EFFICACY AND SOIL RESIDUAL OF HERBICIDES DEVELOPED FOR OPTIMUM GAT (GLYPHOSATE ACETOLACTATE SYNTHASE TOLERANT) CROPS

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Efficacy and Soil Residual of Herbicides Developed for Optimum GAT

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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

Carruth, David James; M.S.; Department of Plant Sciences; College of Agriculture, Food Systems, and Natural Resources; North Dakota State University; April 2011. Efficacy and Soil Residual of Herbicides Developed For Optimum GAT (Glyphosate Acetolactate Synthase Tolerant) Crops. Major Professor: Dr. Richard K. Zollinger.

Field experiments were conducted at five Northern Midwest locations to evaluate one and two pass herbicide programs developed for weed control in Optimum GAT (Glyphosate Acetolactate Synthase Tolerant) corn (*Zea mays* L.). All treatments provided greater than 95% control of grass and broadleaf weed species 14 days after application (DAA) and greater than 80% control 28 DAA. There were no statistical differences in weed control 14 and 28 DAA between one and two pass herbicide treatments.

Field experiments were conducted at three North Dakota locations to evaluate the growth and yield of hard red spring wheat (*Triticum aestivum* L.), field corn, dry bean (*Phaseolus vulgaris* L.), canola (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), and sugar beet (*Beta vulgaris* L.) one year after chlorimuron-ethyl was applied to soils with different pH. Chlorimuron treatments at Valley City (soil pH < 6.2) and Reynolds (soil pH > 8.3) caused 18 to 86% canola injury 28 days after emergence (DAE). All treatments at these locations delayed canola flowering 2 to 7 days compared to the control. Pinto bean yield at Reynolds was reduced from the control by 25% at 11.6 g ha^{-1} and 34% at 17.5 g ha^{-1}. Chlorimuron applied at 11.6 g ha^{-1} and 17.5 g ha^{-1} at Alice (soil pH 6.2 to 7.8) resulted in 21 to 26% corn injury 28 DAE, but yield was unaffected. Sugar beet yield at Alice and Reynolds was reduced from the control by 43 to 86% at 11.6 and 17.5 g ha^{-1}. These data confirmed that low rates of chlorimuron can injure canola and sugar beet one year after application. These data also suggest that minor injury may occur to pinto bean,

hard red spring wheat, and corn when 5.8 g ha^{-1} or less of chlorimuron is applied the previous year; however, yield should not be significantly impacted.

Field experiments were conducted near Mapleton and Casselton, North Dakota, to evaluate the enhancement of glyphosate plus rimsulfuron, tribenuron methyl, and mesotrione (Trigate™) and glyphosate plus chlorimuron ethyl, tribenuron methyl, and thifensulfuron methyl (Freestyle™) from adjuvants of different classes on flax (*Linum usitatissimum* L.), quinoa (*Chenopodium quinoa* Willd.), tame buckwheat (*Fagopyrum esculentum* Moench.), and conventional corn. Adjuvants containing ammonium sulfate (AMS) or an AMS replacement provided greater enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on flax and corn compared to oil-based adjuvants. The enhancement of these herbicides on quinoa and tame buckwheat appeared to be somewhat similar for oil-based adjuvants compared to AMS-based adjuvants. Cut Rate and ET 4000 adjuvants provided little to no enhancement of these herbicides on flax and quinoa. The addition of Class Act NG to glyphosate plus Trigate™ or glyphosate plus Freestyle™ provided 68 to 94% control on species tested 28 DAA.

Greenhouse experiments were conducted to evaluate the effect of pH on the efficacy of Trigate™ and Freestyle™ on common lambsquarters (*Chenopodium album* L.) and velvetleaf (*Abutilon theophrasti* Medik.). Adjusting the pH of the spray solution did not appear to influence the efficacy of Trigate™ and Freestyle™ herbicides on common lambsquarters. Control of velvetleaf was greater and dry weights were lower compared to other pH treatments for glyphosate plus Freestyle™ applied when the pH was raised to 9 and lowered to 2; however, this pattern was not observed with glyphosate plus Trigate™ or with Trigate™ and Freestyle™ applied alone.

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INTRODUCTION

Corn (*Zea mays* L.) production in North Dakota has increased in recent years because of genetic advancements in herbicide and insecticide resistance, selective breeding for shorter maturing varieties, and higher market prices. In 2010, North Dakota farmers harvested 737,000 hectares of corn for grain (USDA-NASS 2010). This area was up 32,000 hectares from 2009. In proportion to total corn production, North Dakota grows more genetically modified (GM) corn than most states (USDA-NASS 2009). This increase in the use of GM corn has led to the extensive use of glyphosate for weed control. In North Dakota in 2008, glyphosate was applied on nearly 1.45 million hectares of corn with 141 percent of the hectares being treated due to multiple applications (Zollinger et al. 2008). The abundant use of glyphosate may select for resistant weed biotypes resulting in reduced efficacy of this herbicide (Powles 2008). DuPont has developed innovative technology to delay the evolution of glyphosate resistance by genetically modifying corn and soybean so that several acetolactate synthase (ALS) inhibiting herbicides can be applied with glyphosate to help control tolerant and resistant weeds. These GM crops are referred to as Optimum GAT (Glyphosate Acetolactate Synthase Tolerant).

DuPont has created multiple commercial blend products to be applied with glyphosate in Optimum GAT crops; however, only two of these products will be available for use in the Northern Plains. Trigate™ contains rimsulfuron and tribenuron methyl which are ALS-inhibiting herbicides and mesotrione which inhibits *p*-hydroxyphenylpyruvate dioxygenase (HPPD). Trigate™ applied with glyphosate postemergence in Optimum GAT corn will offer three modes of action and will provide contact plus residual control of grass and broadleaf weeds. Freestyle™ contains chlorimuron ethyl, thifensulfuron methyl, and tribenuron methyl, which are ALS-inhibiting herbicides. Freestyle^{TM} applied with glyphosate preemergence or postemergence in Optimum GAT corn or soybean will offer two modes of action and will provide contact plus residual control.

Chlorimuron is a sulfonylurea herbicide that persists for long periods of time in high pH soils resulting in injury to subsequent crops. Susceptible crops grown in the Northern Midwest include hard red spring wheat (*Triticum aestivum* L.), field corn, dry bean (*Phaseolus vulgaris* L.), canola (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), and sugar beet (*Beta vulgaris* L.) (DuPont 2006). The rate of chlorimuron in Freestyle^{TM} is lower than other registered products which could reduce chlorimuron residues present the year after application thus eliminating or minimizing crop injury. Research is needed in the Northern Plains to determine if chlorimuron residues from low application rates will injure susceptible crops planted the year after treatment.

Adjuvants are added to spray tank mixtures to increase herbicide performance. There are several classes of activator adjuvants, and each provides a specific function such as improvement of retention, deposition, absorption, or translocation. These functions are carried out by modifying the spray solution or by altering the cuticle characteristics of the plant to help increase the concentration of herbicide that reaches its effective target site. Little research has been done to determine which classes of adjuvants will enhance the performance of several active ingredients applied together such as those in Trigate^{TM} and Freestyle^{TM}.

Trigate^{TM} and Freestyle^{TM} both contain weak acid herbicides that can gain or lose a proton depending on the pH of the surrounding solution. This chemical property can influence the solubility, uptake, and biological activity of these herbicides (Green and Hale 2005a). Research is needed to determine if alterations in pH will influence the efficacy of Trigate™ and Freestyle™.

The four main objectives of this research are: (1) to evaluate weed control from herbicides developed for Optimum GAT corn; (2) to determine the influence of chlorimuron soil residues on the growth and yield of canola, dry edible bean, sunflower, hard red spring wheat, corn, and sugar beet; (3) to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes; and (4) to evaluate the effect of pH on the efficacy of Trigate™ and Freestyle™ herbicides on common lambsquarters (*Chenopodium album* L.) and velvetleaf (*Abutilon theophrasti* Medik.).

LITERATURE REVIEW

Glyphosate Acetolactate Synthase Tolerant Corn

Glyphosate is a non-selective herbicide that inhibits the enzyme enolpyruvylshikimate-3-phosphate synthase (EPSPS) which is located in the chloroplasts of plant cells (Padgette et al. 1996). This enzyme is important for the biosynthesis of aromatic amino acids that are essential for the production of alkaloids, flavonoids, lignin, and several proteins (Weaver and Herrmann 1997). Current glyphosate tolerant crops have an EPSPS enzyme that is not inhibited by glyphosate, but glyphosate remains in the plant and accumulates in meristems (Gougler and Geiger 1981). DuPont has created a new herbicide technology in corn and soybean called Optimum GAT (Glyphosate Acetolactate Synthase Tolerance). These crops contain a glyphosate N-acetyltransferase (*gat*) gene that codes for the acetyl coenzyme A (ACCoA) that allows for metabolism of glyphosate by transforming it into the non-phytotoxic metabolite N-acetylglyphosate (Castle et al. 2004). The gene for this enzyme was derived from a benign saprophytic soil bacterium called *Bacillus licheniformis*. Gene shuffling was used to improve the metabolism carried out by this enzyme. The Optimum GAT trait also confers a high level of herbicide resistance to acetolactate synthase (ALS)-inhibiting herbicides. This resistance is the result of a highly herbicide-resistant allele (*hra*) of the (ALS) gene that has two point mutations. The first mutation is proline to alanine at position 197, and this substitution gives a ten-fold increase in resistance to specific sulfonylurea and triazolopyrimidine herbicides. The second mutation is tryptophan to leucine at position 574, and this substitution gives resistance to all ALS-inhibiting herbicides. The two mutations together provide slightly more resistance than the stronger single mutation (Green et al. 2008).

Optimum GAT Herbicides

No single herbicide controls all weed species; therefore, the use of mixtures of two or more active ingredients may help broaden the spectrum of weeds that are controlled (DeFelice et al. 1989; Devlin et al. 1991; Green 1991). Tank mixing herbicides can also increase the performance of one of the herbicides. For example, tank mixing glyphosate and chlorimuron increased absorption of chlorimuron resulting in greater control of Palmer amaranth and velvetleaf (Starke and Oliver 1998). The use of Trigate™ and Freestyle™ with glyphosate can provide better control of glyphosate-resistant and-tolerant weeds because these herbicides have different target sites; however, Freestyle™ will not control ALS-resistant weeds. The key weakness of glyphosate is that it only controls emerged weeds because it is rapidly inactivated by soil (Spranke et al. 1975). Some of the ALS-inhibiting herbicides in Trigate™ and Freestyle™ provide both contact and residual control that can last from several days up to two years depending on the environmental conditions present. Mixtures of ALS herbicides with glyphosate may help control weed species that each individual herbicide may not control. For example, chlorimuron is an effective postemergence herbicide on broadleaf weeds such as common cocklebur (*Xanthium strumarium* L.), pigweed (*Amaranthus* spp.), sunflower (*Helianthus* spp.), and morningglories (*Ipomoea* spp.) (Claus 1987). However, chlorimuron is weak on common lambsquarters (Green 1991; Wilcut et al. 1990). Thifensulfuron controls common lambsquarters and pigweed species but does not effectively control common cocklebur or common ragweed (*Ambrosia artemisiifolia* L.) (Ahrens 1990; Fielding and Stoller 1990; Wilcut et al. 1990).

Mesotrione is an active ingredient found in Trigate™. This compound belongs to the triketone family of herbicides and provides both contact and residual control. Residual control of mesotrione is influenced by soil pH. This herbicide is a weak acid with a pK_a of 3.1 (Dyson et al. 2002). In higher pH soils, a greater concentration of this herbicide is available for plant uptake because more of the herbicide is in solution due to more molecules in the anionic form. In lower pH soils, more of the herbicide is in the neutral form which adsorbs more easily the negatively charged soil particles. Once the herbicide is adsorbed to the soil, it is no longer available for plant uptake. Soil pH also influences the degradation of mesotrione. As soil pH decreases, the half-life of this herbicide increases (Dyson et al. 2002). This suggests that mesotrione is not degraded by acid hydrolysis and is most likely metabolized by soil microbes. As a member of the triketones, mesotrione causes plant death by inhibiting the enzyme *p*-hydroxyphenylpyruvate dioxygenase (HPPD) (Hess 2000). This enzyme is essential for the conversion of *p*-hydroxyphenylpyruvate to homogentisate. Homogentisate is a precursor of plastoquinone, which is necessary for shuttling electrons along the photosynthetic electron transport in plant chloroplasts. Plastoquinone also is a co-factor of phytoene destaturase which is an enzyme that is vital for the production of carotenoids. The indirect inhibition of carotenoids results in the destruction of these protective pigments in newly developing tissues.

Chlorimuron, rimsulfuron, thifensulfuron, and tribenuron are all sulfonylurea (SU) herbicides found in Trigate™ and/or Freestyle™. These herbicides inhibit the activity of the ALS enzyme, which blocks the biosynthesis of the branched-chain amino acids valine, leucine, and isoleucine (Brown 1990). The inhibition of these essential amino acids leads to the rapid termination of cell growth and division. Sulfonylurea herbicides are commonly known for persistence in the soil. Persistence in soil often occurs under high soil pH, high organic matter (OM), cold temperatures, and low precipitation (Dinelli et al. 1997; Mersie and Foy 1985; Wiese et al. 1988). The primary means of dissipation for SU herbicides is through chemical hydrolysis and, to a much lesser degree for most SUs, microbial degradation.

Chlorimuron Carryover

Chlorimuron is not labeled for use on any crop in North Dakota. Farmers in other Northern Midwest states have refrained from applying chlorimuron to high pH soils due to injury observed on subsequent crops. Crops that are susceptible to chlorimuron injury include hard red spring wheat, field corn, dry bean, canola, sunflower, and sugar beet. The recropping interval listed on the chlorimuron label for these crops is as follows: 4 months for spring wheat, 10 months for field corn, 12 months for dry bean, 18 months for sunflower and canola, and 30 months for sugar beet (DuPont 2006). Little research has been published on the injury caused to hard red spring wheat, dry bean, and canola when planted into a field in which chlorimuron was applied the previous year. Johnson and Talbert (1993) evaluated chlorimuron plus metribuzin injury to sunflower one year after application to soybean. An injury rating of 12 percent was recorded when chlorimuron plus metribuzin at 0.04 plus 0.24 kg ha^{-1} was applied the previous year, but reduction in yield was not noticed. Curran et al. (1991) examined the response of corn to chlorimuron that was applied the previous year to soybean. They observed a reduction in seedling dry weight as well as a reduction in plant height at the three-leaf stage, but grain yield was not different among treatments. Renner and Powell (1991) evaluated the response of sugar beet planted 1 to 2 years after an application of chlorimuron to soybean. They found that chlorimuron plus linuron caused 82 to 98% visible injury to sugar beet planted 1 year after application, and yield loss ranged from 85 to 100% compared with linuron alone. The same treatments 2 years after application caused 50 to 66% injury, and yield loss ranged from 24 to 60% compared with linuron.

Chlorimuron is a weak acid that is strongly influenced by pH and OM. This interaction is related to the pK_a of this herbicide, which is 4.2. As soil pH increases, the solubility of chlorimuron increases allowing more herbicide into solution which increases absorption and phytotoxicity. In low pH soils, more of the herbicide is in the neutral form, which increases adsorption making more of the herbicide unavailable for plant uptake. The pH of the soil also can affect the leaching potential of chlorimuron. Leaching is more probable in higher pH soils with low OM than soils with low pH and high OM, but it usually is not considered a problem. Low pH soils also cause this herbicide to have a strong affinity for OM, further limiting availability and leaching. Chlorimuron mobility and adsorption are not highly correlated with any particular soil type (Goetz et al. 1989). Breakdown of chlorimuron occurs primarily through chemical hydrolysis. This process is largely influenced by soil pH and warm temperatures. The rate of chemical hydrolysis decreases as soil pH increases above 6.8 and as soil temperatures fall below freezing. The reduction in degradation of chlorimuron in high pH soils is the main reason why this herbicide persists for long periods of time. In acidic soils, chlorimuron is degraded into two non-toxic metabolites, aminopyrimidine and sulfonamide (Sarmah and Sabadie 2002). Soil microbes also can degrade small amounts of chlorimuron in warm and moist soils (Anonymous 1984).

Adjuvant Enhancement of Trigate™ and Freestyle™

Spray adjuvants are designed to enhance the performance of herbicides. Adjuvants work to improve spray water quality and to increase retention, deposition, absorption, and translocation of herbicides. No single adjuvant can perform all of these functions, but some adjuvants can perform multiple functions simultaneously. For example, the addition of ammonium sulfate (AMS) to glufosinate improved the efficacy of this herbicide on velvetleaf and giant foxtail (*Setaria faberi* Herrm.) (Maschhoff et al. 2000). The increase in control was attributed to an increase in absorption and translocation of glufosinate. Adjuvant enhancement varies by herbicide selection, targeted plant species, and the environmental conditions present (Zollinger 2000). Every herbicide has different chemical and physical properties, which result in different interactions between the adjuvant and the particular herbicide. Plant species differ greatly in the composition and structure of leaf cuticles, which can also vary in thickness depending on the age of the plant and the environment in which it is growing (Bukovac et al. 1990; Schonherr and Baur 1994). Adjusting the rate of a herbicide or tank mixing two or more herbicides also will affect the ability of an adjuvant to boost herbicidal efficacy (Zollinger 2000).

Spray adjuvants generally can be divided into three broad categories: surfactants, oils, and fertilizers. The main function of surfactants is to decrease the surface tension of spray droplets. This improves retention of the herbicide because fewer spray droplets bounce off the leaf surface after impact (Rutter et al. 1990). Oil-based adjuvants increase herbicide absorption by altering plant cuticles. These adjuvants solubilize leaf waxes which allows for easier passage of oil based herbicides through the nonpolar lipophilic cuticle (Manthey and Nalewaja 1992). Fertilizers used as adjuvants generally contain a form of nitrogen. Ammonium sulfate is a commonly used fertilizer adjuvant because it reduces the number of antagonistic salts in water that bind with glyphosate resulting in reduced efficacy (Thelen et al. 1995). Ammonium sulfate also increases the permeation of weak acid herbicides through plant cell membranes resulting in more herbicide inside the cytoplasm (Gronwald et al. 1993).

Adjusting pH of Spray Solution

The solubility, uptake, and biological activity of sulfonylurea herbicides can be drastically affected by changing the pH of the spray solution. The water solubility of most SU herbicides is directly related to the pH of the spray mixture and the pK_a of a hydrogen atom on the urea bridge (Green and Hale 2005b). Increasing the pH of the spray water above the pK_a of the SU herbicide results in increased solubility of the herbicide because more of it is in the ionic form. This may improve the efficacy of the herbicide if solubility is the limiting factor, but the anionic charge of the herbicide may limit penetration through the non-polar lipophilic cuticle and the negatively charged cell membrane and cell wall. If the pH is lowered below the pKa of the herbicide, solubility is reduced, but the herbicide is converted to a neutral form that can more quickly penetrate the cuticle and negatively charged barriers (Green and Hale 2005a).

MATERIALS AND METHODS

Weed Control in Optimum GAT Corn

Field experiments were established in 2009 near Arlington, Wisconsin; Brookings, South Dakota; Prosper, North Dakota; and Waseca, Minnesota to evaluate weed control from herbicides developed for Optimum GAT corn. The experiment was repeated in 2010 near Prosper, North Dakota. Plot dimensions for this experiment were 3 by 9 m at Waseca and Prosper, 3 by 8 m at Arlington, and 3 by 12 m at Brookings. The soil properties for all locations except for Waseca can be found in Table 1.

Table 1. Soil properties by location for experiments to evaluate weed control in Optimum GAT corn in 2009 and 2010.

Location	Sample depth	pH	Organic matter	sand	silt	clay	Textural classification
	--cm--		---%---		--------%--------		
Arlington	0-15	6.7	3.7	6	71	23	Silt loam
Brookings	0-15	6.2	3.3	42	30	28	Clay loam
Prosper 2009	0-15	7.2	4.6	27	49	24	Loam
Prosper 2010	0-15	7.9	4.2	29	55	17	Silt loam

Optimum GAT corn from source number N1PNE22288-00 was sown at each location in 2009 and at Prosper in 2010. The sowing dates for the 2009 locations were: Arlington on May 21, Brookings on May 15, Prosper on May 28, and Waseca on May 20. In 2010, corn was sown at Prosper on April 28. Row width, sowing depth, and sowing population varied at each location due to the availability of equipment. This planting information was only available for Prosper. Corn at Prosper in both years was sown with a four-row John Deere Flex planter[1] providing 76-cm row spacing. The seed was placed at a depth of 3.8 to 5.1 cm, and the sowing population was approximately 69,000 seeds ha^{-1}.

[1] Deere & Company, One John Deere Place Moline, IL 61265.

Herbicide treatments and application timings were identical for all locations (Table 2). All pre-emergence (PRE) applications were applied at or near planting. Postemergence treatments were applied at three different application timings: early postemergence (EPOST) when the corn reached the 2nd vegetative leaf stage, mid-postemergence (MPOST) when weed species were 10 to 15 cm tall, and postemergence (POST) when weed species were 10 to 15 cm tall following the PRE applications.

Table 2. Herbicide treatments and application timings for five locations to evaluate weed control in Optimum GAT corn.

#	Treatment[a]	Rate[b]	Application timing[c]
		g ai ha^{-1}	
1	Acetochlor fb[d] glyphosate + rimsulfuron + tribenuron + mesotrione	900 fb 865 + 18 + 13 + 88	PRE fb POST
2	Acetochlor fb glyphosate + rimsulfuron + tribenuron + mesotrione + atrazine	900 fb 865 + 18 + 13 + 88 + 565	PRE fb POST
3	Acetochlor fb glyphosate + thifensulfuon + tribenuron + dicamba	900 fb 865 + 9 + 9 + 140	PRE fb POST
4	Chlorimuron + rimsulfuron + mesotrione fb glyphosate	23 + 23 + 150 fb 865	PRE fb POST
5	Acetochlor + glyphosate + rimsulfuron + tribenuron + mesotrione + atrazine	900 + 630 + 18 + 13 + 88 + 565	EPOST
6	Glyphosate	865	MPOST
7	Glyphosate + rimsulfuron + tribenuron + mesotrione	865 + 18 + 13 + 88	MPOST
8	Glyphosate + chlorimuron + thifensulfuron + tribenuron	865 + 6 + 9 + 9	MPOST
9	Glyphosate + thifensulfuron + tribenuron + dicamba	865 + 9 + 9 + 140	MPOST
10	Control	-	-

[a] All postemergence treatments included ammonium sulfate at 2.25 kg ha^{-1}.
[b] Glyphosate rates = grams acid equivalent ha^{-1}.
[c] PRE = preemergence, MPOST = mid-postemergence, and POST = postemergence.
[d] fb = followed by.

Height and/or density of weed species present at each location were recorded prior to all post-emergence applications (Tables A1-A5). The environmental conditions along with application dates for each timing at all locations can be found in Tables A6-A10. Preemergence and postemergence treatments at Arlington were applied with a hand boom sprayer that was 3 meters wide and equipped with six 8003XR TeeJet flat-fan nozzles[2] delivering 190 L ha^{-1} at 160 kPa. Preemergence and postemergence treatments at Brookings were applied with a bicycle sprayer that was 3 meters wide and equipped with six 8003XR TeeJet flat-fan nozzles[2] delivering 190 L ha^{-1} at 210 kPa. Preemergence and postemergence treatments for both years at Prosper were made with a back-pack type sprayer attached to a 2-meter-wide boom. Preemergence treatments were applied using four 11002 Turbo TeeJet flat-fan nozzles[2] delivering 160 L ha^{-1} at 280 kPa, and postemergence treatments were applied using four 11001 Turbo TeeJet nozzles[2] delivering 80 L ha^{-1} at 280 kPa. Preemergence and postemergence treatments at Waseca were applied with a tractor-mounted sprayer that was 3 meters wide and equipped with seven 8002 TeeJet flat-fan nozzles[2] delivering 190 L ha^{-1} at 280 kPa.

Weed control from preemergence applications was evaluated 20 to 35 days after application (DAA). EPOST, MPOST, POST applications were evaluated 14 to 16 DAA. A second evaluation was taken 28 to 38 days after EPOST application, 22 to 35 days after MPOST applications, and 26 to 33 days after POST applications. Weed control for individual species present at each location was estimated visually using a percentage scale with 0 representing no weed control and 99 representing all weeds dead. Yield was not measured due to the regulation of Optimum GAT corn and the risk of pollen transfer to neighboring corn fields. Corn at each location was destroyed prior to tasseling.

The experimental design for all locations was a randomized complete block with four replicates except for the Brookings location which had three replicates. An average was determined for each treatment for control of all grass and all broadleaf weed species at Arlington, WI, Brookings, SD, Prosper, ND (2009 and 2010), and Waseca, MN. Data

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

from all locations were combined and subjected to ANOVA. Treatment mean separation was determined using Fisher's protected LSD test at the 0.05 probability level. Control ratings for grass species included yellow foxtail (*Setaria glauca* L.), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.], giant foxtail, large crabgrass (*Digitaria sanguinalis* L. Scop.), and green foxtail (*Setaria viridis* L. Beauv.). Control ratings for broadleaf species included redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters, wild buckwheat (*Polygonum convolvulus* L.), hairy nightshade (*Solanum sarrachoides* Sendt.), common cocklebur, giant ragweed (*Ambrosia trifida* L.), and velvetleaf. PRE ratings included data from all five locations. The first postemergence evaluation only included data from Arlington and both years at Prosper because a 14-day rating was not provided for Brookings or Waseca. The second postemergence evaluation included data from all five locations.

Chlorimuron Carryover

Field experiments were established in 2009 and continued in 2010 near Valley City, Alice, and Reynolds, North Dakota to determine the effect of chlorimuron soil residues on the growth and yield of canola, dry edible bean, sunflower, hard red spring wheat, corn, and sugar beet. Locations were chosen based on soil pH in anticipation that Valley City would have pH near 6, Alice would have pH near 7, and Reynolds would have pH near 8. The soil at Valley City was a loam textured soil with 44.8% sand, 41.3% silt, and 13.9% clay. The soil at Alice was also a loam textured soil, but it contained 35% sand, 44% silt, and 21% clay. Reynolds had sandy loam textured soil with 58.3% sand, 30.3% silt, and 11.4% clay.

This experiment was conducted separately for each crop at each location resulting in a total of eighteen experiments. The experimental design for each crop was a randomized complete block with four replicates. Plot dimensions were 3 by 8 m. Chlorimuron ethyl at 3, 5.8, 11.6, and 17.5 g ha^{-1} was applied on June 11, 2009, to cotyledon soybean at Valley City and Alice locations. The same rates were applied to bare soil at Reynolds. Soybean in the plots at Valley City and Alice were destroyed with an application of dicamba when the soybean reached the first trifoliolate leaf stage. Chlorimuron was applied to the entire plot area using a backpack-type sprayer with six 11002 Turbo TeeJet flat-fan nozzles[2] delivering 160 L ha^{-1} at 280 kPa through a 3-m-wide boom. Plots were kept weed free in 2009 by glyphosate applications and hand weeding. Five soil cores were taken from each plot in 2009 at a depth of 0 to 15 cm to determine soil pH and organic matter. The cores within each plot were combined and tested at the NDSU Soil Testing Laboratory.

All plots at each location were lightly tilled in the fall of 2009 using a tandem disc. The disc was set to a depth of 5 to 8 cm and one parallel pass was made in each plot to minimize the amount of herbicide transferred between plots. Soil samples were taken in the fall of 2009 at each location to determine nutrient concentrations present in the soil. Cores were taken from 0 to 61 cm for nitrogen and 0 to 15 cm for phosphorus, potassium, sulfur, zinc, iron, manganese, and copper. Samples were tested for these nutrients at the NDSU Soil Testing Laboratory.

Appropriate rates of fertilizer for each crop based on soil tests were broadcast at each location in the spring of 2010 using a Whirly Bird hand spreader (Table A11). Fertilizer was incorporated immediately following application using a field cultivator with rolling baskets. Crops were sown in May 2010 (Table 3). Canola and spring wheat were sown using a 2-m Great Plains grain drill[3]. Dry bean, sunflower, sugar beet, and corn were sown using a four-row John Deere flex planter[1].

Table 3. Planting information by crop to evaluate chlorimuron carryover at Valley City, Alice, and Reynolds, ND, in 2010.

Crop	Variety	Date	Depth	Population	Row width
			--cm--	seeds ha^{-1}	---cm---
Canola	Pioneer 45H28	May 19	1.9-2.5	9[a]	19
Dry edible bean (Pinto)	Stampede	May 20	2.5-3.8	180,250	76
Sunflower	Pioneer 63N82	May 20	2.5-3.8	49,400	76
Hard red spring wheat	Glenn	May 19	2.5-3.8	101[a]	19
Corn	Pioneer 39D97	May 20	3.8-5.1	81,500	76
Sugar beet	Crystal 658RR	May 20	1.9-2.5	103,700	76

[a] kg ha^{-1}.

Canola, corn, and sugar beet at Valley City were treated June 16 with glyphosate at 865 g ha^{-1} and ammonium sulfate at 810 g ha^{-1} to control emerged weeds. Edible beans at Valley City were treated June 16 with clethodim at 79 g ha^{-1}, R-11 at 0.25% v/v, and ammonium sulfate at 810 g ha^{-1} to control emerged grass species. Sunflower at Valley City were treated June 16 with tribenuron at 185 g ha^{-1}, clethodim at 79 g ha^{-1}, R-11 at 0.25% v/v, and ammonium sulfate at 810 g ha^{-1} to control emerged broadleaf and grass species. Spring wheat at Valley City was treated June 16 with fenoxaprop at 70 g ha^{-1} to control emerged grass species. Weeds present at the Alice and Reynolds locations and the weeds that emerged after herbicide applications at Valley City were removed by hoeing and hand weeding until harvest.

Crops were visually evaluated approximately 14, 28, and 56 day after emergence (DAE) for herbicide injury with 0% representing no injury and 99% representing all plants dead. Differences in flowering time of canola were observed approximately 56 DAE;

[3] Great Plains Mfg., Inc., P.O. Box 5060 Salina, KS 67401.

therefore, an estimation was made as to the number of days that the treated plots were delayed compared to the control plots. Crop density was measured for canola and spring wheat plots approximately 20 DAE by counting the number of viable stems in one meter of two randomly chosen rows. Crop density for dry edible bean, sunflower, and corn was recorded 20 DAE by counting the number of viable stems in 3 m of the center two rows in each plot. Sugar beet density was measured in a similar manner except recorded approximately 56 DAE. An average of the two rows was calculated for each plot in all experiments. Sugar beet was hand-thinned early in the season to 10 to 13 cm spacing within each row. Plant height was measured for each crop approximately 28 DAE by randomly sampling five plants in each plot. An average of the five plants was calculated for each plot. Canola, dry edible bean, and sunflower were measured to the tip of the apical meristem. Spring wheat, corn, and sugar beet were measured to the top of the tallest leaf.

Spring wheat at all locations and canola at Valley City was harvested on August 24, 2010 using a Hege small plot combine[4] with a 1.2-m header. The harvested plot length was 6.4 m. Samples were bagged, dried, cleaned, and weighed. Canola at Alice was not harvested due to strong winds in July that flattened and tangled the crop making it impossible to feed correctly into the combine. Canola at Reynolds was harvested, but samples were inaccurate due to the variability of maturity between treatments. Pinto beans were pulled by hand from 6.4 m of the center two rows of each plot. Plants were piled to allow for desiccation and were threshed on August 31, 2010. Samples were bagged, dried, cleaned, and weighed. Sunflower at all locations were not harvested due to herbicide drift from growers herbicide applications, wind damage, and insect problems. Corn cobs at all

[4] Wintersteiger Inc., 4705 Amelia Earhart Drive Salt Lake City, UT 84116.

three locations were hand-harvested from 3 m of the center two rows on October 14, 2010. Cobs were threshed using a small plot combine and samples were dried, cleaned, and weighed. Sugar beet at all locations was hand-harvested on October 14, 2010, from 3 m of the center two rows. The sugar beets from each plot were defoliated using a machete and root weight was recorded. Random samples were selected from each plot and delivered to American Crystal Sugar, East Grand Forks, MN where they were analyzed for tare, sugar content, Na, K, and amino-N (NH_2-N). Root yield, impurity index, and extractable sucrose per hectare were calculated using the following formulas:

Root yield (kg ha^{-1}) = (kg root per plot/% of ha)/100

Net root yield (kg ha^{-1}) = root yield * [100-%tare)/100]

Impurity index = [3.5 * (mg L^{-1} Na) + (2.5 * (mg L^{-1} K)) + (9.5 * (mg L^{-1} amino-N)]/% sucrose

Sucrose loss to molasses (%) = [impurity index * (% sucrose/100) * net root yield * 1.5]/10,000

Extractable sucrose (kg ha^{-1}) = [(net root yield * (% sucrose/100)) – sucrose loss to molasses] * 2000

Soil pH, OM, injury ratings, days delayed flowering, plant height, plant population, and yield for all crops at each location were analyzed separately as a randomized complete block. Data were subjected to ANOVA and treatment mean separation was determined using Fisher's protected LSD test at the 0.05 probability level. Data from each crop were not combined across locations because each had a different soil pH resulting in different levels of crop injury.

Adjuvant Enhancement of Trigate™ and Freestyle™

Field experiments were conducted in 2009 near Mapleton, North Dakota, and in 2010 near Casselton, North Dakota, to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes. Experiments were conducted separately for Trigate™ and Freestyle™. Herbicide rates were reduced from normal use rates by 67% to allow differences to be revealed between means without 100% control. Plot dimensions were 3 by 12 m.

Assay species were sown perpendicular to plots. Species included flax (*Linum usitatissimum* L.), quinoa (*Chenopodium quinoa* Willd.), tame buckwheat (*Fagopyrum esculentum* Moench.), and conventional corn. All species were sown on June 4, 2009, and on June 2, 2010, using a Great Plains grain drill[3] with 19-cm row spacing. The flax variety York was sown at a depth of 1.9 to 2.5 cm at a population of 250 to 300 seeds m^{-2}. Quinoa was sown at a depth of 1 to 1.3 cm at a population of approximately 100 to 200 seeds m^{-2}. The tame buckwheat variety Mancan was sown at a depth of 2.5 to 3.8 cm at a population of 150 to 250 seeds m^{-2}. The conventional corn hybrid Pioneer 39B22 was sown at a depth of 3.8 to 5.1 cm at a population of 60 to 150 seeds m^{-2}.

POST treatments were applied with a backpack-type sprayer. The spray boom was 2 m wide and equipped with four 11001 Turbo TeeJet nozzles[2] delivering 80 L ha^{-1} at 276 kPa. Application dates and environmental data present at the time of application can be found in Table A12. Species stage, height, and density at the time of application can be found in Tables 4 and 5.

Table 4. Application information by species to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes at Mapleton, ND, in 2009.

Species	Stage	Height	Density
		--cm--	--plants m^{-2}--
Flax	75% flowering	36	270
Quinoa	95% budding	33	70
Tame buckwheat	98% flowering	69	160
Corn	V5-V6	84	110

Table 5. Application information by species to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes at Casselton, ND, in 2010.

Species	Stage	Height	Density
		--cm--	--plants m^{-2}--
Flax	-	51	270
Quinoa	90% budding	58	190
Tame buckwheat	90% flowering	66	270
Corn	V6	69	65

All treatments in the Trigate™ experiment contained glyphosate at 290 g ha^{-1}, rimsulfuron at 6 g ha^{-1}, tribenuron at 4.3 g ha^{-1}, mesotrione at 29 g ha^{-1}, and one of the adjuvants listed in Table 6. All treatments in the Freestyle™ experiment contained glyphosate at 290 g ha^{-1}, chlorimuron at 1.9 g ha^{-1}, tribenuron at 2.9 g ha^{-1}, thifensulfuron at 2.9 g ha^{-1}, and one of the adjuvants listed in Table 6.

Visual control of species was evaluated 14 and 28 DAA. The treated 2 meters of each plot was compared with the untreated area on the outside border of the plot. Ratings were based on a percentage scale with 0 representing no control and 99 representing all plants were dead.

Each experiment was a randomized complete block with three replicates. Adjuvant treatment and time were considered fixed effects and experiment location and rep were considered random effects. Data from the 14 and 28 ratings for each species were analyzed using split plot in time. Data were subjected to ANOVA and mean separation was determined using Fisher's protected LSD test at the 0.05 probability level.

Table 6. Adjuvant treatments to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes.

Adjuvant	Rate	Adjuvant Class
R-11	0.25% v/v	Surfactant
Sylgard 309	0.13% v/v	Surfactant & Silicone
Class Act NG	2.5% v/v	Surfactant & AMS[a]
Alliance	1.25% v/v	AMS & WCA[b] (AMS Replacement)
Veracity	0.75% v/v	AMS & AMS Replacement (WCA) & Surfactant & Deposition/Retention & Defoamer
N-Tense	0.5% v/v	Surfactant & AMS Replacement (WCA)
Flame	0.5% v/v	Surfactant & AMS Replacement (WCA)
Import	1% v/v	Acidic AMS Replacement (WCA)
Cut Rate	4.8 g L^{-1}	AMS Replacement/WCA
ET 4000	1% v/v	Acidic AMS Replacement (WCA)
Quad 7	1% v/v	Basic pH Blend
Prime Oil	2.34 L ha^{-1}	Petroleum Oil Concentrate
Superb HC	1.17 L ha^{-1}	High Surfactant Oil Concentrate
Soy-Stik	1.46 L ha^{-1}	MSO[c]
Destiny HC	1.17 L ha^{-1}	High Surfactant Oil Concentrate
Trophy Gold	2.34 L ha^{-1}	Oil Based Surfactant
Renegade	1.46 L ha^{-1}	MSO & Basic pH Blend
Syl-Tac	0.29 L ha^{-1}	MSO & Organosilicone Surfactant

[a] AMS = ammonium sulfate

[b] WCA = water conditioning agent

[c] MSO = methylated seed oil

Data from 2009 and 2010 were combined for each experiment because error mean squares from experiment repetitions were homogeneous.

Adjusting pH of Spray Solution

Greenhouse experiments were conducted in the winter and spring of 2009-2010 to evaluate the effect of pH on the efficacy of Trigate™ and Freestyle™ herbicides on common lambsquarters and velvetleaf. Each weed species was conducted as a separate experiment. All experiments were designed as a randomized complete block with six replicates, and each experiment was repeated.

Common lambsquarters and velvetleaf seeds were sown in a peat-based potting mix in 3.8-cm diameter cones (Table 7). Several seeds were sown in each cone, and seedlings were thinned to one plant per cone approximately 1 week after emergence. Cones were watered daily and fertilized with Miracle-Gro to promote healthy plants. The temperature in the greenhouse was 22 ± 5 C. Natural daylight was artificially supplemented 16 hours per day with metal halide lights that provided an illumination of 450 $\mu E/m^2/s$. Trays in which the cones were held were rotated once a week to avoid uneven lighting.

Table 7. Planting and application date along with species height at time of application in the greenhouse.

	Run 1		Run 2	
Factor	Lambsquarters	Velvetleaf	Lambsquarters	Velvetleaf
Planting date	Dec 22, 2009	Jan 5, 2010	Feb 11, 2010	Dec 16, 2009
Application date	Feb 3	Feb 10	Mar 22	Feb 11
Height at application (cm)	13-15	8-9	15-20	13-15

Five herbicide treatments were sprayed at four different pH values for each experiment. Herbicides were dissolved in water, and the pH of the solution was adjusted to 2, 6, or 9 (Table 8). In the fourth pH treatment, herbicides were dissolved in water, and the pH of the solution was raised to 9 for 15 to 20 minutes to allow herbicides to completely dissolve. The pH was then lowered to 2, and the solution was sprayed on both species. Each herbicide treatment was sprayed on both species with all combinations of pH levels. Hydrochloric acid was used to lower the pH of the spray solution and ammonium hydroxide was used to raise the pH. A pH meter was used to confirm that treatments were at the desired pH. Treatments were applied in a cabinet-type sprayer with an E650067 nozzle[2] delivering 90 L ha^{-1} at 240 kPa. Herbicide rates were reduced from normal use rates by 67% to allow differences between means without 100% control.

Table 8. Treatments for evaluating the effect of pH on the efficacy of Trigate™ and Freestyle™ herbicides in the greenhouse.

Treatment[a]	Rate	pH of spray solution
	----g ai ha^{-1}----	
Glyphosate	290	2
Glyphosate	290	6
Glyphosate	290	9
Glyphosate	290	9 to 2
Rimsulfuron + Tribenuron + Mesotrione	6 + 4.3 + 29	2
Rimsulfuron + Tribenuron + Mesotrione	6 + 4.3 + 29	6
Rimsulfuron + Tribenuron + Mesotrione	6 + 4.3 + 29	9
Rimsulfuron + Tribenuron + Mesotrione	6+ 4.3 + 29	9 to 2
Chlorimuron + Tribenuron + Thifensulfuron	1.9 + 2.9 + 2.9	2
Chlorimuron + Tribenuron + Thifensulfuron	1.9 + 2.9 + 2.9	6
Chlorimuron + Tribenuron + Thifensulfuron	1.9 + 2.9 + 2.9	9
Chlorimuron + Tribenuron + Thifensulfuron	1.9 + 2.9 + 2.9	9 to 2
Glyphosate + Rimsulfuron + Tribenuron + Mesotrione	290 + 6 + 4.3 + 29	2
Glyphosate + Rimsulfuron + Tribenuron + Mesotrione	290 + 6 + 4.3 + 29	6
Glyphosate + Rimsulfuron + Tribenuron + Mesotrione	290 + 6 + 4.3 + 29	9
Glyphosate + Rimsulfuron + Tribenuron + Mesotrione	290 + 6 + 4.3 + 29	9 to 2
Glyphosate + Chlorimuron + Tribenuron + Thifensulfuron	290 + 1.9 + 2.9 + 2.9	2
Glyphosate + Chlorimuron + Tribenuron + Thifensulfuron	290 + 1.9 + 2.9 + 2.9	6
Glyphosate + Chlorimuron + Tribenuron + Thifensulfuron	290 + 1.9 + 2.9 + 2.9	9
Glyphosate + Chlorimuron + Tribenuron + Thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2
Control	-	-

[a]All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).

Water with an adjusted pH of 2, 6, and 9 was applied to both species before the experiments were conducted and no phytotoxicity was observed from the different pH treatments.

A visual evaluation of control was recorded 14 and 28 days after application (DAA) using a percentage scale with 0% representing a healthy plant and 99% representing a dead plant. Plants were harvested 28 DAA by cutting the stems at the soil surface and fresh weight was measured. Plants were then dried and dry weight of the shoots was recorded.

Data for lambsquarters and velvetleaf were analyzed separately as a randomized complete block design with a 5 by 4 factorial arrangement with 6 reps. Data were subjected to ANOVA and mean separation was determined using Fisher's protected LSD test at the 0.05 probability level.

RESULTS AND DISCUSSION

Weed Control in Optimum GAT Corn

Field experiments were conducted in 2009 and 2010 to evaluate weed control from herbicide combinations developed for Optimum GAT corn. The percent control provided by each treatment was recorded for individual weed species present at each location. Weed species at each location were separated into grass and broadleaf groups, and an average for control was determined for each group according to herbicide treatment. These averages were combined across all five locations.

Weed control from PRE treatments was extremely variable depending on weed species and location (Tables A11-A15). Efficacy of the PRE herbicides at each location was most likely influenced by the amount of moisture received after application. Moisture is needed for activation of PRE herbicides to ensure that they are in the soil solution and available for plant uptake (Stickler et al. 1969).

Acetochlor treatments applied PRE provided nearly 25% greater control of grass species compared to broadleaf species (Table 9).

Table 9. Percent weed control for preemergence treatments averaged across five locations for grass and broadleaf species in Optimum GAT corn.

Treatment	Rate	Grass	Broadleaf
	--g ai ha^{-1}--	-----% control-----	
Acetochlor	900	72	49
Acetochlor	900	72	50
Acetochlor	900	75	51
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	80	78
LSD (0.05)		NS	15

Chlorimuron plus rimsulfuron plus mesotrione gave 78% control of broadleaf species and provided equal control of grass species compared to acetochlor. Preemergence treatments in Table 9 correspond with the postemergence treatments 1, 2, 3 and 4 in Table 10, respectively.

Differences were not found among postemergence treatments for control of grass and broadleaf species 14 and 28 DAA (Table 10). All treatments provided greater than 95% control 14 DAA and greater than 80% 28 DAA for both types of weeds. Although not statistically different, Treatment six containing only glyphosate provided 10 to 15% less control of grass and broadleaf weed species 28 DAA compared to other treatments. The reason for this appeared to be due to the lack of residual control provided by glyphosate. The high percentage of grass and broadleaf weed species control provided by the treatments in this experiment was not surprising due to the several different active ingredients included in the majority of treatments.

Chlorimuron Carryover

Field experiments were established in 2009 and continued in 2010 to determine the effect of chlorimuron soil residues on the growth and yield of canola, dry edible bean, sunflower, hard red spring wheat, corn, and sugar beet. Chlorimuron rates applied at each location in all experiments were 3, 5.8, 11.6, and 17.5 g ha^{-1}. No statistical differences were found between treatments for soil pH and OM for several of the crops at each location; however, differences were found between treatments for the soil pH for spring wheat at Valley City, the soil pH for sugar beet at Alice, the OM for canola at Alice, and the OM for corn at Reynolds (ANOVA not shown). These statistical differences were not relevant because the differences between means were relatively small. Soil pH and OM were presented as an average of all the plots in each experiment.

Table 10. Percent weed control averaged across five locations for grass and broadleaf species 14 and 28 DAA[a] in Optimum GAT corn.

	Treatment[b]	Rate[c]	14 DAA[d]		28 DAA	
			Grass	Broadleaf	Grass	Broadleaf
		----g ai ha^{-1}----	----------------% control------------			
1	Acetochlor fb[e] glyphosate + rimsulfuron + tribenuron + mesotrione	900 fb 865 + 18 + 13 + 88	97	98	96	98
2	Acetochlor fb glyphosate + rimsulfuron + tribenuron + mesotrione + atrazine	900 fb 865 + 18 + 13 + 88 + 565	96	98	97	98
3	Acetochlor fb glyphosate + thifensulfuon + tribenuron + dicamba	900 fb 865 + 9 + 9 + 140	96	98	92	96
4	Chlorimuron + rimsulfuron + mesotrione fb glyphosate	23 + 23 + 150 fb 865	98	99	95	99
5	Acetochlor + glyphosate + rimsulfuron + tribenuron + mesotrione + atrazine	900 + 630 + 18 + 13 + 88 + 565	98	99	91	93
6	Glyphosate	865	96	96	81	83
7	Glyphosate + rimsulfuron + tribenuron + mesotrione	865 + 18 + 13 + 88	98	97	93	96
8	Glyphosate + chlorimuron + thifensulfuron + tribenuron	865 + 6 + 9 + 9	98	98	92	96
9	Glyphosate + thifensulfuron + tribenuron + dicamba	865 + 9 + 9 + 140	99	98	90	95
	LSD (0.05)		NS	NS	NS	NS

[a] DAA = days after application.

[b] All postemergence treatments included ammonium sulfate at 2.25 kg ha^{-1}.

[c] Glyphosate rates presented as acid equivalent per hectare.

[d] Only includes data from Arlington 2009, Prosper 2009, and Prosper 2010.

[e] fb = followed by.

Canola. Chlorimuron injury to canola consisted of delayed emergence, stunted plants, purple seedlings, delayed flowering, and plant death. No statistical differences were found between chlorimuron treatments for canola injury at Valley City 14 and 28 DAE (Table 11). All treatments except for 5.8 g ha^{-1} caused injury compared to the control 14 DAE.

Table 11. Canola injury, delayed flowering, height, plant population, and yield as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	Delayed flowering	Height	Plant population	Yield
---g ai ha^{-1}---	---% injury---		-----days-----	--cm--	-plants m^{-2}-	--kg ha^{-1}--
			Valley City - pH=6.2, OM=4.1			
0	0	0	0	45	32	2130
3	36	21	2	33	25	2050
5.8	29	18	2	38	30	1870
11.6	54	45	4	27	26	1720
17.5	43	33	3	33	30	1820
LSD (0.05)	32	36	2	11	NS	NS
			Alice - pH=6.2, OM=4.2			
0	0	0	0	64	31	-
3	0	0	0	63	30	-
5.8	0	0	0	62	26	-
11.6	0	0	0	63	29	-
17.5	5	1	0.4	61	29	-
LSD (0.05)	NS	NS	NS	NS	NS	-
			Reynolds - pH=8.4, OM=3.0			
0	0	0	0	45	25	-
3	36	31	3	20	26	-
5.8	56	61	6	14	23	-
11.6	75	73	7	7	20	-
17.5	86	85	8	4	15	-
LSD (0.05)	9	14	2	6	8	-

[a] DAE = days after emergence.

This pattern changed 28 DAE because only chlorimuron applied at 11.6 g ha^{-1} was significantly different from the control. Flowering time for all treatments was 2 to 4 days behind the control. Canola height 28 DAE was reduced from the control for all treatments except for 5.8 g ha^{-1}. Canola population was reduced by some treatments; however, they were not statistically different. Yield was unaffected by chlorimuron treatments. The large LSD values for injury and the insignificance between treatments for yield may be explained by the variability of injury that occurred in this experiment. This variability may also explain why injury ratings did not always increase with increasing chlorimuron rates. The first repetition of this experiment had a soil pH that was slightly above neutral which resulted in higher injury ratings. The other three repetitions had a soil pH below 6, but considerable plant injury still occurred in some plots where as plants in other plots displayed minimal injury. One would assume that at this low pH little injury should occur; however, the reasons for variation in injury are unknown.

Canola injury was not observed at Alice except for a portion of an individual plot that received 17.5 g ha^{-1} of chlorimuron. This injury was most likely due to an increase in soil pH since the injury only occurred in a portion of the plot. Yield was not taken at this location due to strong straight-line winds that flattened the canola on July 14, 2010, making harvest difficult with a combine.

Canola at Reynolds showed substantial injury compared to the control for all treatments 14 and 28 DAE. Injury increased with increasing chlorimuron rates, and injury for all treatments ranged from 31 to 86% 14 and 28 DAE. Flowering time 56 DAE was delayed approximately 3 days behind the control at 3 g ha^{-1} and delayed nearly one week behind the control at 5.8, 11.6, and 17.5 g ha^{-1}. Canola height was reduced from the control by all treatments 28 DAE, and height decreased with increasing chlorimuron rates. Chlorimuron at 17.5 g ha^{-1} was the only treatment that reduced the canola population compared to the control. Yield was not measured at Reynolds because chlorimuron injury resulted in delayed maturity making it difficult to combine the green treated plots when the control plots were ready to harvest.

Pinto Bean. Injury was not observed on pinto beans at Valley City and Alice. This was most likely associated with the low soil pH at these locations (Table 12).

Table 12. Pinto bean injury, height, plant population, and yield as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	56 DAE	Height	Plant population	Yield
---g ai ha^{-1}---	----------% injury--------			--cm--	--plants m^{-2}--	---kg ha^{-1}--
			Valley City - pH=6.1, OM=4.5			
0	0	0	0	20	17	1460
3	0	0	0	21	18	1490
5.8	0	0	0	20	17	1460
11.6	0	0	0	20	18	1540
17.5	0	0	0	20	17	1470
LSD (0.05)	-	-	-	NS	NS	NS
			Alice - pH=6.3, OM=4.5			
0	0	0	0	25	15	2520
3	0	0	0	25	16	2740
5.8	0	0	0	25	14	2560
11.6	0	0	0	25	14	2410
17.5	0	0	0	24	14	2230
LSD (0.05)	-	-	-	NS	NS	NS
			Reynolds - pH=8.5, OM=3.3			
0	0	0	0	14	15	1660
3	0	0	5	15	15	1500
5.8	0	0	10	15	16	1530
11.6	0	4	13	14	14	1250
17.5	0	5	16	13	15	1090
LSD (0.05)	-	3	7	NS	NS	396

[a] DAE = days after emergence.

Injury at Reynolds appeared to increase as the season progressed. Chlorimuron applied at 5.8, 11.6, and 17.5 g ha^{-1} resulted in 10, 13, and 16% injury 56 DAE, respectively. Injury symptoms included interveinal chlorosis of new trifoliolates and a reduction in plant height even though this was not proven statistically different. Excessive moisture in 2009 and early in 2010 could have leached some of the chlorimuron down through the soil profile. This would have minimized injury early in the season because of limited uptake of the herbicide due to the pinto beans having a shallow root system. Injury symptoms also could have been influenced by iron chlorosis due to the high soil pH. The chlorimuron label restricts use on soils with a history of nutrient deficiency such as iron chlorosis because crop injury may occur (DuPont 2006). Pinto bean yield at Reynolds was unaffected at 3 and 5.8 g ha^{-1}, but yield was reduced from the control by 25% at 11.6 g ha^{-1} and 34% at 17.5 g ha^{-1}. White mold also was present at all locations and could have slightly influenced yields.

Sunflower. Sunflower injury from chlorimuron was not observed 14, 28, and 56 DAE at all locations (Table 13). The significant difference in sunflower population at Valley City was most likely due to random chance because of the small level of difference. Yield was not measured at all locations due to the following reasons. Valley City and Alice received strong straight-line winds on July 14, 2010, that knocked over several plants in plots. The Valley City location also had a severe infestation of sunflower midge. The Alice and Reynolds locations had phytotoxic herbicides drift onto the sunflowers from grower applications which resulted in plant death or severe head deformation. The Reynolds location also had a heavy infestation of sunflower seed weevil which destroyed several of the seeds. Lastly, all locations had problems with blackbirds eating seeds

Table 13. Sunflower injury, height, and plant population as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	56 DAE	Height	Plant population
------g ai ha^{-1}------	-----------% injury--------			--cm--	---plants m^{-2}---
	Valley City - pH=6.2, OM=3.6				
0	0	0	0	25	5
3	0	0	0	27	4
5.8	0	0	0	25	4
11.6	0	0	0	26	4
17.5	0	0	0	26	4
LSD (0.05)	-	-	-	NS	0.34
	Alice - pH=6.7, OM=4.1				
0	0	0	0	37	4
3	0	0	0	37	4
5.8	0	0	0	37	3
11.6	0	0	0	36	4
17.5	0	0	0	34	4
LSD (0.05)	-	-	-	NS	NS
	Reynolds - pH=8.5, OM=3.3				
0	0	0	0	28	4
3	0	0	0	25	4
5.8	0	0	0	25	4
11.6	0	0	0	24	4
17.5	0	0	0	24	4
LSD (0.05)	-	-	-	NS	NS

[a] DAE = days after emergence.

Hard Red Spring Wheat. HRSW injury was not observed from chlorimuron applied at Valley City and Alice. Five percent injury occurred at Reynolds 28 and 56 DAE when 17.5 g ha^{-1} of chlorimuron was applied (Table 14). Injury manifested as a slight reduction in height which was validated when plant height was measured 28 DAE. HRSW population at Reynolds was reduced from the control at 5.8, 11.6, and 17.5 g ha^{-1}, but

Table 14. HRSW injury, height, plant population, and yield as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	56 DAE	Height	Plant population	Yield
----g ai ha^{-1}----	--------% injury--------			--cm--	-plants m^{-2}-	--kg ha^{-1}--
			Valley City - pH=5.4, OM=5.0			
0	0	0	0	32	56	4020
3	0	0	0	32	57	4170
5.8	0	0	0	32	54	4130
11.6	0	0	0	33	54	4240
17.5	0	0	0	32	54	4050
LSD (0.05)	-	-	-	NS	NS	NS
			Alice - pH=6.9, OM=4.8			
0	0	0	0	46	57	3390
3	0	0	0	47	54	3020
5.8	0	0	0	46	54	3130
11.6	0	0	0	47	55	3440
17.5	0	0	0	45	53	3570
LSD (0.05)	-	-	-	NS	NS	NS
			Reynolds - pH=8.4, OM=3.4			
0	0	0	0	43	57	3850
3	0	0	0	42	56	4020
5.8	0	0	0	42	55	3820
11.6	0	0	0	41	53	3870
17.5	0	5	5	38	53	3910
LSD (0.05)	-	1	1	2	2	NS

[a] DAE = days after emergence.

plants must have produced more tillers than the control because yield was unaffected.

Corn. Corn injury was not observed from chlorimuron applied at Valley City (Table 15). Corn injury did occur at Alice, but injury was only different from the control at 17.5 g ha^{-1}. Visible injury symptoms on corn included stunting, streaking of the leaves, purpling of the stems, and chlorosis. The injury at 17.5 g ha^{-1} also resulted in a reduction in plant height

Table 15. Corn injury, height, plant population, and yield as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	56 DAE	Height	Plant population	Yield
------g ai ha^{-1}------	----------% injury--------			--cm--	-plants m^{-2}-	--kg ha^{-1}--
		Valley City - pH=5.3, OM=4.6				
0	-	0	0	54	8	10350
3	-	0	0	52	8	10520
5.8	-	0	0	51	7	10350
11.6	-	0	0	52	7	10130
17.5	-	0	0	54	8	11130
LSD (0.05)	-	-	-	NS	NS	NS
		Alice - pH=7.1, OM=4.3				
0	0	0	-	64	7	11870
3	0	1	-	67	7	10640
5.8	2	4	-	60	7	11030
11.6	16	21	-	51	8	10570
17.5	26	30	-	44	7	10700
LSD (0.05)	17	22	-	17	NS	NS
		Reynolds - pH=8.3, OM=3.3				
0	0	0	0	46	7	11120
3	0	0	0	43	7	11080
5.8	0	4	4	40	7	11650
11.6	13	24	24	29	6	10310
17.5	18	26	26	29	7	10550
LSD (0.05)	4	8	8	4	NS	NS

[a] DAE = days after emergence.

compared to the control. The large LSD values for injury and plant height at Alice were mostly likely due to the variability of injury that occurred throughout the experiment. This variability appeared to be related to changes in soil pH (Data not shown). An injury rating was not recorded 56 DAE at Alice due to strong straight-line winds that knocked over several plants and resulted in goose-necking. Significant corn injury was not observed at

Reynolds when 5.8 g ha^{-1} or less of chlorimuron was applied. Chlorimuron applied at 11.6 and 17.5 g ha^{-1} resulted in approximately 25% injury 28 DAE and 56 DAE. Corn height at Reynolds 28 DAE was significantly reduced from the control by 13% at 5.8 g ha^{-1} and by 37% at 11.6 and 17.5 g ha^{-1}. Despite the injury observed at Alice and Reynolds, yield was not negatively impacted at either location. The strong winds in July at Valley City and Alice could have reduced yields because the corn had not pollinated at this point.

Sugar Beet. Sugar beet at Valley City were not rated 14 DAE due to poor germination and delayed emergence. Sugar beet emergence was also poor in control plots which indicated that factors other than chlorimuron carryover (i.e. other herbicide residue) were responsible for the reduction in plant population. The poor germination and delayed emergence resulted in a reduction in plant population compared to sugar beet grown at the other locations (Table 16). Injury was not observed 28 and 56 DAE. Sugar beet root yield at Valley City was only reduced from the control at 5.8 g ha^{-1}; however, this data is inaccurate due to lack of uniformity of the plant population throughout the experiment.

Chlorimuron residue was severely phytotoxic to sugar beet at Alice and Reynolds. Severe injury occurred with all treatments at both locations, and symptoms included delayed germination and emergence, discolored cotyledons, interveinal chlorosis, stunted plants, and plant death. Injury increased while height, population, yield and extractable sucrose decreased with increasing chlorimuron rates at both locations. All chlorimuron rates at Alice resulted in at least 73% sugar beet injury. Chlorimuron applied at 11.6 and 17.5 g ha^{-1} resulted in a yield loss of 75 and 86%, respectively, compared to the control as well as a similar reduction in extractable sucrose. Plots that received chlorimuron at 11.6 and 17.5 g ha^{-1} had from 0 to 9 beets in the entire plot.

Table 16. Sugar beet injury, height, plant population, yield, and extractable sucrose as affected by chlorimuron rate at three North Dakota locations in 2010.

Chlorimuron rate	14 DAE[a]	28 DAE	56 DAE	Height	Plant population	Yield	Extractable sucrose
--g ai ha^{-1}--	---------% injury--------			--cm--	-plants m^{-2}-	----kg ha^{-1}-----	
			Valley City - pH=5.6, OM=4.3				
0	-	0	0	13	3	61460	8760
3	-	0	0	12	3	59170	8880
5.8	-	0	0	12	3	52130	7380
11.6	-	0	0	12	3	60000	8760
17.5	-	0	0	12	4	58170	8420
LSD (0.05)	-	-	-	NS	NS	5178	NS
			Alice - pH=7.8, OM=4.1				
0	0	0	0	25	5	79400	11180
3	91	73	73	8	4	75030	10050
5.8	94	83	83	7	3	71000	9540
11.6	99	96	96	4	0.5	19880	2560
17.5	99	99	99	3	0.25	10870	1310
LSD (0.05)	3	13	13	5	1	23827	3094
			Reynolds - pH=8.3, OM=3.4				
0	0	0	0	14	7	77680	10960
3	45	38	38	10	6	73720	10210
5.8	55	66	66	6	4	66470	9200
11.6	74	86	86	3	1	43890	5760
17.5	83	91	91	3	0.5	16520	2000
LSD (0.05)	4	12	12	3	1	8286	1370

[a] DAE = days after emergence.

The surviving beets were abnormally large which is why the yield is larger than expected based on the injury ratings. Considerable injury at Alice was observed with 3 and 5.8 g ha^{-1} even though root yield for these treatments was not less than the control. These results are supported by the substantial reduction in plant height and population at these rates. These conclusions also apply to injury observed at Reynolds when 3 g ha^{-1} of chlorimuron was applied. The application of chlorimuron at 5.8 g ha^{-1} or greater at Reynolds resulted in 14 to 79% yield loss compared to the control. The reduction in extractable sucrose for these rates can be represented by a similar percentage range. The decrease in extractable sucrose with increasing chlorimuron rates at both locations was most likely due to the reduction in population as well as the large size of the few beets that survived the higher rates.

Adjuvant Enhancement of Trigate™ and Freestyle™

Field experiments were conducted in 2009 and 2010 to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes. Reduced rates of glyphosate plus Trigate™ and glyphosate plus Freestyle™ were applied with different adjuvants on flax, quinoa, tame buckwheat, and corn. Visual evaluations were taken 14 and 28 DAA, and data for each rating were averaged over the two years for each experiment. Fourteen-and 28-day ratings were presented for each species to reveal final ratings even though the treatment by time interaction was only significant for quinoa. This significant interaction for quinoa in both experiments appeared to be due to an increase in magnitude between the 14-and 28-day ratings. The treatment by time interaction for flax in the Trigate™ experiment was not calculated due to missing data for 2009. The 14-day rating for flax was analyzed using data from both years where as the 28-day rating was analyzed using data from only 2010 (Table 17).

The large LSD values for several of the species in both experiments made it difficult to determine differences among treatments; however, some generalizations can be made from both sets of data (Tables 17 &18). Similar trends were observed between the two experiments. Control ratings for all species generally increased from 14 to 28 DAA.

Table 17. Percent control of flax, quinoa, tame buckwheat, and corn in 2009 and 2010 for adjuvant enhancement of Trigate™.

		Flax		Quinoa		Tame buckwheat		Corn	
Adjuvant[a]	Rate	14 DAA[b]	28 DAA[c]	14 DAA	28 DAA	14 DAA	28 DAA	14 DAA	28 DAA
		---% control---							
R-11	0.25 % v/v	33	52	47	65	41	43	38	49
Sylgard 309	0.13 % v/v	15	17	46	64	44	51	33	43
Class Act NG	2.5 % v/v	58	94	73	85	62	68	71	90
Alliance	1.25 % v/v	55	88	53	60	49	61	62	81
Veracity	0.75 % v/v	39	63	42	61	38	46	48	59
N-Tense	0.5 % v/v	55	87	61	79	44	53	46	55
Flame	0.5% v/v	33	50	35	53	32	48	39	48
Import	1 % v/v	54	93	42	46	43	58	57	70
Cut Rate	4.8 g L^{-1}	11	13	9	13	28	40	45	48
ET 4000	1 % v/v	20	28	11	13	35	48	46	57
Quad 7	1 % v/v	35	47	68	96	44	63	37	42
Prime Oil	2.34 L ha^{-1}	22	22	35	81	46	57	35	42
Superb HC	1.17 L ha^{-1}	20	24	47	78	43	60	35	42
Soy-Stik	1.46 L ha^{-1}	20	17	49	86	45	50	31	40
Destiny HC	1.17 L ha^{-1}	28	35	49	94	47	56	37	45
Trophy Gold	2.34 L ha^{-1}	34	45	59	89	41	48	30	38
Renegade	1.46 L ha^{-1}	45	79	61	90	49	65	41	49
Syl-Tac	0.29 L ha^{-1}	20	22	38	71	35	35	33	39
LSD (0.05)		34	8	------37------		------20------		------23------	

[a] All treatments included glyphosate, rimsulfuron, tribenuron, and mesotrione at 290, 6, 4.3, and 29 g ha^{-1}, respectively.
[b] DAA = days after application.
[c] Data presented is only for 2010.

Table 18. Percent control of flax, quinoa, tame buckwheat, and corn in 2009 and 2010 for adjuvant enhancement of Freestyle™.

		Flax		Quinoa		Tame buckwheat		Corn	
Adjuvant[a]	Rate	14 DAA[b]	28 DAA	14 DAA	28 DAA	14 DAA	28 DAA	14 DAA	28 DAA
		--------% control--------							
R-11	0.25 % v/v	34	48	48	85	26	40	31	48
Sylgard 309	0.13 % v/v	14	17	35	86	33	44	33	38
Class Act NG	2.5 % v/v	58	71	73	92	49	70	72	93
Alliance	1.25 % v/v	55	70	67	88	43	67	69	89
Veracity	0.75 % v/v	45	46	73	91	32	56	47	60
N-Tense	0.5 % v/v	55	85	72	94	38	59	46	56
Flame	0.5% v/v	30	38	42	76	27	44	36	50
Import	1 % v/v	52	67	38	50	37	56	57	71
Cut Rate	4.8 g L^{-1}	10	13	7	17	24	33	34	43
ET 4000	1 % v/v	12	17	8	24	27	41	40	60
Quad 7	1 % v/v	19	28	61	94	31	53	34	47
Prime Oil	2.34 L ha^{-1}	19	17	48	91	34	54	33	43
Superb HC	1.17 L ha^{-1}	23	24	46	87	33	64	39	48
Soy-Stik	1.46 L ha^{-1}	19	15	48	90	28	48	28	41
Destiny HC	1.17 L ha^{-1}	26	28	49	89	32	56	34	48
Trophy Gold	2.34 L ha^{-1}	27	38	64	93	31	49	28	38
Renegade	1.46 L ha^{-1}	44	58	61	92	41	62	38	55
Syl-Tac	0.29 L ha^{-1}	18	18	46	86	33	43	33	39
LSD (0.05)		------45------		------19------		------15------		------21------	

[a] All treatments included glyphosate, chlorimuron, tribenuron, and thifensulfuron at 290, 1.9, 2.9, and 2.9 g ha^{-1}, respectively.
[b] DAA = days after application.

Cut Rate and ET 4000 provided little to no enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on flax and quinoa.

The addition of Class Act NG to glyphosate plus Trigate™ or glyphosate plus Freestyle™ provided between 68 and 94% control of all four species 28 DAA. The significant enhancement from Class Act NG applied with low rates of glyphosate plus Trigate™ and glyphosate plus Freestyle™ suggest that this adjuvant may increase the performance of these herbicides on several different species.

Adjuvants containing ammonium sulfate (AMS) or an AMS replacement such as Class Act NG, Alliance, and Import provided greater enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on flax and corn 28 DAA compared to oil-based adjuvants. The enhancement achieved from AMS-based adjuvants can most likely be explained by previous research. Hard-water cations such as Ca^{+2} and Mg^{+2} are often found in water used for application of herbicides. These cations form chemical bonds with glyphosate resulting in large molecules that are unable to penetrate the leaf cuticle (Thelen et al. 1995). The NH_4^+ ion in AMS competes with Ca^{+2} and Mg^{+2} for positions on the glyphosate molecule. When NH_4^+ bonds with glyphosate, it forms a smaller molecule that can more easily diffuse through the cuticle, resulting in more glyphosate entering the plant. AMS can also increase the permeation of weak acid herbicides through the plasma membranes of plant cells (Gronwald et al. 1993). The NH_4^+ ion in AMS acidifies the cell wall area of the cell forcing more of the herbicide into the nonpolar form. This form of the herbicide can more easily diffuse through the lipophilic region of the plasma membrane. Once inside the cell, the higher pH of the cytoplasm forces the herbicide into an ionic form which has difficulty passing back through the nonpolar membrane. Diffusion then moves the herbicide towards the site of action in cells. This process of ion trapping is another reason why AMS can greatly enhance weak acid herbicides.

The enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on quinoa and tame buckwheat 28 DAA appeared to be similar for oil-based and AMS-based adjuvants. Oil-based adjuvants can solubilize leaf waxes in plant cuticles allowing more herbicide to enter into plants (Manthey and Nalewaja 1992). This could explain the higher control ratings observed on these two species; however, lower control ratings were also observed with oil-based adjuvants on flax and corn 28 DAA. This may be the result of glyphosate antagonism from oil-based adjuvants (Nalewaja and Matysiak 1993). If glyphosate antagonism occurred, the individual active ingredients in Trigate™ and Freestyle™ would have been responsible for the majority of control. The problem is that not all of these active ingredients provide effective control of flax or corn. For example, Trigate™ contains rimsulfuron, tribenuron, and mesotrione. Rimsulfuron and mesotrione are both labeled for use on corn and should not cause injury. This suggests that tribenuron was most likely responsible for the phytotoxicity, but research has shown that tribenuron causes little phytotoxicity on corn (Zollinger et al. 2010). Glyphosate antagonism and natural crop tolerance may explain the lower control ratings observed for flax and corn with oil-based adjuvants.

The large LSD values in both experiments may be due to different environmental conditions. The summer of 2009 was slightly cooler compared to the summer of 2010. This is a possible explanation for why lower control ratings were observed in 2009 and considerably higher ratings were observed in 2010 (Data not shown). Also, combining the data over the two years resulted in high variability which can produce large LSD values.

Johnson and Young (2002) observed that changes in temperature affected the foliar activity of mesotrione on five weed species. They found that an increase in temperature from 18 to 32 C increased the efficacy of mesotrione on common cocklebur and velvetleaf up to three-fold. They also concluded that common waterhemp (*Amaranthus rudis*) and large crabgrass were six-to-sevenfold more susceptible at 18 C than at 32 C. This demonstrates that the influence of temperature on the efficacy of herbicides can be species dependent and may also explain why control of some of the species was different between the 2009 and 2010 environments.

The addition of the adjuvant Flame to glyphosate plus Trigate™ and glyphosate plus Freestyle™ resulted in physical incompatibility. The dry granule herbicides in these mixtures precipitated out of solution shortly after mixing and floated to the top of the bottle. This made application difficult because the thick mixture plugged the screens and the nozzles on the boom. It was thought that this incompatibility was due to extreme change in pH. This was proven incorrect by a series of tests that were conducted in the laboratory (data not shown). The reasons for physical incompatibility of Flame with these herbicides are unknown.

Adjusting pH of Spray Solution

Greenhouse experiments were conducted to determine the affect of pH on the efficacy of Trigate™ and Freestyle™ herbicides. Five herbicide treatments mixed in four different pH solutions were applied to common lambsquarters and velvetleaf. Visual control ratings were taken 14 and 28 DAA and dry weight was measured 28 DAA.

Common Lambsquarters. The treatment by pH and treatment by pH by run interactions were significant for control of lambsquarters; however, the treatment by pH by time interaction was not significant (Table A18). Control ratings for lambsquarters were presented by run 28 DAA to reveal the final outcome of each treatment (Table 19). The 14-day ratings for both runs were lower than the 28-day ratings and were removed to simplify the results. The treatment by pH by run interaction for control appeared to be mostly due to a change in magnitude; however, changes in rank were observed. This interaction can possibly be explained by different greenhouse conditions between the two runs such as photoperiod and temperature as well as different heights of lambsquarters at the time of application (Table 7). The treatment by pH and treatment by pH by run interactions were not significant for dry weight of lambsquarters (Table A19). Dry weights were presented as an average of the two runs for each treatment even though the treatment by pH interaction was insignificant.

Control of herbicide and pH treatments were often inconsistent across runs. In the first run, glyphosate applied at pH 6 gave greater control of lambsquarters compared to other pH treatments; however, no significance was found between pH treatments for the second run. Trigate™ applied at pH 2 or 6 gave greater than 69% control in the first run, but in the second run these treatments were significantly lower compared to when the pH was raised to 9 and lowered to 2. Glyphosate plus Trigate™ at pH 2 provided 75% control in the first run, but in the second run this treatment was significantly lower compared to when the pH was raised to 9 and lowered to 2. Glyphosate plus Freestyle™ applied at pH 6 provided at least 85% control in both runs. Treatments containing Freestyle™, regardless of pH, provided slightly higher control ratings than other herbicides. This can be explained by the excellent control that thifensulfuron provides on common lambsquarters.

Table 19. Percent control of common lambsquarters 28 days after application and dry weight averaged across two runs for an experiment conducted in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1 28 DAA	Run 2 28 DAA	Average of runs	Dry weight Average of runs
	----g ai ha^{-1}----		--------------% Control-------------			-----g-----
Glyphosate	290	2	25	20	23	0.499
Glyphosate	290	6	35	18	27	0.478
Glyphosate	290	9	24	14	19	0.378
Glyphosate	290	9 to 2	19	17	18	0.631
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	70	40	55	0.265
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	78	42	60	0.219
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	61	44	53	0.231
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	59	71	65	0.266
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	85	77	81	0.249
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	65	82	74	0.193
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	63	74	69	0.228
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	64	79	72	0.305
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	75	57	66	0.174
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	63	43	53	0.236
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	54	56	55	0.242
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	64	84	74	0.200
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	71	51	61	0.224
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	90	85	88	0.223
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	64	80	72	0.211
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	60	59	60	0.300
Control	-	-	0	0	0	0.694
LSD (0.05)[d]			9	9	7	0.091
LSD (0.05)[e]						0.079

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).

[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.

[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.

[d] LSD used to compare control of treatment means within a run.

[e] LSD used to compare control of treatment means to control.

For example, Monks et al. 1993 found that thifensulfuron applied at 2, 3, or 4 g ha^{-1} gave at least 99% control of 2-to10-leaf lambsquarters.

All herbicide and pH treatments significantly reduced dry weight of lambsquarters compared to the control except for glyphosate applied when the pH was raised to 9 andlowered to 2. All treatments containing Trigate™ or Freestyle™ reduced dry weight of lambsquarters by at least 56% compared to the control. Glyphosate applied at pH 9 provided a significant reduction in dry weight compared to other pH treatments. Differences in dry weight were not found between pH treatments for Trigate™, glyphosate plus Trigate™, and glyphosate plus Freestyle™. Freestyle™ applied at pH 2, 6, or 9 resulted in similar reductions in dry weight.

The treatment by pH interaction was significant for control of lambsquarters, but was found insignificant for dry weight. The lack of consistent control across runs from any particular pH treatment combined with the insignificance found between treatments for dry weight suggests that adjusting the pH of the spray solution does not appear to affect the efficacy of Trigate™ and Freestyle™ on common lambsquarters.

Velvetleaf. The treatment by pH and treatment by pH by time interactions were not significant for control of velvetleaf; however, the treatment by pH by run interaction was significant (Table A20). Control ratings for velvetleaf were presented by run 28 DAA to reveal the final outcome for each treatment even though the treatment by pH interaction was insignificant (Table 20). The 14-day ratings for both runs generally were lower than the 28-day ratings and were removed to simplify the results. The treatment by pH by run interaction appeared to be due to a difference in magnitude between the two runs; however, there were some changes in rank. The differences in magnitude between the runs can most

Table 20. Percent control of velvetleaf 28 days after application and dry weight averaged across two runs for an experiment conducted in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1 28 DAA	Run 2 28 DAA	Average of runs	Dry weight Average of runs
	----g ai ha^{-1}----		--------------% Control------------			-----g-----
Glyphosate	290	2	19	12	16	0.691
Glyphosate	290	6	20	10	15	0.753
Glyphosate	290	9	9	2	6	0.812
Glyphosate	290	9 to 2	5	11	8	0.899
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	44	40	42	0.282
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	44	50	47	0.258
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	49	45	47	0.269
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	91	36	64	0.182
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	51	34	43	0.513
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	50	34	42	0.63
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	41	40	41	0.733
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	77	32	55	0.437
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	64	46	55	0.262
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	64	55	60	0.23
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	54	41	48	0.305
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	95	58	77	0.153
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	53	21	37	0.549
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	54	33	44	0.503
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	57	27	42	0.599
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	80	50	65	0.322
Control	-	-	0	0	0	1.06
LSD (0.05)[d]			10	10	7	0.131
LSD (0.05)[e]						0.114

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).
[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.
[d] LSD used to compare control of treatment means within a run.
[e] LSD used to compare control of treatment means to control.

likely be explained by different greenhouse conditions such as photoperiod and temperature as well as different heights of velvetleaf at the time of application (Table 7). The treatment by pH interaction was significant for dry weight of velvetleaf; however, the treatment by pH by run interaction was not (Table A21). Dry weight was presented for each treatment as an average of the two runs.

Although the treatment by pH interaction was not significant for control, some patterns can still be observed from the data. In the first run, all herbicide treatments applied when the pH was raised to 9 and lowered to 2 except for glyphosate resulted in significantly greater control of velvetleaf compared to other pH treatments. It appeared that this pH treatment was more efficacious when the velvetleaf plants were smaller in the first run. Control from this pH treatment with Trigate™ in the second run resulted in control being equal to pH 2 and 9 and being significantly less than pH 6. No significance was found between pH treatments for Freestyle in the second run. Glyphosate plus Trigate™ applied at pH 6 and when the pH was raised to 9 and lowered to 2 resulted in similar control in the second run. Glyphosate plus Freestyle™ applied when the pH was raised and then lowered gave greater than 50% control in both runs. The slightly higher control ratings observed with the herbicide Trigate™ can most likely be explained by mesotrione and rimsulfuron. These two herbicides generally provide excellent control of velvetleaf. Schuster et al. (2008) found that mesotrione plus rimsulfuron at 26 and 5 g ha^{-1} gave 99% control of velvetleaf 21 days after application.

All herbicide and pH treatments significantly reduced dry weight of velvetleaf compared to the control. Glyphosate applied at pH 2 or 6 significantly reduced dry weight compared to when the pH was raised to 9 and lowered to 2. Statistical differences for dry weight were not found between pH treatments for Trigate™ applied alone. The dry weight value for Freestyle™ applied when the pH was raised to 9 and lowered to 2 should be used with caution because this treatment was inconsistent across runs. Dry weights for glyphosate plus Trigate™ applied at pH 2 and 6 were similar to the dry weight produced when the pH was raised to 9 and lowered to 2. Glyphosate plus Freestyle™ applied when the pH was adjusted from 9 to 2 provided a significant reduction in dry weight compared to other pH treatments. This data supports the higher control ratings observed with this treatment. It appeared that herbicide treatments containing Trigate™ resulted in lower dry weights regardless of pH. This was most likely associated with the high efficacy of mesotrione and rimsulfuron on velvetleaf that was previously described.

The treatment by pH interaction was not significant for control of velvetleaf, but was found to be significant for dry weight. Glyphosate plus Freestyle™ applied when the pH was raised to 9 and lowered to 2 resulted in higher control ratings and lower dry weights compared to other pH treatments. This conclusion supports a treatment by pH interaction. The inconsistency of control across runs for Trigate™ and Freestyle™ along with the insignificance found between dry weights suggests that adjusting the pH of the spray solution does not appear to affect the efficacy of Trigate™ and Freestyle™ applied alone on velvetleaf.

It is difficult to determine the influence of pH on the efficacy of Trigate™ and Freestyle™ because both contain several different active ingredients. Each active ingredient may behave slightly differently under acidic or alkaline conditions. Further research is needed to evaluate the affect that pH has on the efficacy of each individual active ingredient in Trigate™ and Freestyle™.

SUMMARY

Field and greenhouse experiments were conducted to fulfill the following research objectives: 1) to evaluate weed control from herbicides developed for Optimum GAT corn; (2) to determine the influence of chlorimuron soil residues on the growth and yield of canola, dry edible bean, sunflower, hard red spring wheat, corn, and sugar beet; (3) to evaluate the enhancement of Trigate™ and Freestyle™ herbicides from adjuvants of different classes; (4) to evaluate the affect of pH on the efficacy of Trigate™ and Freestyle™ herbicides on common lambsquarters and velvetleaf.

Preemergence herbicides developed for Optimum GAT corn provided variable control of grass and broadleaf weed species. This was most likely due to different environmental conditions present at each location. Acetochlor treatments applied PRE provided nearly 25% greater control of grass species compared to broadleaf species. Chlorimuron plus rimsulfuron plus mesotrione applied PRE gave 78% control of broadleaf species and provided equal control of grass species compared to acetochlor. Statistical differences were not found between postemergence treatments for control of grass and broadleaf species 14 and 28 DAA. All treatments provided greater than 95% control 14 DAA and greater than 80% 28 DAA for both types of species. Although not statistically different, glyphosate applied alone provided 10 to 15% less control of grass and broadleaf weed species 28 DAA compared to other treatments. This research validates that one and two pass programs developed for Optimum GAT corn can deliver excellent control of several different weed species 28 DAA.

Chlorimuron injury to susceptible crops one year after application was highly dependent on the soil pH, the susceptibility of the crop, and the chlorimuron application

rate. Canola injury at Valley City was extremely variable for unknown reasons. Injury ranged from 18 to 45% 28 DAE; however, injury did not always increase with increasing chlorimuron rates. Flowering was delayed 2 to 4 days behind the control for all treatments. Differences were not found between treatments for yield, but this conclusion should be used with caution because of the great amount of variability within this experiment. No significant injury to canola from chlorimuron was observed at Alice. Canola injury at Reynolds increased with increasing chlorimuron rates, and injury for all treatments ranged from 31 to 86% 14 and 28 DAE. Flowering time 56 DAE was approximately 3 days behind the control at 3 g ha^{-1} and nearly one week behind the control at 5.8, 11.6, and 17.5 g ha^{-1}. Canola height was reduced from the control by all treatments 28 DAE, and height decreased with increasing chlorimuron rates. Chlorimuron at 17.5 g ha^{-1} was the only treatment that reduced the canola population compared to the control. Yield was not recorded at Alice or Reynolds due to wind damage and harvest complications.

Pinto bean injury from chlorimuron was not observed at Valley City and Alice. This was most likely attributed to the low soil pH at these locations. Injury at Reynolds appeared to increase as the season progressed. Chlorimuron applied at 5.8, 11.6, and 17.5 g ha^{-1} resulted in 10, 13, and 16% injury 56 DAE. Pinto bean yield at Reynolds was unaffected at 3 and 5.8 g ha^{-1}, but yield was reduced from the control by 25% at 11.6 g ha^{-1} and 34% at 17.5 g ha^{-1}.

Sunflower injury from chlorimuron was not observed 14, 28, and 56 DAE at all locations; however, yield was not recorded for various reasons. HRSW injury from chlorimuron was not observed at Valley City and Alice. Five percent injury occurred at

Reynolds 28 and 56 DAE when 17.5 g ha^{-1} of chlorimuron was applied, but no differences in yield were found between chlorimuron treatments at any location.

Corn injury from chlorimuron was not observed at Valley City. Corn injury did occur at Alice, but injury was only significantly different from the control at 17.5 g ha^{-1}. The injury at 17.5 g ha^{-1} also resulted in a reduction in plant height compared to the control. Significant corn injury was not observed at Reynolds when 5.8 g ha^{-1} or less of chlorimuron was applied. Injury 28 DAE and 56 DAE was approximately 25% for treatments of 11.6 and 17.5 g ha^{-1}. Corn height 28 DAE at Reynolds was reduced from the control by 13% at 5.8 g ha^{-1} and by 37% at 11.6 and 17.5 g ha^{-1}. Despite the injury observed at Alice and Reynolds, no differences in yield were found between treatments at any location.

Sugar beet injury from chlorimuron was not observed at Valley City 28 and 56 DAE, but a reduction in population occurred for an unknown reason which skewed the root yield and extractable sucrose data. Sugar beet injury at Alice and Reynolds increased while height, population, yield and extractable sucrose decreased with increasing chlorimuron rates. All rates of chlorimuron at Alice resulted in at least 73% injury of sugar beet. Chlorimuron applied at 11.6 and 17.5 g ha^{-1} resulted in a yield loss of 75 and 86% compared to the control as well as a similar reduction in extractable sucrose. The application of chlorimuron at 5.8 g ha^{-1} or greater at Reynolds resulted in 14 to 79% yield loss compared to the control with a similar percentage range for the reduction in extractable sucrose.

The data obtained from these experiments suggest that insignificant injury may occur to pinto bean, HRSW, and corn when 5.8 g ha^{-1} or less of chlorimuron is applied the previous year; however, yield should not be significantly impacted. The lack of visible injury on sunflower suggests that low rates of chlorimuron would not reduce yield, but further research is needed to confirm this statement. The data collected also suggest that low rates of chlorimuron can cause significant injury on sugar beet and canola one year after application.

Adjuvant enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ was variable depending on the targeted plant species and the environmental conditions present at application. Several adjuvants performed similarly with both herbicide combinations. Adjuvants containing AMS or an AMS replacement such as Class Act NG, Alliance, and Import provided greater enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on flax and corn 28 DAA compared to oil-based adjuvants. The enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on quinoa and tame buckwheat 28 DAA appeared to be somewhat similar for oil-based and AMS-based adjuvants; however, lower control ratings with oil-based adjuvants were observed on flax and corn. The addition of the adjuvant Flame to glyphosate plus Trigate™ and glyphosate plus Freestyle™ resulted in physical incompatibility for unknown reasons. Cut Rate and ET 4000 provided little to no enhancement of glyphosate plus Trigate™ and glyphosate plus Freestyle™ on flax and quinoa. The addition of Class Act NG to glyphosate plus Trigate™ or glyphosate plus Freestyle™ provided between 68 and 94% control of all four species 28 DAA. The enhancement observed from Class Act NG with low rates of these herbicides suggests that this adjuvant could enhance control on several species; however, further research is needed.

The lack of consistent control across runs from any particular pH treatment combined with the insignificance found between treatments for dry weight suggest that adjusting the pH of the spray solution does not appear to affect the efficacy of Trigate^{TM} and Freestyle^{TM} on common lambsquarters. Glyphosate plus Freestyle^{TM} applied when the pH was raised to 9 and lowered to 2 resulted in significantly higher control ratings and lower dry weights for velvetleaf compared to other pH treatments. This suggests that this pH treatment may improve control of velvetleaf with these herbicides; however, further research is needed to verify these results. The inconsistency of control across runs along with the insignificance found between dry weights suggests that adjusting the pH of the spray solution does not appear to affect the efficacy of Trigate^{TM} and Freestyle^{TM} applied alone on velvetleaf. Further research is needed to evaluate the affect that pH has on the efficacy of each individual active ingredient in Trigate^{TM} and Freestyle^{TM}.

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APPENDIX

Table A1. Corn and weed height at the time of application in Optimum GAT corn at Arlington, WI, in 2009.

Species	EPOST[a]	MPOST[b]	POST[c]
	-----cm-----		
Corn	10	33	33
Giant foxtail	2	13	5
Common lambsquarters	2	6	8
Ladysthumb	1	23	-
Velvetleaf	3	5	8
Eastern black nightshade	3	-	-

[a] EPOST = early postemergence.
[b] MPOST = mid-postemergence.
[c] POST = postemergence.

Table A2. Corn and weed height at the time of application in Optimum GAT corn at Brookings, SD, in 2009.

Species	EPOST[a]	MPOST/POST[b]
	-----cm-----	
Corn	10	15
Redroot pigweed	-	5
Green foxtail	1	5
Wild buckwheat	3	10

[a] EPOST = early postemergence.
[b] MPOST = mid-postemergence; POST = postemergence; applications made on same date.

Table A3. Corn and weed leaf stage along with height at the time of application in Optimum GAT corn at Waseca, MN, in 2009.

	EPOST[a]		MPOST[b]		POST[c]	
Species	Leaf Stage	Height	Leaf Stage	Height	Leaf Stage	Height
		--cm--		--cm--		--cm--
Corn	V2	8	V3	13	V4	15
Giant foxtail	2 leaf	5	4 leaf	10	4 leaf	10
Giant ragweed	2 leaf	10	4 leaf	18	4 leaf	20
Common lambsquarters	4 leaf	5	8 leaf	8	8 leaf	8
Velvetleaf	2 leaf	3	3 leaf	3	3 leaf	3

[a] EPOST = early postemergence.
[b] MPOST = mid-postemergence.
[c] POST = postemergence.

Table A4. Weed height and density at the time of application in Optimum GAT corn at Prosper, ND, in 2009.

	EPOST[a]		MPOST[b]		POST[c]	
Species	Height[d]	Density	Height	Density	Height	Density
	--cm--	plants m^{-2}	--cm--	plants m^{-2}	--cm--	plants m^{-2}
Yellow foxtail	3	270	9	380	13	325
Redroot pigweed	cotyl-1	4	10	30	11	60
Wild mustard	cotyl-3	2	10	2	18	2
Common lambsquarters	cotyl-1	2	9	2	18	7
Wild buckwheat	cotyl-3	1	5	2	8	1
Hairy nightshade	cotyl-1	2	5	2	9	2
Common ragweed	-	-	5	2	8	1

[a] EPOST = early postemergence.
[b] MPOST = mid-postemergence.
[c] POST = postemergence.
[d] cotyl = cotyledon.

Table A5. Weed height and density at the time of application in Optimum GAT corn at Prosper, ND, in 2010.

	EPOST[a]		MPOST[b]		POST[c]	
Species	Height	Density	Height	Density	Height	Density
	--cm--	plants m^{-2}	--cm--	plants m^{-2}	--cm--	plants m^{-2}
Common lambsquarters	6	270	18	325	19	160
Common ragweed	5	2	9	< 1	9	< 1
Common cocklebur	5	< 1	11	< 1	13	3
Wild buckwheat	5	< 1	10	4	18	54
Yellow foxtail	5	5	9	160	11	160
Hairy nightshade	-	-	10	6	6	3
Kochia	-	-	11	4	14	< 1

[a] EPOST = early postemergence.
[b] MPOST = mid-postemergence.
[c] POST = postemergence.

Table A6. Environmental and application data for evaluating weed control in Optimum GAT corn at Arlington, WI, in 2009.

	Application Timing			
Factor	PRE[a]	EPOST[b]	MPOST[c]	POST[d]
Application date	May 22	June 12	June 23	June 26
Time	11:25 am	11:31 am	7:45 am	11:30 am
Air temperature (°C)	21	21	26	30
Soil temperature (°C)	17	21	21	32
Relative humidity (%)	53	49	89	37
Wind speed (km h^{-1})	14	4	0	5
Wind direction	Southeast	Southwest	-	Southwest
Cloud cover	70	65	5	50
Soil surface moisture	Dry	Dry	Wet	Dry
Subsoil moisture	Moist	Moist	Wet	Moist

[a] PRE = preemergence.
[b] EPOST = early postemergence.
[c] MPOST = mid-postemergence.
[d] POST = postemergence.

Table A7. Environmental and application data for evaluating weed control in Optimum GAT corn at Brookings, SD, in 2009.

	Application Timing			
Factor	PRE[a]	EPOST[b]	MPOST[c]	POST[d]
Application date	May 16	June 1	June 16	June 16
Time	7:30 pm	9:00 am	9:00 am	9:00 am
Air temperature (°C)	14	18	21	21
Soil temperature (°C)	16	14	16	16
Relative humidity (%)	26	61	78	78
Wind speed (km h^{-1})	2	8	8	8
Wind direction	North	East	East	East
Cloud cover	10	10	100	100
Soil moisture	Dry	Moist	Moist	Moist

[a] PRE = preemergence.
[b] EPOST = early postemergence.
[c] MPOST = mid-postemergence.
[d] POST = postemergence.

Table A8. Environmental and application data for evaluating weed control in Optimum GAT corn at Waseca, MN, in 2009.

	Application Timing			
Factor	PRE[a]	EPOST[b]	MPOST[c]	POST[d]
Application date	May 22	June 12	June 22	June 24
Air temperature (°C)	20	20	30	22
Soil temperature (°C)	18	17	27	22
Relative humidity (%)	50	55	60	100
Wind speed (km h^{-1})	16	11	16	13
Wind direction	North	South	Southwest	East

[a] PRE = preemergence.
[b] EPOST = early postemergence.
[c] MPOST = mid-postemergence.
[d] POST = postemergence.

Table A9. Environmental and application data for evaluating weed control in Optimum GAT corn at Prosper, ND, in 2009.

	Application Timing			
Factor	PRE[a]	EPOST[b]	MPOST[c]	POST[d]
Application date	May 28	June 17	June 30	July 7
Time	1:00 pm	9:30 am	9:00 am	9:30 am
Air temperature (°C)	24	18	17	24
Soil temperature (°C)	12	18	18	23
Relative humidity (%)	39	97	72	51
Wind speed (km h^{-1})	15	12	16	8
Wind direction	North	Southeast	Northwest	Northeast
Cloud cover	10	100	0	90
Soil surface moisture	Dry	Moist	Dry	Dry
Subsoil moisture	Moist	Wet	Wet	Moist

[a] PRE = preemergence.
[b] EPOST = early postemergence.
[c] MPOST = mid-postemergence.
[d] POST = postemergence.

Table A10. Environmental and application data for evaluating weed control in Optimum GAT corn at Prosper, ND, in 2010.

	Application Timing			
Factor	PRE[a]	EPOST[b]	MPOST[c]	POST[d]
Application date	April 29	June 3	June 9	June 14
Time	8:00 am	10:20 am	10:30 am	9:45 am
Air temperature (°C)	12	22	16	17
Soil temperature (°C)	11	28	18	19
Relative humidity (%)	100	37	82	77
Wind speed (km h^{-1})	14	6	20	5
Wind direction	Southeast	South	Northwest	Northeast
Cloud cover	100	0	100	100
Soil surface moisture	Dry	Dry	Dry	Dry
Subsoil moisture	Wet	Moist	Moist	Moist

[a] PRE = preemergence.
[b] EPOST = early postemergence.
[c] MPOST = mid-postemergence.
[d] POST = postemergence.

Table A11. Percent weed control 28 DAA[a] for preemergence treatments in Optimum GAT corn at Arlington, WI, in 2009.

Treatment	Rate	Gift[b]	Colq[c]	Vele[d]	Rrpw[e]
	--g ai ha^{-1}--	-----------% control-----------			
Acetochlor	900	93	70	90	99
Acetochlor	900	92	60	5	99
Acetochlor	900	92	65	15	99
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	93	99	35	99
LSD (0.05)		NS	10	17	NS

[a] DAA = days after application.
[b] Gift = giant foxtail.
[c] Colq = common lambsquarters.
[d] Vele = velvetleaf.
[e] Rrpw = redroot pigweed.

Table A12. Percent weed control 32 DAA[a] for preemergence treatments in Optimum GAT corn at Brookings, SD, in 2009.

Treatment	Rate	Smcg[b]	Rrpw[c]	Wibw[d]
	--g ai ha^{-1}--	--------% control--------		
Acetochlor	900	77	99	68
Acetochlor	900	85	98	60
Acetochlor	900	85	98	63
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	88	98	98
LSD (0.05)		NS	NS	12

[a] DAA = days after application.
[b] Smcg = smooth crabgrass.
[c] Rrpw = redroot pigweed.
[d] Wibw = wild buckwheat.

Table A13. Percent weed control 20 DAA[a] for preemergence treatments in Optimum GAT corn at Waseca, MN, in 2009.

Treatment	Rate	Gift[b]	Colq[c]	Girw[d]	Vele[e]
	--g ai ha^{-1}--	-----------% control-----------			
Acetochlor	900	69	60	16	33
Acetochlor	900	70	59	20	49
Acetochlor	900	71	60	13	25
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	61	69	28	45
LSD (0.05)		NS	NS	NS	NS

[a] DAA = days after application.
[b] Gift = giant foxtail.
[c] Colq = common lambsquarters.
[d] Girw = giant ragweed.
[e] Vele = velvetleaf.

Table A14. Percent weed control 33 DAA[a] for preemergence treatments in Optimum GAT corn at Prosper, ND, in 2009.

Treatment	Rate	Yeft[b]	Rrpw[c]	Colq[d]	Wibw[e]	Hans[f]
	--g ai ha^{-1}--	-----------------% control-----------------				
Acetochlor	900	71	58	29	3	40
Acetochlor	900	69	63	29	4	47
Acetochlor	900	75	65	54	4	48
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	64	75	69	10	67
LSD (0.05)		NS	NS	32	NS	NS

[a] DAA = days after application.
[b] Yeft = yellow foxtail.
[c] Rrpw = redroot pigweed.
[d] Colq = common lambsquarters.
[e] Wibw = wild buckwheat.
[f] Hans = hairy nightshade.

Table A15. Percent weed control 35 DAA[a] for preemergence treatments in Optimum GAT corn at Prosper, ND, in 2010.

Treatment	Rate	Yeft[b]	Wibw[c]	Colq[d]	Hans[e]	Cocb[f]
	--g ai ha^{-1}--	-----------------% control-----------------				
Acetochlor	900	50	30	53	36	24
Acetochlor	900	45	23	63	33	16
Acetochlor	900	50	22	54	34	15
Chlorimuron + rimsulfuron + mesotrione	23 + 23 + 150	95	99	98	94	86
LSD (0.05)		18	17	27	20	15

[a] DAA = days after application.
[b] Yeft = yellow foxtail.
[c] Wibw = wild buckwheat.
[d] Colq = common lambsquarters.
[e] Hans = hairy nightshade.
[f] Cocb = common cocklebur.

Table A16. Fertilizer type and rate applied to each crop at three North Dakota locations for experiments to evaluate chlorimuron carryover.

	Valley City		Alice		Reynolds		
Crop	46-0-0[a]	21-0-0-24[b]	46-0-0	21-0-0-24	46-0-0	11-52-0[c]	21-0-0-24
	--------	--------	--------	kg ha^{-1}	--------	--------	--------
Canola	260	105	65	105	-	85	105
Pinto bean	85	65	-	65	-	65	-
Sunflower	170	65	-	65	-	45	-
Spring wheat	320	65	260	65	215	65	-
Corn	280	65	85	65	-	105	65
Sugar beet	235	65	45	65	-	85	65

[a] 46-0-0 = urea.
[b] 21-0-0-24 = ammonium sulfate.
[c] 11-52-0 = monoammonium phosphate.

Table A17. Application date and environmental information at time of application for evaluation of adjuvant enhancement with Trigate™ and Freestyle™ herbicides at Mapleton, ND, in 2009 and at Casselton, ND, in 2010.

	Trigate™	Freestyle™	Trigate™	Freestyle™
Factor	2009		2010	
Application date	July 20	July 20	July 9	July 9
Time	7:30 am	8:20 am	9:00 am	9:25 am
Air temperature (°C)	19	19	24	25
Soil temperature (°C)	19	19	26	27
Relative humidity (%)	85	85	53	51
Wind speed (km h^{-1})	6	10	3	3
Wind direction	East	East	Northwest	Northwest
Cloud cover	60	65	0	0
Soil surface moisture	Dry	Dry	Dry	Dry
Subsoil moisture	Moist	Moist	Moist	Moist

Table A18. Sources of variation, degrees of freedom (df), and means squares for percent control of common lambsquarters for an experiment conducted in the greenhouse.

Sources of variation	df	Means squares
Trt	4	33189.4*
pH	3	1253.2
Trt x pH	12	1345.8*
Time	1	115568.1*
Trt x time	4	3840.1
pH x time	3	1221.7
Trt x pH x time	12	197.6
Run	1	3819.4*
Trt x run	4	801.8*
pH x run	3	2524.6*
Trt x pH x run	12	359.3*
Time x run	1	91.9
Trt x time x run	4	2135.7*
pH x time x run	3	166.4
Trt x pH x time x run	12	285.5*
Rep (run)	10	324.1*

* Significant at the 0.05 probability level.

Table A19. Sources of variation, degrees of freedom (df), and means squares for dry weight of common lambsquarters for an experiment conducted in the greenhouse.

Sources of variation	df	Means squares
Trt	4	0.661*
pH	3	0.08
Trt x pH	12	0.029
Run	1	3.82
Trt x run	4	0.009
pH x run	3	0.039*
Trt x pH x run	12	0.021
Rep (run)	10	0.063*

* Significant at the 0.05 probability level.

Table A20. Sources of variation, degrees of freedom (df), and means squares for percent control of velvetleaf for an experiment conducted in the greenhouse.

Sources of variation	df	Means squares
Trt	4	22730.9*
pH	3	9569.6
Trt x pH	12	1140.9
time	1	7142.7
Trt x time	4	1031
pH x time	3	444.4
Trt x pH x time	12	58.3
Run	1	16024.9*
Trt x run	4	1109.7*
pH x run	3	3384*
Trt x pH x run	12	860.5*
Time x run	1	1704.4*
Trt x time x run	4	436*
pH x time x run	3	51.8
Trt x pH x time x run	12	63.5
Rep (run)	10	282.7*

* Significant at the 0.05 probability level.

Table A21. Sources of variation, degrees of freedom (df), and means squares for dry weight of velvetleaf for an experiment conducted in the greenhouse.

Sources of variation	df	Means squares
Trt	4	2.43
pH	3	0.199
Trt x pH	12	0.078*
Run	1	2.03*
Trt x run	4	0.651*
pH x run	3	0.121*
Trt x pH x run	12	0.026
Rep (run)	10	0.011

* Significant at the 0.05 probability level.

Table A22. Dry weight of common lambsquarters averaged over four pH values and two runs in the greenhouse.

Treatment	Rate	Dry weight
	------g ai ha^{-1}-----	----g----
Glyphosate	290	0.496
Rimsulfuron + tribenuron + mesotrione[a]	6 + 4.3 + 29	0.245
Chlorimuron + tribenuron + thifensulfuron[b]	1.9 + 2.9 + 2.9	0.243
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	0.213
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	0.239
Control	-	0.694
LSD (0.05)[c]		0.095
LSD (0.05)[d]		0.082

[a] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[b] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.
[c] LSD used to compare dry weight of two treatment means.
[d] LSD used to compare dry weight of treatment means to control.

Table A23. Percent control of velvetleaf by run averaged over four pH values and two timings in the greenhouse.

Treatment	Rate	Run 1	Run 2	Average
	---g ai ha^{-1}---	--------% Control-------		
Glyphosate	290	13	11	12
Rimsulfuron + tribenuron + mesotrione[a]	6 + 4.3 + 29	52	39	46
Chlorimuron + tribenuron + thifensulfuron[b]	1.9 + 2.9 + 2.9	52	32	42
Glyphosate + rimsulfuron + tribenuron + Mesotrione	290 + 6 + 4.3 + 29	61	47	54
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	47	30	39
LSD (0.05)[c]		7	7	5
LSD (0.05)[d]		----38----		

[a] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[b] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.
[c] LSD used to compare two treatment means within a run.
[d] LSD used to compare two treatment means across different runs.

Table A24. Percent control of common lambsquarters according to herbicide and pH combination for two runs in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1 14 DAA	Run 1 28 DAA	Run 2 14 DAA	Run 2 28 DAA
	----g ai ha^{-1}----		---------------% Control---------------			
Glyphosate	290	2	3	25	11	20
Glyphosate	290	6	14	35	6	18
Glyphosate	290	9	3	24	6	14
Glyphosate	290	9 to 2	1	19	6	17
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	20	70	15	40
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	20	78	15	42
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	14	61	16	44
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	8	59	15	71
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	69	85	32	77
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	57	65	44	82
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	52	63	45	74
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	23	64	31	79
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	13	75	20	57
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	16	63	14	43
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	14	54	20	56
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	18	64	21	84
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	63	71	29	51
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	77	90	44	85
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	68	64	45	80
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	33	60	20	59
LSD (0.05)			9	9	9	9

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).
[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.

Table A25. Dry weight of common lambsquarters by run according to herbicide and pH combination in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1	Run 2	Average of runs
	----g ai ha^{-1}----		--------------g---------------		
Glyphosate	290	2	0.332	0.665	0.499
Glyphosate	290	6	0.27	0.685	0.478
Glyphosate	290	9	0.355	0.4	0.378
Glyphosate	290	9 to 2	0.445	0.817	0.631
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	0.117	0.413	0.265
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	0.063	0.375	0.219
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	0.135	0.327	0.231
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	0.158	0.373	0.266
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	0.113	0.385	0.249
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	0.112	0.273	0.193
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	0.113	0.342	0.228
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	0.192	0.417	0.305
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	0.03	0.318	0.174
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	0.088	0.383	0.236
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	0.143	0.34	0.242
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	0.128	0.272	0.200
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	0.08	0.367	0.224
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	0.083	0.363	0.223
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	0.068	0.353	0.211
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	0.197	0.403	0.300
Control	-	-	0.558	0.829	0.694
LSD (0.05)[d]			0.129	0.129	0.091
LSD (0.05)[e]			0.112	0.112	0.079
LSD (0.05)[f]			------0.167------		

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).
[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.
[d] LSD used to compare control of two treatment means within a run.
[e] LSD used to compare control of treatment means to control.
[f] LSD used to compare control of two treatment means across different runs.

Table A26. Percent control of velvetleaf according to herbicide and pH combination for two runs in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1 14 DAA	Run 1 28 DAA	Run 2 14 DAA	Run 2 28 DAA
	----g ai ha^{-1}----		---------------% Control---------------			
Glyphosate	290	2	19	19	19	12
Glyphosate	290	6	13	20	10	10
Glyphosate	290	9	5	9	5	2
Glyphosate	290	9 to 2	11	5	18	11
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	33	44	28	40
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	35	44	41	50
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	40	49	40	45
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	81	91	34	36
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	44	51	27	34
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	46	50	23	34
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	37	41	34	40
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	74	77	34	32
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	45	64	38	46
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	44	64	43	55
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	40	54	40	41
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	84	95	55	58
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	18	53	14	21
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	23	54	23	33
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	20	57	24	27
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	73	80	48	50
LSD (0.05)			10	10	10	10

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).
[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.

Table A27. Dry weight of velvetleaf by run according to herbicide and pH combination in the greenhouse.

Treatment[a]	Rate	pH of spray solution	Run 1	Run 2	Average of runs
	----g ai ha^{-1}----		----------------g----------------		
Glyphosate	290	2	0.47	0.908	0.691
Glyphosate	290	6	0.464	1.04	0.753
Glyphosate	290	9	0.618	1.01	0.812
Glyphosate	290	9 to 2	0.618	1.17	0.899
Rimsulfuron + tribenuron + mesotrione[b]	6 + 4.3 + 29	2	0.262	0.298	0.282
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	6	0.301	0.205	0.258
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9	0.298	0.235	0.269
Rimsulfuron + tribenuron + mesotrione	6 + 4.3 + 29	9 to 2	0.115	0.248	0.182
Chlorimuron + tribenuron + thifensulfuron[c]	1.9 + 2.9 + 2.9	2	0.446	0.575	0.513
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	6	0.466	0.79	0.63
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9	0.564	0.898	0.733
Chlorimuron + tribenuron + thifensulfuron	1.9 + 2.9 + 2.9	9 to 2	0.145	0.728	0.437
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	2	0.244	0.275	0.262
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	6	0.306	0.15	0.23
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9	0.426	0.18	0.305
Glyphosate + rimsulfuron + tribenuron + mesotrione	290 + 6 + 4.3 + 29	9 to 2	0.125	0.18	0.153
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	2	0.402	0.692	0.549
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	6	0.346	0.655	0.503
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9	0.478	0.715	0.599
Glyphosate + chlorimuron + tribenuron + thifensulfuron	290 + 1.9 + 2.9 + 2.9	9 to 2	0.122	0.522	0.322
Control	-	-	0.874	1.25	1.06
LSD (0.05)[d]			0.186	0.186	0.131
LSD (0.05)[e]			0.161	0.161	0.114
LSD (0.05)[f]			------0.532------		

[a] All treatments included nonionic surfactant (NIS) at 0.25% v/v (R-11 from Wilbur-Ellis).
[b] Rimsulfuron + tribenuron + mesotrione = Trigate™.
[c] Chlorimuron + tribenuron + thifensulfuron = Freestyle™.
[d] LSD used to compare control of two treatment means within a run.
[e] LSD used to compare control of treatment means to control.