Alfalfa Autotoxicity: Effects of Reseeding Delay, Original Stand Age, and Cultivar

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ABSTRACT

Autotoxicity may reduce plant population and productivity of alfalfa (*Medicago sativa* L.) reseeded into winterkilled alfalfa stands; however, the interaction of important variables such as reseeding delay, stand age, and cultivar with autotoxicity has not been evaluated. We determined the effects of stand age (1-, 2-, or 3-yr-old alfalfa stands), reseeding delay (none or 2-wk delay) after plowing the original stands in May, and cultivar reseeded ('5262' or 'Wrangler') on populations and productivity of reseeded alfalfa. Oat (*Avena sativa* L.), corn (*Zea mays* L.), or tall fescue (*Festuca arundinaceae* Schreb.) served as controls. There was no consistent evidence for autotoxicity in the reseeding year, as populations and forage yields were similar when seeding followed alfalfa or the control crops, regardless of the age of the previous alfalfa stand or the alfalfa cultivar reseeded. Delaying seeding had inconsistent effects on alfalfa plant population but consistently reduced yields in the seeding year, with yields averaging 4.9 and 6.3 Mg ha^{-1} with and without a 2-wk reseeding delay, respectively. In three of six experiments, yields at the first harvest in the year following reseeding averaged 15% lower following alfalfa than a control crop (3.6 and 4.2 Mg ha^{-1}, respectively), suggesting that alfalfa autotoxic response may be delayed. The lack of consistent evidence of autotoxicity, coupled with yield reductions in the seeding year associated with delayed seeding, suggest that the recommendation to delay alfalfa reseeding 2 wk following plowing of winterkilled stands may be unjustified.

Rotation of legume and nonlegume crops has been recommended as an effective crop management practice for centuries (Martin and Leonard, 1967). In Upper Midwest rotations, corn is often grown following 2 to 3 yr of alfalfa to utilize the biologically fixed N (Peterson and Russelle, 1991). In addition, continuous production of alfalfa by re-establishment of alfalfa immediately after plowing or by no-till seeding into depleted stands is not recommended because of potential problems due to soil water depletion, plant diseases, and autotoxicity (Martin and Leonard, 1967; Kehr et al., 1983; Miller, 1983; Tesar, 1993). Of these factors, autotoxicity has been most frequently identified as a cause of reseeding failure (Webster et al., 1967; Tesar, 1993; Miller, 1996).

Autotoxicity is an intraspecific type of allelopathy that occurs when a plant releases chemicals harmful to plant growth and development (Miller, 1996). Alfalfa autotoxicity reduces establishment of alfalfa by reducing seed germination and seedling growth on soils where alfalfa was recently grown. Root growth and forage yield may also be decreased (Nelson et al., 1997). Alfalfa plants contain water-soluble compounds that are released from fresh leaf, stem, and crown tissue as well as from seeds, hay, and dried roots (Nielsen et al., 1960; Hall and Henderlong, 1989; Hegde and Miller, 1992, Chung and Miller, 1995b; Miller, 1996); however, based on in vitro assays, herbage is thought to be the most autotoxic plant component. Phenolic compounds, including medicarpin (Dornbos et al., 1990), coumarin (Hegde and Miller, 1992), and chlorogenic acid (Chung et al., 2000), are among those considered phytotoxic; however, autotoxicity is likely caused by an interaction of phytotoxic chemicals (Hegde and Miller, 1992).

Although the direct effect of these compounds on alfalfa development has been demonstrated in greenhouse and laboratory studies, their effects under field conditions are not well elucidated because of the interaction of many factors. For example, Jennings and Nelson (1998) reported that management recommendations could be influenced by soil texture, which might affect the activity water-soluble phytotoxic chemicals, and rainfall patterns, which might affect their movement and concentration. They reported that effects of autotoxic chemicals were greater on a fine sandy loam than on a silty clay loam soil but that the chemicals moved faster through the sandy loam soil.

Stand age may also be an important factor determining the extent of the autotoxic response because plant residues and the autotoxic constituents may accumulate over time (Angler, 1992); however, there have been no studies designed to test stand-age effects. Tesar (1993) inferred from independent studies with 1-, 4-, and 6-yr-old alfalfa stands that stand age had no influence on autotoxicity if there was an adequate interval between plowing and reseeding. He contended that a progressive buildup of autotoxic compounds would not occur in older stands because most of the herbage, which contains the greatest concentration of autotoxic compounds, is harvested. However, his analysis does not consider the potential accumulation of organic com-

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pounds due to leaching from leaves; root exudation; turnover and death of small roots; and decaying, dead plants.

Laboratory studies also suggested that alfalfa cultivars and germplasm might differ in susceptibility to autotoxicity (Chung and Miller, 1995a; Chon et al., 2000); however, differences among cultivars in response to autotoxic situations have not been observed under field conditions (Miller, 1983; Cosgrove, 1996).

Although the concept and importance of alfalfa autotoxicity has been intensively debated and researched in the past decades, there is still a lack of comprehensive field studies including multiple environments and management variables, especially in the Upper Midwest. In this region, winter injury often reduces alfalfa stand productivity and necessitates untimely reseeding. Unfortunately, winter injury is often observed in the spring when farmers depending on alfalfa have little flexibility regarding field selection because of herbicide use and fertilization programs for upcoming crops. Consequently, seeding alfalfa immediately following alfalfa is the desired option. For these situations, based on the research of Tesar (1993) and Cosgrove (1996), it is currently recommended for the North-Central region (Undersander et al., 2000) to delay reseeding for 2 wk after plowing an alfalfa stand and delay no-till seeding for 3 wk after herbicide application to kill an old alfalfa stand. Recommendations from other states are to delay reseeding for 1 yr (Miller, 1996). Our objective was to determine the effects of interval between plowing and reseeding, stand age, and reseeded cultivar on alfalfa autotoxicity at three locations differing in soil characteristics and annual rainfall.

MATERIALS AND METHODS

Experiments were conducted at Lamberton (44°15′ N, 95°19′ W), Rosemount (44°43′ N, 93°06′ W), and Waseca (44°04′ N, 93°31′ W), MN, USA. At each location, experiments were repeated in a subsequent year, giving a total of six experiments or environments. The soil at Rosemount was a Waukegan silt loam (fine-silty over sandy-skeletal, mixed mesic Typic Hapludoll); at Waseca, it was a Webster clay loam (fine-loamy, mixed mesic Typic Haplaquoll); and at Lamberton, it was a Normania loam (fine-loamy, mixed, mesic Aquic Hapludoll). The soil pH (6.5–7.0), exchangeable K (>350 kg ha^{-1}), and Bray-1 P (>40 kg ha^{-1}) at all locations were considered nonlimiting for alfalfa establishment and growth (Rehm and Schmitt, 1989). In some experiments, temperature and precipitation deviated considerably from the 30-yr average in the seeding year (Table 1). Temperature and precipitation data for each experiment were retrieved from nearby weather-recording stations.

The experimental design at each location was a randomized complete block design with split-split plot restriction and four replications. Whole-plot treatments included alfalfa stand ages of 3-, 2-, and 1-yr-old and a nonalfalfa control; subplots were intervals between spring tillage and reseeding (none or 2-wk delay), and sub-subplots were reseeded alfalfa cultivars (‘Pioneer 5262’, and ‘Wrangler’). The nonalfalfa control species for Lamberton, Rosemount, and Waseca were oat, tall fescue, and corn, respectively. It was assumed that these species would not cause a positive or negative allelopathic response in alfalfa. Corn and oat controls were reseeded annually (at rates of 25 and 90 kg ha^{-1}, respectively) while the tall fescue control was seeded (10 kg ha^{-1}) at the same time as the 3-, 2-, and 1-yr-old alfalfa. Split-split plots were 2 by 7 m at Rosemount and Waseca and 3 by 7 m at Lamberton.

Original stands of 5262 alfalfa were established by broadcast-seeding in a conventionally prepared seedbed at 15 kg ha^{-1} in May of 1991, 1992, and 1993 for reseeding in spring 1994 and in 1992, 1993, and 1994 for reseeding in spring 1995. Weeds were controlled using preplant incorporation of 0.5 kg a.i. ha^{-1} trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl) benzenamine]. In the seeding year of the original stands, alfalfa was harvested two times at first flower. In the years following seeding, three harvests were made at first flower. According to standard management recommendations to minimize winter injury, the final harvest occurred about 1 September, and regrowth was allowed to accumulate. Oat and corn controls were harvested at maturity in July and October, respectively. The tall fescue control was harvested three times per season at 45-d intervals beginning in June.

To simulate winterkill, regrowth of the original alfalfa stands was treated with a broadcast application of 2,4-D [(2,4-dichlorophenoxy) acetic acid] at 2.0 kg a.i. ha^{-1} on 15 October. A similar approach to simulate winterkill was used by Asbil and Coulman (1992). Because night air temperatures after application were frequently <0°C, it is unlikely that this treatment resulted in immediate kill of alfalfa. Treated plants likely stopped normal physiological processes within 7 to 10 d after

Table 1. Monthly precipitation (mm) and average air temperature (°C) at Lamberton, Rosemount, and Waseca, MN, April to October 1994 and 1995, and the 30-yr average (1961–1990) (Minnesota Climatology Working Group, 2001).

	Lamberton			Rosemount			Waseca		
	1994	1995	Average	1994	1995	Average	1994	1995	Average
					mm				
April	134	113	69	129	74	73	142	28	75
May	34	114	79	67	105	100	43	87	93
June	113	42	88	190	120	109	84	138	104
July	68	176	94	89	106	102	125	46	107
August	103	85	71	99	126	101	126	201	107
September	87	56	76	180	40	90	111	46	90
October	29	61	53	137	127	65	114	74	62
					°C				
April	6	3	7	8	5	8	6	4	7
May	16	13	15	17	14	15	16	12	14
June	19	20	20	20	20	20	20	19	20
July	20	22	22	21	23	22	20	21	22
August	19	22	21	20	24	21	19	21	20
September	16	13	16	17	15	16	16	14	15
October	10	8	9	11	9	10	11	9	9

herbicide treatment and altered winterhardiness. Regardless, by the following spring, all alfalfa plants were dead. At Rosemount, the tall fescue control was killed with a fall application of glyphosate [*N*-(phosphonomethyl) glycine] at 1.12 kg a.i. ha^{-1}.

At each location in 1994 and 1995, the soil was chisel-plowed to a 12-cm depth immediately before disking on 1 May. A finishing harrow smoothed and firmed the seedbed before reseeding. Weeds were controlled with preplant application of 0.5 kg a.i. ha^{-1} trifluralin. Alfalfa was broadcast-seeded at 15 kg ha^{-1}. Seeds were inoculated with appropriate rhizobial inoculant and treated with metalaxyl [*N*-(2,6-dimethylphenyl)-*N*-(methoxyacetyl) alanine methyl ester]. The first reseeding date (no delay) occurred on about 1 May while the second reseeding date occurred on 15 May, 2 wk after plowing as is currently recommended (Undersander et al., 2000).

Thirty days after each seeding date and in October of the reseeding year, plant populations were determined by counting number of plants within two 0.2-m^2 quadrats in each plot. In the reseeding year, alfalfa was harvested twice at first flower, with the first harvest occurring about 60 d following emergence; seeding date and climate influenced the harvest dates. No harvest occurred after the first week of September. In the year following reseeding, plots were harvested once at late bud to first flower on about 25 May. At each harvest, a 1- by 3-m area was cut in each plot with a flail harvester to a 5-cm stubble height, and a 500-g subsample was used to determine dry matter content. All samples were dried in a forced-air oven at 60°C for 48 h. During the experiments, plots were sprayed as needed with permethrin [3-phenoxy-phenylmethyl + *cis*, *trans*-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanepropanecarboxylate] for potato leafhopper (*Empoasca fabae* Harris) control.

Results from each location and year were analyzed separately because of differences in the control species and climatic conditions. Experiments were analyzed as a split-split plot using PROC ANOVA (SAS, 1985). When interactions were significant at $P < 0.1$, data were reanalyzed for each factor by all levels of the other factor with which it was interacting. Treatments mean comparisons in each experiment were made when *F*-tests were significant at $P < 0.1$ using the least significant difference (LSD) test at the $P < 0.1$ level. This *P*-level was selected to minimize Type II errors.

RESULTS AND DISCUSSION

Alfalfa Populations

Thirty Days after Reseeding

Treatment effects on alfalfa populations 30 d after reseeding were not consistent (Tables 2 and 3). Although reduced plant population has been reported to be an indicator of alfalfa autotoxicity (Miller, 1996), alfalfa populations were similar ($P > 0.1$) in three of six experiments when alfalfa was reseeded after alfalfa, regardless of stand age, or the control crops. Stand age [0- (nonalfalfa control), 1-, 2-, or 3-yr-old alfalfa] affected plant populations in Lamberton and Rosemount in 1995 and Waseca in 1994. At Rosemount in 1995, populations were lower with 2-yr-old alfalfa stands than

Table 2. Analysis of variance for alfalfa plant populations and yields. Alfalfa was reseeded using different alfalfa cultivars (5262 or Wrangler) in killed alfalfa stands of different ages (1-, 2-, or 3-yr old) or a control with or without a reseeding delay of 2 wk after plowing these stands. Results are for 2 yr from three locations in Minnesota.

	Source of variation	Lamberton		Rosemount		Waseca	
Reseeding year		1994	1995	1994	1995	1994	1995
Plant populations 30 d after reseeding	Stand age (A)	NS†	*	NS	*	**	NS
	Seeding delay (D)	*	NS	***	NS	***	***
	A × D	NS	NS	NS	***	‡	NS
	Cultivar (C)	*	‡	NS	NS	NS	*
	C × A	NS	NS	NS	NS	NS	NS
	C × D	NS	NS	NS	NS	*	NS
	C × A × D	NS	NS	‡	NS	*	NS
Plant populations in October	Stand age (A)	NS	NS	NS	NS	NS	NS
	Seeding delay (D)	*	NS	***	*	‡	***
	A × D	NS	NS	NS	‡	NS	NS
	Cultivar (C)	NS	NS	NS	NS	NS	***
	C × A	NS	NS	*	NS	NS	NS
	C × D	NS	NS	NS	NS	NS	NS
	C × A × D	NS	NS	‡	NS	NS	NS
Yield Total	Stand age (A)	NS	*	NS	NS	***	NS
	Seeding delay (D)	***	***	***	**	*	**
	A × D	‡	NS	NS	NS	‡	**
	Cultivar (C)	**	*	***	**	*	‡
	C × A	NS	NS	NS	NS	NS	NS
	C × D	NS	NS	NS	NS	NS	‡
	C × A × D	NS	NS	NS	NS	NS	NS
Postreseeding year		1995	1996	1995	1996	1995	1996
Yield at the first harvest	Stand age (A)	NS	NS	‡	***	NS	*
	Seeding delay (D)	***	NS	***	NS	***	NS
	A × D	‡	NS	NS	NS	NS	NS
	Cultivar (C)	NS	NS	NS	NS	NS	***
	C × A	‡	NS	NS	NS	NS	NS
	C × D	NS	NS	‡	‡	NS	NS
	C × A × D	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS, not significant.
‡ Significant at the 0.1 level.

other treatments. At Lamberton in 1995 and Waseca in 1994, populations were similar ($P > 0.1$) following reseeding after the nonalfalfa control and 2- and 3-yr-old alfalfa stands but lower following termination of 1-yr-old alfalfa stands. This may suggest autotoxicity; however, 1-yr-old alfalfa stands generally had the least whole-plant dry matter in the fall before reseeding (data not presented). In addition, there was little correlation across experiments between stand characteristics before reseeding, such as plant populations and amount of forage, and alfalfa populations 30 d after reseeding (data not presented). Tesar (1993) also reported that alfalfa autotoxic response was not correlated with the amount of forage dry matter incorporated before alfalfa reseeding.

Significant interactions occurred between the stand age [0- (nonalfalfa control), 1-, 2-, and 3-yr-old alfalfa] and the reseeding delay treatments at Rosemount in 1995 and Waseca in 1994 (Table 2). However, these interactions were not due to an autotoxic response. The rationale for delaying alfalfa reseeding is to avoid autotoxicity. Hence, with the presence of autotoxicity, delaying reseeding would be expected to increase populations or productivity compared with a control if a delay was beneficial. However, at Rosemount in 1995, with 1- and 3-yr old alfalfa stands, alfalfa populations were higher without a seeding delay than with a 2-wk delay while the reverse was observed with the control (Table 3). At Rosemount and Waseca in 1994, there were significant three-way interactions among stand age, reseeding delay, and cultivar reseeded. Observation of the data and their reanalysis did not provide a trend between these two experiments as responses varied greatly and were highly complex (data not presented). Furthermore, the interactions did not appear related to an autotoxic response. Treatment differences could be due to interactions among several factors, including environmental and edaphic conditions at time of reseeding.

Effects of reseeding delay and cultivar were observed in four and three experiments, respectively (Table 2). The response to reseeding delay was inconsistent across experiments, suggesting that environmental conditions before, during, and after reseeding varied, causing subsequent variability in seed germination and seedling development rate. Indeed, variation and deviations from 30-yr average precipitation occurred across environments (Table 1). Finally, plant populations of 5262 were greater than those of Wrangler in three of the six experiments. In previous research in Minnesota, 5262 alfalfa has been shown to have greater yield and persistence than Wrangler, but there is no evidence to suggest that these cultivars differ in seedling establishment (Martin and Sheaffer, 1996).

Table 3. Alfalfa populations 30 d after reseeding as affected by original stand age, reseeding delay, and cultivar reseeded at three locations in Minnesota. Results represent main treatments effects for 1994 and 1995 seedings.

	Lamberton		Rosemount		Waseca	
	1994	1995	1994	1995	1994	1995
Stand age (yr)	Plants m^{-2}					
0 (control)†	376	418	578	738	415	278
1	312	293	609	726	291	297
2	292	363	562	554	421	319
3	290	377	516	726	415	345
$LSD_{0.1}$	NS‡	56	NS§	99§	63§	NS
CV%	44	24	27	22	25	27
Seeding delay (wk)						
0	346	359	467	688	487	415
2	289	365	666	669	284	205
$LSD_{0.1}$	41	NS	48§	NS§	54§	41
CV%	29	24	19	18	31	30
Cultivar reseeded						
5262	342	377	578	657	371	353
Wrangler	293	347	554	699	400	266
$LSD_{0.1}$	34	26	NS§	NS	NS§	58
CV%	25	17	17	17	35	43

† Control (previous crop is not alfalfa): oat, corn, and tall fescue at Lamberton, Rosemount, and Waseca, respectively.
‡ NS, not significant.
§ An interaction due to a crossover effect including this factor was also present. At Rosemount in 1994 and Waseca in 1994, there were significant three-way interactions ($P < 0.1$ and $P < 0.05$); however, no clear trend appeared after reanalysis of the data (data not presented). At Rosemount in 1995, the interaction between previous crop and seeding delay was significant ($P < 0.001$). Reanalysis of the data indicated that with the control, plant populations were lower without a seeding delay while the reverse was observed with 1 and 3-yr-old alfalfa stands.

Fall

Plant populations in October (Tables 2 and 4) were lower than at 30 d after seeding, but treatment effects on alfalfa populations remained inconsistent. There was no effect of stand age on populations in any experiments. Populations following the control crops were similar to those following alfalfa, irrespective of the

Table 4. Alfalfa population in October of the reseeding year as affected by original stand age, reseeding delay, and cultivar reseeded at three locations in Minnesota. Results represent main treatments effects for 1994 and 1995 seedings.

	Lamberton		Rosemount		Waseca	
	1994	1995	1994	1995	1994	1995
Stand age (yr)	Plants m^{-2}					
0 (control)†	264	22	526	381	261	121
1	264	249	504	355	208	104
2	256	273	470	364	205	124
3	242	271	474	394	216	122
$LSD_{0.1}$	NS‡	NS	NS§	NS§	NS	NS
CV%	17	25	17	16	33	24
Seeding delay (wk)						
0	243	247	394	401	244	133
2	270	260	593	346	201	103
$LSD_{0.1}$	21	NS	36§	40§	40	10
CV%	18	30	16	24	40	20
Cultivar reseeded						
5262	260	258	513	378	219	131
Wrangler	253	249	475	370	226	104
$LSD_{0.1}$	NS	NS	NS§	NS	NS	10
CV%	14	20	19	21	23	19

† Control (previous crop is not alfalfa): oat, corn, and tall fescue at Lamberton, Rosemount, and Waseca, respectively.
‡ NS, not significant.
§ An interaction due to a crossover effect including this factor was also present. At Rosemount in 1994, there was a significant three-way interactions ($P < 0.1$). Reanalysis of the data indicated that with a seeding delay, with all stand ages except 2 yr, plant populations were greater with 5262 than with Wrangler. With no seeding delay, with the control, populations were greater with Wrangler than with 5262 while the reverse was observed for 3-yr alfalfa stands. At Rosemount in 1995, there was a stand age × seeding delay interaction ($P < 0.1$). Reanalysis of the data indicated that with the control, alfalfa plant populations were greater with a seeding delay while the reverse was observed with alfalfa stands of all ages.

stand age, suggesting that if autotoxicity was present, its effect on plants was relatively minor and undetectable.

Effects due to reseeding delay were observed in October in five of six experiments. As with plant populations 30 d after seeding, delaying seeding had inconsistent effects on plant populations in the fall, and trends were generally the same as at 30 d. Again, this may be attributable to variation in environmental conditions at the time of seeding. The lack of consistent interaction of reseeding delay with stand age indicates that its effect on alfalfa populations was unrelated to the stand age and, thus, to autotoxicity. A stand age × seeding delay interaction occurred only at Rosemount in 1995, and as occurred for populations 30 d after seeding, results did not appear to be associated with autotoxicity (i.e., alfalfa plant populations following the tall fescue control crop were greater with a seeding delay while the reverse was observed with alfalfa stands of all ages). At Rosemount in 1994, there was a significant cultivar × stand age × seedling delay interaction that was related to a shift in populations of the two cultivars as stand age changed; however, as occurred for the 30-d plant count, this response was not consistently related to autotoxicity (data not shown)

Stand differences between alfalfa cultivars were less in October than at 30 d following seeding. Stands of the two cultivars were similar in five of six experiments. As had occurred 30 d after seeding, populations of 5262 were greater than those of Wrangler at Waseca in 1995.

Alfalfa Yields in Reseeding Year

Stand age affected alfalfa yield in the reseeding year in two of six experiments, but no consistent response was observed that would suggest the occurrence of autotoxicity (Tables 2 and 5). Similar responses were observed at the first harvest (data not presented). At Lamberton in 1995 and Waseca in 1994, when significant stand age effects occurred, total alfalfa yields were similar to or greater following alfalfa of most stand ages than following the nonalfalfa control. In both experiments, alfalfa yields were lower following 1-yr-old alfalfa than following all other treatments. As reported with plant populations, there was no consistent association between yield response and characteristics of killed alfalfa stands (data not presented).

In all environments, delaying alfalfa reseeding in an attempt to avoid a possible autotoxic response resulted in a reduction of total alfalfa yields. A similar response was observed for yields at the first harvest (data not presented). Delayed seeding compared with reseeding directly after tillage of killed alfalfa stands reduced yield by an average of 23% and as much as 67% at Lamberton in 1994. These important yield reductions due to the delay are attributable to the shorter season available for dry matter accumulation and the less favorable moisture and temperatures that usually occur later than in early spring (Sheaffer, 1983). Finally, there was a cultivar effect in all of the six experiments due to greater productivity of 5262 than Wrangler. This has also been observed in standard alfalfa cultivar evaluation trials conducted at the University of Minnesota (Martin and Sheaffer, 1996).

Table 5. Alfalfa yield in the reseeding year as affected by original stand age, reseeding delay, and cultivar reseeded at three locations in Minnesota. Results represent main-treatment effects for 1994 and 1995 seedings.

	Lamberton		Rosemount		Waseca	
	1994	1995	1994	1995	1994	1995
	Mg ha^{-1}					
Stand age (yr)						
0 (control)†	5.12	4.74	4.60	7.38	7.34	4.41
1	4.99	4.00	4.95	7.04	5.55	4.67
2	4.81	4.91	5.16	7.15	7.43	5.06
3	5.03	4.87	4.80	7.56	7.72	5.04
$LSD_{0.1}$	NS‡	0.48	NS	NS	0.58§	NS§
CV%	12	16	13	14	13	23
Seeding delay (wk)						
0	7.48	4.92	5.53	7.64	7.18	5.11
2	2.49	4.34	4.22	6.92	6.83	4.48
$LSD_{0.1}$	0.27	0.25	0.22	0.32	0.29§	0.33§
CV%	12	12	10	10	9	15
Cultivar reseeded						
5262	5.13	4.77	5.12	7.50	7.19	4.93
Wrangler	4.85	4.49	4.64	7.07	6.83	4.66
$LSD_{0.1}$	0.16	0.19	0.16	0.27	0.29	0.27§
CV%	8	10	8	9	10	13

† Control (previous crop is not alfalfa): oat, corn, and tall fescue at Lamberton, Rosemount, and Waseca, respectively.

‡ NS, not significant.

§ An interaction due to a crossover effect including this factor was also present. At Waseca in 1994 and 1995, there was a significant stand age crop × seeding delay interaction, $P < 0.1$, respectively. Reanalysis of the data indicate that in 1994, with the control and 2- and 3-yr-old alfalfa stands, yields were greater without a delay. The reverse was observed with 1-yr-old stands. In 1995, with the control and 3-yr-old stands, yields were greater without a delay while no differences were observed with 1- and 2-yr-old stands.

Crossover interactions between reseeding delay or cultivar with previous crop seldom occurred except for the reseeding delay × stand age interaction at Waseca in both years. Again, however, no consistent trend occurred that could be associated with autotoxicity. It is more likely that treatment differences were due to differences in seeding and growing conditions, which resulted from the interaction of several factors, including soil moisture and temperature, that varied between treatments.

Alfalfa Yields in Year after Reseeding

At the first harvest in the year following alfalfa reseeding (Tables 2 and 6), the previous crop had an effect on yields in 1995 and 1996 at Rosemount and in 1996 at Waseca. In these experiments, average yields were 15% lower after alfalfa than after the nonalfalfa control crop, suggesting evidence of delayed autotoxicity. Tesar (1993) reported postreseeding year yield reduction of the same magnitude under similar management conditions. The yield reductions we observed were not associated with effects on stand density, yield in the reseeding year, or stand characteristics of the killed stands. There was no consistent effect due to the age of the killed alfalfa stands on yields 1 yr after reseeding.

Seeding delay affected yields in the spring of the following year in three of the six experiments; however, the effect was inconsistent over experiments. In 1995 at Lamberton, yields were greatest with no seeding delay.

Table 6. Alfalfa yield at the first harvest in the year following reseeding as affected by original stand age, reseeding delay, and cultivar reseeded at three locations in Minnesota. Results represent main treatments.

	Lamberton		Rosemount		Waseca	
	1995	1996	1995	1996	1995	1996
Stand age (yr)	Mg ha^{-1}					
0 (control)†	5.15	3.51	4.12	4.43	6.46	4.10
1	4.56	3.05	3.69	4.01	6.35	2.79
2	4.75	2.95	3.57	3.63	6.57	3.20
3	4.88	3.09	3.57	3.73	6.47	4.09
$LSD_{0.1}$	NS‡§	NS	0.41	0.22	NS	0.68
CV%	19	29	17	9	14	29
Seeding delay (wk)						
0	5.13	3.27	3.43	3.93	6.10	3.71
2	4.53	3.03	4.04	3.97	6.82	3.37
$LSD_{0.1}$	0.20	NS	0.19§	NS§	0.32	NS
CV%	9	26	11	10	11	26
Cultivar reseeded						
5262	4.88	3.15	3.74	4.03	6.51	3.85
Wrangler	4.80	3.15	3.73	3.88	6.41	3.23
$LSD_{0.1}$	NS§	NS	NS§	NS§	NS	0.24
CV%	10	19	14	10	12	16

† Control (previous crop is not alfalfa): oat, corn, and tall fescue at Lamberton, Rosemount, and Waseca, respectively.
‡ NS, not significant.
§ An interaction due to a crossover effect including this factor was also present. At Lamberton in 1995, there was a significant cultivar × seeding delay interaction ($P < 0.1$). Reanalysis of the data indicated that with the control, yields were greater with 5262 than with Wrangler while the reverse was observed with 1- and 3-yr-old alfalfa stands. At Rosemount in 1995 and 1996, there were seeding delay × cultivar interactions ($P < 0.1$). In 1995, yields were greater with Wrangler than with 5262 without a delay while the reverse was observed with a delay. In 1996, yields were greater with 5262 than with Wrangler with a delay while similar with both cultivars without a delay.

However, in 1995 at Rosemount and Waseca, the no-seeding-delay treatment actually was the lowest yielding. At Lamberton in 1995, there was a stand age × reseeding delay interaction; however, it was not associated with a possible autotoxic effect. Yields were greater for 5262 than Wrangler in one of six experiments while in the others, yields were similar for the cultivars. Interactions between cultivars reseeded and either stand age or seeding delay occurred in three of the six environments; however, these were not associated with a possible autotoxic response.

These results suggest that the autotoxic response in alfalfa might be subtle and hard to detect in the seeding year but more apparent in the year following reseeding. This delayed response could be the result of changes in root morphology that might result from autotoxicity as reported by Nelson et al. (1997). They showed that chemicals involved in autotoxicity result in a permanent modification of alfalfa root morphology. We did not examine root morphology in our study, and thus were not able to confirm this hypothesis.

SUMMARY AND CONCLUSIONS

There was no consistent evidence among six experiments for autotoxicity in alfalfa in our study where we simulated winterkill by fall herbicide application and incorporated dead residue in spring before planting. Alfalfa plant densities and yields in the reseeding year were relatively unaffected by the previous crop or age of alfalfa stand that preceded reseeding. However, a possible autotoxic response appeared in some environments in spring of the year following reseeding.

It is possible that the lack of a consistent autotoxic response in our study may have been because original alfalfa stands were incorporated by chisel plowing. In some studies reporting alfalfa autotoxicity, alfalfa was no-till seeded into existing stands (e.g., Mueller-Warrant and Koch, 1981; Tesar, 1993; Nelson et al., 1997). Tesar (1993) suggested that autotoxicity may be a greater problem with the absence of plowing as allelochemical compounds in such conditions have direct, early contact with developing alfalfa seed and seedlings. Consistent with our results, Kehr et al. (1983) in Nebraska and Bortnem et al. (1990) in South Dakota also reported no evidence of autotoxicity during the seeding year when original stands were plowed.

Contrary to our findings, Tesar (1993) in Michigan reported autotoxicity in the reseeding year when alfalfa was seeded immediately after spring incorporation of the original alfalfa stands. Differences between his results and ours may be because we used a fall herbicide application to induce winterkill, whereas he plowed or applied glyphosate to spring regrowth of alfalfa that had accumulated from 1.4 to 4.0 Mg ha^{-1} herbage. Our approach was successful in killing alfalfa plants as may occur anytime during the winter and early spring in Minnesota. We attempted to simulate actual field situations where plants do not regrow in the spring due to winterkill, in contrast to the approach of Tesar (1993) who killed living plants with significant regrowth in the spring. Because the amount of residue on plants present in the sward might influence the incidence of autotoxicity (Miller, 1996), Tesar (1993) may have established a situation with considerable potential for autotoxicity that is unlikely to occur under field conditions where winterkill was prevalent.

Laboratory studies of Jennings and Nelson (1998) demonstrated that the severity of autotoxicity varies, depending on soil texture and rainfall patterns. In our study, there was no clear association between precipitation and incidence of autotoxicity. However, based on their results, the effects of autotoxic factors might be reduced in the short term in the finer-textured soils of our studies, but their impact may be longer lasting. This could explain why we observed autotoxicity in some experiments in the year following reseeding.

The traditional recommendation to rotate from alfalfa to another crop upon termination of alfalfa stands is still an effective approach to utilize alfalfa N and to minimize potential plant disease and allelopathy. However, in emergency situations, when reseeding without an intervening crop is necessary, our results show a lack of autotoxicity and a yield reduction in the reseeding year when reseeding was delayed. This suggests that the recommendation of delaying alfalfa reseeding in spring 2 wk following incorporation of winterkilled alfalfa may be unsound. Our results also show the need for investigating long-term alfalfa autotoxic response in diverse environments.

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