Yield of Glufosinate-Resistant Sugarbeet in Response to Postemergence Glufosinate

Ines Rothe, Alan G. Dexter, and John L. Luecke

North Dakota State University, Dept.of Plant Sciences
Loftsgard Hall, Fargo, ND 58105

ABSTRACT

Experiments were conducted to determine the effect of glufosinate rate and herbicide starting time on glufosinate-resistant sugarbeet (*Beta vulgaris L.*) injury and yield. Sequential glufosinate applications starting two weeks or later and ending five to seven weeks after the sugarbeet cotyledon stage caused significant visible sugarbeet injury while injury was minimal with treatments starting at the cotyledon stage or one week later. Sugarbeet yield declined when sequential glufosinate treatments were applied at weekly intervals and the first treatment was delayed until four weeks or one week after the sugarbeet cotyledon stage in 1998 and 1999, respectively. Sugarbeet yield loss may be attributed to sugarbeet injury or prolonged weed competition prior to the first sequential glufosinate application. As the glufosinate rate increased from 0.2 to 0.4 and 0.8 kg ha^{-1}, glufosinate had to be applied to younger sugarbeet to avoid sugarbeet injury. Glufosinate-resistant sugarbeet treated three times with glufosinate yielded less in 1998 than sugarbeet that was hand weeded at the same time pattern as glufosinate was applied.

Similar results were found in 1999 at one location, but yield from glufosinate-treated and hand-weeded plots did not differ at two locations, despite the significant herbicide-induced sugarbeet injury observed seven days after the last treatment. Glufosinate, regardless of rate, can safely be applied to sugarbeet starting at the cotyledon stage or one week thereafter without causing yield loss.

Key Words: *Beta vulgaris* L., weed management, herbicide injury.

Sugarbeet producers are challenged with difficult weed control decisions to ensure profitability of a sugarbeet farming enterprise. Despite considerable expenditure of time and money aimed at weed-free sugarbeet, 53% of the sugarbeet growers in eastern North Dakota and Minnesota still considered weeds their most serious production problem in 2002 (Dexter and Luecke 2003).

Weeds interfere with plant growth and reduce yields severely by competing with sugarbeet for water, nutrients, light, and space. Season-long competition from uncontrolled annual weeds can cause extensive economic losses in sugarbeet production (Brimhall et al. 1965; Dawson 1965; Weatherspoon and Schweizer 1969; Wicks and Wilson 1983; Winter and Wiese 1982). Weeds have been the target of determined attempts at control but reductions in yield still occur from only a few vigorous, annual weeds per sugarbeet. Broadleaf weeds are especially competitive compared to grass species (Brimhall et al. 1965; Dawson 1974; Zimdahl and Fertig 1967) and even small infestations that survive can compete with sugarbeet (Dawson 1965; Evans 1983; Schweizer 1983; Schweizer and Bridge 1982; Schweizer and Lauridson 1985; Weatherspoon and Schweizer 1971).

Herbicides are recognized as a cost-effective and reliable tool with the potential for increasing sugarbeet yield; reducing tillage and resulting soil erosion, soil compaction, and moisture loss; and saving fuel, labor, and time in sugarbeet production. However, herbicide inputs in sugarbeet are often high, and current herbicide systems include a multitude of herbicide combinations that must be chosen carefully to ensure a wide weed control spectrum and a reduced risk of sugarbeet injury. A typical sugarbeet herbicide program in eastern North Dakota and Minnesota would consist of a tank mix of postemergence (POST) broadleaf herbicides such as: desmedipham plus phenmedipham plus triflusulfuron plus clopyralid plus a grass herbicide plus a methylated seed oil adjuvant, which is priced at about $ 55 ha^{-1} for each of three to five applications (Dexter and Luecke 2003).

Present herbicide systems in sugarbeet, in conjunction with cultivation and hand labor, generally provide acceptable weed control. However, the high cost and limited availability of hand labor for weeding has led to a greater reliance on herbicides. Weed populations have shifted to species that are more difficult to control, and weed resistance to herbicides has increased in many crops (Dexter and Zollinger 2003; Heap 2003), including sugarbeet (Dexter and Luecke 2003). This trend is expected to continue unless new herbicide options for sugarbeet are developed.

Some of the currently available broadleaf POST sugarbeet herbicides, such as phenmedipham and desmedipham, lack absolute selectivity and may injure sugarbeet at commercial use rates (Bray 1983; Eshel et al. 1976; Norris 1974; Preston and Briscoe 1983; Winter and Wiese 1978). Sugarbeet crops suffer most from sequential POST herbicide application starting at the cotyledon growth stage, whereas less injury occurs with delayed POST treatments at the two- to four, four- to six, or six- to eight-leaf stage (Wilson 1998a; Wicks and Wilson 1983). However, as sugarbeet plants gain herbicide tolerance with size (Norris 1991), weeds also become more tolerant as they grow larger (Edmund Jr. and York 1987; Lee and Oliver 1982; Ritter and Coble 1984; Weinlaeder and Dexter 1972), and may survive delayed POST treatments (Eshel et al. 1976). Therefore, timing of single POST herbicide applications in sugarbeet aimed at optimal weed control is difficult (Breay 1983; Dexter and Zollinger 2003). For example, the narrow time frame of a few days in which broadleaf weeds are most susceptible to phenmedipham and desmedipham greatly restricts the window for timing the POST herbicide treatments in sugarbeet (Norris 1991). The situation worsens and the optimal application window can be missed when weather conditions do not permit POST applications.

Glufosinate is a non-selective POST herbicide and its lack of crop selectivity has restricted the use of glufosinate during the growing season. Low use-rates, a high degree of safety to non-target organisms, rapid degradation in the environment resulting in minimal residue persistence in soil, negligible residues in crops, a unique mode of action, application flexibility, and excellent efficacy on a broad weed spectrum are the main advantages of glufosinate over some of the currently available sugarbeet herbicides (Ahrens 1994; Vasil 1996). Genes for resistance to glufosinate isolated from soil bacteria have been inserted into conventional sugarbeet lines to allow the use of glufosinate in-season with a low risk of sugarbeet injury (D' Halluin et al. 1992; Vasil 1996).

Wilson (1998b) reported 99% weed control with glufosinate at 0.30 kg ha^{-1} applied two times at the four-leaf and again at the six-leaf sugarbeet growth stage. The use of glufosinate gave weed control similar to a conventional weed program. Two applications of glufosinate at 0.40 kg ha^{-1} to sugarbeet starting at the two-leaf stage gave at least 96% weed control (Dexter and Luecke 1999). Nitschelm and Regitnig (1997) suggested that a third glufosinate application would be necessary to control late weed flushes due to the lack of soil residual. According to Steward et al. (1998) and Thorsness (1998), weed control improved as the rate of glufosinate increased and treatments were applied to small weeds. However, Mesbah et al. (1997) observed total weed control regardless of glufosinate rates. The literature regarding sugarbeet tolerance to POST glufosinate treatments is inconsistent. The application time of high glufosinate rates was reported to be more important for crop injury than for weed control efficacy (Regitnig and Nitschelm 1998). They observed sugarbeet leaf chlorosis after the third application of glufosinate at 0.4 kg ha^{-1} shortly before row closure. Thorsness et al. (1998) reported no visible sugarbeet injury when glufosinate was applied from emergence to the 10-leaf sugarbeet stage. Similarly, timing of glufosinate, even at twice the recommended rates, did not affect sugarbeet injury nor weed control efficacy under various weather conditions (Wevers 1998).

This research was initiated to assess the practical agronomic value of POST weed control using glufosinate in glufosinate-resistant sugarbeet, to deliver additional herbicide options, and to avoid several problems with prevailing weed management technologies. The objectives were to determine the effect of glufosinate rate and application starting time to avoid yield loss from weed interference (Weed Infested Period) in glufosinate-resistant sugarbeet and to compare glufosinate treatments to hand weeding.

MATERIALS AND METHODS

General field procedure

Field experiments were conducted near Fargo, ND, and Crookston, MN, in 1998 and near Fargo and St. Thomas, ND, and Crookston, MN, in 1999. Glufosinate-resistant 'Beta 2012' sugarbeet was seeded 3 cm deep and 7.6 cm apart in 56-cm wide rows with a conventional sugarbeet planter. Individual experimental units consisted of six 9-m-long sugarbeet rows of which the two outer rows were untreated check rows. Terbufos was applied modified in-furrow with seeding for root maggot [*Tetanops myopaeformis* (Röder)] control and fungicides were sprayed throughout the growing season when necessary for Cercospora leaf spot control (*Cercospora beticola Sacc.*). Sugarbeet at the seedling stage was hand thinned to 5 to 6 plants per m of row. Planting, thinning, and harvest dates are listed in Table 1.

Glufosinate was applied to the four inside rows in 80 L ha^{-1} water at 280 kPa through 8001 flat fan nozzles using a CO_2 pressurized bicycle-wheel-type plot sprayer traveling at 4.8 km h^{-1}. In 1999, glufosinate was applied in 160 L ha^{-1} water using 8002 flat fan nozzles.

Treatments in 1998 and 1999 included hand weeding and glufosinate at the recommended normal rate of 0.4 kg ai. ha^{-1}; at half the normal rate, 0.2 kg ha^{-1}; and at twice the normal rate, 0.8 kg ha^{-1}.

Table 1. Glufosinate-resistant sugarbeet in 1998 and 1999.

	Planting date		Hand-thinning date		Harvest date	
Location	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**
Fargo, ND	May 22	April 30	July 20	June 3	Oct. 1	Oct. 1
St. Thomas, ND	-	May 13	-	June 11	-	Sept. 28
Crookston, MN	May 22	May 21	July 16	June 29	Oct. 9	Sept. 30

Ammonium sulfate was not added to glufosinate. Glufosinate in 1998 was applied three times to sugarbeet with approximately seven days between applications except for a 17-day interval between June 12 and June 29 at Crookston, MN, due to excessive rain (Table 2). In 1999, glufosinate was applied four times with approximately seven day intervals between applications. The fourth application was necessary to achieve nearly complete, season-long weed control with non-residual glufosinate so that sugarbeet yield was not affected by late weed emergence and competition. In 1998 three glufosinate applications were sufficient to maintain glufosinate-treated plots weed free until harvest.

Applications of glufosinate were initiated at five starting times during the growing season. The earliest starting time was at the cotyledon growth stage of sugarbeet. Subsequent starting times followed at weekly intervals with the latest beginning at the cotyledon plus four-week stage. Five untreated control plots were hand weeded at the same time as the herbicide treatments so that hand-weeded treatments corresponded to the five glufosinate starting time treatments. Weeds remained uncontrolled until the starting time for hand weeding and glufosinate treatment was initiated. Treatment dates, environmental conditions, and sugarbeet growth stages at application time for each location during 1998 and 1999 are shown in Tables 2 and 3, respectively.

Sugarbeet injury and weed control in the center four rows was scored visually on a scale of zero to 100 (0 = no leaf chlorosis or biomass reduction; and 100 = complete kill) approximately 7 and 21 days after the last herbicide treatments (DALT) were applied. For this purpose, the glufosinate-treated and hand-weeded center rows were compared to the two outer untreated check rows of each plot. Weed density before glufosinate treatments and hand weeding were initiated in each experiment was not evaluated.

Sugarbeet populations were determined by counting sugarbeet roots in the two center harvested rows of each plot. Harvested roots were weighed in the field and 10 to 15 uniform, visibly disease-free roots were taken from each plot. Percent tare, impurity, and sucrose

Table 2. Environmental conditions and sugarbeet growth stage at the time of glufosinate application in 1998.

Glufosinate application†	Location: Fargo	Crookston	Fargo	Crookston	Fargo	Crookston	Fargo	Crookston
	Date		Air temperature		Relative humidity		Sugarbeet growth stage	
			C		%		V‡	
C	06/17	06/05	19	14	85	70	1.0 - 4.5	1.0 - 2.0
C+1	06/23	06/12	22	21	69	81	3.0 - 5.7	1.0 - 4.3
C+2	06/30	06/29	23	21	70	77	5.0 - 9.5	6.0 - 10.5
C+3	07/09	07/08	33	29	45	60	5.0 - 13.5	5.7 - 13.5
C+4	07/14	07/15	33	23	68	69	10.0 - 16.3	10.0 - 18.3
C+5	07/20	07/21	34	19	63	85	14.3 - 16.7	11.7 - 20.5
C+6	07/27	07/27	21	26	76	53	14.5 - 25.5	15.0 - 31.3

† Abbreviations indicate the time when glufosinate was applied in reference to the sugarbeet development stage: C = sugarbeet cotyledon growth stage, C+1 = one week after C, C+2 = two weeks after C, etc. C, C+1, C+2, C+3, and C+4 indicate the five starting times of sequential glufosinate treatments. Glufosinate was applied three times in all starting time treatments, therefore, the "C" starting time treatment included glufosinate applications at C, C+1, and C+2 in one-week intervals. Correspondingly, the latest "C+4" treatment, for example, included three sequential glufosinate applications at C+4, C+5, and C+6.

‡ V1.0 = sugarbeet cotyledon stage, V2.0 = sugarbeet with two unrolled true leaves, and V2.5 = sugarbeet with two unrolled true leaves and a third leaf 50% unrolled, etc.

Table 3. Environmental conditions and sugarbeet growth stage at the time of glufosinate application in 1999.

Glufosinate application†	Location‡											
	Far.	St. Th.	Cro.	Far.	St. Th.	Cro.	Far.	St. Th.	Cro.	Far.	St. Th.	Cro.§
	Date			Air temperature			Relative humidity			Sugarbeet growth stage		
				C			%			v¶		
C	05/26	06/01	06/11	26	23	23	28	78	58	1.0-2.5	1.0-3.0	1.0-4.0
C+1	06/02	06/08	06/17	26	24	24	54	61	48	1.0-5.5	2.5-4.3	2.0-6.3
C+2	06/09	06/15	06/25	24	29	29	70	53	56	4.0-8.3	4.0-7.3	4.0-10.3
C+3	06/16	06/22	07/01	23	22	22	33	58	73	6.0-9.0	6.5-9.0	6.0-12.5
C+4	06/23	06/29	07/12	26	28	28	64	67	72	10.3-14.5	6.0-13.0	8.5-18.7
C+5	06/30	07/06	07/16	25	21	21	60	53	68	9.0-15.3	11.0-13.3	10.3-21.3
C+6	07/07	07/13	07/23	21	33	33	53	59	72	12.7-15.3	10.0-18.5	12.0-23.7
C+7	07/14	07/20	07/30	24	23	23	100	69	82	13.5-19.3	12.3-21.5	14.5-24.0

† Abbreviations indicate the time when glufosinate was applied in reference to the sugarbeet development stage: C = sugarbeet cotyledon growth stage, C+1 = one week after C, C+2 = two weeks after C, etc. C, C+1, C+2, C+3, and C+4 indicate the five starting times of sequential glufosinate treatments. Glufosinate was applied four times in all starting time treatments, therefore, the "C" starting time treatment included glufosinate applications at C, C+1, C+2, and C+3 in one-week intervals. Correspondingly, the latest "C+4" treatment, for example, included four sequential glufosinate applications at C+4, C+5, C+6, and C+7.

‡ Abbreviations: Far. = Fargo, ND, St. Th. = St. Thomas, ND, and Cro. = Crookston, MN.

§ The "C" starting time treatment at the Crookston site was first applied when most sugarbeet plants had two- to four leaves.

¶ V1.0 = sugarbeet cotyledon stage, V2.0 = sugarbeet with two unrolled true leaves, and V2.5 = sugarbeet with two unrolled true leaves and a third leaf 50% unrolled, etc content in these sugarbeet samples were determined by the American Crystal Sugar Company research laboratory at Moorhead, MN, using standard laboratory procedures developed by the company.

Statistical procedure

The experimental design for all studies was a randomized complete block with five replicates. Experiments during 1998 were combined over locations based on homogeneous error mean squares (MS) obtained from the single analysis of variance (ANOVA) tested according to Barlett's Chi-square test. The following yield-affecting factors occurred during that growing season: sugarbeet plots at Fargo, ND, were partially damaged by carry-over of imazethapyr in the soil; root maggot infestations affected sugarbeet growth at St. Thomas, ND; and glufosinate was first applied when the majority of sugarbeet plants, with some exceptions, were already at the two- to four-leaf stage in Crookston, MN, rather than the desired sugarbeet cotyledon stage. This treatment delay occurred because of weather conditions and timing constraints. The observed severity level of the adverse impact from those factors within each experiment was considered tolerable regarding the validity of the research outcomes and treatment response trends. However, in order to minimize the experimental error caused by each separate factor and to avoid the accumulation of their impact, experiments in 1999 were not combined over locations.

ANOVA included separate analyses of all treatments (full non-factorial model), including hand weeding and herbicide treatments, only the herbicide treatments (factorial model with time and rate considered fixed factors) and only the hand-weeded treatments (non-factorial model). The sum of squares (SS) of the treatment source of variation in the non-factorial model and the factorial model were added together, and the sum was subtracted from the treatment SS in the full non-factorial model. The difference in SS represents the contrast of hand weeding versus herbicide treatments. The Error MS of the full non-factorial model was used to conduct all pertinent F-Tests. Significant individual treatment means were separated using Fisher's Protected LSD at $p \leq 0.05$.

RESULTS AND DISCUSSION

Sequential glufosinate treatments and hand weeding, regardless of application starting time and glufosinate rate, gave nearly complete and season-long control of weed species; such as redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), wild oats (*Avena fatua* L.), yellow foxtail (*Setaria glauca*

(L.) Beauv.), and green foxtail (*Setaria viridis* (L.) Beauv.) in all experiments during 1998 and 1999 (data not shown). A few exceptions existed, where weed control was in the lower 90% range, but the surviving weeds had no significant adverse effect on sugarbeet root yield or extractable sucrose and therefore, will not be discussed further.

Glufosinate experiments in 1998, combined over Fargo, ND, and Crookston, MN.

In general, hand-weeded sugarbeet plots differed significantly from glufosinate-treated plots in all measured traits (Table 4). Sugarbeet injury at both evaluations was slightly higher from glufosinate treatments compared with hand weeding, but the difference was small, and the greatest herbicide injury was minimal (7%).

Despite fewer sugarbeet plants per 100 m of row, hand-weeded plots gave higher sugarbeet root yield and extractable sucrose than glufosinate-treated sugarbeet (Table 4). This yield difference probably was not due to the slightly higher sugarbeet injury caused by glufosinate treatments compared to hand weeding. The yield result rather suggests a possible compensatory effect of individual sugarbeet within the rows for missing sugarbeet plants in a non-uniform stand, which is similar to observations reported by Dexter and Kern (1977).

Timing of glufosinate application relative to sugarbeet development and glufosinate rate, either as main effects or in interactions including both time and rate, was critical to sugarbeet injury, stand, and yield. Injury 7 DALT caused by three sequential glufosinate treatments applied at 0.2 kg ha^{-1} ranged from 0 to 4% over starting times compared to greatest sugarbeet injury of 13 or 33% when glufosinate was applied at 0.4 or 0.8 kg ha^{-1}, respectively (Table 5). Other authors also reported crop injury from glufosinate in glufosinate-resistant corn (Owen 2000), soybean (Culpepper et al. 2000), and sugarbeet (Regitnig and Nitschelm 1998) perhaps due to insufficient expression of the herbicide resistance trait in the transformed cultivar.

Herbicide injury increased significantly as the first application of the treatment sequence was delayed until two to three weeks after the sugarbeet cotyledon growth stage (Table 5). The last sequential glufosinate applications that started at the cotyledon stage or one week thereafter ended three or four weeks after the sugarbeet cotyledon stage, respectively. No significant sugarbeet injury was observed with these early season treatments, but the sequential glufosinate applications with late season treatments starting three or four weeks after the sugarbeet cotyledon stage caused significant sugarbeet injury.

Regitnig and Nitschelm (1998) concluded that application tim-

Table 4. Effect of hand weeding and glufosinate applications on sugarbeet stand, yield, and injury, combined over Fargo, ND, and Crookston, MN, 1998.

Treatment contrast[†]	Sugarbeet stand	Root yield	Extractable sucrose	Sugarbeet injury 7 DALT[‡]	Sugarbeet injury 14 DALT
	plants/100 m	t ha^{-1}	kg ha^{-1}	---------------- %	----------------
Hand weeding vs Factorial	(544 vs 578)*	(41.4 vs 40.0)*	(6570 vs 6300)*	(0 vs 7)*	(0 vs 3)*

† Single-degree of freedom contrast between hand weeding and glufosinate treatments. Factorial = glufosinate treatments analyzed in a 5x3 (time x rate) factorial arrangement.

‡ Abbreviation: DALT = days after the last treatment.

* Significant F-test at the 0.05 probability level.

Table 5. Time-by-rate interaction of glufosinate on sugarbeet stand and injury, combined over Fargo, ND, and Crookston, MN, 1998.

Glufosinate starting time[†]	Glufosinate rate kg ha^{-1}								
	0.2	0.4	0.8	0.2	0.4	0.8	0.2	0.4	0.8
	Sugarbeet stand			Sugarbeet injury					
				7 DALT[‡]			21 DALT		
	plants/100 m			%					
Cotyledon	578	567	567	0	0	1	0	0	0
Cotyledon + 1 week	600	600	533	1	1	1	0	0	0
Cotyledon + 2 weeks	555	533	600	1	2	12	0	0	4
Cotyledon + 3 weeks	578	600	578	3	10	17	0	4	6
Cotyledon + 4 weeks	578	555	578	4	13	33	2	7	16
LSD (0.05)	44			4			2		

[†] Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied three times at a weekly interval.

[‡] Abbreviation: DALT = days after the last treatment.

ing of high glufosinate rates was not as important for sufficient weed control as for sugarbeet injury. They, similarly to this research, observed significant sugarbeet leaf chlorosis in one location after the third application of glufosinate at 0.4 kg ha-1 shortly before row closure. In contrast, Thorsness et al. (1998) saw no visible sugarbeet injury from glufosinate applied from emergence to the 10-leaf sugarbeet growth stage.

Main effects of time and rate significantly affected sugarbeet root yield and extractable sucrose. Root yield and extractable sucrose were significantly reduced only by glufosinate applications starting four weeks after the cotyledon stage, perhaps because of prolonged competition from uncontrolled weeds prior to the first glufosinate application (Table 6). Based on the results in this experiment, the first sequential glufosinate application needed to be applied earlier than four weeks after the sugarbeet cotyledon stage to avoid significant yield loss. The time duration, during which sugarbeet can tolerate the presence of weeds without significant yield loss from weed competition, varies depending upon weed species and density, planting date, time of weed emergence relative to sugarbeet emergence, and environmental conditions (Scott et al. 1979). Dexter and Luecke (1998), for example, showed that delaying the first glufosinate treatment until two weeks after the sugarbeet cotyledon stage caused significant loss of extractable sucrose.

Sugarbeet root yield, averaged over glufosinate starting times, was greatest when glufosinate was applied at 0.2 kg ha^{-1} and progres-

Table 6. Sugarbeet yield as affected by glufosinate application starting time, averaged over glufosinate rates, and combined over Fargo, ND, and Crookston, MN, 1998.

Glufosinate starting time[†]	Root yield	Extractable sucrose
	t ha^{-1}	kg ha^{-1}
Cotyledon	41.0	6510
Cotyledon + 1 week	41.7	6530
Cotyledon + 2 weeks	40.8	6460
Cotyledon + 3 weeks	39.9	6270
Cotyledon + 4 weeks	36.8	5790
LSD (0.05)	2.3	350

[†] Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied three times at a weekly interval.

Table 7. Sugarbeet yield as affected by glufosinate rate averaged over glufosinate application starting times, and combined over Fargo, ND, and Crookston, MN, 1998.

Glufosinate rate† kg ha^{-1}	Root yield t ha^{-1}	Extractable sucrose kg ha^{-1}
0.2	42.6	6710
0.4	40.0	6290
0.8	37.5	5920
LSD (0.05)	1.8	270

† Each glufosinate treatment was applied three times at a weekly interval.

sively declined at glufosinate rates of 0.4 and 0.8 kg ha^{-1} (Table 7). Similarly, extractable sucrose yield was greater in plots treated with glufosinate at 0.2 kg ha^{-1} compared with 0.4 or 0.8 kg ha^{-1}.

Sugarbeet treated with 0.4 or 0.8 kg ha^{-1} had plant populations similar to sugarbeet treated with 0.2 kg ha^{-1} with two exceptions (Table 5). Plots treated with 0.8 kg ha^{-1} one week after the cotyledon stage had fewer sugarbeet plants than plots treated at the same time at 0.2 or 0.4 kg ha^{-1}. Plots treated with glufosinate at 0.4 kg ha^{-1} starting two weeks after the sugarbeet cotyledon stage had fewer sugarbeet plants than plots treated with 0.8 kg ha^{-1}. Sugarbeet stand was similar for all glufosinate rates when averaged over treatment starting times, suggesting that yield differences in Table 6 cannot be explained by changes in plant populations but rather by weed competition prior to the first glufosinate application.

Glufosinate in 1999 at Fargo, and St. Thomas, ND, and Crookston, MN.

Similar to results from 1998, hand weeding and glufosinate-treatments differed in sugarbeet injury, stand, and yield at Crookston, MN in 1999 (Table 8). Glufosinate caused an average of 15 and 7% sugarbeet injury at 7 and 21 DALT, respectively, compared to 5 or 4% for hand-weeded sugarbeet at Crookston, MN. Hand weeding reduced sugarbeet stand compared to glufosinate, but root yield and extractable sucrose were increased by hand weeding. The yield increase by hand weeding was probably due to injury from glufosinate and also suggests a possible compensatory yield effect of individual sugarbeet within a reduced non-uniform sugarbeet stand.

Sugarbeet injury at Fargo, and St. Thomas, ND, also varied among hand weeding and glufosinate treatments averaged over starting times and rates (Table 8). Hand-weeded sugarbeet at Fargo, ND, was evaluated as 7% injury 7 DALT, and glufosinate-treated plants had 18% injury. At St. Thomas, ND, injury at 7 DALT was 16 versus 33% and at 21 DALT was 10 versus 18% for hand-weeded versus glufosinate-treated sugarbeet, respectively. Injury, observed as sporadic chlorosis and patches of missing sugarbeet plants, was unexpectedly high in hand-weeded sugarbeet at Fargo, and St. Thomas, ND, perhaps as a result of soil-residual of imazethapyr at Fargo and root maggot infestations at St. Thomas.

Compared with 1998, similar trends were found in sugarbeet injury and yield response to glufosinate rates, starting times, or the interaction of both main effects in 1999; however, responses varied among locations. Time-by-rate interaction was significant for sugarbeet injury at all locations.

Sugarbeet injury 7 DALT at Crookston, MN, was similar from glufosinate at 0.2 kg ha^{-1}, regardless of application starting time, and ranged from 2 to 9% (Table 9). In contrast, injury levels reached 35 and 63% following four sequential applications of glufosinate at 0.4 and 0.8 kg ha^{-1}, respectively. Glufosinate application may be delayed a short time without significantly increasing sugarbeet injury. However, the time frame during which glufosinate was not phytotoxic to sugarbeet depended on the glufosinate rate. For example, glufosinate at 0.4 kg ha^{-1} was safely applied until two weeks after the sugarbeet cotyledon stage, whereas glufosinate at 0.8 kg ha^{-1} caused significant sugarbeet injury one week after the sugarbeet cotyledon stage.

Time-by-rate interaction was significant for sugarbeet root yield and extractable sucrose at Crookston, MN. Plots treated with glufosinate four times at 0.2 and 0.8 kg ha^{-1} starting at two weeks after the sugarbeet cotyledon stage, or with glufosinate at 0.4 kg ha^{-1} starting at four weeks after the sugarbeet cotyledon stage yielded less than plots treated with glufosinate starting at the cotyledon stage (Table 9). Regardless of glufosinate rates, root yield and extractable sucrose were similar from plots treated at the sugarbeet cotyledon stage or one week thereafter. These results indicate that glufosinate, regardless of rate, can safely be applied to sugarbeet starting at the cotyledon stage or one week thereafter without causing yield loss.

Sugarbeet injury from glufosinate at 0.2 kg ha^{-1} at Fargo, ND, was greater when the first application was delayed four weeks after the sugarbeet cotyledon stage of growth (Table 10). Glufosinate at 0.4 kg ha^{-1} and 0.8 kg ha^{-1} caused greater sugarbeet injury when the first application was delayed three and two weeks after the cotyledon stage, respectively, compared to glufosinate at these rates applied first at the sugarbeet cotyledon stage.

Table 8. Effect of hand weeding and glufosinate applications on sugarbeet stand, yield, and injury, for each location during 1999.

	Crookston, MN				
				Sugarbeet injury	
Treatment contrast[†]	Sugarbeet stand	Root yield	Extractable sucrose	7 DALT[‡]	4 DALT
	plants/100 m	t ha^{-1}	kg ha^{-1}	------------------ %	------------------
Hand weeding vs Factorial	(539 vs 583)*	(42.8 vs 39.2)*	(7090 vs 6340)*	(5 vs 15)*	(4 vs 7)*
	Fargo, ND				
				Sugarbeet injury	
Treatment contrast[†]	Sugarbeet stand	Root yield	Extractable sucrose	7 DALT[‡]	4 DALT
	plants/100 m	t ha^{-1}	kg ha^{-1}	------------------ %	------------------
Hand weeding vs Factorial	NS	NS	NS	(7 vs 18)*	NS
	St. Thomas, ND				
				Sugarbeet injury	
Treatment contrast[†]	Sugarbeet stand	Root yield	Extractable sucrose	7 DALT[‡]	4 DALT
	plants/100 m	t ha^{-1}	kg ha^{-1}	------------------ %	------------------
Hand weeding vs Factorial	NS	NS	NS	(16 vs 33)*	(10 vs 18)*

[†] Single-degree of freedom contrast between hand weeding and glufosinate treatments. Factorial = glufosinate treatments analyzed in a 5x3 (time x rate) factorial arrangement.
[‡] Abbreviation: DALT = days after the last treatment.
NS=Non-significant F-test at the 0.05 probability level.
* Significant F-test at the 0.05 probability level.

Table 9. Time-by-rate interaction of glufosinate on sugarbeet yield and injury at Crookston, MN, 1999.

	Glufosinate rate kg ha^{-1}											
	0.2	**0.4**	**0.8**	**0.2**	**0.4**	**0.8**	**0.2**	**0.4**	**0.8**	**0.2**	**0.4**	**0.8**
							Sugarbeet injury					
Glufosinate starting time[†]	**Root yield**			**Extractable sucrose**			**7 DALT**[‡]			**21 DALT**		
	t ha^{-1}			kg ha^{-1}			%					
Cotyl.	44.6	42.6	47.5	7300	7010	7510	3	1	4	2	3	2
Cotyl. + 1wk	40.6	46.4	45.3	6590	7690	7350	2	5	9	2	1	4
Cotyl. + 2wk	38.3	46.2	39.7	6200	7460	6520	6	6	18	3	2	7
Cotyl. + 3wk	37.4	37.0	35.6	5990	5960	5540	9	19	36	4	7	13
Cotyl. + 4 wk	27.6	34.3	25.3	4270	5630	4020	6	35	63	5	22	28
LSD (0.05)	5.8			900			8			6		

[†] Starting time indicates the time of the first glufosinate application in reference to the sugarbeet development stage. Abbreviations: Cotyl. = sugarbeet cotyledon stage, cotyl. + 1wk = one week after the cotyledon stage, and the number preceding wk indicates the number of weeks after the sugarbeet cotyledon stage. Each glufosinate treatment was applied four times at a weekly interval.

[‡] Abbreviation: DALT = days after the last treatment.

Glufosinate applications beginning one, two, or three weeks after the sugarbeet cotyledon stage gave injury similar to glufosinate first applied at the cotyledon stage, averaged over glufosinate rates at Fargo, ND (Table 11). Sugarbeet injury increased when the first sequential glufosinate application started four weeks after the sugarbeet cotyledon stage. Sugarbeet injury 21 DALT at Fargo, ND, tended to increase as glufosinate rate increased, averaged over all starting times (Table 12). However, differences were minimal.

The time-by-rate interaction or single effect of treatment starting time and rate was non-significant for sugarbeet yield at Fargo, ND, suggesting that plots treated with glufosinate at all tested rates and starting times gave similar yield (data not shown). The unexpected lack of differences may be a result of variations in the yield data partially due to imazethapyr soil-residue problems at this site.

Sugarbeet injury at St. Thomas, ND, evaluated 7 and 21 DALT, was influenced by glufosinate starting times and rates (Table 13). Sugarbeet injury ratings ranged from 5 to 74% at 7 DALT and from 3 to 51% at 21 DALT. These high levels of sugarbeet injury at St. Thomas, ND perhaps were not solely a result of herbicide effects. Symptoms may have been intensified and glufosinate phytotoxicity enhanced due to an interaction with other abiotic and biotic crop injury factors, such as environment, damage from insecticides and root maggot larvae feeding on sugarbeet roots. Although unknown, injury from root maggot may have led to a temporary suppression of plant-internal

Table 10. Time-by-rate interaction of glufosinate on sugarbeet injury at Fargo, ND, 1999.

	Glufosinate rate		
	---------- $kg\ ha^{-1}$ ----------		
	0.2	**0.4**	**0.8**
Glufosinate starting time[†]	**Sugarbeet injury 7 days after the last treatment**		
	---------- % ----------		
Cotyledon	6	8	10
Cotyledon + 1 week	2	10	9
Cotyledon + 2 weeks	13	16	23
Cotyledon + 3 weeks	9	19	22
Cotyledon + 4 weeks	26	36	61
LSD (0.05)	---------- 9 ----------		

[†] Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied four times at a weekly interval.

Table 11. Sugarbeet injury as affected by glufosinate application starting time, averaged over glufosinate rates at Fargo, ND, 1999.

Glufosinate starting time[†]	Injury 21 days after the last treatment
	%
Cotyledon	3
Cotyledon + 1 week	2
Cotyledon + 2 weeks	6
Cotyledon + 3 weeks	5
Cotyledon + 4 weeks	12
LSD (0.05)	3

† Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied four times at a weekly interval.

Table 12. Sugarbeet injury as affected by glufosinate rate, averaged over glufosinate application starting times at Fargo, ND, 1999.

Glufosinate rate†	Injury 21 days after the last treatment
kg ha-1	%
0.2	3
0.4	5
0.8	8
LSD (0.05)	3

† Glufosinate was applied four times at a weekly interval.

glufosinate detoxification processes. Terbufos was applied at planting, and chlorpyrifos was applied POST on June 5 for control of root maggot, but the infestation was severe and control was not complete. Insufficient soil moisture immediately after the chlorpyrifos application may have contributed to poor root maggot control. Irrespective of the level of insect control, insecticides may also have caused minor sugarbeet injury.

Sugarbeet plants at St. Thomas, ND, were injured more 7 DALT by glufosinate at 0.2 kg ha^{-1} first applied three or four weeks after the sugarbeet cotyledon stage as compared to glufosinate first applied at the cotyledon stage (Table 13). Injury was similar from glufosinate at 0.2 kg ha^{-1} first applied at one, two, three, and four weeks after sugarbeet had cotyledons. Glufosinate at 0.4 kg ha^{-1} caused 48% sugarbeet injury when the first application was three weeks after the sugarbeet cotyledon stage, greater injury than from the first application at the cotyledon stage or one week thereafter.

Glufosinate applied four times at 0.8 kg ha^{-1} only caused 5% injury when first applied to sugarbeet at the cotyledon stage, suggesting that glufosinate at twice the recommended rate is safe on glufosinate-resistant sugarbeet as long as the last sequential application is applied to young sugarbeet (Table 13). In comparison, when the first of four glufosinate treatments was delayed three or four weeks after the cotyledon stage, injury was 69 or 74%, respectively. The last two of the sequential glufosinate applications with late season starting times caused severe sugarbeet injury, but plants at this stage may have been susceptible to glufosinate at 0.8 kg ha^{-1} because of damage from root maggot or insecticides.

Sugarbeet yield at St. Thomas, ND, was adversely affected as the starting time of sequential glufosinate applications became later (Table 14). Averaged over all glufosinate rates, sugarbeet root yield significantly declined when the first glufosinate application was delayed until after the sugarbeet cotyledon stage. Sugarbeet plots that were treated with sequential applications of glufosinate one, two, three, or four weeks after the sugarbeet cotyledon stage had similar yield.

Extractable sucrose was less when the first application of glufosinate did not start until at least one week after sugarbeet had cotyledons rather than at the sugarbeet cotyledon stage (Table 14). However, plots treated four times with glufosinate starting at one, two, or three

Table 13. Time-by-rate interaction of glufosinate on sugarbeet injury at St. Thomas, ND, 1999.

	Glufosinate rate					
	kg ha^{-1}					
	0.2	0.4	0.8	0.2	0.4	0.8
Glufosinate starting time[†]	Injury 7 DALT[‡]			Injury 21 DALT		
	%					
Cotyledon	8	27	5	5	12	3
Cotyledon + 1 week	24	23	10	13	13	3
Cotyledon + 2 weeks	23	36	41	12	19	22
Cotyledon + 3 weeks	27	48	69	13	24	41
Cotyledon + 4 weeks	32	42	74	16	21	51
LSD (0.05)	17			19		

[†] Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied four times at a weekly interval.

[‡] Abbreviation: DALT = days after the last treatment.

Table 14. Sugarbeet yield as affected by glufosinate application starting time, averaged over glufosinate rates at St. Thomas, ND, 1999.

Glufosinate starting time†	Root yield	Extractable sucrose
	t ha^{-1}	kg ha^{-1}
Cotyledon	39.5	6090
Cotyledon + 1 week	34.3	5300
Cotyledon + 2 weeks	33.2	5180
Cotyledon + 3 weeks	31.8	4760
Cotyledon + 4 weeks	30.0	4540
LSD (0.05)	4.4	730

† Starting time indicates the time of the first glufosinate application in reference to the sugarbeet growth stage. Glufosinate was applied four times at a weekly interval.

weeks after the cotyledon stage yielded similar extractable sucrose.

Although sugarbeet stand was significantly affected by glufosinate rate at St. Thomas, the effect was not a typical herbicide dose response because sugarbeet stand was similar in plots treated with glufosinate at 0.2 and 0.8 kg ha^{-1} but lower than with glufosinate at 0.4 kg ha^{-1} (Table 15). The observed difference of 33 sugarbeet plants per 100 m among plots treated with 0.2 and 0.4 kg ha^{-1} would not be expected to be large enough to account for substantial yield effects. Sugarbeet stand, in contrast to sugarbeet injury, was not influenced by glufosinate application starting time (data not shown). Thus, plant population probably had no significant role in the observed yield loss with late season glufosinate starting times.

The majority of sugarbeet yield data in these experiments indicated that sequential glufosinate treatments need to be started at the sugarbeet cotyledon or cotyledon-plus-one-week stage to avoid sugarbeet yield reductions from prolonged weed interference prior to the first glufosinate application. Glufosinate should be applied to sugarbeet no later than five weeks after the cotyledon stage to minimize visible crop injury. Sugarbeet injury from glufosinate treatments starting between two and four weeks, and ending five to seven weeks after the sugarbeet cotyledon stage, may have contributed to sugarbeet yield loss. However, the results in this research could not answer the question about how much of the yield loss was due to weed interference prior to the first sequential glufosinate treatment and how much was due to the sugarbeet injury from late season glufosinate treatments. Therefore, the objective regarding the primary cause of sugarbeet yield loss should be addressed in a different experiment.

Table 15. Sugarbeet stand as affected by glufosinate rate, averaged over glufosinate application starting times at St. Thomas, ND, 1999.

Glufosinate rate†	Sugarbeet stand
kg ha^{-1}	plants/100 m
0.2	417
0.4	450
0.8	428
LSD (0.05)	22

† Glufosinate was applied four times at a weekly interval.

ACKNOWLEDGMENTS

Appreciation is expressed to the Sugarbeet Research and Education Board of Minnesota and North Dakota for financial support, to the personnel of the Northwest Research and Outreach Center University of MN Crookston for their assistance in managing the research sites, to the summer student and sugarbeet harvest crews for their valuable field work, and to American Crystal Sugar Company for sugarbeet quality analysis.

LITERATURE CITED

Ahrens, W. H. (ed.) 1994. Herbicide Handbook. 7th Edition. Champaign, IL: Weed Sci. Soc. Am. pp. 147-149.

Bray, W. E. 1983. Crop damage from herbicide use in sugarbeet. In Aspects of applied biology. 3. Crop sensitivity to herbicides. Wellesbourne, UK: Association of Applied Biologists pp. 103-110.

Breay, H. T. 1983. The effect of timing of post-emergence herbicides and implications on the management of weed control in the sugarbeet crop. In Aspects of applied biology. 2. Pests, diseases, weeds and weed beets in sugarbeet. Wellesbourne, UK: Association of Applied Biologists pp. 139-147.

Brimhall, P. B., E. W. Chamberlain, and H. P. Alley. 1965. Competition of annual weeds and sugarbeets. Weeds. 13:33-35.

Culpepper, A. S., A. C. York, R. B. Batts, and K. M. Jennings. 2000. Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14:77-88.

Dawson, J. H. 1965. Competition between irrigated sugar beets and annual weeds. Weeds 13:245-249.

Dawson, J. H. 1974. Full-season weed control in sugarbeets. Weed Sci. 22:330-335.

Dexter, A. G. and J. J. Kern. 1977. Reponse of several sugarbeet varieties to EPTC. Proc. North Cent. Weed Control Conf. 32:35-36.

Dexter, A. G. and J. L. Luecke. 1998. Weed Control in Transgenic Sugarbeet in North Dakota and Minnesota –1997. In 1997 Sugarbeet Research and Extension Reports. Fargo, ND: NDSU Extension Serv. 28:82-87.

Dexter, A. G. and J. L. Luecke. 1999. Conventional herbicides at micro-rates, glyphosate and glufosinate for weed control in sugarbeet. Proc. North Cent. Weed Sci. Soc. 54:158-159.

Dexter, A. G. and J. L. Luecke. 2003. Survey of weed control and production practices on sugarbeet in eastern North Dakota and Minnesota – 2002. In 2002 Sugarbeet Research and Extension Reports. Fargo, ND: NDSU Extension Serv. 33:35-64.

Dexter, A. G. and R. K. Zollinger. 2003. Weed control guide for sugarbeet. In 2002 Sugarbeet Research and Extension Reports. Fargo, ND: NDSU Extension Serv. 33:3-34.

D'Halluin, K. D., M. Bossut, E. Bonne, B. Mazur, J. Leemans, and J. Botterman. 1992. Transformation of sugarbeet (*Beta vulgaris* L.) and evaluation of herbicide resistance in transgenic plants. Bio/Technol. 10:309-314.

Edmund, R. M., Jr. and A. C. York. 1987. Factors affecting postemergence control of sicklepod (*Cassia obtusifolia*) with imazaquin and DPX-F6025; spray volume, growth stage, and soil-applied alachlor and vernolate. Weed Sci. 35:216-223.

Eshel, Y., E. E. Schweizer, and R. L. Zimdahl. 1976. Sugarbeet tolerance of postemergence applications of desmedipham and ethofumesate. Weed Res. 16:249-254.

Evans, R. R. 1983. Weed competition in sugarbeet (*Beta vulgaris*). Ph.D. Thesis. North Dakota State Univ., Fargo, North Dakota.

Heap, I. 2003. The international survey of herbicide resistant weeds. Online. December 11,2003. Available www.weedscience.com.

Lee, S. D. and L. R. Oliver. 1982. Efficacy of acifluorfen on broadleaf weeds. Times and methods for application. Weed Sci. 30:520-526.

Mesbah, A. O., S. D. Miller, and W. Cecil. 1997. Weed control in transgenic sugarbeets. Proc. North Cent. Weed Sci. Soc. 52:144.

Nitschelm, J. J. and P. J. Regitnig. 1997. Effect of Liberty herbicide formulations, rates and timing on broad-spectrum weed control and Liberty Link sugar beets-1997. In Annual Research Report 1997. Winnipeg, Canada: Rogers Sugar Ltd. pp. 49-66.

Norris, R. F. 1974. Influence of environment on activity of phenmedipham. Proc. Calif. Weed Conf. 26:123-125.

Norris, R. F. 1991. Sugarbeet tolerance and weed control efficacy with split applications of phenmedipham plus desmedipham. Weed Res. 31:317-331.

Owen, M. D. K. 2000. Current use of transgenic herbicide-resistant soybean and corn in the USA. Crop Prot. 19:765-771.

Preston, P. E. and P. V. Briscoe. 1983. The tolerance of sugar beet to post-emergence herbicide applications. In Aspects of applied biology. 2. Pests, diseases, weeds and weed beet in sugar beet. Wellesbourne, UK: Assoc. of Applied Biologists pp. 131-138.

Regitnig, P. J. and J. J. Nitschelm. 1998. Effect of Liberty herbicide formulations, rates and timing on broad-spectrum weed control and Liberty Link sugar beets-1998. In Annual Research Report 1998. Winnipeg, Canada: Rogers Sugar Ltd. pp. 35-56.

Ritter, R. L. and H. D. Coble. 1984. Influence of crop canopy, weed maturity, and rainfall on acifluorfen activity. Weed Sci. 32:185-190.

Schweizer, E. E. 1983. Common lambsquarters (*Chenopodium album*) interference in sugarbeets (*Beta vulgaris*). Weed Sci. 31:5-8.

Schweizer, E. E. and L. D. Bridge. 1982. Sunflower (Helianthus annuus L.) and velvetleaf (*Abutilon theophrasti*) interference in sugarbeets (*Beta vulgaris*). Weed Sci. 30:514-519.

Schweizer, E. E. and T. C. Lauridson. 1985. Powell amaranth (*Amaranthus powellii*) interference in sugarbeet (*Beta vulgaris*). Weed Sci. 33:518-520.

Scott, R. K., S. J. Wilcockson, and F. R. Moisey. 1979. The effects of time of weed removal on growth and yield of sugar beet. J. Agric. Sci. (Cambridge). 93:693-709.

Stewart, J. K., K. B. Thorsness, D. W. Maruska, and T. W. Mayberry. 1998. Weed control with glufosinate ammonium in transgenic herbicide-resistant sugarbeet. Proc. West. Soc. Weed Sci. 51:103.

Thorsness, K. B., J. F. Stewart, T. W. Kleven, and C. P. Hicks. 1998. An overview: Glufosinate in transgenic sugarbeets. Proc. North Cent. Weed Sci. Soc. 53:136-137.

Vasil, I. K. 1996. Phosphinothricin-resistant crops. In S. O. Duke, ed. Herbicide-resistant crops. Agricultural, environmental, economic, regulatory, and technical aspects. Boca Raton, FL: CRC Press pp. 85-91.

Weatherspoon, D. M. and E. E. Schweizer. 1969. Competition between kochia and sugarbeets. Weed Sci. 17:464-467.

Weatherspoon, D. M. and E. E. Schweizer. 1971. Competition between sugarbeets and five densities of kochia. Weed Sci. 19:125-128.

Weinlaeder, R. A. and A. G. Dexter. 1972. Several factors influencing sugarbeet injury in the field and growth chamber. Proc. North Cent. Weed Control Conf. 27:33.

Wevers, J. D. A. 1998. Agronomic and environmental aspects of herbicide-resistant sugar beet in the Netherlands. In Aspects of applied biology. 52. Protection and production of sugar beet and potatoes. Wellesbourne, UK: Association of Applied Biologists. pp. 393-399.

Wicks, G. A. and R. G. Wilson. 1983. Control of weeds in sugarbeets (*Beta vulgaris*) with hand hoeing and herbicides. Weed Sci. 31:493-499.

Wilson, R. G. 1998a. Postemergence herbicide timing for maximum weed control in sugarbeet. J. Sugar Beet Res. 35:15-27.

Wilson, R. G. 1998b. Glyphosate and glufosinate for weed control in herbicide tolerant sugarbeet. Proc. West. Soc. Weed. Sci. 51:102.

Winter, S. R. and A. F. Wiese. 1978. Phytotoxicity and yield response of sugarbeets (*Beta vulgaris*) to a mixture of phenmedipham and desmedipham. Weed Sci. 26:1-4.

Winter, S. R. and A. F. Wiese. 1982. Economical control of weeds in sugarbeets (*Beta vulgaris*). Weed Sci. 30:620-623.

Zimdahl, R. L., and S. N. Fertig. 1967. Influence of weed competition on sugarbeets. Weeds 15:336-339.