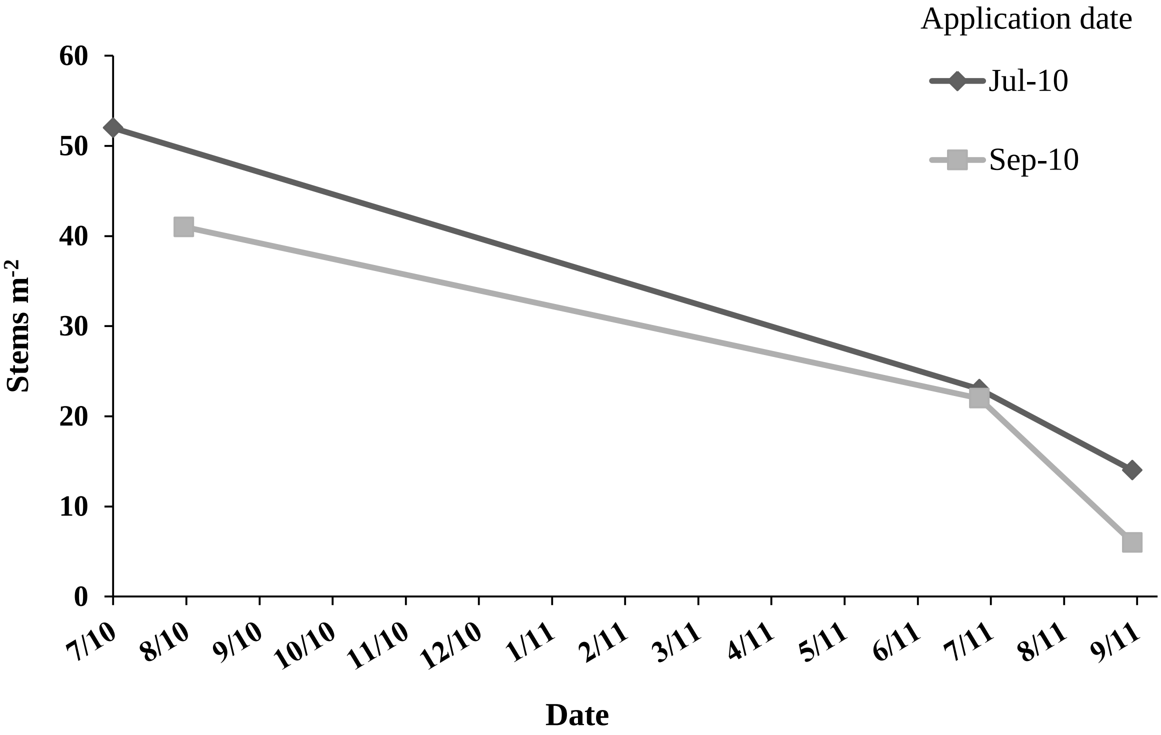


Figure 2. Yellow toadflax density in untreated plots from July 2010 until September 2011 at the Knudtson Waterfowl Production Area near Jamestown, North Dakota.

Absinth Wormwood Control. Aminocyclopyrachlor generally provided long-term absinth wormwood control when applied at 140 g ha^{-1} or more during vegetative growth in the spring or vegetative regrowth in the fall after mowing in July (Tables 5 and 6). Aminocyclopyrachlor applied in the spring at 140 to 210 g ha^{-1} provided an average of 85% absinth wormwood control 12 and 16 MAT (Table 5). Aminocyclopyrachlor applied at 140 g ha^{-1} or lower provided less than 45% control 12 MAT, and would not be suitable for absinth wormwood management. Similarly, aminocyclopyrachlor plus chlorsulfuron applied at 105 + 42 g ha^{-1} provided only 44% control 12 MAT. Application rate was not important when aminocyclopyrachlor was applied in the fall (Table 6). Aminocyclopyrachlor applied alone regardless of rate or with chlorsulfuron provided

Table 5. Absinth wormwood control with aminocyclopyrachlor applied alone or with chlorsulfuron during the vegetative growth stage on May 21, 2010 at Valley City, North Dakota.

		Evaluation (mo after treatment)		
Treatment[a]	Rate	3	12	16
	— g ai ha^{-1} —		% control	
Aminocyclopyrachlor	70	74	28	24
Aminocyclopyrachlor	105	88	44	76
Aminocyclopyrachlor	140	96	89	88
Aminocyclopyrachlor	175	95	83	82
Aminocyclopyrachlor	210	95	89	82
Aminocyclopyrachlor + chlorsulfuron	105 + 42	83	44	47
Chlorsulfuron	42	54	0	0
Aminopyralid[b]	90	42	0	0
Untreated	...	0	0	0
LSD (0.05)		23	64	65

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

100% absinth wormwood control 12 MAT.

Aminocyclopyrachlor applied in the spring or fall provided better absinth wormwood control than the current standard, aminopyralid, in this study (Tables 5 and 6). Aminopyralid applied in the spring did not reduce absinth wormwood density compared to the control, although similar research conducted in North Dakota found that aminopyralid applied at 90 to 123 g ha^{-1} in the spring provided 100% absinth wormwood control 12 MAT (Lym 2010; Lym and Samuel 2006).

The differences in these results cannot be explained. Aminopyralid applied in the fall averaged 65% absinth wormwood control 12 MAT and was similar to aminopyralid applied at 90 g ha^{-1} in the fall which provided 56% control 12 MAT (Lym and Samuel 2006).

Table 6. Absinth wormwood control with aminocyclopyrachlor applied alone or with chlorsulfuron during vegetative regrowth[a] on September 17, 2010 at Valley City, North Dakota.

		Evaluation (mo after treatment)	
Treatment[b]	Rate	8	12
	— g ai ha^{-1} —	% control	
Aminocyclopyrachlor	70	100	100
Aminocyclopyrachlor	105	95	100
Aminocyclopyrachlor	140	100	100
Aminocyclopyrachlor	175	100	100
Aminocyclopyrachlor	210	100	100
Aminocyclopyrachlor + chlorsulfuron	105 + 42	100	100
Chlorsulfuron	42	0	0
Aminopyralid[c]	90	5	65
Untreated	...	0	0
LSD (0.05)		54	62

[a] Plants were mowed in July and allowed to regrow.

[b] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[c] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Houndstongue Control. The houndstongue study near Kathryn, North Dakota may have been adversely affected by previous herbicide applications, or herbicide treatments may have caused injury to untreated plants due to the small plot size. Houndstongue in untreated plots showed injury at the first evaluation, and throughout the experiment period (data not shown). The results of this experiment were not used to evaluate the efficacy of aminocyclopyrachlor on houndstongue. The subsequent experiments near McLeod, North Dakota, were conducted to more accurately estimate aminocyclopyrachlor efficacy on houndstongue.

Aminocyclopyrachlor applied at 70, 105, and 140 g ha^{-1} in September 2010 provided 7, 82, and 0% houndstongue control 9 MAT (Table 7). These results indicate that houndstongue

Table 7. Houndstongue control with aminocyclopyrachlor applied alone or with 2,4-D or chlorsulfuron to rosettes on September 8, 2010 or rosette to mature plants on June 16, 2011 near McLeod, North Dakota.

Treatment[a]	Rate	9 MAT[b] in September 2010	3 MAT in June 2011
	— g ai ha^{-1} —	% control	
Aminocyclopyrachlor	70	7	47
Aminocyclopyrachlor	105	82	60
Aminocyclopyrachlor	140	0	53
Aminocyclopyrachlor + 2,4-D amine	70 + 532	46	20
Aminocyclopyrachlor + chlorsulfuron	70 + 28	75	100
Untreated	...	0	0
LSD (0.05)		72	55

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] MAT = months after treatment

control with aminocyclopyrachlor alone may be inconsistent. Aminocyclopyrachlor plus 2,4-D applied at 70 + 532 g ha^{-1} and aminocyclopyrachlor plus chlorsulfuron applied at 70 + 28 g ha^{-1} provided 46 and 75% houndstongue control, respectively, 9 MAT.

Aminocyclopyrachlor applied at 70, 105, and 140 g ha^{-1} in June 2011 averaged 53% houndstongue control 3 MAT (Table 7). The addition of chlorsulfuron improved houndstongue control compared to aminocyclopyrachlor alone and averaged 100% 3 MAT; however, 2,4-D did not improve houndstongue control compared to aminocyclopyrachlor alone.

Aminocyclopyrachlor applied at 70 to 140 g ha^{-1} provided inconsistent houndstongue control and would not be suitable for the management of this weed. Aminocyclopyrachlor plus chlorsulfuron provided adequate houndstongue control when applied in the spring or fall and may be useful for houndstongue management.

Aminocyclopyrachlor Soil Dissipation. Aminocyclopyrachlor DT_{50} ranged from 3 to >112 d in four North Dakota soils. The time to degrade was dependent on several factors including soil type, moisture content, and temperature (Tables 8 and 9). Aminocyclopyrachlor dissipation was more rapid when soil organic matter content was greater than 6%. Additionally, the rate of dissipation generally increased as soil moisture content, or temperature increased.

Moisture Study. The effect of moisture on aminocyclopyrachlor dissipation was dependent on soil type. In Fargo silty clay soil, aminocyclopyrachlor DT_{50} values decreased from > 50 to 5 d as moisture content increased from 22.5 to 90% FC, respectively (Table 8). Although not significant, the DT_{50} in the Lamoure loamy sand decreased from 44 d at 22.5% FC to 21 d at 90%. Similarly, in sandy loam soil the rate of picloram degradation was influenced by moisture (Meikle et al. 1973). As soil moisture content increased from 18 to 192% of 1/3 bar tension, picloram decomposition increased from 17 to 40% of applied herbicide.

Aminocyclopyrachlor dissipation in Fargo and Lamoure soils would be more rapid during a wet spring or summer than in dry conditions. Long periods of moist soil conditions could reduce the period of weed control in these soils; however, if the treated land is converted into cropland wet conditions could reduce the rotation restriction for planting sensitive crops.

Table 8. Effect of moisture on aminocyclopyrachlor dissipation to 50% (DT_{50}) in four soils 56 days after treatment with 36 µg kg^{-1} and held at 16 C.

	Soil series			
Moisture content	Fargo	Glendive-Havre	Lamoure	Svea-Barnes
% Field capacity	DT_{50}			
22.5	> 50[a] a[b]	20 a	44 a	7 a
45	17 b	54 b	30 a	3 a
90	5 c	19 a	21 a	11 a

[a] Actual DT_{50} exceeds the sensitivity of the test; however, means were separated using the estimated value.

[b] Numbers followed by the same letter within each soil are not significantly different according to probability of difference ($P \leq 0.05$).

In Glendive-Havre clay soil, aminocyclopyrachlor DT_{50} values averaged 20 d at 22.5 and 90% FC, compared to 54 d when moisture was held at 45% FC (Table 8). The decrease in DT_{50} values from 45 to 90% FC was consistent with the trend in Fargo and Lamoure soils; however, rapid dissipation at 22.5% FC was not expected. Since aminocyclopyrachlor is degraded by microbes in the soil (Anonymous 2009a; Finkelstein et al. 2008) and aerobic microbial activity is greatest at intermediate soil moisture of 50 to 60% water-filled pore space (Franzluebbers 1999; Linn and Doran 1984), the DT_{50} value at 22.5% FC was expected to be greater than at 45 or 90%.

Low adsorption properties of the Glendive-Havre soil could explain why the aminocyclopyrachlor DT_{50} value was higher at 45% than 22.5% FC (Table 8). The Glendive-Havre soil had a high pH (8.1) and low organic matter (1.2%) (Table 1) which would decrease aminocyclopyrachlor sorption compared to the Fargo and Lamoure soils. A study conducted with Morey silty clay loam soil that had a pH of 7.3 and 1.3% organic matter found that as moisture decreased the concentration of plant-available clomazone in the soil solution also decreased (Lee et al. 2004). Green and Obien (1969) concluded that although soils with weak herbicide adsorption have an increased concentration of herbicide in solution, the herbicide will not always be more phytotoxic in dry conditions. In low soil moisture hydrophilic adsorptive sites become more available to the herbicide, and can result in reduced herbicide toxicity (Grover 1966). Only plant available herbicide was detected with the bioassay method used in this study. Chemical evaluation to determine if aminocyclopyrachlor is present, but not available to the plant in the Glendive-Havre soil could be important to understand the persistence of aminocyclopyrachlor in soils with weak adsorption.

Aminocyclopyrachlor dissipation in the Svea-Barnes loam soil was not affected by moisture and the average DT_{50} was 11 d (Table 8). The rapid decrease in plant availability observed in this soil could be due to enhanced microbial degradation of aminocyclopyrachlor. The Svea Barnes soil was collected from a field used for corn production. Commercial fertilizers used for crop production may have increased soil nutrients which could increase microbial activity and diversity and may increase aminocyclopyrachlor degradation.

The most rapid dissipation of aminocyclopyrachlor in Fargo soil will likely occur when the soil moisture content is greater than 45% FC; however in soils with higher sand content such as the Lamoure and Svea-Barnes soils low moisture did not affect aminocyclopyrachlor dissipation

(Table 8). In field dissipation studies submitted to the EPA (2010) for herbicide registration, the half-life of aminocyclopyrachlor ranged from 22 to 126 d, generally higher than the range of 3 to > 50 d reported here (Table 8). The shorter half-life observed in this study could be due to limitations of the bioassay which report only plant available herbicide.

Temperature Study. Aminocyclopyrachlor DT_{50} values tended to decrease as temperature increased regardless of soil type (Table 9). Aminocyclopyrachlor DT_{50} values were lowest in Fargo soil and decreased from 37 to 11 d as temperature increased from 8 to 24 C. Aminocyclopyrachlor dissipation followed a similar trend in the Glendive-Havre soil, but DT_{50} values were longer, and ranged from 51 to > 112 d. As previously described, the Glendive-Havre soil has properties which would decrease aminocyclopyrachlor sorption, and could make the herbicide more available for plant uptake. A similar study indicated that aminopyralid dissipation was also more rapid in Fargo-Ryan soil than Glendive-Havre soil, and reasoned that high organic matter content may support greater microbial populations (Mikkelson 2010).

Table 9. Effect of temperature on aminocyclopyrachlor dissipation to 50% (DT_{50}) in four soils 56 days after treatment with 36 μg kg^{-1} and held at 45% field capacity.

	Soil series			
Temperature	Fargo	Glendive-Havre	Lamoure	Svea-Barnes
C	DT_{50}			
8	37 b[a]	> 112 [b] b	> 80 b	> 88 a
16	18 a	54 a	52 b	22 a
24	11 a	51 a	13 a	13 a

[a] Numbers followed by the same letter within each soil are not significantly different according to probability of difference ($P \leq 0.05$).

[b] Actual DT_{50} exceeds the sensitivity of the test; however, means were separated using the estimated value.

The effect of temperature on aminocyclopyrachlor dissipation was similar to the response of other growth regulator herbicides. Aminopyralid dissipation increased with increased temperature, and was approximately 8 times faster at 24 C than 8 C in Lamoure and Svea-Barnes soil (Mikkelson 2010). In this study, the DT_{50} values of aminocyclopyrachlor in Lamoure and Svea-Barnes soil aged at 8 C were > 80 and > 88 d, respectively, but decreased to 13 d each when temperature was increased to 24 C (Table 9). Similarly, picloram (Guenzi and Beard 1976) and clopyralid (Ahmad et al. 2003) degradation were maximized when soil was incubated at $\geq$ 30 C and were influenced by microbial activity.

The DT_{50} values in the temperature study ranged from 11 to > 112 d (Table 9). The DT_{50} values that exceeded the sensitivity of the test could be much longer than 112 d, and in EPA's diverse environments (conditions not given) aminocyclopyrachlor has persisted with a half-life as long as 373 d (EPA 2010). The potential of aminocyclopyrachlor to persist is a concern since herbicide in the soil or plant material could harm non-target species (EPA 2011).

Ultimately, aminocyclopyrachlor dissipation was slowed by cold temperatures, and degradation in the field would be minimal during the fall and winter months in northern climates. Additionally, the results suggest that aminocyclopyrachlor degradation may be slower in soils with low organic matter and high pH.

Aminocyclopyrachlor persistence in the soil will be beneficial for long term weed control; however, land managers should be cautious when re-seeding pasture and rangeland with sensitive forb species or converting CRP to cropland where aminocyclopyrachlor was applied. Although a bioassay would be the best method to determine plant sensitivity, some estimates can be made based on other herbicides. The reported half-life of clopyralid (12 to 70 d) (Senseman 2007b) is similar to what was observed in all soils in the moisture and temperature studies, except at 8 C where DT_{50} values were longer (Tables 8 and 9). Clopyralid has a rotation restriction of 10.5 to 18 mo for sensitive species with additional time required for soil with low organic matter and less than 38 cm of rainfall 12 mo after application (Anonymous 2010). A similar restriction may be adequate for aminocyclopyrachlor; however, research to identify the "diverse" environmental conditions that increase aminocyclopyrachlor persistence would be useful to determine more specific restrictions.

Herbicide Efficacy to Seedling Grasses. Cool season grass establishment was excellent in both 2010 and 2011; however, warm season grass establishment varied by year (Table 10). Green needlegrass density averaged 107 and 67 seedlings m^{-2} in 2010 and 2011, respectively, and was greater than the required 54 seedlings m^{-2} necessary to obtain an adequate stand of a bunchgrass

Table 10. Grass stand evaluation recorded approximately 1 mo after planting in 2010 or 2011 near Fargo, North Dakota.

	Density		Frequency	
Grass species	2010	2011	2010	2011
	seedlings m^{-2}		%	
Cool-season				
Green needlegrass	107	67	93	77
Intermediate wheatgrass	99	102	86	89
Western wheatgrass	70	98	72	88
Warm-season				
Big bluestem	29	112	50	86
Sideoats grama	24	114	37	81
Switchgrass	30	112	42	87

species (USDA-NRCS 2011). Big bluestem, a warm season bunchgrass, averaged only 29 seedlings m^{-2} in 2010, and was not considered adequate; however, big bluestem density was excellent in 2011, and averaged 112 seedlings m^{-2}. The poor big bluestem establishment observed in 2010 compared to 2011 could be due to Canada thistle, perennial sowthistle, and yellow foxtail competition observed after planting and/or environmental factors. Heavy rainfall on June 17, 2010 resulted in accumulated moisture 216% greater than normal (NDAWN 2012), and warm season seedlings were flooded for a period of at least 3 d.

Cool season rhizomatous species, intermediate and western wheatgrass, averaged 99 and 70 seedlings m^{-2}, respectively, in 2010, and 102, and 98 seedlings m^{-2}, respectively in 2011 (Table 10). Density was well above adequate for the rhizomatous species which require at least 32 seedlings m^{-2} (USDA-NRCS 2011). Warm season rhizomatous species, sideoats grama and switchgrass, averaged only 24 and 30 seedlings m^{-2}, respectively, in 2010, and were not considered adequate stands. Establishment was much better in 2011, and sideoats grama and switchgrass averaged 114 and 112 seedlings m^{-2}, respectively. Differences observed in sideoats grama and switchgrass establishment between 2010 and 2011 could be due to weed competition and/or environmental factors previously described.

Green Needlegrass. Minimal green needlegrass injury was observed up to 6 WAT in 2010 regardless of herbicide treatment (Table 11); however, by 8 WAT green needlegrass injury averaged 30 and 48% when aminocyclopyrachlor was applied alone at 168 and 329 g ha^{-1}, respectively. Aminocyclopyrachlor applied at the same rates with chlorsulfuron at 63 and 133 g ha^{-1} resulted in 5 and 16% green needlegrass injury, respectively. The reduced injury when chlorsulfuron was applied with aminocyclopyrachlor may indicate herbicide antagonism, although this type of antagonism (reduced crop injury) is desirable if weed control is not compromised.

Table 11. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 24, 2010 to green needlegrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	——— % injury ———			
Aminocyclopyrachlor	91	0	0	0	8
Aminocyclopyrachlor	112	0	0	0	8
Aminocyclopyrachlor	168	0	1	2	30
Aminocyclopyrachlor	329	0	1	4	48
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	0	0	4
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1	0	0	3
Aminocyclopyrachlor + chlorsulfuron	168 + 63	1	0	0	5
Aminocyclopyrachlor + chlorsulfuron	329 + 133	0	0	2	16
Aminocyclopyrachlor + metsulfuron	91 + 14	0	0	0	3
Chlorsulfuron	42	0	0	0	10
Chlorsulfuron	63	0	0	0	9
Chlorsulfuron	133	0	0	0	6
Metsulfuron	14	0	0	0	11
Aminopyralid[b]	126	0	0	0	3
Control	...	0	0	0	0
LSD (0.05)		NS	NS	2	9

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Chlorsulfuron antagonism with herbicides has reduced injury to other grass species including wheat (*Triticum aestivum* L.) and wild oat (*Avena fatua* L.) (Gillespie and Nalewaja 1989; O'Sullivan and Kirkland 1984). When applied preplant incorporated, chlorsulfuron plus triallate resulted in greater wheat emergence and reduced wheat injury compared to triallate applied alone (Gillespie and Nalewaja 1989). Chlorsulfuron plus diclofop, difenzoquat, or flamprop applied post emergence in wheat did not affect wheat production, but reduced wild oat control compared to the same herbicide treatments that did not include chlorsulfuron (O'Sullivan and Kirkland 1984).

Green needlegrass production 14 mo after seeding (MAS) was maximized when aminocyclopyrachlor was applied with either chlorsulfuron or metsulfuron, and averaged 3446 kg ha^{-1} (Table 12). Similarly, when aminocyclopyrachlor was applied alone at 91 to 168 g ha^{-1} green needlegrass biomass averaged 2420 kg ha^{-1}, but when aminocyclopyrachlor rate increased to 329 g ha^{-1} crop biomass declined to 1355 kg ha^{-1}. The biomass decrease was likely the result of increased green needlegrass injury when aminocyclopyrachlor was applied alone (Table 11). Aminocyclopyrachlor plus 2,4-D, or aminopyralid, chlorsulfuron, and metsulfuron applied alone did not improve biomass production compared to the control probably due to broadleaf weed competition (Table 12).

Aminocyclopyrachlor applied alone or with chlorsulfuron, regardless of rate, effectively reduced grass weed biomass to an average of 390 kg ha^{-1} compared to 1345 kg ha^{-1} in the control (Table 12). Broadleaf weed biomass was reduced to an average of 43 kg ha^{-1} when aminocyclopyrachlor was applied alone at 91 to 168 g ha^{-1}. Similarly, when aminocyclopyrachlor plus 2,4-D, chlorsulfuron, or metsulfuron was applied at 91 + 742, 112 + 42, or 91 +14 g ha^{-1}, respectively, broadleaf weed biomass averaged only 57 kg ha^{-1}. Increased rates of aminocyclopyrachlor plus chlorsulfuron did not result in decreased broadleaf weed biomass, nor did aminopyralid, chlorsulfuron, or metsulfuron applied alone.

Table 12. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on green needlegrass (GNG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	GNG	GW	BW
	— g ai ha^{-1} —		kg ha^{-1}	
Aminocyclopyrachlor	91	2135	425	40
Aminocyclopyrachlor	112	2560	285	30
Aminocyclopyrachlor	168	2565	360	60
Aminocyclopyrachlor	329	1355	675	245
Aminocyclopyrachlor + 2,4-D amine	91 + 742	1210	1035	40
Aminocyclopyrachlor + chlorsulfuron	112 + 42	3680	670	90
Aminocyclopyrachlor + chlorsulfuron	168 + 63	2925	110	105
Aminocyclopyrachlor + chlorsulfuron	329 + 133	3525	205	195
Aminocyclopyrachlor + metsulfuron	91 + 14	3655	800	40
Chlorsulfuron	42	350	655	485
Chlorsulfuron	63	180	265	425
Chlorsulfuron	133	145	240	680
Metsulfuron	14	290	880	205
Aminopyralid[b]	126	1030	1156	410
Control	...	595	1345	305
LSD (0.05)		1530	625	215

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Green needlegrass injury was more severe 8 WAT in 2011 than 2010, and averaged 93% compared to only 11%, respectively (Tables 11 and 13). Green needlegrass seedling stress and

Table 13. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2011 to green needlegrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	37	88	92	93
Aminocyclopyrachlor	112	3	78	90	93
Aminocyclopyrachlor	168	59	98	99	100
Aminocyclopyrachlor	329	35	91	97	99
Aminocyclopyrachlor + 2,4-D amine	91 + 742	45	100	100	100
Aminocyclopyrachlor + chlorsulfuron	112 + 42	35	84	96	98
Aminocyclopyrachlor + chlorsulfuron	168 + 63	48	100	100	100
Aminocyclopyrachlor + chlorsulfuron	329 + 133	55	98	99	100
Aminocyclopyrachlor + metsulfuron	91 + 14	39	99	99	99
Chlorsulfuron	42	35	98	99	100
Chlorsulfuron	63	54	80	88	90
Chlorsulfuron	133	41	98	98	100
Metsulfuron	14	23	77	73	81
Aminopyralid[b]	126	18	52	49	51
Control	...	15	73	83	90
LSD (0.05)		NS	NS	NS	NS

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

death was observed in 2011 prior to and after herbicide applications in all plots (personal observation), so crop response could have been related to environmental factors. Green needlegrass emergence was considered complete 35 and 21 d after seeding in 2010 and 2011, respectively, and herbicides were applied approximately 30 d later, so precipitation during and up to 60 d after seeding was considered. Rainfall in 2011 was 24.4 cm compared to 16.2 cm in 2010, and although precipitation did not reduce grass establishment in 2011 (Table 10), the stress of wet and flooded conditions could explain the severe green needlegrass injury observed even in the control.

The efficacy of aminocyclopyrachlor on seedling green needlegrass could not be determined from this study. The severe injury observed in 2011 could not be solely attributed to aminocyclopyrachlor since similar injury was observed in control plots which was likely due to environmental stress rather than aminocyclopyrachlor. Research in a more controlled environment could provide more consistent results and better estimate green needlegrass sensitivity to aminocyclopyrachlor.

Intermediate Wheatgrass. Aminocyclopyrachlor applied in 2010 for weed control in intermediate wheatgrass caused minimal crop injury up to 4 WAT regardless of rate, but injury rapidly increased by 6 and 8 WAT (Table 14). Intermediate wheatgrass injury 8 WAT increased from 39 to 97% as aminocyclopyrachlor rate increased from 91 to 112 g ha^{-1}, respectively; however, similar to green needlegrass, intermediate wheatgrass injury was reduced to an average of 49% when aminocyclopyrachlor was applied at 168 or 329 g ha^{-1} with chlorsulfuron. The addition of 2,4-D, chlorsulfuron, or metsulfuron to aminocyclopyrachlor applied at 91 or 112 g ha^{-1} did not alter intermediate wheatgrass injury compared to aminocyclopyrachlor alone.

Table 14. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 14, 2010 to intermediate wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	0	23	39
Aminocyclopyrachlor	112	0	0	18	38
Aminocyclopyrachlor	168	2	6	58	81
Aminocyclopyrachlor	329	4	16	80	97
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	0	12	30
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1	2	31	45
Aminocyclopyrachlor + chlorsulfuron	168 + 63	1	3	36	53
Aminocyclopyrachlor + chlorsulfuron	329 + 133	4	14	58	76
Aminocyclopyrachlor + metsulfuron	91 + 14	1	3	29	33
Chlorsulfuron	42	1	1	8	7
Chlorsulfuron	63	1	1	6	7
Chlorsulfuron	133	1	0	10	7
Metsulfuron	14	0	1	6	6
Aminopyralid[b]	126	0	0	0	0
Control	...	0	0	0	0
LSD (0.05)		2	3	20	17

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Intermediate wheatgrass production 14 MAS was maximized when aminocyclopyrachlor was applied with either chlorsulfuron or metsulfuron (Table 15), and was higher than production reported by Berti et al. (2011) and Hendrickson et al. (2007) in North Dakota. Intermediate wheatgrass biomass averaged 6905 kg ha^{-1} when aminocyclopyrachlor plus chlorsulfuron was applied at 112 + 42 g ha^{-1} or 329 + 133 g ha^{-1} and aminocyclopyrachlor plus metsulfuron was applied at 91 + 14 g ha^{-1}. In addition, these treatments tended to reduce broadleaf weed biomass to an average of 15 kg ha^{-1} and grass weed biomass to 115 kg ha^{-1}. Intermediate wheatgrass yield averaged 4800 kg ha^{-1} when aminocyclopyrachlor was applied alone at 91 and 112 g ha^{-1}, and despite increased crop injury when aminocyclopyrachlor rate increased to 168 and 329 g ha^{-1}, production averaged 4285 kg ha^{-1}. Aminopyralid, chlorsulfuron, and metsulfuron applied alone did not affect crop yield.

Intermediate wheatgrass injury was more severe earlier in 2011 than 2010 (Tables 15 and 16). Crop injury 4 WAT increased from 14 to 65% when aminocyclopyrachlor was applied alone at 91 to 329 g ha^{-1} and continued to increase up to 86% by 8 WAT. Intermediate wheatgrass injury was unchanged when 2,4-D, chlorsulfuron, or metsulfuron were applied with aminocyclopyrachlor compared to the corresponding rate of aminocyclopyrachlor applied alone.

Although aminocyclopyrachlor injured intermediate wheatgrass, most herbicide treatments that included aminocyclopyrachlor resulted in greater biomass yields than those that did not compared to the control (Table 15). The higher yield is believed to be the result of decreased weed competition. Since low injury and adequate biomass was observed when aminocyclopyrachlor was applied at 91 to 112 g ha^{-1} alone or with chlorsulfuron or metsulfuron, these treatments could be useful for weed control during intermediate wheatgrass establishment.

Table 15. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on intermediate wheatgrass (IWG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	IWG	GW	BW
	— g ai ha^{-1} —	———— kg ha^{-1} ————		
Aminocyclopyrachlor	91	5455	135	20
Aminocyclopyrachlor	112	4140	205	40
Aminocyclopyrachlor	168	4555	215	35
Aminocyclopyrachlor	329	4015	505	465
Aminocyclopyrachlor + 2,4-D amine	91 + 742	4060	305	20
Aminocyclopyrachlor + chlorsulfuron	112 + 42	6930	105	25
Aminocyclopyrachlor + chlorsulfuron	168 + 63	4825	360	15
Aminocyclopyrachlor + chlorsulfuron	329 + 133	7645	100	0
Aminocyclopyrachlor + metsulfuron	91 + 14	6135	140	15
Chlorsulfuron	42	3715	145	410
Chlorsulfuron	63	3680	140	270
Chlorsulfuron	133	3785	85	280
Metsulfuron	14	2080	260	985
Aminopyralid[b]	126	2920	375	260
Control	...	2740	420	155
LSD (0.05)		1540	NS	NS

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 16. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2011 to intermediate wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	—— % injury ——			
Aminocyclopyrachlor	91	0	14	23	32
Aminocyclopyrachlor	112	2	46	55	59
Aminocyclopyrachlor	168	3	44	50	54
Aminocyclopyrachlor	329	6	65	84	86
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	15	25	27
Aminocyclopyrachlor + chlorsulfuron	112 + 42	4	63	73	74
Aminocyclopyrachlor + chlorsulfuron	168 + 63	10	50	66	72
Aminocyclopyrachlor + chlorsulfuron	329 + 133	19	88	93	95
Aminocyclopyrachlor + metsulfuron	91 + 14	1	23	30	31
Chlorsulfuron	42	1	30	36	39
Chlorsulfuron	63	0	13	23	25
Chlorsulfuron	133	0	25	31	34
Metsulfuron	14	0	21	21	31
Aminopyralid[b]	126	1	21	30	33
Control	...	0	15	21	18
LSD (0.05)		5	35	36	38

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Western Wheatgrass. Severe western wheatgrass injury was observed by 4 WAT when aminocyclopyrachlor was applied alone or with other herbicides, and continued to increase throughout the 2010 growing season (Table 17). Western wheatgrass injury 4 WAT averaged 41% when aminocyclopyrachlor was applied alone at 91 to 329 g ha^{-1} while crop injury 8 WAT averaged 92%. The addition of 2,4-D, chlorsulfuron, or metsulfuron to aminocyclopyrachlor did not improve the safety of the herbicide on western wheatgrass as occurred in the green needlegrass and intermediate wheatgrass trials (Tables 11 and 14). Aminopyralid, chlorsulfuron, and metsulfuron applied alone resulted in 10% or less crop injury.

Western wheatgrass production 14 MAS was negatively impacted by the use of aminocyclopyrachlor alone or in combination with chlorsulfuron (Table 18). Western wheatgrass biomass decreased from 560 to 0 kg ha^{-1} as aminocyclopyrachlor rate increased from 91 to 329 g ha^{-1}. Similarly, as aminocyclopyrachlor plus chlorsulfuron rates increased from 112 + 42 g ha^{-1} to 329 + 133 g ha^{-1} crop production decreased from 1520 to 0 kg ha^{-1}. The addition of 2,4-D or metsulfuron to aminocyclopyrachlor had no effect on western wheatgrass production. Grass and broadleaf weed biomass was not affected by herbicide treatment when harvested 14 MAS (Table 18), although visual evaluations made in 2010 indicated aminocyclopyrachlor treatments provided excellent grass and broadleaf weed control (data not shown). Weed biomass was probably influenced by a large infestation of foxtail barley (*Hordeum jubatum* L.) and curly dock (*Rumex crispus* L.) which appeared during the wet spring of 2011 prior to harvest.

Western wheatgrass injury was observed as early as 2 WAT in 2011 when aminocyclopyrachlor was applied alone at 91 to 329 g ha^{-1}, and increased to 58% by 8 WAT (Table 19). As observed in 2010, western wheatgrass injury was unchanged when 2,4-D, chlorsulfuron, or metsulfuron were applied with aminocyclopyrachlor compared to the corresponding rate of aminocyclopyrachlor applied alone. Crop injury was lowest when aminopyralid, chlorsulfuron, or metsulfuron were applied alone, and averaged only 22% 8 WAT.

Table 17. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on June 21, 2010 to western wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	1	35	62	78
Aminocyclopyrachlor	112	2	57	77	93
Aminocyclopyrachlor	168	0	35	93	96
Aminocyclopyrachlor	329	1	38	99	100
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	37	63	80
Aminocyclopyrachlor + chlorsulfuron	112 + 42	3	50	92	99
Aminocyclopyrachlor + chlorsulfuron	168 + 63	1	59	96	100
Aminocyclopyrachlor + chlorsulfuron	329 + 133	3	65	95	100
Aminocyclopyrachlor + metsulfuron	91 + 14	2	45	68	80
Chlorsulfuron	42	0	7	0	2
Chlorsulfuron	63	0	3	3	3
Chlorsulfuron	133	0	10	7	8
Metsulfuron	14	0	10	10	10
Aminopyralid[b]	126	0	0	3	7
Control	...	0	0	0	0
LSD (0.05)		NS	30	33	24

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 18. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on western wheatgrass (WWG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	WWG	GW	BW
	— g ai ha^{-1} —	kg ha^{-1}		
Aminocyclopyrachlor	91	560	870	420
Aminocyclopyrachlor	112	120	710	580
Aminocyclopyrachlor	168	180	355	910
Aminocyclopyrachlor	329	0	280	385
Aminocyclopyrachlor + 2,4-D amine	91 + 742	1245	440	150
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1520	110	255
Aminocyclopyrachlor + chlorsulfuron	168 + 63	200	575	305
Aminocyclopyrachlor + chlorsulfuron	329 + 133	0	1150	10
Aminocyclopyrachlor + metsulfuron	91 + 14	1530	370	180
Chlorsulfuron	42	1015	290	470
Chlorsulfuron	63	1320	215	635
Chlorsulfuron	133	145	550	315
Metsulfuron	14	705	720	400
Aminopyralid[b]	126	1270	570	415
Control	...	1090	800	990
LSD (0.05)		965	NS	NS

---

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 19. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 18, 2011 to western wheatgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	32	30	52	55
Aminocyclopyrachlor	112	42	39	53	53
Aminocyclopyrachlor	168	13	10	32	40
Aminocyclopyrachlor	329	73	63	73	83
Aminocyclopyrachlor + 2,4-D amine	91 + 742	27	27	40	43
Aminocyclopyrachlor + chlorsulfuron	112 + 42	37	43	47	62
Aminocyclopyrachlor + chlorsulfuron	168 + 63	43	52	57	63
Aminocyclopyrachlor + chlorsulfuron	329 + 133	50	47	63	73
Aminocyclopyrachlor + metsulfuron	91 + 14	22	17	20	35
Chlorsulfuron	42	3	3	12	10
Chlorsulfuron	63	25	25	32	30
Chlorsulfuron	133	3	3	5	5
Metsulfuron	14	12	12	30	27
Aminopyralid[b]	126	7	23	27	25
Control	...	0	0	0	0
LSD (0.05)		38	NS	38	36

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Aminocyclopyrachlor applied at 91 to 329 g ha^{-1} alone or with other herbicides resulted in severe western wheatgrass injury in both 2010 and 2011 (Tables 17 and 19). Although crop biomass 14 MAS was not always reduced by herbicide treatments, the injury observed during the growing season would not justify the use of aminocyclopyrachlor for western wheatgrass establishment.

Big Bluestem. Big bluestem injury averaged as high as 64% in the control from 4 to 8 WAT in 2010, so herbicide efficacy was difficult to evaluate (Table 20). Injury in the control was noted as weak plants and was probably due to flooding in June.

Big bluestem biomass production was low regardless of treatment, which was directly attributed to a poor initial stand (Tables 10 and 21). Aminocyclopyrachlor plus 2,4-D or plus metsulfuron increased big bluestem production to an average of 725 kg ha^{-1}, but big bluestem production was much lower than average production of 4040 kg ha^{-1} reported in Minnesota, North Dakota, and South Dakota (Madakadze 1998). In addition to poor establishment, standing water was observed in the experimental area from the spring of 2011 until grass harvest in August, and big bluestem growth appeared stunted which would have contributed to low production (personal observation).

Big bluestem injury in 2011 was minimal throughout the evaluation period (Table 22). No crop injury was observed 8 WAT when aminocyclopyrachlor was applied alone at 91 and 112 g ha^{-1}, but as rate increased to 329 g ha^{-1}, injury averaged 21%. The greatest injury occurred when aminocyclopyrachlor plus chlorsulfuron was applied at 329 + 133 g ha^{-1}, and averaged 55%.

Aminocyclopyrachlor efficacy on seedling big bluestem could not be determined due to poor grass establishment in 2010 and waterlogged conditions during the spring and summer of harvest. Big bluestem seeded in 2011 had excellent establishment, and minimal injury occurred when aminocyclopyrachlor was applied alone or with other herbicides at 91 to 168 g ha^{-1}.

Table 20. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2010 to big bluestem seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	6	19	6
Aminocyclopyrachlor	112	0	7	19	12
Aminocyclopyrachlor	168	0	19	34	15
Aminocyclopyrachlor	329	1	33	58	41
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	6	1	2
Aminocyclopyrachlor + chlorsulfuron	112 + 42	0	13	26	21
Aminocyclopyrachlor + chlorsulfuron	168 + 63	0	29	42	34
Aminocyclopyrachlor + chlorsulfuron	329 + 133	0	50	78	77
Aminocyclopyrachlor + metsulfuron	91 + 14	0	4	18	16
Chlorsulfuron	42	0	1	8	13
Chlorsulfuron	63	0	22	29	27
Chlorsulfuron	133	0	15	33	26
Metsulfuron	14	0	2	11	7
Aminopyralid[b]	126	0	9	16	9
Control	...	0	59	64	44
LSD (0.05)		NS	21	34	25

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 21. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on big bluestem (BBS), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	BBS	GW	BW
	— g ai ha^{-1} —		— kg ha^{-1} —	
Aminocyclopyrachlor	91	270	1100	425
Aminocyclopyrachlor	112	485	555	280
Aminocyclopyrachlor	168	480	950	350
Aminocyclopyrachlor	329	80	1435	425
Aminocyclopyrachlor + 2,4-D amine	91 + 742	750	590	105
Aminocyclopyrachlor + chlorsulfuron	112 + 42	140	1095	740
Aminocyclopyrachlor + chlorsulfuron	168 + 63	415	860	210
Aminocyclopyrachlor + chlorsulfuron	329 + 133	45	125	210
Aminocyclopyrachlor + metsulfuron	91 + 14	700	870	670
Chlorsulfuron	42	275	200	1105
Chlorsulfuron	63	175	155	1285
Chlorsulfuron	133	45	95	1885
Metsulfuron	14	330	235	990
Aminopyralid[b]	126	455	150	760
Control	...	155	185	1440
LSD (0.05)		420	595	665

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 22. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2011 to big bluestem seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	0	0	0
Aminocyclopyrachlor	112	1	0	0	0
Aminocyclopyrachlor	168	0	0	5	4
Aminocyclopyrachlor	329	0	8	19	21
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	0	0	0
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1	15	11	11
Aminocyclopyrachlor + chlorsulfuron	168 + 63	0	11	20	24
Aminocyclopyrachlor + chlorsulfuron	329 + 133	5	44	54	55
Aminocyclopyrachlor + metsulfuron	91 + 14	1	5	11	33
Chlorsulfuron	42	2	5	10	6
Chlorsulfuron	63	3	6	15	14
Chlorsulfuron	133	6	13	20	18
Metsulfuron	14	3	8	6	5
Aminopyralid[b]	126	0	0	0	0
Control	...	0	0	0	0
LSD (0.05)		3	11	12	21

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Sideoats Grama. Minimal sideoats grama injury was observed in 2010 when aminocyclopyrachlor was applied alone or with 2,4-D or metsulfuron (Table 23). Sideoats grama injury 8 WAT was greater when aminocyclopyrachlor plus chlorsulfuron was applied in combination, and averaged 67% compared to aminocyclopyrachlor alone which averaged 15%. Crop injury increased from 47 to 81% as aminocyclopyrachlor plus chlorsulfuron rate increased from 112 + 42 g ha^{-1} to 329 + 133 g ha^{-1}.

Sideoats grama biomass harvested 14 MAS was not affected by herbicide treatments applied in 2010 (Table 24). Crop production averaged only 68 kg ha^{-1} across all treatments, and was much less than average production of 2525 kg ha^{-1} reported in northern states (USDA-NRCS 1977). Inadequate sideoats grama biomass was probably severely impacted by poor establishment (Table 10) and water logged conditions prior to harvest as previously described for big bluestem.

Sideoats grama injury was less than 14% in 2011, regardless of herbicide treatment (Table 25). Sideoats grama was not injured by aminocyclopyrachlor applied alone or with 2,4-D or metsulfuron. When aminocyclopyrachlor was applied with chlorsulfuron sideoats grama injury 8 WAT averaged 10% which was considered acceptable.

Sideoats grama was tolerant of aminocyclopyrachlor applied at 91 to 168 g ha^{-1} alone or with 2,4-D, or metsulfuron in both 2010 and 2011. These results indicate aminocyclopyrachlor could be useful for sideoats grama establishment; however, biomass production 14 MAS was inadequate due to poor establishment and flooding.

Switchgrass. Switchgrass was tolerant of aminocyclopyrachlor applied at 91 to 168 g ha^{-1} alone or with 2,4-D, chlorsulfuron, or metsulfuron with an average of 12% injury 8 WAT (Table 26). When aminocyclopyrachlor rate was increased to 329 g ha^{-1} switchgrass injury increased

Table 23. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 12, 2010 to sideoats grama seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	1	2	1
Aminocyclopyrachlor	112	1	1	1	3
Aminocyclopyrachlor	168	0	3	0	8
Aminocyclopyrachlor	329	1	9	34	34
Aminocyclopyrachlor + 2,4-D amine	91 + 742	3	0	2	0
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1	5	28	47
Aminocyclopyrachlor + chlorsulfuron	168 + 63	1	6	35	74
Aminocyclopyrachlor + chlorsulfuron	329 + 133	6	20	63	81
Aminocyclopyrachlor + metsulfuron	91 + 14	0	1	2	3
Chlorsulfuron	42	0	2	4	4
Chlorsulfuron	63	0	2	11	19
Chlorsulfuron	133	0	4	9	21
Metsulfuron	14	0	0	3	0
Aminopyralid[b]	126	0	0	0	0
Control	...	0	0	3	1
LSD (0.05)		3	8	19	27

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 24. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on sideoats grama (SOG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	SOG	GW	BW
	— g ai ha^{-1} —		kg ha^{-1}	
Aminocyclopyrachlor	91	10	770	455
Aminocyclopyrachlor	112	20	1025	75
Aminocyclopyrachlor	168	95	660	140
Aminocyclopyrachlor	329	40	865	240
Aminocyclopyrachlor + 2,4-D amine	91 + 742	230	1215	215
Aminocyclopyrachlor + chlorsulfuron	112 + 42	35	605	680
Aminocyclopyrachlor + chlorsulfuron	168 + 63	35	610	480
Aminocyclopyrachlor + chlorsulfuron	329 + 133	155	15	0
Aminocyclopyrachlor + metsulfuron	91 + 14	38	840	185
Chlorsulfuron	42	0	290	875
Chlorsulfuron	63	10	235	1130
Chlorsulfuron	133	0	100	1155
Metsulfuron	14	30	405	805
Aminopyralid[b]	126	40	420	850
Control	...	285	605	1080
LSD (0.05)		NS	570	480

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 25. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 18, 2011 to sideoats grama seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	1	0	1	1
Aminocyclopyrachlor	112	0	0	1	1
Aminocyclopyrachlor	168	3	0	0	0
Aminocyclopyrachlor	329	4	1	3	1
Aminocyclopyrachlor + 2,4-D amine	91 + 742	3	0	0	0
Aminocyclopyrachlor + chlorsulfuron	112 + 42	5	9	14	13
Aminocyclopyrachlor + chlorsulfuron	168 + 63	3	4	6	3
Aminocyclopyrachlor + chlorsulfuron	329 + 133	7	19	26	14
Aminocyclopyrachlor + metsulfuron	91 + 14	1	0	1	0
Chlorsulfuron	42	0	0	3	0
Chlorsulfuron	63	1	4	3	3
Chlorsulfuron	133	1	10	11	10
Metsulfuron	14	1	0	0	0
Aminopyralid[b]	126	0	0	0	1
Control	...	0	0	0	0
LSD (0.05)		4	8	9	7

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 26. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2010 to switchgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	0	6	4
Aminocyclopyrachlor	112	0	8	18	9
Aminocyclopyrachlor	168	1	11	33	13
Aminocyclopyrachlor	329	2	41	75	83
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	2	13	5
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1	6	26	15
Aminocyclopyrachlor + chlorsulfuron	168 + 63	0	20	38	33
Aminocyclopyrachlor + chlorsulfuron	329 + 133	4	40	80	78
Aminocyclopyrachlor + metsulfuron	91 + 14	0	4	15	6
Chlorsulfuron	42	0	1	6	7
Chlorsulfuron	63	0	3	6	10
Chlorsulfuron	133	1	10	14	9
Metsulfuron	14	0	1	4	6
Aminopyralid[b]	126	0	0	3	2
Control	...	0	5	5	2
LSD (0.05)		1	11	15	10

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

substantially to 83% by 8 WAT. Similarly, as aminocyclopyrachlor plus chlorsulfuron rate increased from 112 + 42 g ha^{-1} to 329 + 133 g ha^{-1} crop injury 8 WAT increased from 15 to 78%, respectively. Switchgrass injury was unchanged when aminocyclopyrachlor plus 2,4-D or metsulfuron was applied, compared to aminocyclopyrachlor alone at 91 g ha^{-1}.

Switchgrass biomass harvested 14 MAS was much lower than the average production of 6720 kg ha^{-1} reported in North Dakota (Berdahl et al. 2005) (Table 27). The only treatment that provided greater switchgrass production than the control was aminocyclopyrachlor plus chlorsulfuron applied at 112 + 42 g ha^{-1} which averaged 1365 kg ha^{-1}. Even though switchgrass injury was low in 2010 (Table 26), biomass production 14 MAS was inadequate and probably the result of poor establishment in 2010 and wet conditions prior to harvest as described for big bluestem.

Aminocyclopyrachlor applied in 2011 resulted in an average of 23% switchgrass injury and was similar to the average of 27% observed in 2010 (Tables 26 and 28). Switchgrass injury 8 WAT increased from 3 to 49% as aminocyclopyrachlor rate increased from 91 to 329 g ha^{-1}. The combination of aminocyclopyrachlor plus chlorsulfuron applied at 329 + 133 g ha^{-1} increased injury to 71%. Aminopyralid, chlorsulfuron, and metsulfuron applied alone resulted in 23% or less crop injury.

Switchgrass injury observed in 2010 and 2011 was considered acceptable when aminocyclopyrachlor was applied at 91 to 168 g ha^{-1} alone or with 2,4-D, chlorsulfuron, or metsulfuron. Unfortunately, switchgrass harvested 14 MAS did not produce adequate biomass, and was not useful for the evaluation of aminocyclopyrachlor in switchgrass establishment. Since stand establishment in 2011 was excellent, harvest in 2012 could provide a better estimate of the impact aminocyclopyrachlor had on biomass production.

Table 27. Effect of aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on switchgrass (SG), grass weed (GW), and broadleaf weed (BW) production 14 mo after seeding near Fargo, North Dakota.

Treatment	Rate	SG	GW	BW
	— g ai ha^{-1} —	kg ha^{-1}		
Aminocyclopyrachlor	91	830	655	110
Aminocyclopyrachlor	112	975	1280	30
Aminocyclopyrachlor	168	1075	1140	55
Aminocyclopyrachlor	329	480	400	70
Aminocyclopyrachlor + 2,4-D amine	91 + 742	670	1225	75
Aminocyclopyrachlor + chlorsulfuron	112 + 42	1365	1255	90
Aminocyclopyrachlor + chlorsulfuron	168 + 63	905	1210	80
Aminocyclopyrachlor + chlorsulfuron	329 + 133	175	305	45
Aminocyclopyrachlor + metsulfuron	91 + 14	1130	370	125
Chlorsulfuron	42	450	575	580
Chlorsulfuron	63	520	510	910
Chlorsulfuron	133	345	405	1185
Metsulfuron	14	480	570	185
Aminopyralid[b]	126	995	365	185
Control	...	685	710	140
LSD (0.05)		495	495	230

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

Table 28. Aminocyclopyrachlor applied alone or with either 2,4-D, chlorsulfuron, or metsulfuron on July 21, 2011 to switchgrass seedlings 4 weeks after emergence near Fargo, North Dakota.

		Weeks after treatment			
Treatment[a]	Rate	2	4	6	8
	— g ai ha^{-1} —	% injury			
Aminocyclopyrachlor	91	0	0	0	3
Aminocyclopyrachlor	112	0	3	6	8
Aminocyclopyrachlor	168	3	20	29	33
Aminocyclopyrachlor	329	8	18	36	49
Aminocyclopyrachlor + 2,4-D amine	91 + 742	0	1	0	0
Aminocyclopyrachlor + chlorsulfuron	112 + 42	6	17	20	23
Aminocyclopyrachlor + chlorsulfuron	168 + 63	14	28	33	35
Aminocyclopyrachlor + chlorsulfuron	329 + 133	19	36	58	71
Aminocyclopyrachlor + metsulfuron	91 + 14	0	9	10	11
Chlorsulfuron	42	0	5	9	9
Chlorsulfuron	63	4	13	18	23
Chlorsulfuron	133	3	15	19	21
Metsulfuron	14	0	4	8	8
Aminopyralid[b]	126	0	1	1	4
Control	...	0	0	0	0
LSD (0.05)		10	17	19	20

[a] All treatments were applied with 0.25% v/v nonionic surfactant, Induce®, by Helena Chemical Company, 225 Shilling Boulevard, Suite 300, Collierville, TN 38017.

[b] Commercial formulation, Milestone®, by Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268

SUMMARY

A single herbicide that provides long-term control of multiple weed species at low use rates while safe to desired species would be ideal for land managers. Broad spectrum weed control reduces the need to tank-mix herbicides, and a low application rate makes field use and pesticide storage simpler. The efficacy of aminocyclopyrachlor on yellow toadflax and absinth wormwood was similar or better than the industry standard comparisons. Aminocyclopyrachlor applied at rates as low as 147 g ha^{-1} provided excellent long-term control of yellow toadflax treated in the flowering growth stage, although was not effective when applied during the fall vegetative growth stage. Additionally, aminocyclopyrachlor applied at 140 g ha^{-1} provided long-term control of absinth wormwood in both the spring vegetative growth stage, and after mowing in the fall. Aminocyclopyrachlor applied alone at 70 to 140 g ha^{-1} did not consistently control houndstongue; however, the additions of chlorsulfuron improved efficacy on this species.

Aminocyclopyrachlor will provide long-term control of several invasive weeds in non-cropland; however herbicide persistence may be unfavorable if land management changes are made. Aminocyclopyrachlor soil dissipation was influenced by moisture content, temperature, and soil type. In Fargo, Glendive-Havre, Lamoure, and Svea-Barnes soil aminocyclopyrachlor dissipation generally increased as soil moisture content increased, but had less of an impact in sandy soils. Aminocyclopyrachlor dissipation also increased as temperature increased in the four soils. The range of DT_{50} values observed was from 3 to > 112 d and the most rapid dissipation occurred in the Fargo and Svea-Barnes soils which had the highest organic matter content. Seeding sensitive pasture, range, or crop species after aminocyclopyrachlor applications should be done with caution since the herbicide has potential for long persistence in the soil.

Injury to desirable species, especially grasses, could reduce the usefulness of aminocyclopyrachlor for weed control in non-crop land. Seedling grass response to aminocyclopyrachlor applied 30 d after emergence varied among the six grass species and between experimental years. Intermediate wheatgrass was the most tolerant cool season grass species, and aminocyclopyrachlor applied at 91 to 112 g ha^{-1} alone or with chlorsulfuron or metsulfuron resulted in adequate weed control and excellent biomass production. The addition of chlorsulfuron appeared to reduce injury to both intermediate wheatgrass and green needlegrass in the first year of the study, possibly due to antagonism, although, weed control was not compromised. The efficacy of aminocyclopyrachlor on green needlegrass could not be determined due to extreme variability in the two experimental years, and western wheatgrass was severely injured by aminocyclopyrachlor.

Minimal grass injury was observed on warm season species when aminocyclopyrachlor was applied at 91 to 168 g ha^{-1} alone or with 2,4-D or metsulfuron. Aminocyclopyrachlor could be useful for weed control in seedling sideoats grama and switchgrass. The addition of chlorsulfuron appeared to increase injury to these grasses in 2010, and unfortunately the effect on biomass production could not be evaluated due to overall poor stand establishment. Additionally, aminocyclopyrachlor efficacy on big bluestem seedlings could not be determined due to injury observed in the control.

Aminocyclopyrachlor has characteristics of a very useful herbicide for weed control in pasture, range, and wild lands. Application rates as low as 147 g ha^{-1} provided excellent control of yellow toadflax and absinth wormwood. Additionally, the persistence of the herbicide in soil will lengthen the period of weed control, but could also cause increased injury to sensitive species. Follow-up research to evaluate seedling grass tolerance will improve the understanding of aminocyclopyrachlor efficacy to prairie grasses.

LITERATURE CITED

Ahmad R., T. K. James, A. Rahman, and P. T. Holland. 2003. Dissipation of the herbicide clopyralid in an allophonic soil: laboratory and field studies. J. Env. Sci. Health 38: 683-695.

Almquist, T. L. 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.

Andreas, J. E., M. Schwarzländer, and R. De Clerc-Floate. 2008. The occurrence and potential relevance of post-release, nontarget attack by *Mogulones cruciger*, a biocontrol agent for *Cynoglossum officinale* in Canada. Biol. Control 46:304-311.

Anonymous. 2009a. DuPont: DPX-MAT28 Technical Bulletin. E.I. du Pont de Nemours and Company. Available at https://lists.alaska.edu/pipermail/cnipm-l/attachments/20090310/f10dfb94/MAT28TechBulletin.pdf. Accessed: January 19, 2012.

Anonymous. 2009b. Milestone label. Dow AgroSciences. Available at: http://www.cdms.net/LDat/ld77N009.pdf. Accessed: December 15, 2011.

Anonymous. 2010. Stinger label. Dow AgroSciences. Available at: http://www.cdms.net/LDat/ld02P044.pdf. Accessed: March 13, 2012.

Asay, K. H. and R. P. Knowles. 1985. The wheatgrasses. Pages 166-176 in M. E. Heath, R. F. Barnes, and D. S. Metcalfe 4th ed. Forages: The science of grassland agriculture. Iowa: Iowa State University Press.

Bell, J. L., I. C. Burke, and T. S. Prather. 2011. Uptake, translocation and metabolism of aminocyclopyrachlor in prickly lettuce, rush skeletonweed and yellow starthistle. Pest Manag. Sci. 67:1338-1348.

Berdahl, J. D., A. B. Frank, J. M. Krupinsky, P. M. Carr, J. D. Hanson, and H. A. Johnson. 2005. Biomass yield, phenology, and survival of diverse switchgrass cultivars and experimental strains in western North Dakota. Agron. J. 97:549-555.

Berti, M., R. Nudell, R. Anifrud, D. Samarappuli, and B. Johnson. 2011. Forage resources as feedstocks for the biofuel industry in North Dakota. In Proc. European Biomass Conf. Exhib. Berlin, Germany.

Borsari, B. and I. Onwueme. 2008. A new lease on life for marginal farmland: convergence of prairie restoration with biofuel production. Modena, Italy: 16th IFOAM Organic World Congress. Available at http://www.winona.edu/green/BorsariIFOAMpaperTemplated_2008__Oct_2_edit.pdf. Accessed: May 4, 2010.

Buhler, D. D., D. A. Netzer, D. E. Riemenschneider, and R. G. Hartzler. 1998. Weed management in short rotation poplar and herbaceous perennial crops grown for biofuel production. Biomass Bioenergy 14:385-394.

Bukun, B., T. A. Gains, S. J. Nissen, P. Westra, G. Brunk, D. L. Shaner, B. B. Sleugh, and V. F. Peterson. 2009. Aminopyralid and clopyralid absorption and translocation in Canada thistle (*Cirsium arvense*). Weed Sci. 57:10-15.

Bukun, B. R., B. Lindenmayer, S. J. Nissen, P. Westra, D. L. Shaner, and G. Brunk. 2010. Absorption and translocation of aminocyclopyrachlor and aminocyclopyrachlor methyl ester in Canada thistle (*Cirsium arvense*). Weed Sci. 58:96-102.

Canode, C. L. and W. C. Robocker. 1970. Selective weed control in seedling cool-season grasses. Weed Sci. 18:288-291.

ChemSpider. 2011. The free chemical database. http://www.chemspider.com. Accessed: October 10, 2011.

Claus, J., R. Turner, J. Meredith, M. Holliday, C. S. Williams. 2010. Aminocyclopyrachlor development and registration update. Denver, CO: Weed Sci. Soc. Am. Abstr. O-303. Available at https://srm.conference-services.net/programme.asp?conferenceID=1756&action=prog_list&session=7601. Accessed: May 4, 2010.

Coyne, M. S. and J. A. Thompson. 2006. Math for Soil Scientists. Canada: Thomson Delmar Learning. pp. 53-62.

De Clerck-Floate, R. and V. Miller. 2002. Overwintering mortality of and host attack by the stem-boring weevil, *Mecinus janthinus* Germar, on Dalmatian toadflax [*Linaria dalmatica* (L.) Mill.] in western Canada. Biol. Control 24:65-74.

De Clerck-Floate, R. A. and M. Schwarzländer. 2002. Host specificity of *Mongulones cruciger* (Coleoptera: Curculionidae), a biocontrol agent for houndsontgue (*Cynoglossum officinale*), with emphasis on testing of native north American boraginaceae. Biocontrol Sci. Tech. 12:293-306.

De Clerck-Floate, R. A., B. Wikeem, and R. S. Bourchier. 2005. Early establishment and dispersal of the weevil, *Mogulones crucier* (Coleoptera: Curculionidae) for biological control of houndstongue (*Cynoglossum officinale*) in British Columbia, Canada. Biocontrol Sci. Tech. 15:173-190.

Dickerson, J. R. and P. K. Fay. 1982. Biology and control of houndstongue (*Cynoglossum officinale*). Proc. West. Soc. Weed Sci. 35:83-85.

Douglass, C. H., J. D. Vassios, M. Bridges, R. B. Lindenmayer, K. Lair, and S. J. Nissen. 2009. Susceptibility of restoration grass species to aminocyclopyrachlor and aminopyralid. Proc. West. Soc. Weed Sci. 62:45.

Douglass, C., J. D. Vassios, S. Nissen, and V. F. Peterson. 2011. Rangeland grass species tolerance to pre-plant applications of aminopyralid and aminocyclopyrachlor. Proc. West. Soc. Weed Sci. 64:63.

Eberle, D. O. and H. R. Gerber. 1976. Comparative studies of instrumental and bioassay methods for the analysis of herbicide residues. Arch. Environ. Contam. Toxicol. 4:101-118.

Edwards, R., M. T. Edwards, and K. G. Beck. 2010. The effects of aminocyclopyrachlor on native and non-native prairie species. Denver, CO: Weed Sci. Soc. Am. Abstr. O-210. Available at https://srm.conference-services.net/programme.asp?conferenceID=1756& action=prog_list& session=7580. Accessed: May 4, 2010.

Enloe, S. F., R. G. Lym, R. Wilson, P. Westra, S. Nissen, G. Beck, M. Moechnig, V. Peterson, R. A. Masters, and M. Halstvedt. 2007. Canada thistle (*Cirsium arvense*) control with aminopyralid in range, pasture, and noncrop areas. Weed Technol. 21:890-894.

[EPA] Environmental Protection Agency. 2010. Registration of the new active ingredient aminocyclopyrachlor for use on non-crop areas, sod farms, turf, and residential lawns. Available at http://www.epa.gov/pesticides/chemical/pesticideregistrations/aminocyclopyrachlor.html. Accessed: October 24, 2011.

[EPA] Environmental Protection Agency. 2011. EPA Issues Stop Sale Order to DuPont on Sale and Distribution of Imprelis Herbicide. Available at http://yosemite.epa.gov/opa/admpress.nsf/eeffe922a687433c85257359003f5340/284e7190e1187415852578e9005e49c6!OpenDocument. Accessed: March 15, 2012.

Finkelstein, B. L., G. R. Armel, S. A. Bolgunas, D. A. Clark, J. S. Claus, R. J. Crosswicks, C. M. Hirata, G. J. Hollingshaus, M. K. Koeppe, P. L. Rardon, V. A. Wittenbach, and M. D. Woodward. 2008. Discovery of aminocyclopyrachlor (proposed common name) (DPX-MAT28): a new broad-spectrum auxinic herbicide. Philadelphia, PA: ACS National Meeting Abst. AGRO 19. Available at http://oasys2.confex.com/acs/236nm/techprogram. Accessed: November 23, 2011.

Franzluebbers, A. J. 1999. Microbial activity in response to water-filled pore space of variably eroded sourthern Piedmont soils. Appl. Soil Ecol. 11:91-101.

Gillaspy, G., H. Ben-David, and W. Gruissem. 1993. Fruits: a developmental perspective. Plant Cell 5:1439-1451.

Gillespie, G. R. and J. D. Nalewaja. 1989. Wheat (*Triticum aestivum*) response to triallate plus chlorsulfuron. Weed Technol. 3:20-23.

Goetz, H. 1969. Composition and yields of native grassland sites fertilized at different rates of nitrogen. J. Range Manage. 22:384-390.

Gould, F. W. 1959. Notes on apomixes in sideoats grama. J. Range Manage. 12:25-28.

Green, R. E. and S. R. Obien. 1969. Herbicide equilibrium in soils in relation to soil water content. Weed Sci. 17:514-519.

Grover, R. 1966. Influence of organic matter, texture, and available water on the toxicity of simazine in soil. Weeds 14:148-151.

Guenzi W. D. and W. E. Beard. 1976. Picloram degradation in soils as influenced by soil water content and temperature. J. Environ. Qual. 5:189-192.

Hall, K. E., J. R. George, and R. R. Riedl. 1982. Herbage dry matter yields of switchgrass, big bluestem, and indiangrass with N fertilization. Agron. J. 74:47-51.

Harlan, J. R. 1949. Apomixis in side-oats grama. Am. J. Bot. 36:495-499.

Harris, P. 1961. Control of toadflax by *Brachypterolus pulicarius* (L.) (Coleoptera: Nitidulidae) and *Gymnaetron antirrhini* (Payk.) (Coleoptera: Curculionidae) in Canada. Can. Entomol. 93:977-981.

Hellerstein, D. and S. Malcolm. 2011. Economic Research Service, U.S. Department of Agriculture. The influence of rising commodity prices on the conservation reserve program. Economic Research Report Number 110. Available at http://www.ers.usda.gov/Publications/ERR110/ERR110.pdf. Accessed: January 19, 2012.

Hendrickson, J., J. Berdahl, M. Liebig, and W. Duckwitz. 2007. Manifest: the planned release of a new intermediate wheatgrass cultivar. Available at http://www.plantmaterials.nrcs.usda.gov/pubs/ndpmcpo7437.pdf. Accessed: December 21, 2011.

Hoefing, J. L. and B. M. Jenks. 2010. Yellow toadflax control in rangeland with DPX-MAT28. Proc. N. Cent. Weed Sci. Soc. 65:21.

Kinch, R. C. and L. E. Wiesner. 1963. Seed quality in green needlegrass. J. Range Mange. 16:187-190.

Knight, A. P, C. V. Kimberling, F. R. Stermitz, and M. R. Roby. 1984. *Cynoglossum officinale* (hound’s-tongue) – a cause of pyrrolizidine alkaloid poisoning in horses. J. Amer. Vet. Med. Assoc. 185:647-650.

Kniss, A. R. and D. J. Lyon. 2011. Winter wheat response to preplant applications of aminocyclopyrachlor. Weed Technol. 25:51-57.

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.

Larson, K. L. and J. F. Carter. 1970. Lodorm green needlegrass – A new variety for revegetating rangeland. North Dakota Farm Research 27: 6-8. Available at http://library.ndsu.edu/tools/dspace/load/?file=/repository/bitstream/handle/10365/8958/farm_27_03_03.pdf?sequence=1. Accessed: December 19, 2011.

Lauriault, L. M., R. E. Kirksey, and D. M. VanLeeuwen. 2005. Performance of perennial cool-season forage grasses in diverse soil moisture environments, southern High Plains, USA. Crop Sci. 45:909-915.

Lawrence, T. 1956. Emergence of intermediate wheatgrass lines from five depths of seeding. Can. J. Plant Sci. 37:215-219.

Lee, D., V. N. Owens, A. Boe, and B. Koo. 2009. Biomass and seed yield of big bluestem, switchgrass, and intermediate wheatgrass in response to manure and harvest timing at two topographic positions. GCB Bioenergy 1:171-179.

Lee, D., S. A. Senseman, J. H. O'Barr, J. M. Chandler, L. J. Krutz, G. N. McCauley, Y. I. Kuk. 2004. Soil characteristics and water potential effects on plant-available clomazone in rice. Weed Sci. 52:310-318.

Lin, Y. and S. Tanaka. 2006. Ethanol fermentation from biomass resources: current state and prospects. Appl. Microbiol. Biotechnol. 69:627-642.

Linn, D. M. and J. W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Am. J. 48:1267-1272.

Lindenmayer, B., P. Westra, G. Brunk, S. Nissen, and D. Shaner. 2010. Field and laboratory studies with aminocyclopyrachlor (DPX-MAT28). Denver, CO: Weed Sci. Soc. Am. Abstr. O- 281. Available at https://srm.conference-services.net/programme.asp?conferenceID=1756&action=prog_list&session=759. Accessed: May 4, 2010.

Lindenmayer, B., P. Westra, S. Nissen, and D. Shaner. 2011. Characterization of aminocyclopyrachlor, aminopyralid, and clopyralid soil activity. Proc. West. Soc. Weed Sci. 64:64.

Lym, R. G. 2007. Control of yellow toadflax with various herbicides and application timings in North Dakota. Res. Prog. Rep. West. Soc. Weed Sci. Pp. 22-24.

Lym, R. G. 2008 Maximum use rates of aminopyralid for control of invasive species. Res. Prog. Rep. West. Soc. Weed Sci. Pp. 13-16.

Lym, R. G. 2009. Evaluation of DPX KJM44-062 for weed control in pasture and rangeland. Res. Prog. Rep. West. Soc. Weed Sci. Pp. 9-11.

Lym, R. G. 2010. Aminopyralid applied alone or in combination with metsulfuron or picloram for absinth wormwood control. Res. Prog. Rep. West. Soc. Weed Sci. Pp. 34-36.

Lym, R. G. and C. G. Messersmith. 1985. Leafy spurge control with herbicides in North Dakota: 20-year summary. J. Range Manage. 38:149-154.

Lym, R. G. and C. G. Messersmith. 1986. Absinth wormwood control with clopyralid and picloram. Res. Prog. Rep. West. Soc. Weed Sci. p. 8.

Lym, R. G. and C. G. Messersmith. 1988. Survey for picloram in North Dakota groundwater. Weed Technol. 2:217-222.

Lym, R. G. and L. W. Samuel. 2006. Control of invasive weeds with aminopyralid in North Dakota. Res. Prog. Rep. West. Soc. Weed Sci. pp. 30-35.

Madakadze, I. C., B. E. Coulman, A. R. Mcelroy, K. A. Stewart, and D. L. Smith. 1998. Evaluation of selected warm-season grasses for biomass production in areas with a short growing season. Bioresource Technol. 65:1-12.

Martin, A. R., R. S. Moomaw, and K. P. Vogel. 1982. Warm season grass establishment with atrazine. Agron. J. 74:916-920.

Maw, M. G. and D. Schroeder. 1981. *Euzophora cinerosella* (Zellar) (Lep.:Pyralidae) not suitable for release to control *Artemisia absinthium* L. (Compositae) in Canada. J. Appl. Entomol. 92:178-184.

Maw, M. G., A. G. Thomas, and A. Stahevitch. 1985. The biology of Canadian weeds. 66. *Artemisia absinthium* L. Can. J. Plant Sci. 65:389-400.

McClay, A. S. and R. B. Hughes. 2007. Temperature and host-plant effects on development and population growth of *Mecinus janthinus* (Coleoptera:Curculionidae), a biological control agent for invasive *Linaria* spp. Biol. Control 40:405-410.

McCullough, P. E., S. E. Hart, J. T. Brosnan, and G. K. Breeden. 2011. Aminocyclopyrachlor enhances fenoxaprop efficacy for smooth crabgrass control. Weed Technol. 25:506-510.

McLaughlin, S. B., R. Samson, D. Bransby, and A. Wiselogel. 1996. Evaluating physical, chemical, and energetic properties of perennial grasses as biofuels. Nashville, TN. The Seventh National Bioenergy Conference. Available at http://www.reap-canada.com/online_library/feedstock_biomass/Evaluating%20physical,%20chemical,%20and%20energetic%20properties...%20%20(McLaughlin%20et%20al.,%201996).pdf. Accessed: January 3, 2012.

Meikle, R. W., C. R. Youngson, R. T. Hedlund, C. A. I. Goring, J. W. Hamaker, W. W. Addington. 1973. Measurement and prediction of picloram disappearance rates from soil. Weed Sci. 21:549-555.

Mikkelson, J. R. 2010. Effect of aminopyralid on crop rotations and native forbs. M.S. thesis. North Dakota State University, Fargo, ND. 63 p.

Mikkelson, J. R. and R. G. Lym. 2011. Aminopyralid soil residues affect crop rotation in North Dakota soils. Weed Technol. 25:422-429.

Mitich, L. W. 1993. Yellow toadflax. Weed Technol. 7:791-793.

Moechnig, M. J., D. L. Deneke, J. K. Alms, and D. A. Vos. 2009. Absinth wormwood control programs that include mowing, fertilization, or herbicides. Proc. N. Cent. Weed Sci. Soc. 64:57.

Mooney, D. F., R. K. Roberts, B. C. English, D. D. Tyler, and J. A. Larson. 2009. Yield and breakeven price of ‘Alamo’ switchgrass for biofuels in Tennessee. Agron. J. 101:1234-1242.

Morishita, D. W. 1991. Dalmatian toadflax, yellow toadflax, black henbane, and tansymustard: 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.

Moser, L. E. and K. P. Vogel. 2005. Switchgrass, bigbluestem, and indiangrass. Pages 409-420 in R. F. Barnes, D. A. Miller, and C. J. Nelson 5th ed. Forages: An Introduction to Grassland Agriculture. Iowa: Iowa State University Press.

Moses, A. J. 1985. Factors affecting *Artemisia absinthium* control. Ph.D. thesis. North Dakota State University, Fargo, ND. 85 p.

Nadeau, L. B., J. R. King, and K. N. Harker. 1992. Comparison of growth of seedling and plants grown from root pieces of yellow toadflax (*Linaria vulgaris*). Weed Sci. 40:43-47.

Nanita, S. C., A. M. Pentz, J. Grant, E. Vogl, T. J. Devine, and R. M. Henze. 2009. Mass spectrometric assessment and analytical methods for quantitation of the new herbicide aminocyclopyrachlor and its methyl analogue in soil and water. Anal. Chem. 81:797-808.

[NDAWN] North Dakota Agricultural Weather Network. 2012. Daily Data Table. Available at http://ndawn.ndsu.nodak.edu/daily-table-form.html. Accessed: February 23, 2012.

[NDDOA] North Dakota Department of Agriculture. 2011. Noxious weeds. Available at http://www.nd.gov/ndda/program/noxious-weeds. Accessed: November 25, 2011.

Nowierski, R. M. 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.

Ogle, D. G., L. St. John, and K. B. Jensen. 2003. Intermediate wheatgrass. Available at ftp://ftp-fc.sc.egov.usda.gov/ID/programs/plant/wheatgrass.pdf. Accessed: December 29, 2011.

O’Sullivan, A. and Kirkland, K. J. 1984. Chlorsulfuron reduced control of wild oat (*Avena fatua*) with diclofop, difenzoquat, and flamprop. Weed Sci. 32:285-289.

Painter, E. L. and J. K. Detling. 1981. Effects of defoliation on net photosynthesis and regrowth of western wheatgrass. J. Range Manage. 34:68-71.

Peters, T. J., R. S. Moomaw, and A. R. Martin. 1989. Herbicides for postemergence control of annual grass weeds in seedling forage grasses. Weed Sci. 37:375-379.

Pfister, J. A., R. J. Molyneux, and D. C. Baker. 1992. Pyrrolizidine alkaloid content of houndstongue (*Cynoglossum officinale* L.). J. Range Manage. 45:254-256.

Propheter, J. L., S. A. Staggenborg, X. Wu, and D. Wang. 2010. Performance of annual and perennial biofuel crops: yield during the first two years. Biofuels 102:806-814.

Robins, J. G. 2010. Cool-season grasses produce more total biomass across the growing season than do warm-season grasses when managed with an applied irrigation gradient. Biomass Bioenergy 34:500-505.

Rogler, G. A. 1960. Relation of seed dormancy of green needlegrass (*Stipa viridula* Trin.) to age and treatment. Agron. J. 52:467-469.

Samson, R. A. and J. A. Omielan. 1992. Switchgrass: a potential biomass energy crop for ethanol production. Windsor, Ontario: 13th N. Am. Prairie Conf. Available at http://images.library.wisc.edu/EcoNatRes/EFacs/NAPC/NAPC13/reference/econatres.napc13.rsamson.pdf. Accessed: May 4, 2010.

Saner, M. A., D. R. Clements, M. A. Hall, D. J. Doohan, and C. W. Crompton. 1995. The biology of Canadian weeds. 105. *Linaria vulgaris* Mill. Can. J. Plant Sci. 75:525-537.

Schaaf, H. M. and G. A. Rogler. 1960. Selecting green needlegrass for low-dormancy seed. Agron. J. 52:704-707.

Schmer, M., K. P. Vogel, R. B. Mitchell, L. E. Moser, and K. M. Eskridge. 2006. Establishment stand thresholds for switchgrass grown as a bioenergy crop. Crop Sci. 46:157-161.

Sebastian, J. R. and K. G. Beck. 2008. Absinth wormwood control in Colorado. Res. Prog. Rep. West. Soc. Weed Sci. pp. 19-22.

Sebastian, J. R. and K. G. Beck. 2009. Effective herbicides for controlling yellow toadflax? Proc. West. Soc. Weed Sci. 62:8.

Sebastian, J. R. and K. G. Beck. 2010a. Houndstongue control in Colorado. Res. Prog. Rep. West. Soc. Weed Sci. pp. 18-19.

Sebastian, J. R. and K. G. Beck. 2010b. Yellow toadflax control in Colorado. Res. Prog. Rep. West. Soc. Weed Sci. pp. 30- 31.

Selleck, G. W. 1964. Absinth wormwood: its control in Saskatchewan. Weeds. 12:95-96.

Selleck, G. W. and R. T. Coupland. 1961. Studies in the life history of *Artemisia absinthium*. Weeds. 9:485-490.

Senseman, S. A. 2007a. Aminopyralid. Pages 331-332 in 9th ed. Herbicide Handbook. Lawrence, KS: Weed Science Society of Americia.

Senseman, S. A. 2007b. Clopyralid. Pages 333-335 in 9th ed. Herbicide Handbook. Lawrence, KS: Weed Science Society of Americia.

Senseman, S. A. 2007c. Picloram. Pages 353-356 in 9th ed. Herbicide Handbook. Lawrence, KS: Weed Science Society of Americia.

Sexton, S., D. Zilberman, D. Rajagopal, and G. Hochman. 2009. The role of biotechnology in a sustainable biofuel future. AgBioForum 12:130-140.

Sharma, M. P., F. Y. Chang, and W. H. Vanden Born. 1971. Penetration and translocation of picloram in Canada thistle. Weed Sci. 19:349-355.

Sing, S. E., R. K. D. Peterson, D. K. Weaver, R. W. Hansen, and G. P. Markin. 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/. Accessed: December 5, 2011.

Stevens, R. and I. C. Burke. 2009. Response of rush skeletonweed to postemergence foliar vs. soil treatments of aminocyclopyrachlor, aminopyralid, and clopyralid. Proc. West. Soc. Weed Sci. 62:43.

Strachan, S. D., M. S. Casini, K. M. Heldreth, J. A. Scocas, S. J. Nissen, B. Bukun, R. B. Lindenmayer, D. L. Shaner, P. W. Westra, and G. Brunk. 2010. Vapor movement of synthetic auxin herbicides: aminocyclopyrachlor, aminocyclopyrachlor-methyl ester, dicamba, and aminopyralid. Weed Sci. 58:103-108.

Strachan, S. D., S. C. Nanita, M. Ruggiero, M. S. Casini, K. M. Heldreth, L. H. Hageman, H. A. Flanigan, N. M. Ferry, and A. M. Pentz. 2011. Correlation of chemical analysis of residual levels of aminocyclopyrachlor in soil to biological responses of alfalfa, cotton, soybean, and sunflower. Weed Technol. 25:239-244.

Taylor-Lovell, S., G. K. Sims, and L. M. Wax. 2002. Effects of moisture, temperature, and biological activity on the degradation of isoxaflutole in soil. J. Agric. Food Chem. 50: 5626-5633.

Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314:1598-1600.

Turner, R. G., J. R. Pitts, E. Hidalgo, A. J. Parsells, and R. M. Ashley. 2009. Introduction to DuPont's new aminocyclopyrachlor herbicide for vegetation management weed and brush control. Proc. West. Soc. Weed Sci. 62:43-44.

Upadhyaya, M. K. and R. S. Cranston. 1991. Distribution, biology, and control of hound's-tongue in British Columbia. Rangelands 13:103-106.

Upadhyaya, M. K., H. R. Tilsner, and M. D. Pitt. 1988. The biology of Canadian weeds. 87. *Cynoglossum officinale* L. Can. J. Plant Sci. 68:763-774.

[USDA-APHIS] U.S. Department of Agriculture. 2010. Pest alert: *Mogulones cruciger*. Animal and Plant Health Inspection Service Publ. APHIS 81-35-014. Available at http://www.aph is.usda.gov/publications/plant_health/content/printable_version/ Mogulones_Cruciger.pdf. Accessed: December 29, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 1977. 'Pierre' sideoats grama. Available at http://www.plant-materials.nrcs.usda.gov/pubs/ndpmcrbbocupierr.pdf. Accessed: December 27, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 1988. 'Rodan' western wheatgrass. Available at http://www.plant-materials.nrcs.usda.gov/pubs/ndpmcrbpasmroda.pdf. Accessed December 27, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 1990. 'Dacotah' switchgrass. Available at http://www.plant-materials.nrcs.usda.gov/pubs/ndpmcrbpavi2daco.pdf. Accessed: December 29, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 2002. Western wheatgrass. Available at http://plants.usda.gov/factsheet/pdf/fs_pasm.pdf. Accessed: December 27, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 2005a. 'Bison' big bluestem. Available at http://www.plant-materials.nrcs.usda.gov/pubs/ndpmcbr6152.pdf. Accessed: December 27, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 2005b. 'Lodorm' green needlegrass. Available at http://www.plant-materials.nrcs.usda.gov/pubs/ndpmcbr6147.pdf. Accessed: December 3, 2011.

[USDA-NRCS] U. S. Department of Agriculture. 2011. Herbaceous Vegetation Establishment Guide. Available at http://efotg.sc.egov.usda.gov//references/public/ND/Herbaceous_ Veg_Est_Guide.pdf. Accessed February 23, 2012.

[USDC-NOAA] U. S. Department of Commerce. 1981-2010. National Climatic Data Center, U.S. Monthly Climate Normals. Available at http://ggweather.com/normals/monthly.htm. Accessed: January 27, 2012.

[USDC-NOAA] U. S. Department of Commerce. 2010-2011. National Climatic Data Center, Climatological Data North Dakota. Available at http://www.rcc-acis.org/. Accessed: January 27, 2012.

[USDOE] U.S. Department of Energy. 2007. Energy Independence and Security Act of 2007. Available at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills &docid=f:h6enr.txt.pdf. Accessed: April 18, 2010.

Vassios, J., S. Nissen, C. Douglass, B. Lindenmayer, M. Bridges, P. Westra, and K. Lair. 2010a. Canada thistle (*Cirsium arvense*) control and grass tolerance using aminopyralid and aminocyclopyrachlor. Denver, CO: Weed Sci. Soc. Am. Abstr. O-222. Available at https://srm.conference-services.net/programme.asp?conferenceID=1756&action=prog_list &session=7581. Accessed: May 4, 2010.

Vassios, J. D., S. J. Nissen, J. R. Sebastian, K. George Beck, and C. H. Douglass. 2010b. Aminopyralid and aminocyclopyrachlor impacts on grass establishment. Proc. West. Soc. Weed Sci. 63:42-43.

Voigt, P. W. and R. S. MacLauchlin. 1985. Native and other western grasses. Pages 177-187 in M. E. Heath, R. F. Barnes, and D. S. Metcalfe 4th ed. Forages: The science of grassland agriculture. Iowa: Iowa State University Press.

Walker, A. 1987. Herbicide persistence in soil. Rev. Weed Sci. 3:1-17.

Wallace, J. and T. Prather. 2011. Yellow toadflax control with combinations of aminocyclopyrachlor and sulfonylureas. Res. Prog. Rep. West. Soc. Weed Sci. Pp. 13-14.

Washburn, B. E. and T. G. Barnes. 2000. Native warm-season grass and forb establishment using imazapic and 2,4-D. Native Plants J. 1:61-69.

Westra, P., B. Lindenmayer, S. Nissen, D. Shaner, T. D’Amato, and B. Goeman. 2010. Integrating aminocyclopyrachlor into weed management plans. Denver, CO: Weed Sci. Soc. Am. Abstr. O-304. Available at https://srm.conference-services.net/programme.asp? conferenceID=1756&action=prog_list&session=7601. Accessed: May 4, 2010.

Westra, P., S. Nissen, T. Gaines, B. Bekun, B. Lindenmayer, and D. Shaner. 2008a. Aminocyclopyrachlor for invasive weed management and restoration grass safety in the central great plains. Champaign, IL: North Cent. Weed Sci. Soc. Abstr. 203. Available at http://www.ncwss.org/proceed/2008/abstracts/203.pdf. Accessed: May 4, 2010.

Westra, P., R. Wilson, and M. Edwards. 2008b. Agronomic crop responses to KJM-44 herbicide. Proc. West. Soc. Weed Sci. 61:62.

White, L. M. ad J. R. Wight. 1984. Forage yield and quality of dryland grasses and legumes. J. Range Manage. 37:233-236.

Zollinger, R., M. Christoffers, G. Endres, G. Gramig, K. Howatt, B. Jenks, R. Lym, J. Stachler, A. Thostenson, and H.H. Valenti. 2011. North Dakota Weed Control Guide. North Dakota State Univ. Ext. Serv. Publ. W-253. p. 52.

Zollinger, R., M. McMullen, J. Knodel, J. Gray, D. Jantzi, G. Kimmet, K. Hagemeister, and C. Schmitt. 2008. Pesticide Use and Pest Management Practices in North Dakota. North Dakota State Univ. Ext. Serv. Publ. W-1446. p. 27.