EFFECT OF AMINOPYRALID ON CROP ROTATIONS AND NATIVE FORBS

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

MASTER OF SCIENCE

ABSTRACT

Mikkelson, Jonathan Randall; M.S.; Program of Natural Resources Management; College of Agriculture, Food Systems, and Natural Resources; North Dakota State University; April 2010. Effect of Aminopyralid on Crop Rotations and Native Forbs. Major Professor: Dr. Rodney G. Lym.

Aminopyralid often is used for invasive weed control in Conservation Reserve Program (CRP) land. As CRP land is returned to crop production, aminopyralid persistence in soil could limit future planting options. Field experiments were established near Casselton and Fargo, ND to evaluate the effect of aminopyralid soil residue on alfalfa, corn, soybean, and sunflower planted one or two growing seasons after treatment. Aminopyralid caused no injury or yield reduction to alfalfa, corn, and sunflower when seeded 20 or 23 mo after treatment (MAT) in Fargo. However, soybean yield was reduced when aminopyralid at 120 or 240 g ae/ha was fall- or spring-applied 20 or 23 months prior to seeding. In Casselton, aminopyralid applied in September caused much greater crop injury than when applied in June the year prior to planting. For example, aminopyralid at 120 g/ha applied in September caused 95, 94, and 100% injury to alfalfa, sunflower, and soybean, respectively, compared to 10, 8, and 44% injury when applied in June. Corn yield was not affected by any aminopyralid treatment when planted 8 or 11 MAT. Corn appeared to be the best cropping option for land that was recently treated with aminopyralid. The effect of temperature and moisture content on aminopyralid dissipation in four North Dakota soils was evaluated in growth chamber and greenhouse studies. Aminopyralid dissipated 2 to 8 times faster at 24 C than at 8 C and aminopyralid 50% dissipation rates (DT_{50}) ranged from 9 d in a Svea-Barnes loam at 24 C to 256 d in a Lamoure loamy sand at 8 C. Aminopyralid dissipation rates were similar in soils with moisture contents of 22.5 to 90% field capacity (FC) when incubated at 16 C and the average aminopyralid DT_{50} ranged from 66 to 200 d.

Soil conditions favorable to microbiological growth such as warm temperatures, moderate moisture contents, and high organic matter contents appeared to favor aminopyralid dissipation. In greenhouse trials, prairie forb susceptibility to aminopyralid varied by species. Azure aster, blanket flower, closed bottle gentian, purple coneflower, and showy goldenrod exhibited good tolerance to aminopyralid while great blue lobelia, harebell, prairie coneflower, and white prairie clover were sensitive.

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INTRODUCTION

Invasive weeds threaten natural ecosystems and public health and cost Americans approximately 6 billion dollars annually in control costs and lost production (Pimentel et al. 2000). One of the most problematic invasive weed species in the upper Midwest is Canada thistle [*Cirsium arvense* (L.) Scop.]. Canada thistle was one of the most common weeds on Conservation Reserve Program (CRP) land in Minnesota, found in almost three quarters of CRP fields in the state (Jewett et al. 1996). The aggressive growth characteristics of Canada thistle make the weed very difficult to control (Donald 1990). Multiple control methods have been tried, but herbicides have been the most effective method. However, the herbicides used to control noxious weeds on wild and CRP lands often have long soil residuals and negatively impact native plant populations.

Aminopyralid has been used to control Canada thistle on non-crop areas such as range, pasture, and land in the CRP (Carrithers et al. 2005). Recent high crop prices have enticed farmers to return CRP land to agricultural production (USDA-FSA 2009). However, the period that aminopyralid residue remains active in the soil must be determined before crop-specific planting recommendations can be made. Temperature and moisture may influence aminopyralid degradation rate in soil (Anonymous 2005), but the effect of these factors has not been reported.

Since Canada thistle often inhabits areas of desirable native vegetation, impacts of herbicide treatments on non-target plants must be considered. Herbicide treatments that eliminate or severely injure desirable plants can diminish ecosystem quality and may leave areas susceptible to further invasions by noxious weed species (Samuel and Lym 2008). Aminopyralid is very effective in controlling Canada thistle (Enloe et al. 2007), but more research is needed to evaluate aminopyralid efficacy on specific desirable forb species.

The objectives of this research were to determine: 1) the effect of aminopyralid soil residue on alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and sunflower (*Helianthus annuus* L.) planted 1 or 2 yr after application; 2) aminopyralid degradation rate in four North Dakota soils (clay, loam, loamy sand, and silty clay) at varying temperature and moisture levels; and 3) the susceptibility of nine native prairie forb species to aminopyralid.

LITERATURE REVIEW

Canada Thistle Control

Canada thistle infested 5.1 million ha of rangeland, pasture, and wildlands in the United States in 2003 (Lym and Duncan 2005), and is listed as a noxious weed in 32 states (USDA-NRCS 2009). Multiple control strategies including cultural, chemical, and biological have been implemented against Canada thistle, but no single treatment method eliminated this weed (Cruttwell-McFadyen 1998; Travnicek et al. 2005). Canada thistle has an extensive spreading root system with multiple adventitious buds which makes long-term control very difficult (Donald 1990). Also, Canada thistle populations often consist of many biotypes (Bodo Slotta et al. 2006) which enable the weed to invade a wide habitat range and resist multiple treatment methods.

Chemical treatment is the most efficient control method of Canada thistle in non-cropland situations because cost-effective alternatives currently are not available. Canada thistle control in rangeland and natural areas has been best accomplished by auxin-type herbicides, such as picloram, clopyralid, and aminopyralid (USDI-NPS 2007). However, high rates and repeated applications often are needed to achieve acceptable long-term Canada thistle control (Donald 1990; Lym 2008). Labeled non-cropland maximum use rates in North Dakota for aminopyralid, picloram, and clopyralid are 120 g ae/ha (240 g/ha spot treatment), 560 g ae/ha (1120 g/ha spot treatment), and 560 g ae/ha, respectively (Zollinger et al. 2010). Herbicides applied sequentially or at high rates sometimes have led to negative environmental consequences such as long-term herbicide persistence in soils (Goring et al. 1965; Herr et al. 1966), groundwater contamination (Lym and Messersmith 1988), and the elimination of desirable plant species (Ralphs 1995).

Picloram is a pyridinecarboxylic acid herbicide that effectively controls deep-rooted perennial weeds, including Canada thistle, in rangeland and wildlands (Donald 1993). Picloram is readily absorbed by foliage and roots and is translocated throughout plants in both the xylem and phloem (Sharma et al. 1971). Picloram accumulation was greatest in the meristematic regions of Canada thistle and soybean which were injured by picloram, but was evenly distributed in barley (*Hordeum vulgare* L.), which was tolerant (Sharma and Vanden Born 1973). Picloram applied at 600 g/ha or higher provided excellent Canada thistle control in rangeland and wildlands, but long soil persistence and potential injury to non-target plant species limited where the herbicide could be used (Donald 1990). Also, picloram has been labeled as a restricted-use pesticide by the EPA and cannot be applied near surface water, to areas with high water tables, or to course textured soils because of the potential to contaminate groundwater (Anonymous 2009).

Clopyralid is another herbicide in the pyridinecarboxylic acid family often used for Canada thistle control in sugarbeet (*Beta vulgaris* L.), pasture, and CRP land (Senseman 2007). Clopyralid was readily absorbed by hydroponically-grown Canada thistle, and 24% of applied ^{14}C-clopyralid was translocated to the roots within 9 d after treatment (DAT) (Turnbull and Stephenson 1985). Clopyralid at 70 to 200 g/ha effectively controlled small Canada thistle plants, but higher rates or sequential applications often were needed for long-term control (Donald 1990). Fall-applied clopyralid at 280 g/ha reduced Canada thistle root carbohydrate concentrations, and provided 92% control the following year (Wilson et al. 2006). Clopyralid reduced Canada thistle regrowth when applied to a sandy soil at 50 g/ha or greater under greenhouse conditions (Hall et al. 1985).

Aminopyralid is a relatively new pyridinecarboxylic acid herbicide developed to control invasive weeds on non-cropland areas such as pastureland, CRP land, and wildlands (Carrithers et al. 2005). Aminopyralid has many economic and environmental advantages compared to traditionally used herbicides in range and wildlife habitats. For instance, aminopyralid controlled Canada thistle and over 70 other broadleaf weed species (Sleugh et al. 2009b) at much lower use rates than picloram and clopyralid (Hare et al. 2005). Canada thistle control with aminopyralid was 90% or greater 1 yr after treatment (YAT) regardless of application rate evaluated, timing, or location in the upper midwestern United States (Enloe et al. 2007). Aminopyralid effectively controlled Canada thistle even when applied to senesced plants in late-fall after several hard frosts (Peterson et al. 2009; Sleugh et al. 2009a). Aminopyralid applied in the fall at 120 g/ha reduced Canada thistle density from an average of 15 stems/m^2 to <0.1 stem/m^2 and reduced foliar cover from 14.5% to 0.1% 10 mo after treatment (MAT) (Almquist and Lym 2010).

Aminopyralid absorption and translocation in Canada thistle was much slower and less complete than clopyralid (Bukun et al. 2009). Clopyralid absorption 8 DAT averaged 80% compared to 60% with aminopyralid while translocation from the treated leaf was 39 and 17% for clopyralid and aminopyralid, respectfully. Although clopyralid absorption and translocation was greater in Canada thistle, aminopyralid provided better efficacy at lower rates than clopyralid. The increased efficacy at much lower absorbed rates with aminopyralid indicated aminopyralid may have higher biological activity at the site of action than clopyralid.

Aminopyralid has many favorable attributes that have reduced environmental risks associated with weed control in rangeland and wildlands (Jachetta et al. 2005).

Aminopyralid is considered practically non-toxic to many important organisms that inhabit prairie ecosystems, which include mammals, birds, fish, honeybees, earthworms, and aquatic invertebrates (EPA 2005b). Aminopyralid is non-volatile and CO_2 was the only metabolite observed during degradation. Aminopyralid has no grazing restrictions for any type of livestock or wildlife (Anonymous 2008), and because of the low K_{ow}, the herbicide is not expected to accumulate in animal tissue (EPA 2005b). Aminopyralid can safely be applied to vegetation near water, making the herbicide an ideal weed control option for riparian environments (Nissen et al. 2006). Groundwater contamination risks are reduced with aminopyralid because of the small amount of product needed, the moderate field degradation rate, and the limited mobility exhibited in field studies (Anonymous 2005).

Diflufenzopyr is a semicarbazone auxin-transport inhibitor that can enhance activity of auxinic herbicides in some broadleaf plants (Grossman et al. 2002; Lym and Deibert 2005). Diflufenzopyr disrupts the polar transport of both naturally occurring and synthetic auxin compounds from the meristematic shoot and root regions of sensitive plants (Senseman 2007).

Diflufenzopyr has a short soil residual with an average half-life of 4 d and should not cause any carryover concerns (Senseman 2007). Diflufenzopyr is typically applied with auxinic herbicides in a 1:2.5 ratio (Grossman et al. 2002; Lym and Deibert 2005). While, weed control was dependent on weed species and the herbicide used in the treatment (Lym and Deibert 2005). Diflufenzopyr increased leafy spurge (*Euphorbia esula* L.) control when applied with dicamba, picloram, and quinclorac. Diflufenzopyr in combination with quinclorac or dicamba increased Canada thistle control compared to herbicides applied alone in the field. However, Canada thistle control in the greenhouse increased only when diflufenzopyr was applied with clopyralid. Aminopyralid efficacy on Canada thistle was similar whether the herbicide was applied alone or in combination with diflufenzopyr (Almquist 2008).

Pyridinecarboxylic Acid Herbicide Persistence in the Environment

Recent high crop prices have led to an increased amount of enrolled CRP land returned, or soon to be returned, to crop production (USDA-FSA 2009). There were over 14 million ha enrolled in the CRP in 2008 (USDA-FSA 2008). However, contracts for nearly 5.1 million CRP ha are set to expire between 2009 and 2011 (USDA-FSA 2009). Much of this land likely will be returned to agricultural production if crop prices remain high. Herbicides such as aminopyralid have been applied to CRP land to control invasive weeds (Carrithers et al. 2005), and aminopyralid soil persistence could limit future planting options. Aminopyralid was applied to approximately 18,000 ha of CRP land in North Dakota in 2008 (Zollinger et al. 2009). While aminopyralid is applied to foliage for optimum activity, aminopyralid also has short-term soil residual which prevents weed seedling emergence (Masters et al. 2005). Herbicide residue in the soil is desirable for weed control, but may injure or kill susceptible broadleaf crops if planted too soon after application.

The persistence, degradation, sorption, and leaching of a herbicide are important factors that influence herbicide fate in soils (Hiltbold 1974). Herbicide bioavailability, movement, and degradation are dependent on herbicide chemistry, the adsorptive qualities of the soil, and environmental factors (Helling 2005). Aminopyralid has similar chemical properties to picloram and clopyralid, and all three herbicides are members of the pyridinecarboxylic acid family (Senseman 2007). Aminopyralid, clopyralid, and picloram chemical structures differ only by an amine group or chlorine molecule on the aromatic ring (Figure 1). Little has been published about aminopyralid persistence in soil, but much is known about picloram and clopyralid.

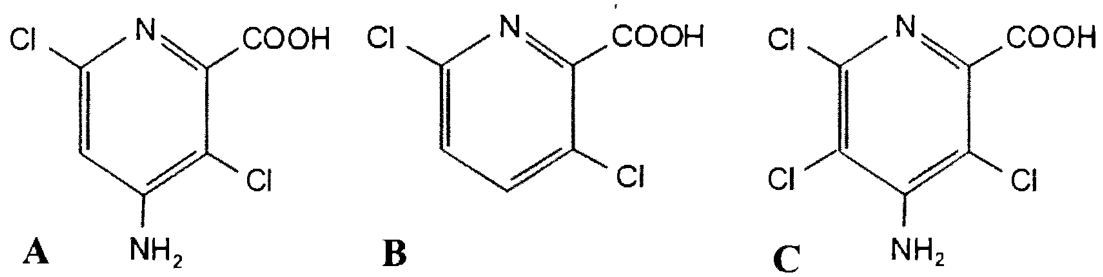

Figure 1. Chemical structures of aminopyralid (A), clopyralid (B), and picloram (C) (adapted from Durkin 2007).

Picloram and clopyralid degradation in soil was influenced by soil properties and environmental conditions (Hunter and Stobbe 1972; Mullison 1985; Pik et al. 1977). The degradation rate depended on application rate; climatic factors such as sunlight, rainfall, temperature, and moisture; and soil characteristics including texture, organic matter content, and microbial populations (Mullison 1985; Pik et al. 1977). Microbial activity was the primary pathway of picloram and clopyralid degradation in soil (Ahmad et al. 2003; Guenzi and Beard 1976; Pik et al. 1977; Youngson et al. 1967). Other factors that aided in degradation included increased soil temperature (Ahmad et al. 2003; Merkle et al. 1967; Mullison 1985; Youngson et al. 1967), increased moisture (Ahmad et al. 2003; Hunter and Strobbe 1972; Mullison 1985; Youngson et al. 1967), and increased organic matter content (Youngson et al. 1967). Picloram degradation was very slow under anaerobic conditions which can occur in compacted or waterlogged soils (Meikle et al. 1974; Mullison 1985).

Aminopyralid was biologically degraded in aerobic soils (Jachetta et al. 2005). Aminopyralid dissipation rate was dependent on soil temperature and moisture content, but several other factors may be involved (Anonymous 2005). Soil organic matter content and soil texture also could influence aminopyralid persistence due to adsorption differences across different soils. Differences in soil composition could also affect microbial populations.

Adsorption of a herbicide by mineral and organic soil colloids ultimately controls the fate of the herbicide (Helling 2005). Herbicide K_{oc} is a term most commonly used to describe how tightly a herbicide is bound to soil and accounts for soil variability. The K_{oc} for aminopyralid, clopyralid, and picloram averaged 10.8, 6, and 16 ml/g, respectively, although adsorption generally increased with time (Senseman 2007). Herbicide pK_a can be used to estimate the amount of herbicide in soil solution that exists as the parent acid or conjugate base at a certain pH. The pK_a of aminopyralid, clopyralid, and picloram are 2.6, 2.3, and 2.3, respectively. Because of their low pK_a, these herbicides exist primarily in the anionic form in most soils ($pH > 3.0$) (Helling 2005). Herbicides with low pK_a and K_{oc} values are weakly adsorbed to soil which results in both increased phytotoxicity and leaching potential.

The half-life, or DT_{50}, of a herbicide is the time period required for the herbicide to degrade to 50% of the original amount. The average half-life of aminopyralid under field conditions was 34.5 d in North American soils and 25 d in European soils (EPA 2005a), which is shorter than clopyralid and picloram which averaged 40 and 90 d, respectively (Senseman 2007). Wide variably in half-life ranges were common with all three of these herbicides across United States soils. For instance, clopyralid half-life ranged from 12 to 70 d, and picloram half-life ranged from 20 to 300 d. In proprietary studies for EPA registration, aminopyralid half-life in five soils ranged from 31.5 to 533.2 d (EPA 2005a).

Fall-applied herbicide treatments generally have a much longer half-life than spring-applied treatments because very little degradation occurs during the fall and winter months when soil temperatures are cool or below freezing (Pik et al. 1977; Scifres et al. 1969). Since many interacting variables (specific microorganisms, environmental conditions, and soil characteristics) are responsible for degradation of these herbicides, prediction of soil persistence across a variety of environments is very difficult (Amonymous 2005; Guenzi and Beard 1976; Pik et al. 1977).

Picloram can be degraded by sunlight (Merkle et al. 1967), but very little photodegradation occurs with clopyralid (Senseman 2007). Photodegradation of picloram occurred fastest in clear, moving water and more slowly on soil and plant surfaces. Picloram exposed to sunlight for 1 wk in an aqueous solution degraded 65%, compared to 15% when exposed on the soil surface (Merkle et al. 1967). Rate of picloram photodegradation increased with ultraviolet (UV) light intensity, which was greatest at high elevations with thin, clear air (Johnsen and Martin 1983).

Aminopyralid is rapidly degraded by photolysis in water with a half-life of 0.6 d (EPA 2005b). The average photolysis half-life of picloram in surface water was 2.6 d (Senseman 2007), but degradation in underground water occurred very slowly (Mullison 1985). Picloram concentration in a North Dakota well only decreased from 12.4 to 6.7 μg/kg in one year (Lym and Messersmith 1988). Picloram present in these concentrations did not pose any human health risks, but minute amounts of picloram (< 1 μg/kg) in irrigation water have injured sensitive broadleaf crops (Mullison 1985).

Herbicide dissipation in soils also has been affected by leaching (Merkle et al. 1967; Scifres et al. 1969). The leaching potential of a herbicide is favored by slow degradation rates (soil $DT_{50} > 21$ d and photolysis $DT_{50} > 4$ d), a low adsorption coefficient (<500), and high water solubility (>30 mg/L) (Arnold 1995). Aminopyralid and clopyralid have a moderate leaching potential, while picloram is considered highly leachable (Senseman 2007). Picloram mobility was greatest when applied at high rates (Hunter and Stobbe 1972) to course-textured soils (Herr et al. 1966) that were low in organic matter content (Keys and Friesen 1968). In addition, a large and rapid precipitation event (12.6 cm in 2 hr) increased picloram movement through a silty clay soil (Hunter and Stobbe 1972).

EPA models suggested aminopyralid movement in the soil profile was limited (Jachetta et al. 2005). However, Samuel (2007) observed considerable movement of aminopyralid through packed soil columns. Aminopyralid mobility was influenced by soil texture and precipitation intensity and duration. After an extreme precipitation event (45 cm in 48 hr), aminopyralid moved completely through the loamy sand in an 8-cm-diameter by 65-cm-deep column but was found throughout the loam and silty-clay soil columns. When 45 cm of water was applied over a 9 wk period, aminopyralid did not leach from the soil surface in loamy sand, loam, and clay soils but did move throughout the soil profile in Fargo silty-clay soil. Cracks often form in heavy textured soils such as Fargo silty-clay which could provide channels for herbicides to penetrate deep into the soil profile (Herr et al. 1966; Phillips and Feltner 1972). Although aminopyralid may not have percolated directly through a continuously uniform soil profile, the presence of aminopyralid deep in the soil profile could still indicate the potential for aminopyralid movement to an unintended site such as groundwater, even in a heavy textured soil with high organic matter content (Samuel 2007).

Determination of aminopyralid persistence in soil is necessary so planting intervals of sensitive crops can be established. The current aminopyralid label does not contain a re-cropping timeline for susceptible crops (Anonymous 2008). Field bioassays are recommended before broadleaf crops are planted into an aminopyralid-treated area. Unfortunately, field bioassays require several weeks before injury can be determined, which may delay planting until the following season.

Injury was not observed in corn or wheat (*Triticum aestivum* L.) grown in soils treated with aminopyralid at 231 g/ha prior to seeding (EPA 2005a). However, many broadleaf crops are susceptible to very low concentrations of pyridinecarboxylic acid herbicides in soils. Soybean seeded in a silt loam the same day picloram was applied at 38 g/ha did not emerge, but were uninjured by clopyralid at the same rate (Jotcham et al. 1989). In field residue trials conducted on three North Dakota soils, soybean height, stand density, and yield were reduced when planted 11 mo after clopyralid was applied at 560 g/ha, and soybean height and yield were reduced when picloram was applied at 35 g/ha (Thorsness and Messersmith 1991). Aminopyralid is extremely injurious to soybean as well. Soybean growth was affected by aminopyralid at 0.75 g/ha when applied to soil before seeding (EPA 2005a), and by aminopyralid concentrations less than 6 μg/kg in soil (L. W. Samuel, personal communication[1]).

Effect of Aminopyralid on Desirable Forb Species

The aminopyralid weed control spectrum is thought to be between clopyralid (narrow) and picloram (wide) (Halstvedt and Rice 2009; Lym 2005). Many native graminoid species are tolerant to aminopyralid at labeled rates (Carrithers et al. 2005), but effects on native forb species are not widely known (Almquist 2008; Sebastian and Beck 2008).

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[1] Luke Samuel, 506 West 40th St., Hays, KS 67601.

Aminopyralid impact on non-target forb species should be evaluated since Canada thistle often invades areas of desirable native vegetation (Lym and Duncan 2005). Land managers desire weed control regimens that preserve diversity of native plant species and maximize weed control. If left untreated, invasive weeds may crowd out native plants which might diminish species diversity (Gordon 1998). Conversely, herbicides that eliminate desirable native species leave environments favorable for Canada thistle re-establishment (Samuel and Lym 2008). The ideal herbicide treatment would eliminate Canada thistle infestations, while having little or no effect on desirable plant species.

The optimal growth stage for Canada thistle control with aminopyralid was in early-May when plants were bolting to prebud or late-September during fall regrowth (Enloe et al. 2007), but forb injury increased with fall application (R. Becker and M. Haar, personal communication[2]). Aminopyralid applied with surfactants increased injury to desirable forbs, but did not increase Canada thistle control.

Many species of the plant families Asteraceae, Fabaceae, Onagraceae, and Rosaceae were susceptible or moderately susceptible to aminopyralid (Almquist and Lym 2010; Becker and Haar 2008; Duncan et al. 2008). Desirable forb species in the *Helianthus*, *Ratibida*, and *Rudbeckia* genera were very susceptible to aminopyralid, but populations seemed to re-establish from the seed bank within 2 YAT (R. Becker and M. Haar, personal communication[2]). Some species demonstrated tolerance to aminopyralid even though flowering and seed production were interrupted during the treatment year.

Aminopyralid applied at 120 g/ha to a North Dakota native plant community reduced

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[2] Roger Becker and Milton Haar, University of Minnesota, Department of Agronomy and Plant Genetics, St. Paul, MN 55108.

species richness 10 MAT from 11.6 to fewer than 9 species in untreated and treated areas, respectively, and species richness remained lower in treated areas 22 MAT (Samuel and Lym 2008). Aminopyralid reduced foliar cover of prairie coneflower [*Ratibida columnifera* (Nutt.) Woot. & Standl.], a native low-seral forb, and five high-seral forb species 22 MAT including rough bedstraw (*Galium boreale* L.), Northern bedstraw (*Galium boreale* L.), Missouri goldenrod (*Solidago missouriensis* Nutt.), American vetch (*Vicia Americana* Muhl. Ex Willd.), and prairie sagewort (*Artemisia frigida* Willd.). High-seral forbs are desirable species that have been shown to increase resistance to weed invasion (Rinella et al. 2007). The loss of high-seral forb species decreases plant community stability, which may increase the likelihood of non-native weedy species establishment (Samuel and Lym 2008).

Species richness, evenness, and diversity were reduced by aminopyralid at 120 g/ha 10 MAT in a Minnesota restored prairie (Almquist and Lym 2010). Native community richness was reduced from 15 to 10 species following aminopyralid treatment, which was attributed to a decline in desirable forb species. Aminopyralid reduced foliar cover of high-seral forbs from 16.3 to 5.6% in Canada thistle-infested communities and from 12.9 to 5.4% in native communities 10 MAT. Foliar cover of white panicled aster (*Aster simplex* Willd.), purple prairie clover (*Dalea purpurea* Vent.), giant sunflower (*Helianthus giganteus* L.), maximilian sunflower (*Helianthus maximiliani* Schrad.), stiff sunflower (*Helianthus pauciflorus* Nutt.), Canada goldenrod (*Solidago canadensis* L.), Missouri goldenrod, and purple meadow-rue (*Thalictrum dasycarpum* Fisch. & Ave-Lall.) was reduced by aminopyralid 10 MAT. However, some of these species recovered from the herbicide injury by the second growing season after aminopyralid application and foliar cover in aminopyralid-treated and untreated plots was similar 22 MAT.

Halstvedt and Rice (2009) developed an aminopyralid plant tolerance/susceptibility guide that compared herbicide treatments to non-treated controls on the basis of canopy cover. Plants were placed into three categories: susceptible (S) 75% or more canopy cover reduction, moderately tolerant (MT) 74 to 16% reduction, and tolerant (T) 15% or less canopy cover reduction. Native forb injury when aminopyralid was applied at 86 g/ha was greater than clopyralid at 280 g/ha but less than picloram at 280 g/ha 2 YAT. The number of species in the S, MT, and T categories 1 yr after aminopyralid treatment were 10, 11, and 12, respectfully, but most species (21) were considered tolerant by 2 YAT. Only a few forb species such as yarrow (*Achillea millefolium* L.) and orange arnica (*Arnica fulgens* Pursh) were adversely affected by aminopyralid for 2 yr or more.

MATERIALS AND METHODS

Soil Residue Impact on Crops

Fargo – 2 YAT. Two field bioassay studies were conducted to determine the effect of aminopyralid soil residue on four North Dakota crops one or two growing seasons after treatment. The first study was conducted at the North Dakota Agricultural Experiment Station, near Fargo, on existing plot land previously used to evaluate aminopyralid efficacy on Canada thistle. The soil type was a Fargo-Ryan silty clay (Fine, smectitic, frigid Typic Epiaquerts; Fine, smectitic, frigid Typic Natraquerts) with an organic matter content of 52 g/kg and pH of 7.6 (Table 1). Fargo has a continental climate with a 30-yr average temperature of 5.3 C and precipitation average of 54 cm at the study site (Table 2).

Table 1. Physical and chemical characteristics of five North Dakota soils included in field or greenhouse experiments.

Location	Soil series[a]	Sand	Silt	Clay	OM[b]	Field capacity water content	CEC[b]	pH
		g/kg					cmol/kg	
Fargo	Fargo-Ryan	20	450	530	52	693	28.6	7.6
Medora	Glendive-Havre	50	350	600	12	400	11.4	8.1
Walcott	Lamoure	860	90	50	26	400	13.0	7.8
Jamestown	Svea-Barnes	370	420	210	64	502	17.7	5.7
Casselton	Kindred-Bearden	80	520	400	53	---[c]	27.7	7.9

[a] Determined from (USDA-NRCS 2010).
[b] Abbreviations: OM = organic matter; CEC = cation exchange capacity.
[c] Field study only.

The effects of aminopyralid and picloram residue on alfalfa, corn, soybean, and sunflower were determined 20 or 23 mo after herbicide application. Aminopyralid at 120 and 240 g/ha, aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, and picloram at 560 g/ha were applied with a nonionic surfactant[3] at 0.25% v/v on June 12 or October 2, 2006, to abandoned cropland. Smooth brome (*Bromus inermis* L.), Canada thistle, and perennial sowthistle (*Sonchus arvense* L.) were the primary weeds present with scattered areas of other annual weeds. A non-sprayed check was included for comparison. The experimental design was a randomized complete block with four replicates and plots were 3 by 9 m. Herbicides were applied with a CO_2-pressurized hand-held boom sprayer with four 8002 flat-fan nozzles[4] delivering 160 L/ha at 240 kPa.

Table 2. Monthly temperature and precipitation at Fargo, ND, from 2006 through 2008.

	2006		2007		2008	
Month	Actual[a]	Deviation[b]	Actual	Deviation	Actual	Deviation
Temperature			C			
Jan - March	- 6.6	+2.3	- 8.3	+0.6	- 11.0	- 2.1
April	10.4	+4.0	6.1	- 0.3	5.0	- 1.4
May	14.9	+0.8	15.8	+1.7	12.2	- 1.9
June	20.3	+1.4	21.1	+2.2	17.6	- 1.3
July	23.8	+2.4	23.3	+1.9	21.3	- 0.1
August	20.9	+0.4	19.6	- 0.9	20.8	+0.3
September	14.8	+0.4	15.9	+1.5	15.4	+1.0
October	6.2	- 1.2	10.0	+2.6	8.2	+0.8
Nov - Dec	- 1.8	+5.0	- 6.3	+0.5	- 7.3	- 0.5
Precipitation			cm			
Jan - March	5.2	- 1.2	7.7	+1.3	4.4	- 2.0
April	3.6	+0.2	8.0	+4.6	5.9	+2.5
May	5.1	- 1.5	9.8	+3.2	4.8	- 1.8
June	3.4	- 5.5	14.7	+5.8	15.4	+6.5
July	5.7	- 1.7	3.1	- 4.3	4.5	- 2.9
August	5.6	- 0.8	6.1	- 0.3	11.6	+5.2
September	9.9	+4.4	8.6	+3.1	12.9	+7.4
October	2.4	- 2.6	4.5	- 0.5	11.3	+6.3
Nov - Dec	3.0	- 1.1	4.3	+0.2	7.4	+3.3

[a] Data were obtained from the nearest National Oceanic and Atmospheric Administration site: Fargo Hector International Airport, Cass County, ND; approximately 2 km from the study site.

[b] Departure from 30-year average (1971-2000).

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[3] Activator 90, alkyl polyoxyethylene ether and free fatty acids, Loveland Industries, Greeley, CO 80634.

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

The study area was mowed and chisel plowed in October 2007 to prepare the seed bed for spring planting. Soil samples were collected May 14, 2008, from three 15-cm-deep cores per plot and stored at -20 C. The replicate samples were combined and shipped to a commercial laboratory[5] for herbicide residue analysis. Fertilizer (N:P:K) was applied at 230:41:41 kg/ha and the area was cultivated twice in May 2008. All tillage was done perpendicular to replicates to minimize soil movement between experimental plots.

'Ameristand 201+2' alfalfa was seeded in twelve 15-cm-spaced rows at 23 kg/ha, and 'Dekalb DKC 38-89' corn, 'Asgrow DKB08-51' soybean, and 'Mycogen 8N 386CL' sunflower were planted at 71,000, 445,000, and 63,000 seeds/ha, respectively, in three 76-cm-spaced rows on May 20, 2008. Aminopyralid residue effect was estimated by evaluation of injury symptoms, stand density, height, and yield. Crops were visually evaluated approximately 7, 14, 30, and 60 d after emergence (DAE) for herbicide injury with 0% equal to no injury and 100% equal to complete kill. Crop density was measured from each plot at 7 and 60 DAE by counting the number of stems in 2 m of all three rows for corn, soybean, and sunflower. Alfalfa density was determined by counting the number of stems in five random 20-cm-long samples per plot. Plant height was measured for each crop at 30 and 60 DAE by randomly sampling five plants per plot. Alfalfa, soybean, and sunflower were measured to the apical growing point and corn to the tallest leaf tip.

Alfalfa and sunflower were treated with clethodim at 140 g ai/ha on June 23, 2008, to control green foxtail [*Setaria viridis* (L.) P. Beauv.], yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult], and smooth bromegrass. Alfalfa was treated with bromoxynil at 360 and 420 g ai/ha on June 23 and July 25, 2008, respectively, to control Canada thistle, perennial

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[5] Carbon Dynamics Institute, LLC., 2835 Via Verde Drive, Springfield, IL 62703-4325.

sowthistle, common ragweed (*Ambrosia artemisiifolia* L.), and field pennycress (*Thlaspi arvense* L.). Corn and soybean were treated with glyphosate at 630 and 770 g ae/ha on June 23 and July 10, 2008, respectively, to control Canada thistle, smooth bromegrass, and other annual weeds. Ammonium sulfate (AMS) at 10 g/L was included with all glyphosate treatments. Weed escapes were removed by hand, hoe, or garden tiller until harvest. Soybean aphid (*Aphis glycines* Matsumura) was controlled with lambda-cyhalothrin at 27 g ai/ha applied on July 25, 2008.

Alfalfa was harvested at 25% flowering by clipping three 0.25-m^2 quadrats, cut 5 cm above the soil surface, from center of each plot on August 6, 2008. Weeds were sorted from alfalfa in the field and alfalfa biomass was bagged, dried at 55 C for 96 h, and weighed. Since lateral herbicide movement within each plot was apparent by soybean injury symptomology, soybean rows in each plot were marked in late-August to ensure a representative harvest for each treatment. Soybean were cut just above the soil surface and plants bagged on October 9, 2008, from 1 m of three rows per plot. Soybean were then dried, threshed, and weighed, and yield was calculated based on 13% moisture content. Corn was hand-picked from the center 1 m of three rows per plot on October 30, 2008. Corn was then bagged, dried, shelled, cleaned, and weighed, and yield was calculated based on 15.5% moisture content. Sunflower heads were not harvested in 2008 because a representative sample could not be collected due to the small plot size and stand variability across plots.

Casselton – 1 YAT. The second study was established on fallowed cropland at the North Dakota Agronomy Seed Farm near Casselton, to evaluate the affect of aminopyralid residue on crops planted 8 or 11 MAT. The soil was a Kindred-Bearden silty clay loam

(Fine-silty, mixed, superactive, frigid Typic Endoaquolls: Fine-silty, mixed, superactive, frigid Aeric Calciaquolls) with an organic matter content of 53 g/kg and pH of 7.9 (Table 1). Casselton has a similar climate to Fargo and has an annual temperature of 5.3 C and annual precipitation of 55 cm (Table 3).

Table 3. Monthly temperature and precipitation at Casselton, ND, for 2008 and 2009.

	2008		2009	
Month	Actual[a]	Deviation[b]	Actual	Deviation
Temperature		C		
Jan - March	- 11.9	- 2.3	- 12.2	- 2.6
April	4.6	- 1.1	4.6	- 1.1
May	12.0	- 1.6	11.7	- 1.9
June	17.2	- 1.2	17.4	- 1.0
July	21.2	0	19.6	- 1.6
August	20.3	- 0.1	18.7	- 1.7
September	15.4*	+1.0*	17.7	+3.1
October	7.8	+0.4	4.6	- 2.8
Nov - Dec	- 8.0	+0.7	- 9.5*	+2.2
Precipitation		cm		
Jan - March	3.4	- 3.1	10.3	+3.8
April	4.4	+0.7	2.9	- 0.8
May	5.3	- 1.4	4.5	- 2.2
June	15.3	+6.2	6.7	- 2.4
July	8.7	+0.5	3.2	- 5.0
August	8.5	+1.7	6.9	+0.1
September	12.9*	+7.5*	6.0	+0.6
October	11.5	+6.7	13.9	+9.1
Nov - Dec	8.1	+4.0	5.5*	+1.4

[a] Data were obtained from the nearest National Oceanic and Atmospheric Administration site: Casselton Agronomy Farm, Cass County, ND; 1 km from study site. Due to missing observations at Casselton, data denoted with an (*) were obtained from Fargo Hector International Airport, approximately 35 km from the study site.

[b] Deviation from 30-year average (1971-2000).

The experiment was similar to the first study except crops were planted 8 or 11 MAT instead of 20 or 23 MAT. Treatments included an untreated control, aminopyralid at 60, 120, and 240 g/ha, aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, and picloram at

560 g/ha. Treatments were applied to scattered vegetation consisting of Venice mallow (*Hibiscus trionum* L.), wild mustard (*Sinapis arvensis* L.), redroot pigweed (*Amaranthus retroflexus* L.), and bare ground on June 23 or September 26, 2008. Glyphosate at 2.1 kg/ha plus AMS at 10 g/L was applied on July 15, 2008, to control annual weeds in the study site. No fall tillage was conducted due to very wet field conditions in October 2008 (Table 3).

Soil samples were collected May 11, 2009, and stored and analyzed as previously described. Fertilizer 230:41:41 kg/ha was applied, and the area was cultivated twice in late May 2009 prior to planting. Experimental procedures were the same as the Fargo experiment, except plots were 5 by 12 m and four rows of the same corn, soybean, and sunflower hybrids were seeded. The alfalfa variety and seeding specifications were the same as the Fargo experiment. Injury ratings and growth parameters were measured as previously described.

Crops were seeded on May 28, 2009. Glyphosate was applied at 1,020 g/ha to corn and soybean on July 1, 2009, and at 770 g/ha to soybean on August 4 to control redroot pigweed, Venice mallow, common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.). Clethodim at 210 g/ha was applied to sunflower on July 1 and imazamox at 35 g ae/ha was applied on July 6 and July 23 to control annual grass and broadleaf weeds. Clethodim and bromoxynil at 210 and 420 g/ha, respectively, were applied to alfalfa on July 1, 2009. A second bromoxynil treatment at 420 g/ha was applied to alfalfa on July 23. Weed escapes were controlled by hand, hoe, or garden tiller until crop maturity.

Alfalfa was harvested on August 11, 2009, by clipping four 0.25-m^2 quadrats from the center of each plot, and yield was determined as previously described. Soybean plants were cut at the soil surface from 3 m of the center two rows of each plot and sunflower heads were collected from 3 m of three rows per plot on October 19, 2009. Corn was hand-picked from 2 m of the center two rows per plot on October 28, 2009. Sunflower heads were dried, thrashed, cleaned, and weighed to determine yield. Corn and soybean harvest samples were dried and processed as previously described.

Data for both field experiments were analyzed similarly. Visual evaluations, height and density measurements, and yield for each crop were analyzed by the PROC GLM procedure of SAS[6]. Fisher's protected LSD ($P = 0.05$) was used for mean separation. The two studies were not combined because of the different re-cropping intervals (1 or 2 yr after treatment) and herbicide rates.

Climatic Influences on Aminopyralid Dissipation in Soil

Two studies were conducted using soybean bioassay to determine the effect of temperature and moisture on aminopyralid dissipation in four North Dakota soils. Soils evaluated included Fargo-Ryan silty clay, Glendive-Havre clay (Coarse-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents; Fine-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents), Lamoure loamy sand (Fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquolls), and Svea-Barnes loam (Fine-loamy, mixed, superactive, frigid Pachic Hapludolls; Fine-loamy, mixed, superactive, frigid Calcic Hapludolls) (Table 1). Soils were collected from 0 to 30 cm and screened through a 6-mm mesh sieve, air-dried, thoroughly mixed, and stored at 23 C.

The field capacity (FC) for each soil was determined in separate study. The soils were

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[6] SAS version 9.1, SAS Institute, Cary, NC 27513.

dried at 75 C for 48 hr. Then 500 g of the oven-dried soil was placed into the same plastic pots used for the soybean bioassay. The soils were saturated with 300 to 500 ml of distilled water and allowed to stand for 8 hr. Pots were then loosely covered with plastic wrap, the soils were allowed to freely drain for 48 hr, pots were reweighed, and gravimetric water content for each soil was determined (Gardner 1986). The gravimetric water content after 48 hr of free drainage was considered the FC (Table 1). The amount of water required to bring each soil to 22.5, 45, and 90% FC was then calculated based on weight for each soil with oven dry soil equal to 0% FC and saturated soil equal to 100% FC.

Temperature. Aminopyralid equivalent to 52 µg/kg soil was applied in 10 ml distilled water to 500 g of soil contained in wax paper bags. Soil was allowed to air dry, then thoroughly mixed by shaking, and placed 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.

Distilled water was added to each soil equal to 45% FC (Table 1), and then pots were placed in darkened constant temperature chambers at 8 ±1C, 16 ±1C, or 24 ±1 C for 28 d. Plastic covers were set on top of each pot to slow evaporation, but enough space remained to allow for air movement. Soil moisture was monitored by weighing pots every 2 to 3 d, and water was added as needed to retain 45% FC. All soils were placed in the greenhouse after 28 d and maintained at 45% FC for 48 hr, until start of the bioassay.

Aminopyralid concentration remaining in soils was estimated by soybean bioassay (Samuel 2007). A standard curve for each soil type was prepared equivalent to aminopyralid at 0, 6.5, 13, 26, and 52 µg/kg soil. The soil was then air dried, mixed, and placed into plastic pots as previously described. Eight 'Traill' soybean seeds were planted

1 cm deep in both the study and standard curve soils. The soil was moistened, and alternately sub- or surface-watered as needed to maintain an approximate 65% FC throughout the assay period. After emergence, soybean were thinned to four plants per pot and a water soluble fertilizer[7] at 85 kg/ha nitrogen was applied. Pots were rotated every 2 d to minimize environmental variability in the greenhouse. The greenhouse was maintained at 22 C, and natural sunlight was supplemented with metal halide lights with an intensity of 450 $\mu E/m^2/s$ for a 16 hr photoperiod. Soybean were cut at the soil surface 11 to 14 d after planting, and height from soil surface to apical meristem was determined.

Moisture. Distilled water was initially added to soils equal to 45% FC to equilibrate aminopyralid and ensure uniform distribution (Table 1). The uncovered pots were placed in a darkened constant temperature growth chamber at 16 ±1 C for 48 h and moisture content was allowed to decrease to 22.5% FC. Water was then added to the 45 and 90% FC soil treatments as appropriate, covers were placed loosely on each pot, and pots were returned to the chamber for 28 d. Soil moisture was maintained at 22.5, 45, or 90% FC. Pots were placed in the greenhouse after 28 d and covers removed. The 90% FC treatments were allowed to dry to 45%, while the 22.5 and 45% treatments were maintained at 45% FC for 48 h. A soybean bioassay was then conducted to determine aminopyralid concentration in each soil as previously described.

Data analysis. The temperature and moisture studies were a randomized complete-block design with four replicates and were repeated. Regression analysis was used to develop linear and curvilinear curves based on soybean stem height from standard curve soils. Curvilinear curves provided the best fit ($R^2 > 0.95$ for both runs of all four soils). The

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[7] Miracle Gro® 15-20-15, The Scotts Miracle-Gro Company, 14111 Scottslawn Road, Marysville, OH 43041.

quadratic equations were then used to estimate herbicide concentrations in treated soils (28 d at various temperatures or moisture contents) using soybean stem height. Least squares means (LSMEANS) compared aminopyralid concentration within and across the four soil types. Separation of means were calculated by probability of difference (PDIFF, $p < 0.10$). Runs were homogeneous (error mean squares within a factor of ten), so the data were combined.

The first-order rate equation

$$\ln(A_t/A_O) = -\mathrm{k}t \qquad [1]$$

was used to describe aminopyralid dissipation (Paul and Clark 1989). A_t was the concentration of aminopyralid contained in the soil at time t, k was the dissipation rate constant (days), and A_O was the initial aminopyralid soil concentration. Time to 50% dissipation (DT_{50}) for aminopyralid in each soil was computed from the formula

$$\mathrm{DT}_{50} = 0.693/\mathrm{k} \qquad [2]$$

where k was the rate constant computed from Equation 1.

Prairie Forb Susceptibility to Aminopyralid

Nine native prairie forb species were evaluated to for susceptibility to aminopyralid in greenhouse trials. Forb species were chosen that had not been evaluated in field studies (Almquist and Lym 2010; Samuel and Lym 2008) and included harebell (*Campanula rotundifolia* L.), white prairie clover (*Dalea candida* Michx. ex Willd.), purple coneflower [*Echinacea purpurea* (L.) Moench], blanket flower (*Gaillardia aristata* Pursh), closed bottle gentian (*Gentiana andrewsii* Griseb.), great blue lobelia (*Lobelia siphilitica* L.), prairie coneflower, showy goldenrod (*Solidago speciosa* Nutt.), and azure aster (*Symphyotrichum oolentangiensis* Riddell). Rough blazing star (*Liatris aspera* L.) and slender penstemon

(*Penstemon gracilis* Pursh) were selected for evaluation as well, but not enough plants survived the establishment phase and therefore were not included in this study.

The prairie forbs were obtained from a nursery[8] in September 2008 and transplanted into conetainers[9] (6.3-cm diameter by 25-cm deep) containing a blend of commercial media[10] and sandy loam soil (4:1 by volume). Plants were grown approximately 20 to 32 wk in a greenhouse maintained between 20 and 28 C, with a 15-hr photoperiod of natural and supplemental metal halide light with an intensity of 450 $\mu E/m^2/s$. In February, the photoperiod was adjusted to 13 hr for purple coneflower and closed bottle gentian, and to 16 hr for blanket flower and showy goldenrod to initiate flowering. Plants were re-randomized weekly and watered and fertilized with a diluted 15-20-15 nutrient solution[5] as necessary (2 to 3 times during study duration). Imidacloprid at 0.005 g ai/conetainer was applied once to harebell, white prairie clover, purple coneflower, closed bottle gentian and twice to blanket flower and prairie coneflower to control aphids [*Myzus persicae* (Sulzer)], greenhouse thrips [*Heliothrips haemorrhoidalis* (Bouche)], and spider mites [*Tetranychus urticae* Koch].

Plants were treated at the approximate growth stage found when aminopyralid is fall-applied for Canada thistle control in the field (Table 4). Aminopyralid at 0, 30, 60, and 120 g/ha was applied with an air-pressurized greenhouse cabinet-type sprayer equipped with an 8002 flat-fan nozzle[2] delivering 160 L/ha at 240 kPa. A non-ionic surfactant[1] at 0.25% v/v was included with all herbicide treatments to maximize potential forb injury.

Plants were visually evaluated for injury 1, 7, and 14 DAT on a scale of 0 to 100%,

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[8] Prairie Restorations, Inc., 31646 128th St., Princeton, MN 55371.

[9] Deepots™, Stuewe & Sons, Inc., 2290 SE Kiger Island Drive, Corvallis, OR 97333.

[10] Sunshine Mix No. 1, patented formulation with wetting agents. Sun Gro Horticulture Canada Ltd., P.O. Box 189, Seba Beach, AB T0E 2B0.

with 0 equal to no effect and 100 equal to all surface material dead. At 14 DAT, the topgrowth was removed 5 cm above the soil surface, and plants were allowed to regrow for 5 to 8 wk. Plant regrowth was visually evaluated for injury, and then plant material was clipped, dried at 50 C for 96 h, and weighed to estimate the long-term effect of aminopyralid on plant production.

Table 4. Forb species and growth stage in the greenhouse to simulate stage when aminopyralid is applied for fall Canada thistle control.

Common name	Scientific name	Family	Growth stage[a]	Height
				— cm —
Harebell	*Campanula rotundifolia*	Campanulaceae	FLW	25-30
White prairie clover	*Dalea candida*	Fabaceae	FLW	25-35
Purple coneflower	*Echinacea purpurea*	Asteraceae	VEG to FLW	15-30
Blanket flower	*Gaillardia aristata*	Asteraceae	VEG to FLW	10-15
Closed bottle gentian	*Gentiana andrewsii*	Gentianaceae	FLW	10-20
Great blue lobelia	*Lobelia siphilitica*	Campanulaceae	FLW	15-25
Prairie coneflower	*Ratibida columnifera*	Asteraceae	FLW	25-35
Showy goldenrod	*Solidago speciosa*	Asteraceae	VEG to FLW	10-30
Azure aster	*Symphyotrichum oolentangiensis*	Asteraceae	FLW	45-65

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

The experiment was a randomized complete-block design with six replicates and was repeated. Each species was analyzed as a separate experiment. Plant injury ratings and regrowth weights were evaluated using PROC GLM procedure of SAS[4] to determine differences in injury, and F-protected LSD (P = 0.05) tested mean separation. Error mean squares from each run were compared for homogeneity of variance. A combined analysis was conducted when error mean squares for each run differed by less than a factor of 10.

RESULTS AND DISCUSSION

Soil Residue Impact on Crops

Fargo – 2 YAT. Aminopyralid concentration in soil was approximately 2 to 3 times greater when fall-applied compared to when spring-applied 20 or 23 MAT (Table 5). For instance, aminopyralid concentration was 0.17 µg/kg when spring-applied at 240 g/ha compared to 0.48 µg/kg when fall-applied at the same rate. Picloram concentration in the soil was 1.21 µg/kg when spring-applied at 560 g/ha and below the detection limit (0.2 µg/kg) when fall-applied at the same rate. The lower picloram concentration from the fall-applied treatment was unexpected since spring-applied picloram had an extra growing season to degrade.

Table 5. Aminopyralid or picloram soil residue from 0 to 15 cm at Fargo, ND on May 14, 2008 from treatments applied June 12 or October 2, 2006.

		Herbicide in soil	
Treatment	Rate	Spring-applied	Fall-applied
	— g/ha —	µg/kg	
Aminopyralid	120	ND[a]	0.10
Aminopyralid	240	0.17	0.48
Aminopyralid + diflufenzopyr	120 + 49	0.12	0.23
Picloram	560	1.21	ND

[a] Abbreviations: ND = no detection (limit of detection: aminopyralid = 0.10 µg/kg and picloram = 0.20 µg/kg).

The growing season after herbicide treatments were applied at Fargo in June 2006 was warmer and dryer than the long-term average, and 2007 was warmer and wetter than normal (Table 2). Precipitation for the 28 month period from June 2006 to October 2008 was 27 cm above the 30-year average, and average temperature was 0.6 C above normal at Fargo. The above average precipitation and temperatures in 2006 and 2007 may have caused greater aminopyralid degradation than if conditions were cool and dry.

Crop establishment in 2008 was slow due to cool, dry conditions in May after planting, and cool and very wet conditions in June (Table 2). Precipitation was 6.5 cm above normal and the average temperature was 1.3 C below normal in June 2008. Air temperatures averaged 0.4 C below normal from May through September 2008 and precipitation was 14.4 cm above normal.

Alfalfa was not injured from aminopyralid or picloram when seeded 20 or 23 MAT (Table 6). Plant height and stand density were unaffected by the herbicides and alfalfa yield was similar to the control.

Table 6. Effect of herbicide residue from treatments applied June 12 or October 2, 2006 on alfalfa seeded May 20, 2008 at Fargo.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	– g/ha –		% injury			– cm–	- plants/m -	– kg/ha –
Spring-applied								
Aminopyralid	120	0	0	0	0	45	19	1,050
Aminopyralid	240	0	0	0	0	53	24	1,780
Aminopyralid + diflu	120 + 49	0	0	0	0	54	28	2,110
Picloram	560	0	0	0	0	48	21	950
Fall-applied								
Aminopyralid	120	0	0	0	0	52	25	1,790
Aminopyralid	240	0	0	0	0	52	24	1,510
Aminopyralid + diflu	120 + 49	0	0	0	0	50	20	1,060
Picloram	560	0	0	0	0	49	23	1,410
Control	--	0	0	0	0	50	23	1,420
LSD (0.05)		NS	NS	NS	NS	NS	NS	NS

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Corn had no visible injury symptoms when planted 20 and 23 mo after aminopyralid or picloram treatments (Table 7). Plant density was reduced from 6.1 plants/m in the control to an average of 5.1 plants/m when aminopyralid was applied at 120 g/ha alone or with diflufenzopyr in the spring. Corn density was also reduced to an average of 5.2 plants/m when picloram at 560 g/ha was spring- and fall-applied. However, corn grew taller and tended to have greater yields when planted in treated plots compared to the control. The average corn yield across herbicide treatments was 10,600 kg/ha compared to 5,900 kg/ha in the control.

Table 7. Effect of herbicide residue from treatments applied June 12 or October 2, 2006 on corn seeded May 20, 2008 at Fargo.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	— g/ha —	—— % injury ——				— cm —	- plants/m -	— kg/ha —
Spring-applied								
Aminopyralid	120	0	0	0	0	215	5.3	9,400
Aminopyralid	240	0	0	0	0	232	5.7	11,100
Aminopyralid + diflu	120 + 49	0	0	0	0	227	4.9	11,600
Picloram	560	0	0	0	0	226	5.0	11,900
Fall-applied								
Aminopyralid	120	0	0	0	0	221	5.9	8,400
Aminopyralid	240	0	0	0	0	228	5.8	10,100
Aminopyralid + diflu	120 + 49	0	0	0	0	232	5.7	12,000
Picloram	560	0	0	0	0	222	5.3	10,000
Control	--	0	0	0	0	198	6.1	5,900
LSD (0.05)		NS	NS	NS	NS	15	0.7	3,800

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

The reason for the increased corn yield in treated plots compared to the control is uncertain. Pollination for corn growing in the control plots was very poor. Many cobs were small and contained only a few scattered kernels at harvest. Plant stress caused by high temperatures or inadequate soil moisture could have affected pollination (Shaw and Newman 1991). Corn growth in the control plots lagged behind the treated areas, and peak pollination may have occurred during a period less conducive to fertilization.

Soybean was the most sensitive crop to aminopyralid residue, but little visible injury appeared before 30 DAE (Table 8). Soybean injury from aminopyralid at 120 to 240 g/ha averaged 35% when spring-applied and 22% when fall-applied 60 DAE. Soybean injury ranged from 20 to 49% when aminopyralid plus diflufenzopyr was applied at 120 plus 49 g/ha in the spring or fall, respectively. Soybean injury was minimal (11% or less) when seeded 20 or 23 mo after picloram at 560 g/ha was applied.

Soybean injury within each treatment varied across replicates. More injury occurred in the third and fourth replicates than the first and second (data not shown). Soil samples collected from each replicate had a similar pH and organic matter content (data not shown). Differences in vegetation cover at the time of application may have contributed to the variable injury observed. Doublet et al. (2009) reported delayed degradation in soil when herbicides were intercepted by plants than when herbicides were applied directly to soil. The plants absorbed the herbicides which were not released into the soil until plant senescence. Although many broadleaf weeds would have been killed by aminopyralid, most grass species are tolerant (Masters et al. 2005). Aminopyralid may have been absorbed by grasses and not released into the soil until fall senescence or the plant material degraded the following growing season. This could have delayed aminopyralid degradation in some replicates more than others and increased soybean injury.

Table 8. Effect of herbicide residue from treatments applied June 12 or October 2, 2006 on soybean seeded May 20, 2008 at Fargo.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	— g/ha —	——— % injury ———				— cm —	- plants/m -	— kg/ha —
Spring-applied								
Aminopyralid	120	0	2	19	36	44	13.5	1,970
Aminopyralid	240	0	2	27	33	48	19.0	1,950
Aminopyralid + diflu	120 + 49	0	0	16	20	54	16.2	2,310
Picloram	560	0	3	14	11	51	15.7	2,300
Fall-applied								
Aminopyralid	120	0	0	7	5	58	14.9	2,600
Aminopyralid	240	0	4	36	38	39	16.3	1,620
Aminopyralid + diflu	120 + 49	0	2	38	49	41	14.1	1,750
Picloram	560	0	3	12	3	55	16.5	2,730
Control	--	0	0	0	0	53	12.5	2,730
LSD (0.05)		NS	2	12	34	NS	3.5	750

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Soybean height was not affected by aminopyralid or picloram residues when seeded 20 or 23 MAT (Table 8). Plant density increased from spring- and fall-applied aminopyralid at 240 g/ha, spring-applied aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, and fall-applied picloram at 560 g/ha compared to the control. Soybean yield was reduced 28, 29, 41, and 36% by residues from spring-applied aminopyralid at 120 g/ha, spring- and fall-applied aminopyralid at 240 g/ha, and aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, respectively, compared to the control. Soybean yield was similar to the control when picloram at 560 g/ha was applied 20 or 23 mo prior to planting.

Sunflower was not injured when seeded 20 or 23 mo after aminopyralid or picloram application (Table 9). Sunflower height and density were not affected by aminopyralid, aminopyralid plus diflufenzopyr, or picloram residues. Density was variable and ranged from 1.3 to 4.5 plants/m, but this variability was likely a result of poor planting conditions (large soil aggregates) rather than herbicide residue.

Table 9. Effect of herbicide residue from treatments applied June 12 or October 2, 2006 on sunflower seeded May 20, 2008 at Fargo.

		Days after emergence					
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]
	— g/ha —	% injury				— cm —	- plants/m -
Spring-applied							
Aminopyralid	120	0	0	0	0	144	4.5
Aminopyralid	240	0	0	0	0	157	2.0
Aminopyralid + diflu	120 + 49	0	0	0	0	156	1.5
Picloram	560	0	0	0	0	159	1.3
Fall-applied							
Aminopyralid	120	0	0	0	0	156	2.4
Aminopyralid	240	0	0	0	3	163	2.8
Aminopyralid + diflu	120 + 49	0	0	0	0	152	1.8
Picloram	560	0	0	0	0	153	1.6
Control	--	0	0	0	0	144	2.5
LSD (0.05)		NS	NS	NS	NS	NS	NS

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Alfalfa, corn, and sunflower were very tolerant to aminopyralid and picloram when seeded 20 or 23 MAT in a Fargo-Ryan silty clay soil (Tables 6, 7, and 9). These species may be potential cropping options the second growing season after aminopyralid treatment in eastern North Dakota soils if aminopyralid concentration is 0.5 µg/kg or less prior to planting. However, soybean was extremely sensitive to aminopyralid (Table 8) and growth was adversely affected when seeded into soil even with aminopyralid concentrations less than 0.10 µg/kg (Table 5).

Casselton – 1 YAT. Aminopyralid concentrations in soil 11 MAT ranged from 0.80 to 2.29 µg/kg when spring-applied and from 4.83 to 14.0 µg/kg 8 MAT when fall-applied (Table 10). Aminopyralid concentration approximately doubled as application rate doubled and was approximately six-fold greater when fall-applied compared to spring-applied at comparable rates. Picloram concentration in soil was 15.5 and 48.8 µg/kg when picloram at 560 g/ha was spring-applied and fall-applied, respectively. Since aminopyralid and picloram concentrations were much less when herbicides were spring-applied than when fall-applied, the summer months appear very important for metabolism and dissipation of these herbicides.

Air temperature and precipitation patterns may have increased herbicide breakdown during the summer and early fall of 2008. Following the June treatment, air temperature was below the long-term average and precipitation was above normal (Table 3). However, air temperature was 0.4 C above normal and precipitation was 6.7 cm above normal in October 2008 following the late-September application at Casselton. The extreme precipitation in October caused surface ponding in the study area and some leaching and lateral movement of herbicides may have occurred during the late fall and early spring. Since aminopyralid degradation is favored by increased moisture (Anonymous 2005), aminopyralid dissipation may have occurred faster than average in 2008.

Planting was delayed until May 28, 2009 due to wet field conditions. Temperatures from May through August 2009 averaged 1.6 C below normal and precipitation was 9.8 cm below normal (Table 3). Crop development was slow throughout the season and corn, soybean, and sunflower were immature when the first killing frost occurred on October 8, 2009.

Table 10. Aminopyralid or picloram concentrations in soil prior to planting and in soybean leaf tissue in mid-September 2009 at Casselton, ND; treatments were applied June 23 or September 26, 2008.[a]

Treatments	Rate	Soil	Soybean leaves
	– g/ha –	μg/kg	
Spring applied			
Aminopyralid	60	0.80	4.43
Aminopyralid	120	1.75	7.90
Aminopyralid	240	2.29	16.70
Aminopyralid + diflufenzopyr	120 + 49	1.19	6.09
Picloram	560	15.50	8.53
Fall applied			
Aminopyralid	60	4.83	--[b]
Aminopyralid	120	8.44	--
Aminopyralid	240	14.00	--
Aminopyralid + diflufenzopyr	120 + 49	8.54	--
Picloram	560	48.80	--
Control	--	ND[c]	ND

[a] Soil samples collected May 11 and leaf samples September 16, 2009.

[b] Soybean were eliminated by all fall-applied treatments so leaf analysis could not be conducted.

[c] Abbreviation: ND = no detection (limit of detection: aminopyralid 0.12 μg/kg and picloram = 0.15 μg/kg).

Alfalfa was injured by aminopyralid and picloram when seeded 8 and 11 MAT (Table 11). Alfalfa injury from spring-applied treatments ranged from 2 to 50% 60 DAE with the most severe injury occurring when aminopyralid at 240 g/ha or aminopyralid plus diflufenzopyr at 120 plus 49 g/ha was applied. Alfalfa injury was 67% when aminopyralid at 60 g/ha was fall-applied compared to 95% or greater for all other fall-applied treatments.

Table 11. Effect of herbicide residue from treatments applied June 23 or September 26, 2008 on alfalfa seeded May 28, 2009 at Casselton.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	– g/ha –	—— % injury ——				– cm –	- plants/m -	– kg/ha –
Spring-applied								
Aminopyralid	60	5	4	2	2	35	33	1020
Aminopyralid	120	38	12	16	10	34	28	960
Aminopyralid	240	54	36	42	39	25	8	620
Aminopyralid + diflu	120 + 49	50	62	63	50	21	11	310
Picloram	560	36	26	48	27	32	23	700
Fall-applied								
Aminopyralid	60	59	45	73	67	23	9	220
Aminopyralid	120	86	94	96	95	8	3	10
Aminopyralid	240	94	98	99	99	1	1	0
Aminopyralid + diflu	120 + 49	92	93	97	96	8	1	30
Picloram	560	89	92	98	99	3	1	40
Control	--	0	3	4	0	33	23	890
LSD (0.05)		27	30	33	32	9	13	550

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Alfalfa height was reduced 36% (to 21 cm) from spring-applied aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, and 30 to nearly 100% from fall-applied aminopyralid and picloram treatments compared to the control (Table 11). Alfalfa stand density was reduced from spring-applied aminopyralid at 240 g/ha and from all fall-applied treatments. Alfalfa yield was reduced by 65% (to 310 kg/ha) from spring-applied aminopyralid plus diflufenzopyr at 120 plus 49 g/ha, by 76% from fall-applied aminopyralid at 60 g/ha, and by nearly 100% from all other fall-applied treatments compared to the control. Reduced yield as a result of aminopyralid and picloram residues tended to be associated with reduced population and plant height.

The aminopyralid plus diflufenzopyr treatment caused more alfalfa injury than aminopyralid alone when spring-applied at 120 g/ha (Table 11). For example, spring-applied aminopyralid plus diflufenzopyr caused 50% injury 60 DAE compared to only 10% when aminopyralid was applied alone. Alfalfa height, stand density, and yield also were reduced when diflufenzopyr was applied with aminopyralid. The aminopyralid concentration prior to planting was 1.75 µg/kg when spring-applied alone at 120 g/ha, and 1.19 µg/kg when aminopyralid plus diflufenzopyr at 120 plus 49 g/ha was applied (Table 10). Thus, aminopyralid soil residue alone does not account for the increased injury symptoms when diflufenzopyr was applied in combination with aminopyralid. Diflufenzopyr half-life in soil under field conditions was less than 4 d (Senesman 2007). Therefore, the cause of the increased injury due to the addition diflufenzopyr is unclear.

Corn was very tolerant to aminopyralid and picloram soil residue when planted 8 or 11 MAT (Table 12). Some minor injury was observed 30 DAE when aminopyralid was fall-applied at 240 g/ha, but corn recovered and no injury was observed for the remainder of the growing season from any treatment. Corn height, density, and yield were similar to the control when aminopyralid or picloram was spring- or fall-applied the previous growing season. Corn yield averaged 10,700 kg/ha across all herbicide treatments compared to 10,300 kg/ha in the control.

Soybean was severely injured by aminopyralid and picloram residues when planted 8 and 11 MAT (Table 13). Soybean injury ranged from 1 to 36% from spring-applied treatments and from 54 to 96% from fall-applied treatments 7 DAE. Injury tended to increase over time, and ranged from 15 to 100% 60 DAE. While injury increased with aminopyralid rate when spring-applied, fall-applied aminopyralid caused nearly 100% injury regardless of rate.

Table 12. Effect of herbicide residue from treatments applied June 23 or September 26, 2008 on corn seeded May 28, 2009 at Casselton.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	– g/ha –		% injury			– cm –	- plants/m -	- kg/ha -
Spring-applied								
Aminopyralid	60	0	0	0	0	217	6.3	9,600
Aminopyralid	120	0	0	0	0	223	6.3	10,600
Aminopyralid	240	1	0	2	0	219	6.2	10,400
Aminopyralid + diflu	120 + 49	0	0	0	0	222	6.6	12,300
Picloram	560	0	0	0	0	218	6.1	10,000
Fall-applied								
Aminopyralid	60	0	0	2	0	223	6.9	10,800
Aminopyralid	120	1	0	0	0	224	6.9	11,400
Aminopyralid	240	3	0	9	0	215	6.5	10,700
Aminopyralid + diflu	120 + 49	2	0	3	0	225	7.1	11,300
Picloram	560	0	0	4	0	231	6.5	9,900
Control	--	0	0	0	0	217	6.9	10,300
LSD (0.05)		NS	NS	2	NS	NS	NS	NS

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Soybean injury averaged 21% in the control 60 DAE (Table 13), even though no aminopyralid or picloram residues were detected in soil prior to planting or in soybean leaf tissue in mid-September (Table 10). Soybean growing in the control were assigned herbicide injury ratings greater than zero because the same soybean variety planted adjacent to study area were taller and much healthier than soybean growing in control plots. The reason for soybean injury in the control plots is not clear, but perhaps aminopyralid or picloram residues were present at concentrations below detection limits or the herbicides leached below the 0 to 15 cm sampling depth. Soybean injury tended to increase from 7 to 30 DAE in the control and spring-applied treatments. Roots were likely rapidly expanding during this period and increased herbicide absorption from below the 15 cm sampling depth may have contributed to the increased injury observed.

Table 13. Effect of herbicide residue from treatments applied June 23 or September 26, 2008 on soybean seeded May 28, 2009 at Casselton.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	– g/ha –	% injury				– cm –	- plants/m -	- kg/ha -
Spring-applied								
Aminopyralid	60	1	7	18	15	32	17.4	1,090
Aminopyralid	120	6	15	47	44	20	15.2	420
Aminopyralid	240	9	35	68	76	12	9.4	70
Aminopyralid + diflu	120 + 49	6	22	47	62	16	13.2	360
Picloram	560	36	46	67	67	13	9.8	240
Fall-applied								
Aminopyralid	60	54	72	95	97	3	1.1	0
Aminopyralid	120	83	86	96	100	0	0	0
Aminopyralid	240	97	96	100	100	0	0	0
Aminopyralid + diflu	120 + 49	83	89	98	100	0	0	0
Picloram	560	96	92	98	100	0	0	0
Control	--	0	8	22	21	29	14.8	740
LSD (0.05)		19	18	17	17	7	3.9	250

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Soybean height was reduced by almost all aminopyralid and picloram treatments when planted 8 or 11 MAT (Table 13). For example, spring-applied aminopyralid at 120 to 240 g/ha and fall-applied aminopyralid at 60 to 240 g/ha reduced average soybean height by 45 and 97% (to 16 cm and 1 cm), respectively, and picloram reduced soybean height by 55 (to 13 cm) and 100% when spring- and fall-applied, respectfully, compared to the control. Soybean density was reduced by spring-applied aminopyralid at 240 g/ha, spring-applied picloram at 560 g/ha, and by all fall-applied herbicide treatments. Spring-applied aminopyralid at 240 g/ha reduced density by 36% (to 9.4 plants/m) whereas fall-applied aminopyralid at 60 g/ha reduced stand density by 93% (to 1.1 plant/m) compared to the control (14.8 plants/m). Soybean height and stand reduction was similar from spring-applied aminopyralid at 240 g/ha and spring-applied picloram at 560 g/ha.

Fall-applied aminopyralid at 60 g/ha or greater completely eliminated soybean yield when planted the following growing season (Table 13). Spring-applied aminopyralid at 120 and 240 g/ha and aminopyralid plus diflufenzopyr at 120 plus 49 g/ha reduced soybean yield by 43, 91, and 51%, respectively, compared to the control (740 kg/ha). Soybean were killed when planted into soils with aminopyralid concentrations of 4.83 μg/kg or greater, and severely injured by aminopyralid concentrations of 1.19 μg/kg (Tables 10 and 13).

Soybean yield increased when aminopyralid was applied at 60 g/ha in the spring (1,090 kg/ha) compared to the control (740 kg/ha) (Table 13). The increased yield may have been caused by the auxinic properties of aminopyralid as crop growth and yield have been enhanced by small quantities of other auxin-type herbicides (Grossmann 2000; Thorsness 1987). The aminopyralid concentration in soybean leaf tissue was 4.43 μg/kg when aminopyralid at 60 g/ha was spring-applied (Table 10). Therefore, it appears that very small quantities of aminopyralid within soybean leaves could increase soybean yield. However, aminopyralid concentrations in soybean leaf tissue were 7.90 and 16.7 µg/kg when aminopyralid was spring-applied at 120 or 240 g/ha, respectively, and yield was reduced from those treatments by 43 and 91% compared to the control (Table 13).

Picloram at 560 g/ha reduced soybean yield by 68% when spring-applied, and by 100% when fall-applied compared to the control (Table 13). Thorsness and Messersmith (1991) reported picloram at 35 g/ha reduced soybean yield by 75% when planted 12 MAT in Fargo, ND. The picloram rate used in this study was 16-fold greater (560 compared to 35 g/ha), yet soybean yield reduction was less. The soil characteristics for both studies were similar, but precipitation for the remainder of application year was 8.9 cm below normal in the Thorsness and Messersmith study and 20.5 cm above normal in this study (Table 3). Increased soil moisture can decrease picloram persistence in soils (Hunter and Strobbe 1972; Youngson et al. 1967), so the above normal precipitation that occurred at Casselton in 2008 likely increased the rate of picloram dissipation.

Sunflower was injured from aminopyralid and picloram, but injury was much less when treatments were spring-applied than when fall-applied the previous growing season (Table 14). For example, sunflower injury 60 DAE averaged 17% when aminopyralid was spring-applied at 60 to 240 g/ha and 89% when fall-applied at the same rates. Sunflower injury averaged 18 and 70% when picloram was applied at 560 g/ha the previous spring or fall, respectively.

Sunflower height was reduced from spring-applied aminopyralid at 240 g/ha and by all fall-applied aminopyralid and picloram treatments (Table 14). Density was reduced an average of 75% (to 1.0 plant/m) by fall-applied aminopyralid at 60 to 120 g/ha compared to the control. Aminopyralid at 240 g/ha and aminopyralid plus diflufenzopyr at 120 plus 49 g/ha eliminated all sunflower when planted 8 MAT. Fall-applied picloram at 560 g/ha caused similar sunflower injury, height reduction, and yield reduction to fall-applied aminopyralid at 60 g/ha. Apparently, aminopyralid is more phytotoxic to sunflower than picloram when soil-applied the previous growing season as picloram rate was nine-fold greater than aminopyralid, but sunflower response was similar.

Table 14. Effect of herbicide residue from treatments applied June 23 or September 26, 2008 on sunflower seeded May 28, 2009 at Casselton.

		Days after emergence						
Treatments[a]	Rate	7	14	30	60	Height[b]	Density[b]	Yield
	— g/ha —		—— % injury ——			— cm —	- plants/m -	- kg/ha -
Spring-applied								
Aminopyralid	60	2	1	3	4	138	4.3	930
Aminopyralid	120	3	8	7	8	143	4.1	600
Aminopyralid	240	16	27	39	38	94	3.2	780
Aminopyralid + diflu	120 + 49	3	12	28	30	125	4.0	210
Picloram	560	1	6	14	18	133	4.7	610
Fall-applied								
Aminopyralid	60	10	61	80	74	47	2.6	20
Aminopyralid	120	55	82	89	94	10	0.5	0
Aminopyralid	240	83	91	96	99	1	0	0
Aminopyralid + diflu	120 + 49	57	84	93	96	5	0	0
Picloram	560	58	76	78	70	53	2.8	40
Control	--	0	0	0	2	143	4.0	1,000
LSD (0.05)		18	17	18	23	34	1.3	440

[a] Abbreviation: diflu = diflufenzopyr. Surfactant Activator 90 at 0.25% v/v was applied with all herbicide treatments, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

[b] Height and density measured 60 days after emergence.

Sunflower yield was reduced by 79% from spring-applied aminopyralid plus diflufenzopyr at 120 plus 49 g/ha (to 210 kg/ha) but was similar to the control (1,000 kg/ha) when aminopyralid at 60 to 240 and picloram at 560 g/ha were spring-applied (Table 14). Yield was reduced an average of 99% when aminopyralid or picloram was applied in the fall of the previous growing season.

The addition of diflufenzopyr at 49 g/ha with aminopyralid at 120 g/ha tended to increase injury and reduce sunflower yield compared aminopyralid at 120 g/ha alone when spring-applied (Table 14). A similar response was observed in alfalfa (Table 11). No diflufenzopyr residue should have remained in the soil 8 MAT (EPA 1999), so the cause of the increased crop injury is unclear. Diflufenzopyr is an auxin-transport inhibitor that can improve efficacy of some auxin herbicides (Grossmann et al. 2002), so perhaps diflufenzopyr or a diflufenzopyr metabolite remained in the soil at very low concentrations and resulted in increased aminopyralid activity in the crops.

Alfalfa, soybean, and sunflower yields were reduced by spring-applied aminopyralid at 120 g/ha alone or in combination with diflufenzopyr at 49 g/ha when seeded 11 MAT (Tables 11, 13, and 14). Therefore, alfalfa and sunflower should not be planted until at least the second growing season after aminopyralid treatment. Since soybean was very sensitive to aminopyralid residue, two or more growing seasons may be needed to degrade aminopyralid before soybean can safely be planted. Corn was very tolerant to aminopyralid residues as yield was not affected even when aminopyralid at 240 g/ha was fall-applied 8 mo prior to planting (Table 12). Corn is likely one of the safest planting options on land recently treated with aminopyralid, although the current aminopyralid label requires a 12 month re-cropping interval between application and corn planting (Anonymous 2008).

Climatic Influences on Aminopyralid Dissipation in Soil

Temperature. Aminopyralid dissipation in soil generally increased as temperature increased and the most rapid dissipation occurred at 24 C regardless of soil type (Table 15). For example, aminopyralid dissipated approximately 8 times faster at 24 C than at 8 C in the Lamoure loamy sand and Svea-Barnes loam. Aminopyralid DT_{50} ranged from 9 d in the Svea-Barnes loam at 24 C to 256 d in the Lamoure loamy sand at 8 C.

Table 15. Effect of temperature on aminopyralid dissipation in four soils 28 DAT which contained 52 µg/kg held at 45% field capacity.

Soil / temperature (C)	Aminopyralid concentration[a]	DT_{50}[b]
	µg/kg	d
Fargo-Ryan silty clay		
8	37.7 a	60
16	36.6 a	55
24	28.1 b	32
Glendive-Havre clay		
8	47.8 a	229
16	46.2 a	165
24	40.3 a	76
Lamoure loamy sand		
8	48.2 a	256
16	42.4 a	95
24	29.9 b	34
Svea-Barnes loam		
8	39.7 a	72
16	33.9 a	45
24	6.3 b	9
Combined soils		
8	43.4	107
16	39.8	72
24	26.2	28

[a] Aminopyralid concentrations followed by the same letter(s) within each soil are not significantly different according to probability of difference ($p < 0.10$).

[b] Abbreviation: DT_{50} = time for 50% dissipation.

Aminopyralid dissipation varied by soil type. For instance, at 24 C the aminopyralid DT_{50} in Svea-Barnes loam was 9 d, compared to 32, 76, and 34 d in the Fargo-Ryan silty clay, Glendive-Havre clay, and Lamoure loamy sand, respectively (Table 15). The Svea-Barnes loam had a high organic matter content (64 g/kg) that may have supported a greater microbial population than the other soils evaluated. Since aminopyralid is degraded in soil primarily by microbially-mediated metabolism (EPA 2005a), soil conditions that favor microbial activity such as warm temperatures, adequate moisture, and high organic matter content should also increase aminopyralid degradation. The Svea-Barnes loam had a pH of 5.7 compared to pH 7.6 or greater for the other three soils. Soil pH is not believed to impact aminopyralid persistence (EPA 2005b), but may have affected the type of microbes in the soil.

The increased dissipation of aminopyralid in soil as temperature increased was expected. Temperature also was an important factor in dissipation of other pyridinecarboxylic herbicides. Guenzi and Beard (1976) reported picloram dissipation occurred very slowly at 5 C, gradually increased at 25 C, and was most rapid at 30 C. In a separate study, picloram dissipation in soil increased 10- to 25-fold when temperature increased from 2 to 34 C (Youngson et al. 1967). Clopyralid DT_{50} in soil incubated at 10 C was 46.2 d compared to 7.3 and 4.1 d at 20 and 30 C, respectively (Ahmad et al. 2003). The increased clopyralid and picloram dissipation at warmer temperatures was attributed to increased microbiological activity (Ahmad et al. 2003; Guenzi and Beard 1976; Youngson et al. 1967).

Although an interaction occurred between soils in the combined analysis, the combined data are presented to demonstrate the general trend of increased aminopyralid dissipation at warmer temperatures (Table 15). Aminopyralid DT_{50} values averaged over all four soils were 106.7, 72.4, and 28 d at 8, 16, and 24 C, respectively, when incubated at 45% FC. Aminopyralid dissipation under field conditions would likely be minimal during late-fall, winter, and early-spring when soil temperatures are near 0 C. Therefore, aminopyralid would probably persist much longer in colder Northern climates than in areas with warm year-round temperatures.

Moisture. Aminopyralid dissipation rates in soil were similar among moisture levels from 22.5 to 90% FC when incubated at 16 C (Table 16). However, dissipation tended to occur slower in soils with high water content (90% FC), compared to soils aged at 22.5 and 45% FC. For instance, the aminopyralid concentration after 28 d in the Svea-Barnes loam at 90% FC decreased only to 51.9 μg/kg (from 52 μg/kg) whereas the aminopyralid concentration in the same soil that contained 22.5 and 45% FC decreased to 35.5 and 33.1 μg/kg, respectively. The 90% FC soils likely were nearly anaerobic so microbiological activity may have been oxygen-limited. Since aerobic microbial degradation is the primary method of aminopyralid dissipation in soil, aminopyralid degradation in saturated soils is believed to be minimal (EPA 2005a).

Aminopyralid dissipation tended to be slowest in the Glendive-Havre clay with DT_{50} ranging from 114 to 198 d when aged at 22.5 to 90% FC (Table 16). The low organic matter content (12 g/kg) may have limited microbiological activity and thus decreased dissipation rates compared to the silty clay and loam soils evaluated. Aminopyralid K_d averaged only 0.03 ml/g in two clay soils (EPA 2005a), so little aminopyralid adsorption likely occurred in the Glendive-Havre clay evaluated in this study.

Table 16. Effect of moisture on aminopyralid dissipation in four soils 28 DAT which contained 52 μg/kg held at 16 C.

Soil / Moisture content (% FC[a])	Aminopyralid concentration[b]	DT_{50}[a]
	—— μg/kg ——	—— d ——
Fargo-Ryan silty clay		
22.5	37.5 a	59
45	40.3 a	76
90	40.8 a	80
Glendive-Havre clay		
22.5	43.8 a	114
45	46.6 a	177
90	47.1 a	198
Lamoure loamy sand		
22.5	38.2 a	63
45	39.0 a	67
90	49.0 a	323
Svea-Barnes loam		
22.5	35.5 b	51
45	33.1 b	43
90	51.9 a	>365
Combined soils		
22.5	38.8 a	66
45	39.8 a	72
90	47.2 a	200

[a] Abbreviation: FC = field capacity; DT_{50} = time for 50% dissipation.

[b] Aminopyralid concentrations followed by the same letter within each soil are not significantly different according to probability of difference ($p < 0.10$).

Aminopyralid dissipation rates were similar across moisture levels when averaged over all four soils (Table 16). Aminopyralid DT_{50} averaged 66, 72, and 200 d when incubated at 22.5, 45, and 90% FC, respectively. The moisture difference between 22.5 and 90% FC may not have been large enough to affect microbial dissipation of aminopyralid. Picloram dissipation rates were nearly constant as soil moisture decreased from field capacity to 15 bars which indicated microorganisms were equally effective in dissipating picloram if adequate water was available (Guenzi and Beard 1976). However, no picloram dissipation occurred in air-dried soils (Guenzi and Beard 1976) and clopyralid did not dissipate when aged in three soils at 10% FC (Baloch and Grant 1991).

Aminopyralid dissipation rates may have decreased in very dry or wet soils, but the moisture range evaluated in this study may not have been enough to affect microbiological activity. Future studies should evaluate aminopyralid persistence when aged at a wider range of moisture regimes including air-dried and saturated soils to determine how dissipation is affected in extreme situations.

The initial rate of 52 µg/kg may have affected soybean bioassay precision since soybean were severely injured when seeded into soils with aminopyralid at 52 µg/kg. Soybean growth was reduced in standard curve soils that contained much lower aminopyralid concentrations, even 6 µg/kg (data not shown). Thus, future studies should utilize lower aminopyralid standard curve rates such as 4 to 32 µg/kg for maximum sensitivity.

The aminopyralid DT_{50} determined in these studies were nearly identical when comparing aminopyralid dissipation at the same temperatures and moistures (Tables 15 and 16) and were consistent with results reported for aminopyralid registration with the EPA (EPA 2005a). The aminopyralid DT_{50}, averaged across soils, was 72 d in both the temperature and moisture studies when incubated at 16 C and 45% FC (Tables 15 and 16). In comparison, aminopyralid DT_{50} was 103.5 d in a silt loam soil when incubated in the dark at 25 C and 75% FC in a laboratory study and averaged 34.5 d in field persistence studies (EPA 2005a). Warmer temperatures favored aminopyralid dissipation while degradation rates were similar when soil was incubated in moderate moisture contents

(22.5 to 90% FC). Other important factors that may affect soil microbiological populations, and hence aminopyralid dissipation, include soil texture and organic matter content.

Prairie Forb Susceptibility to Aminopyralid

Prairie forb susceptibility to aminopyralid varied by species (Tables 17, 18, and 19). Of the forbs evaluated, purple coneflower, azure aster, and showy goldenrod were the most tolerant to aminopyralid while prairie coneflower, white prairie clover, and harebell were the most susceptible. Forb species that were tolerant to aminopyralid in the greenhouse likely would be tolerant in the field as well because steps were taken to maximize potential injury. Aminopyralid was applied at the maximum labeled field use rate (120 g/ha) to plants at or near the flowering stage, a non-ionic surfactant was included, and plants were well-spaced when treated to ensure a complete spray coverage.

Blanket flower was moderately tolerant to aminopyralid (Table 17). Injury averaged 11, 25, and 23% 10 WAT when aminopyralid was applied at 30, 60, and 120 g/ha, respectively. Blanket flower regrowth averaged 0.8 g when plants were treated with aminopyralid at 30 to 120 g/ha, compared to 1.4 g regrowth of the untreated control. Although slightly injured, blanket flower likely would have recovered by the following growing season because almost all plants remained green 10 WAT.

Prairie coneflower was susceptible to aminopyralid at all rates evaluated (Table 17). Prairie coneflower injury increased as aminopyralid rate increased and ranged from 5 to 44% 2 WAT and from 75 to 100% 7 WAT. Aminopyralid caused leaf and stem epinasty and eventually chlorosis and necrosis. There was no regrowth when aminopyralid was applied at 60 or 120 g/ha. Regrowth averaged 0.4 g when aminopyralid was applied at 30 g/ha, compared to 1.7 g regrowth of the untreated control. Similar prairie coneflower injury was reported by Samuel and Lym (2008) following aminopyralid treatment to a western North Dakota native plant community.

Table 17. Blanket flower, prairie coneflower, and purple coneflower injury and regrowth following aminopyralid treatment in the greenhouse.

		Blanket flower			Prairie coneflower			Purple coneflower		
		Injury/WAT[a]			Injury/WAT			Injury/WAT		
Treatment[b]	Rate	2	7	Weight	2	10	Weight	2	7	Weight
	g/ha	—— % ——		– g –	—— % ——		– g –	—— % ——		– g –
Amino[a]	30	7	11	1.4	5	75	0.4	21	1	5.4
Amino	60	21	25	0.5	34	96	0	24	6	3.7
Amino	120	28	23	0.6	44	100	0	32	14	3.4
Untreated	---	0	0	1.4	0	0	1.7	0	0	5.1
LSD (0.05)		9	16	NS	NS	20	1.1	NS	NS	NS

[a] Abbreviations: WAT = weeks after treatment; Amino = aminopyralid.

[b] Surfactant Activator 90 at 0.25% v/v was applied with aminopyralid, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

Purple coneflower was tolerant to aminopyralid regardless of rate evaluated (Table 17). Purple coneflower injury averaged 26% 2 wk after aminopyralid was applied at 30 to 120 g/ha. Injury decreased by 7 WAT and ranged from 1 to 14%. Purple coneflower regrowth averaged 4.2 g for plants treated with aminopyralid at 30 to 120 g/ha, compared to 5.1 g regrowth of the untreated control. Aminopyralid likely will not harm purple coneflower in the long-term, although some slight epinasty and leaf distortion may occur in weeks following treatment.

Azure aster was tolerant to aminopyralid regardless of application rate (Table 18). Injury from aminopyralid was 8% or less 2 WAT and averaged only 1% 9 WAT. Some slight flower deformation was observed after aminopyralid treatment, but all treated plants remained green and healthy throughout the study duration. Regrowth averaged 0.5 g for plants treated with aminopyralid, compared to 0.9 g regrowth in untreated control. Bolting tended to be delayed in treated plants, and this may have contributed to the slightly reduced regrowth weights.

Table 18. Azure aster, closed bottle gentian, and showy goldenrod injury and regrowth following aminopyralid treatment in the greenhouse.

		Azure aster			Closed bottle gentian[a]			Showy goldenrod		
		Injury/WAT[b]			Injury/WAT			Injury/WAT		
Treatment[c]	Rate	2	9	Weight	2	10	Weight	2	10	Weight
	g/ha	— % —		— g —	— % —		— g —	— % —		— g —
Amino[b]	30	3	1	0.6	10	1	1.1	9	5	0.7
Amino	60	3	1	0.5	11	4	0.8	13	3	0.6
Amino	120	8	1	0.4	22	28	0.4	17	10	0.2
Untreated	---	0	0	0.9	0	0	0.7	0	0	1.2
LSD (0.05)		NS	NS	NS	7	13	NS	NS	NS	NS

[a] Only one run of closed bottle gentian was evaluated.

[b] Abbreviations: WAT = weeks after treatment; Amino = aminopyralid.

[c] Surfactant Activator 90 at 0.25% v/v was applied with aminopyralid, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

Although azure aster was tolerant to aminopyralid in this study, similar Asteraceae species have exhibited variable tolerance to aminopyralid in the field. Foliar cover of white panicled aster (*Aster simplex* Willd.) was reduced by aminopyralid 10 MAT in a western Minnesota prairie (Almquist and Lym 2010), while heath aster [*Aster ericoides* (L.) Nesom] foliar cover was not reduced 10 or 22 mo after aminopyralid treatment in western North Dakota (Samuel and Lym 2008).

Closed bottle gentian was moderately tolerant to aminopyralid applied at 30 to 120 g/ha (Table 18). Injury tended to increase with aminopyralid rate and ranged from 10 to 22% 2 WAT and from 1 to 28% 10 WAT. Regrowth of plants treated with aminopyralid at 30 to 120 g/ha was similar to the untreated control and averaged 0.8 g, compared to 0.7 g in the untreated control. Aminopyralid likely will not adversely affect closed bottle gentian in the long-term.

Showy goldenrod was tolerant to aminopyralid at all rates evaluated (Table 18). Injury ranged from 9 to 17% 2 WAT and 3 to 10% 10 WAT. Showy goldenrod regrowth averaged 0.5 g for plants treated with aminopyralid, compared to untreated control regrowth of 1.2 g. All plants remained lush green after aminopyralid treatment, but regrowth was slightly delayed and leaf morphology was affected in some treated plants.

Aminopyralid injured other *Solidago* species in field studies. Aminopyralid applied in the fall at 120 g/ha reduced foliar cover of Canada goldenrod (*Solidago canadensis* L.) and Missouri goldenrod (*Solidago missouriensis* Nutt.) 22 MAT in prairie plant communities in Minnesota (Almquist and Lym 2010) and North Dakota (Samuel and Lym 2008). Velvety goldenrod (*Solidago mollis* Bartl.) foliar cover was reduced by more than 75% compared to the untreated control 10 mo after aminopyralid was applied (Almquist and Lym 2010). Perhaps these species were more sensitive to aminopyralid than showy goldenrod, or they had not had enough time to fully recover by 10 or 22 MAT.

Great blue lobelia was susceptible to aminopyralid (Table 19). Injury from aminopyralid at 30 to 120 g/ha averaged 60% 2 WAT and 76% 8 WAT. Regrowth was reduced by aminopyralid to 0.2 g or less, compared to 0.8 g regrowth of the untreated control. Aminopyralid affected flower morphology and caused considerable epinasty. Stems turned purple within 2 WAT and some callus lesions were observed near the stem base. Although aminopyralid caused severe injury to great blue lobelia, most plants remained living 7 WAT so the species may have been able to recover over time.

Palespike lobelia (*Lobelia spicata* Lam.) was susceptible, but not killed by aminopyralid at 120 g/ha in a Minnesota field study (Almquist and Lym 2010). Palespike lobelia foliar cover was reduced by 67% 10 MAT, and cover continued to be less than the untreated control 22 MAT. Although foliar cover was reduced, aminopyralid did not eliminate the plant from the prairie community even when applied at the maximum use rate.

Table 19. Great blue lobelia, harebell, and white prairie clover injury and regrowth following aminopyralid treatment in the greenhouse.

		Great blue lobelia			Harebell			White prairie clover		
		Injury/WAT[a]			Injury/WAT			Injury/WAT		
Treatment[b]	Rate	2	8	Weight	2	10	Weight	2	7	Weight
	g/ha	— % —		— g —	— % —		— g —	— % —		— g —
Amino[a]	30	51	73	0.2	50	95	0	54	95	0
Amino	60	55	76	0.1	83	100	0	64	99	0
Amino	120	73	78	0.1	88	99	0	69	100	0
Untreated	---	0	0	0.8	0	0	0.7	0	0	0.4
LSD (0.05)		28	14	0.5	49	12	0.4	15	7	0.1

[a] Abbreviations: WAT = weeks after treatment; Amino = aminopyralid.

[b] Surfactant Activator 90 at 0.25% v/v was applied with aminopyralid, United Agri Products, 7251 W. 4th St., Greeley, CO 80643.

Harebell was very sensitive to aminopyralid (Table 19). Injury ranged from 50 to 88% 2 WAT and from 95 to 100% 7 WAT. Harebell did not regrow after treatment with aminopyralid regardless of application rate, while untreated control regrowth averaged 0.7 g. Almost all treated plants were completely dead by 7 WAT even when aminopyralid was applied at 30 g/ha.

White prairie clover was very susceptible to aminopyralid at all rates evaluated. Injury ranged from 54 to 69% 2 WAT and was 95% or greater 10 WAT (Table 19). Leaves of treated plants were mostly yellow or brown by 2 WAT. White prairie clover did not regrow after treatment with aminopyralid while the untreated control regrowth averaged 0.4 g.

White prairie clover is in the Fabaceae family which is known to be very susceptible to aminopyralid (Almquist and Lym 2010; Becker and Haar 2008; Samuel and Lym 2008). Aminopyralid reduced purple prairie clover (*Dalea purpurea* Vent) foliar cover by approximately 95% 22 MAT (Almquist and Lym 2010). In the same study, aminopyralid tended to reduce white prairie clover foliar cover 10 and 22 MAT, although the reduction was not statistically significant due to uneven distribution. Round-headed bush clover (*Lespedeza capitata* Michx.) and silky prairie clover (*Petalostemum villosum* Nutt.) were adversely affected by aminopyralid as well (Becker and Haar 2008).

Aminopyralid likely will not have a long-term affect on purple coneflower, closed bottle gentian, blanket flower, azure aster, or showy goldenrod. However, aminopyralid severely injured or killed harebell, white prairie clover, great blue lobelia, and prairie coneflower when applied at rates as low as 30 g/ha. Caution is advised when treating invasive weeds with aminopyralid if preservation of these species is important.

Most species included in this study had not or could not be evaluated in the field for aminopyralid tolerance because of their rarity or tendency to grow singularly in the wild. Since the results of this study closely followed the results of similar species in the field, these data could be used to estimate tolerance of these particular species to aminopyralid. This information is valuable to land managers, who must balance the benefits of an aminopyralid application to control invasive weeds with the potential of unintentional injury to desirable plant species.

SUMMARY

Aminopyralid is commonly applied on CRP land to control invasive weeds. As CRP land is returned to crop production, aminopyralid residue could injure sensitive crops if planted too soon after treatment. Field bioassay studies were conducted near Fargo and Casselton, North Dakota to evaluate crop susceptibility to aminopyralid soil residue when planted one or two growing seasons after treatment. Alfalfa, corn, and sunflower were not injured by aminopyralid residue when planted 20 or 23 MAT in Fargo. However, soybean yield was reduced when aminopyralid was spring- or fall-applied at 120 and 240 g/ha. Since yield was reduced in soils by aminopyralid concentrations of less than 0.10 μg/kg, soybean should not be planted for at least three growing seasons after treatment or until all aminopyralid residue is degraded.

In Casselton, aminopyralid concentration in the soil prior to planting ranged from 0.8 to 2.29 μg/kg when aminopyralid was applied at 60 to 240 g/ha in the spring, and 4.83 to 14.0 when fall-applied at the same rates. Corn yield was not affected by aminopyralid residue regardless of application timing or rate and may be a safe planting option for eastern North Dakota soils that were recently treated with aminopyralid. However, aminopyralid injured alfalfa, soybean, and sunflower when planted 8 and 11 MAT. Injury and yield reduction was much less from spring-applied treatments than from treatments applied in the fall. The summer months appear to be very important for degradation of aminopyralid. Alfalfa and sunflower should not be planted within a year after aminopyralid application in eastern North Dakota, but these crops may be safe options if planted 20 or 23 MAT in highly organic soils.

The effect of temperature and moisture content on aminopyralid dissipation was determined in clay, loam, loamy sand, and silty clay soils collected near Medora, Jamestown, Walcott, and Fargo, North Dakota, respectively. The aminopyralid dissipation rate increased 2- to 8-fold as temperature increased from 8 to 24 C. Warm soil temperatures and high organic matter contents likely favored microbiological metabolism of aminopyralid. Moisture levels of 22.5 to 90% FC had little impact on aminopyralid dissipation, although aminopyralid tended to dissipate slower at 90% FC than at 22.5 or 45% FC.

The average aminopyralid DT_{50} was 72 d when soils were incubated with 45% FC at 16 C. Aminopyralid would likely be degraded more rapidly in warm moist climates of the southeastern United States than in cooler dryer climates of the upper Midwest. Also, soils in North Dakota generally are very cold or frozen from late October through early April so minimal aminopyralid degradation would be expected to occur during this time.

Prairie forb susceptibility to aminopyralid varied by species in greenhouse trials. Purple coneflower, closed bottle gentian, blanket flower, azure aster, and showy goldenrod were tolerant or moderately tolerant to aminopyralid at the maximum field use rate (120 g/ha), while harebell, white prairie clover, great blue lobelia, and prairie coneflower were severely injured or killed by aminopyralid at rates as low as 30 g/ha. Since measures were taken to maximize potential injury, species tolerant to aminopyralid in the greenhouse likely would be tolerant in the field as well.

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. Environ. Sci. Health B38:683-695.

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

Almquist, T. L., and R. G. Lym. 2010. Effect of aminopyralid on Canada thistle (*Cirsium arvense*) and the native plant community in a restored tallgrass prairie. Inv. Plant Sci. Manage. 3:(in press).

Anonymous. 2005. Aminopyralid technical bulletin. Dow AgroSciences Publication No. V45-313-001. Indianapolis, IN: Dow AgroSciences. 19 p.

Anonymous. 2008. Milestone® label. Dow AgroSciences. [Online]. http://www.cdms.net/LDat/ld77N006.pdf. Accessed: October 9, 2009.

Anonymous. 2009. Tordon 22K® label. Dow AgroSciences. [Online]. http://www.cdms.net/ldat/ld0AJ013.pdf. Accessed: December 2, 2009.

Arnold, D.J.S. 1995. Movement of pesticides to non-target areas. Pages 116-126 *in* N. N. Ragsdale, P. C. Kearny, and J. R. Plimmer, eds. Eighth International Congress of Pesticide Chemistry: Options 2000. IUPAC Conf. Proc. Ser. Washington, DC: American Chemical Society 450 p.

Baloch, R. I. and R. K. Grant. 1991. The effect of a range of environmental factors on the degradation rate of clopyralid in soil under aerobic conditions. Brighton Crop Protection Conference–Weeds. 2:521-528.

Becker, R. and M. Haar. 2008. Minnesota rankings for native forb tolerance to aminopyralid and clopyralid herbicides. Minnesota Extension Service. http://appliedweeds.cfans.umn.edu/pubs/Forb%20Tolerance%20to%20Aminopyralid%20and%20Clopyralid%20Herbicides.pdf. Accessed: February 16, 2010.

Bodo Slotta, T. A., J. M. Rothhouse, D. P. Horvath, and M. E. Foley. 2006. Genetic diversity of Canada thistle (*Cirsium arvense*) in North Dakota. Weed Sci. 54:1080-1085.

Bukun, B., T. A. Gaines, 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.

Carrithers, V. F., P. L. Burch, W. N. Kline, R. A. Masters, J. A. Nelson, M. B. Halstvedt, J. L. Troth, and J. M. Breuninger. 2005. Aminopyralid: A new reduced risk active ingredient for control of broadleaf invasive and noxious weeds. Proc. West. Soc. Weed Sci. 58:59-60.

Cruttwell-McFadyen, R. E. 1998. Biological control of weeds. Annu. Rev. Entomol. 43:369-393.

Donald, W. W. 1990. Management and control of Canada thistle (*Cirsium arvense*). Rev. Weed Sci. 5:193-250.

Donald, W. W. 1993. Retreatment with fall-applied herbicides for Canada thistle (*Cirsium arvense*) control. Weed Sci. 41:434-440.

Doublet, J., L. Mamy, and E. Barriuso. 2009. Delayed degradation in soil of foliar herbicides glyphosate and sulcotrione previously absorbed by plants: Consequences on herbicide fate and risk assessment. Chemosphere 77:582-589.

Duncan, C., A. Kulla, and M. Halstvedt. 2008. Effect of aminopyralid on non-target vegetation following aerial application. Proc. West. Soc Weed Sci. 61:34-35.

Durkin, P. R. 2007. Human health and ecological risk assessment – Final Report. http://www.fs.fed.us/foresthealth/pesticide/pdfs/062807_Aminopyralid.pdf. Accessed: December 10, 2009.

Enloe, S. F., R. G. Lym, R. W. 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. 1999. Diflufenzopyr pesticide tolerance 1/99. Federal Register 64:4301-4308. http://www.epa.gov/EPA-PEST/1999/January/Day-28/p1901.htm. Accessed: February 15, 2010.

[EPA] Environmental Protection Agency. 2005a. Environmental fate and ecological risk assessment for the registration of aminopyralid. http://www.epa.gov/opprd001/factsheets/aminopyralidEFEDRA.pdf. Accessed: March 28, 2010.

[EPA] Environmental Protection Agency. 2005b. Pesticide fact sheet: aminopyralid. http://www.epa.gov/opprd001/factsheets/aminopyralid.pdf. Accessed: March 21, 2009.

Gardner, W. H. 1986. Water Content. p. 493-544. *in* A. Klute (ed.) Methods of soil analysis: Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gordon, D. R. 1998. Effects of invasive, non-indigenous plant species on ecosystem processes: lessons from Florida. Ecol. App. 8:975-989.

Goring, C.A.I., C. R. Youngson, and J. W. Hamaker. 1965. Tordon herbicide disappearance from soils. Down to Earth 20(4):3-5.

Grossman, K., G. Caspar, J. Kwiatkowaski, and S. J. Bowe. 2002. On the mechanism of selectivity of the corn herbicide BAS 662H: a combination of the novel auxin transport inhibitor diflufenzopyr and the auxin herbicide dicamba. Pest Manage. Sci. 58:1002-1014.

Grossmann, K. 2000. Mode of action of auxin herbicides: a new ending to a long, drawn out story. Trends Plant Sci. 5:506-508.

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, J. C., H. D. Bestman, M. D. Devine, and W. H. Vanden Born. 1985. Contribution of soil spray deposit from postemergence herbicide applications to control of Canada thistle (*Cirsium arvense*). Weed Sci. 33:836-839.

Halstvedt, M. B. and P. M. Rice. 2009. Plant community response to aminopyralid. Proc. West. Weed Sci. 62:41-42.

Hare, D. D., A. G. McFadden, W. R. McGregor, L. T. Juras, N. M. Satchivi, and G. C. Turnbull. 2005. Aminopyralid: a new herbicide for broadleaf weed control in rangeland and pastures in Canada and United States. Proc. West. Soc. Weed Sci. 58:59.

Helling, C. S. 2005. The science of soil residual herbicides. Pages 3-22 *in* R. C. Van Acker, ed. Soil Residual Herbicides: Science and Management. Topics in Canadian Weed Science, Vol. 3, Sainte-Anne-de-Bellevue, Quebec: Canadian Weed Science Society. 125 pp.

Herr, D. E., E. W. Stroube, and D. A. Ray. 1966. The movement and persistence of picloram in soil. Weeds 14:248-250.

Hiltbold, A. E. 1974. Persistence of pesticides in soil. Pages 203-222 *in* W. D. Guenzi ed. Pesticides in Soil and Water. Madison, WI: Soil Science Society of America. 562 pp.

Hunter, J. H. and E. H. Stobbe. 1972. Movement and persistence of picloram in soil. Weed Sci. 20:486-488.

Jachetta, J. J., P. L. Havens, J. A. Dybowski, J. A. Kranzfelder, and C. Tiu. 2005. Aminopyralid: A new reduced risk herbicide for invasive species control: toxicology, ecotoxicology and environmental fate profile. Proc. West. Soc. Weed Sci. 58:60-61.

Jewett, J. G., C. C. Scheaffer, R. D. Moon, N. P. Martin, D. K. Barnes, D. D. Breitbach, and N. R. Jordan. 1996. A survey of CRP land in Minnesota. II. Weeds on CRP land. J. Prod. Agric. 9:535-542.

Johnsen, T. N., Jr. and R. D. Martin. 1983. Altitude effects on picloram disappearance in sunlight. Weed Sci. 31:315-317.

Jotcham, J. R., D. W. Smith, and G. R. Stephenson. 1989. Comparative persistence and mobility of pyridine and phenoxy herbicides in soil. Weed Technol. 3:155-161.

Keys, C. H. and H. A. Friesen. 1968. Persistence of picloram activity in soil. Weed Sci. 16:341-343.

Lym, R. G. 2005. Control of invasive weeds with aminopyralid in North Dakota. Proc. West. Soc. Weed Sci. 58:60.

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

Lym, R. G. and K. J. Deibert. 2005. Diflufenzopyr influences leafy spurge (*Euphorbia esula*) and Canada thistle (*Cirsium arvense*) control by herbicides. Weed Technol. 19:329-341.

Lym, R. G. and C. L. Duncan. 2005. Canada thistle (*Cirsium arvense* L. Scop.). Pages 69-83 *in* C. L. Duncan and J. K. Clark, eds. Invasive Plants of Range and Wildlands and Their Environmental, Economic, and Societal Impacts. Lawrence, KS: Weed Science Society of America. 222 pp.

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

Masters, R. A., P. L. Burch, V. Carrithers, and M. B. Halstvedt. 2005. Control of musk thistle and other biennial thistles with aminopyralid. Proc. West. Soc. Weed Sci. 58:62-63.

Meikle, R. W., C. R. Youngston, R. T. Hedlund, C.A.I. Goring, and W. W. Addington. 1974. Decomposition of picloram by soil microorganisms: a proposed reaction sequence. Weed Sci. 22:263-268.

Merkle, M. G., R. W. Bovey, and F. S. Davis. 1967. Factors affecting the persistence of picloram in soil. Agron. J. 59:413-415.

Mullison, W. R. 1985. A toxicological and environmental review of picloram. Proc. West. Soc. Weed Sci. 38:21-92.

Nissen, S. J., K. G. Beck, P. Westra, R. Lym, R. G. Wilson, L. Wrage, S. Enloe, V. Carrithers, R. A. Masters, and M. Halstvedt. 2006. Canada thistle control with Milestone^{TM}. Proc. West. Soc. Weed Sci. 59:63.

Paul, E. A. and F. E. Clark. 1989. Dynamics of residue decomposition and soil organic matter turnover. Pages 115-130 *in* Soil Microbiology and Biochemistry. San Diego, CA: Academic Press.

Peterson, V. F., M. B. Halstvedt, and R. G. Lym. 2009. Controlling Canada thistle with aminopyralid in mowed and non-mowed sites. Proc. West. Soc. Weed Sci. 62:38.

Phillips, W. M and K. C. Feltner. 1972. Persistence and movement of picloram in two Kansas soils. Weed Sci. 20:110-116.

Pik, A. J., E. Peake, M. T. Strosher, and G. W. Hodgson. 1977. Fate of 3,6-dichloropicolinic in soils. J. Agric. Food Chem. 25:1054-1061.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. BioScience 50:53-65.

Ralphs, M. H. 1995. Long term change in vegetation following herbicide control of larkspur. J. Range Manage. 48:459-464.

Rinella, M. J., M. L. Pokorny, and R. Rekaya. 2007. Grassland invader responses to realistic changes in native species richness. Ecol App. 17:1824-1831.

Samuel, L. W. 2007. Aminopyralid effect on Canada thistle (*Cirsium arvense*) and native plants in western North Dakota. Ph.D. dissertation. Fargo, ND: North Dakota State University. 92 p.

Samuel, L. W. and R. G. Lym. 2008. Aminopyralid effects on Canada thistle (*Cirsium arvense*) and native plant species. Inv. Plant Sci. Manage. 1:265-278.

Scifres, C. J., O. C. Burnside, and M. K. McCarty. 1969. Movement and persistence of picloram in pasture soils of Nebraska. Weed Sci. 17:486-488.

Sebastian, J. R. and K. G. Beck. 2008. Broadleaf herbicide effects on established native forbs, shrubs, and grasses. Proc. West. Soc. Weed Sci. 61:25-26.

Senseman, S. A., ed. 2007. Herbicide Handbook. 9th ed. Lawrence, KS: Weed Science Society of America. p. 331, 333, 353, and 362.

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.

Sharma, M. P. and W. H. Vanden Born. 1973. Uptake, cellular distribution, and metabolism of 14C-picloram by excised plant tissues. Physiol. Plantarum 29:10-16.

Shaw, R. H. and J. E. Newman. 1991. National corn handbook: weather stress in the corn crop. West Lafayette, IN: Purdue University Coop. Ext. Ser. Bull. NCH-18. http://www.ces.purdue.edu/extmedia/NCH/NCH-18.html. Accessed March 30, 2010.

Sleugh, B. S, M. Halsvedt, R. Lym, R. G. Wilson, and M. Meochnig. 2009a. Using aminopyralid to widen the fall application window on Canada thistle. Proc. West. Soc. Weed Sci. 62:40.

Sleugh, B. S., V. F. Peterson, M. Halstvedt, T. D. Whitson, S. A. Dewey, R. G. Lym, S. Z. Knezevic, K. Patten, and J. M. DiTomaso. 2009b. Aminopyralid: new efficacy research on noxious and invasive weeds. Proc. West. Soc. Weed Sci. 62:27.

Thorsness, K. B. 1987. Clopyralid persistence in soil. M.S. thesis. Fargo, ND: North Dakota State University. 45 p.

Thorsness, K. B. and C. G. Messersmith. 1991. Clopyralid influences rotational crops. Weed Technol. 5:159-164.

Travnicek, A. J., R. G. Lym, and C. Prosser. 2005. Fall-prescribed burn and spring-applied herbicide effects on Canada thistle control and soil seedbank in a northern mixed-grass prairie. Rangeland Ecol. Manage. 58:413-422.

Turnbull, G. C. and G. R. Stephenson. 1985. Translocation of clopyralid and 2,4-D in Canada thistle (*Cirsium arvense*). Weed Sci. 33:134-147.

[USDA-FSA] U.S. Department of Agriculture – Farm Service Agency. 2008. Conservation Programs: Conservation Reserve Program. http://www.fsa.usda.gov/FSA/webapp? area=home&subject=copr&topic=crp. Accessed: September 21, 2008.

[USDA-FSA] U.S. Department of Agriculture – Farm Service Agency. 2009. Conservation Reserve Program: Monthly CRP acreage report. http://content.fsa.usda.gov/crpstorpt/rmepegg/MEPEGGR1.HTM Accessed: November 3, 2009.

[USDI-NPS] U.S. Department of the Interior – National Park Service. 2007. Theodore Roosevelt Administrative History Part 3: Resource Management Chapter 8: Terrestrial Research and Management. http://www.nps.gov/archive/thro/adhi/adhi8.htm. Accessed: October 8, 2008.

[USDA-NRCS] U.S. Department of Agriculture – Natural Resources Conservation Service. 2009. The PLANTS Database. National Plant Data Center. Baton Rouge, LA. http://plants.usda.gov. Accessed: December 2, 2009.

[USDA-NRCS] U.S. Department of Agriculture – Natural Resources Conservation Service. 2010. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. Accessed March 22, 2010.

Wilson, R. G., A. R. Martin, and S. D. Kachman. 2006. Seasonal changes in carbohydrates in the root of Canada thistle (*Cirsium arvense*) and the disruption of these changes by herbicides. Weed Technol. 20:242–248.

Youngson, C. R., C.A.I. Goring, R. W. Meikle, H. H. Scott, and J. D. Griffith. 1967. Factors influencing the decomposition of TORDON herbicides in soils. Down To Earth 23(2):3-11.

Zollinger, R. K., M. J. Christoffers, G. J. Endres, G. Gramig, K. A. Howatt, B. M. Jenks, R. G. Lym, J. M. Stachler, A. A. Thostenson, and H. H. Valenti. 2010. North Dakota weed control guide. Fargo, ND: North Dakota State Univ. Ext. Ser. Bull. W-253.

Zollinger, R., M. McMullen, J. Knodel, J. Gray, D. Jantzi, G. Kimmet, K. Hagemeister, and C. Schmitt. 2009. Pesticide use and pest management practices in North Dakota 2008. Fargo, ND: North Dakota State Univ. Ext. Ser. Bull. W-1446.