Glandular-Haired Cultivars Reduce Potato Leafhopper Damage in Alfalfa

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ABSTRACT

Glandular-haired alfalfa (*Medicago sativa* L.) cultivars developed for resistance to potato leafhopper [*Empoasca fabae* Harris] (PLH) have not been evaluated across a wide geographic area. Our objective was to evaluate forage growth, yield, insect damage, and stand density of glandular-haired and standard alfalfa cultivars with and without insecticide control of naturally occurring PLH infestations across the Midwest USA. Nine glandular-haired and five standard cultivars were evaluated from 1996 to 1998 in field experiments in Ohio, Indiana, Wisconsin, and Minnesota. Scheduled insecticide applications increased total yield of all cultivars, the response declining with increasing latitude (yield advantage = 32.7 − 0.72 × latitude; $r^2 = 0.86$, $P = 0.05$). Depending on location, total yield loss due to PLH damage ranged from 5 to 23% for the standard cultivars and 1 to 10% for the glandular-haired, commercially released cultivars (GR). Yield loss from PLH feeding in the GR cultivars was less than half of that observed in standard cultivars in environments where PLH stress was high. The GR cultivars yielded 1.1 Mg ha^{-1} more per year on average than the standard cultivars without insecticide under high PLH stress in Ohio and Indiana. Potato leafhopper nymph densities were lower in glandular-haired cultivars than in standard cultivars. Cultivars had similar yield when treated with insecticide or when PLH populations were low. Glandular-haired alfalfa cultivars were not immune to PLH damage; however, they can substantially reduce yield losses caused by this pest and provide a useful new tool for integrated pest management strategies.

The potato leafhopper (PLH) is a serious insect pest of alfalfa throughout much of the eastern half of the USA (Cuperus et al., 1983). The feeding characteristics of this pest result in an enhanced wound response in alfalfa that leads to phloem blockage and accumulation of photoassimilates in the leaves (Kabrick and Backus, 1990; Ecale and Backus, 1995). The visible symptoms in alfalfa are stem stunting and leaf chlorosis, a condition commonly called hopperburn (Flinn and Hower, 1984; Manglitz and Ratcliffe, 1988). This pest can be especially damaging in seedling stands, sometimes severe enough to lead to plant death (Flinn and Hower, 1984). In established stands, the first harvest is usually not affected because this pest does not overwinter in the Midwest; however, damaging PLH populations often develop in the second, third, and occasionally fourth growth cycles during the summer months. Reductions in plant height and yield are the most commonly documented responses to PLH feeding (Faris et al., 1981; Hower and Flinn, 1986; Hutchins et al., 1989; Oloumi-Sadeghi et al., 1988). Although nutritive value can be affected, economic loss from this pest is primarily linked to reductions in forage biomass or nutrient yield (Hower and Flinn, 1986; Hutchins et al., 1989).

Considerable research has been undertaken to evaluate alfalfa host resistance or tolerance to PLH injury (Sorensen et al., 1988). Resistance to hopperburn in the field has long been used as a selection criterion in alfalfa breeding programs (Dudley et al., 1963; Hanson et al., 1972; Kindler et al., 1971). Alfalfa cultivars with tolerance to PLH yellowing have been commercially released; however, there is little published evidence that selection for this trait reduces the severe stunting and yield loss caused by high PLH populations (McCaslin, 1994). Insecticide application has been the primary method for limiting yield loss when PLH densities are high (Hower et al., 1999).

In 1997, seed companies released for sale several alfalfa cultivars that were marketed as a breakthrough in PLH resistance (Holin, 1997). Parent clones of these cultivars trace to populations derived from crosses of modern commercial germplasm sources and three germplasm releases with the glandular-hair phenotype (Shade and Kitch, 1986; Sorensen et al., 1985; Sorensen et al., 1986). The glandular-haired germplasm releases were derived from crosses of *M. sativa* L. with various perennial wild-type tetraploid and diploid *Medicago* species reported to have significant antibiosis and antixenosis to PLH (Brewer et al., 1986; Shade et al., 1979). Since the mid-1980s, alfalfa breeders have used recurrent phenotypic selection to incorporate the glandular-haired germplasm into modern germplasm sources, with the objective of combining adequate levels of PLH resistance with acceptable agronomic performance (McCaslin, 1994; Moutray, 1996). The result has been the recent commercialization of glandular-haired cultivars that are claimed to be more resistant to PLH.

Lefko et al. (2000a) evaluated new PLH-resistant alfalfa (glandular haired) cultivars and a susceptible (normal non-glandular-haired) cultivar in field trials in Iowa. Herbage growth differed significantly among alfalfa types in only 1 of 15 harvests taken across two locations; however, the trend was for resistant cultivars to produce more herbage than the susceptible cultivar when PLH

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Abbreviations: GN, glandular-haired cultivars not commercially released; GR, glandular-haired, commercially released cultivars; NR, normal non-glandular-haired, commercially released cultivars; PLH, potato leafhopper.

Table 1. Geographic and other information pertinent to the trial.

					Harvests		
State	**Location**	**Coordinates**	**Soil type**	**Seeding date**	**1996**	**1997**	**1998**
Minnesota	**University of Minnesota Research and Outreach Center, Rosemount**	**44°43′ N, 93°6′ W**	**Waukegon silt loam (fine-silty over sandy-skeletal, mixed, mesic Typic Hapludoll)**	**13 May 1996**	**†,2**	**1,2,3**	**1,2,3**
Wisconsin	**University of Wisconsin Arlington Agricultural Research Center, Arlington**	**43°18′ N, 89°21′ W**	**Plano silt loam (fine-silty, mixed, mesic, Typic Argiudolls)**	**26 Apr. 1996**	**1,2**	**1,2,3**	**‡**
Indiana	**Purdue University Agronomy Research Center, West Lafayette**	**40°25′ N, 86°54′ W**	**Raub silt loam (fine-silty, mixed, mesic, Aquic Argiudolls)**	**10 Apr. 1996**	**1,2**	**1,2,3,4**	**1,2,3,4**
Ohio	**Ohio Agricultural Research and Development Center's Western Branch, South Charleston**	**39°51′ N, 83°40′ W**	**Crosby silt loam (fine, mixed, mesic Aeric Ochraqualfs)**	**20 May 1996**	**1,2**	**1,2,3,4**	**1,2,3,4**

† First-cut data not taken because of excessive weed infestation.
‡ Trial was terminated at the end of the second year at Wisconsin.

pressure was high. The potential for resistant alfalfa to outperform susceptible alfalfa in the presence of PLH began after initial seedling growth and continued through the third year (Lefko et al., 2000b). The authors of the study concluded that while glandular-haired cultivars were not immune to this pest, they had favorable growth characteristics that could translate into greater yields when PLH density is high (Lefko et al., 2000a).

The findings of Lefko et al. (2000a, 2000b) need to be tested across a wider geographic area and under a wider range of naturally occurring PLH densities. Toward this end, the objective of our research was to evaluate forage growth, yield, insect damage, and stand density in PLH-susceptible (non-glandular-haired) and resistant (glandular haired) cultivars across a wide geographic area without and with insecticide applications to control PLH.

MATERIALS AND METHODS

Field experiments were established in spring 1996 in Ohio, Indiana, Wisconsin, and Minnesota (Table 1). Initial soil pH (1:1 soil/water extract) across the four sites ranged from 6.5 to 7.1, available P (Bray P-1 extraction) ranged from 21 to 330 mg kg^{-1}, and available K (ammonium acetate extraction) ranged from 110 to 220 mg kg^{-1}. Preplant and maintenance fertilizer applications during the course of the experiment were made according to university guidelines in each state. The previous crop was soybean [*Glycine max* (L.) Merr.] at Ohio and corn (*Zea mays* L.) at Minnesota, Wisconsin, and Indiana. The experiment was continued for 3 yr (1996–1998) at Minnesota, Indiana, and Ohio and for 2 yr (1996 and 1997) at Wisconsin.

The experimental design at all locations was a randomized complete block with four replicates and a split-plot restriction on treatment arrangement. Whole-plot treatments consisted of insecticide-treated and untreated controls. Subplot treatments were alfalfa cultivars. In the insecticide-treated whole plots, PLH populations were prevented from reaching damaging levels by applying cyfluthrin [cyano (4-fluoro-3-phenoxyphenyl)-methyl-3-(2,2-dichloroethenyl) 2,2-dimethylcyclopropanecarboxylate] at 0.028 kg a.i. ha^{-1}. In the seeding year (1996), insecticide was applied to the first growth of alfalfa ≈68 d after seeding at Indiana and Wisconsin and 36 and 53 d after seeding at Ohio. No insecticide was necessary in the first growth at Minnesota. Cyfluthrin was again applied ≈15 d after the first harvest in the seeding year at all locations. In subsequent years, cyfluthrin was applied ≈15 d after the first and second harvests at Minnesota and Wisconsin and ≈15 d after the first, second, and third harvests at Indiana and Ohio. Although insecticide applications were made on a scheduled basis to the treated plots, they often coincided with the time when PLH populations reached economic threshold levels (Willson et al., 2000) in the unsprayed plots.

Fourteen cultivars (subplot treatments) were included in

Table 2. Pertinent information about the alfalfa cultivars used in this study. All trial locations were established from a common seed lot for each entry.

			Cultivar type			
No.	**Experimental line or cultivar**	**Generation**	**Designation**	**Morphology**	**Release status**	**Developed by**
1	**ZH9549 (Ameriguard 301)†**	**Syn_1**	**GR**	**glandular**	**released**	**ABI Alfalfa**
2	**ZH9548 (Interceptor)†**	**Syn_1**	**GR**	**glandular**	**released**	**ABI Alfalfa**
3	**XAM411 (5347/LH)†**	**Syn_1**	**GR**	**glandular**	**released**	**Pioneer Hi-Bred Int.**
4	**CW4242**	**Syn_2**	**GN**	**glandular**	**not released**	**Cal/West Seeds**
5	**CW5351**	**Syn_2**	**GN**	**glandular**	**not released**	**Cal/West Seeds**
6	**CS5332**	**Syn_2**	**GN**	**glandular**	**not released**	**Cal/West Seeds**
7	**9602b (Trailblazer)†**	**Syn_1**	**GR**	**glandular**	**released**	**Forage Genetics**
8	**96H2 (DK121HG)†**	**Syn_1**	**GR**	**glandular**	**released**	**Forage Genetics**
9	**R562 (Arrest)†**	**Syn_1**	**GR**	**glandular**	**released**	**Forage Genetics**
10	**Rushmore**	**NCSL‡**	**NR**	**nonglandular**	**released**	**Forage Genetics**
11	**AlfaLeafII**	**NCSL**	**NR**	**nonglandular**	**released**	**Cal/West Seeds**
12	**Innovator+Z**	**NCSL**	**NR**	**nonglandular**	**released**	**ABI Alfalfa**
13	**5454**	**Certified seed**	**NR**	**nonglandular**	**released**	**Pioneer Hi-Bred. Int.**
14	**Vernal**	**Certified seed**	**NR**	**nonglandular**	**released**	**Public, Univ. of Wisconsin**

† Seed used for this study was from the generation preceding the release under the name indicated in parentheses.
‡ NCSL, noncertified commercial seed lots.

the experiment (Table 2). Nine were experimental cultivars representing the recently developed glandular-haired lines selected for resistance to PLH. Six of these experimental lines were released for commercial sale beginning in 1997 and were reviewed by the National Alfalfa Variety Review Board (http://www.naaic.org/Resources/Cultivars.html; verified 20 Aug. 2001). Parent clones of the released lines trace to populations derived from a combination of modern non-glandular-haired, commercial germplasm and three glandular-haired germplasm releases, specifically 81IND2 (Shade and Kitch, 1986), KS108-GH5 (Sorensen et al., 1985), and KS94GH6 (Sorensen et al., 1986). Seed tested from the nine experimental lines was either Syn_1 or Syn_2 generation (Table 2). The other five cultivars were selected to represent commercially available non-glandular-haired, PLH-susceptible alfalfa. The six glandular-haired cultivars that were released for commercial sale were designated as GR (glandular-haired, released), the three experimental glandular-haired cultivars not commercially released were designated as GN (glandular-haired, not released), and the five non-glandular-haired, commercially released cultivars were designated as NR (non-glandular-haired, released).

The range in seeding dates in 1996 (Table 1) reflects spring rainfall patterns and the first opportunity for planting at each location. All seed was inoculated with *Rhizobium meliloti* Dangeard and treated with metalaxyl [*N*-(2,6-dimethylphenyl)-*N*-(methoxy-acetyl)-alanine methyl ester] before planting. Conventional tillage was used to prepare the seedbed. The alfalfa cultivars were seeded at 11 kg ha^{-1} in rows spaced 15 cm apart. Experimental units (cultivar subplots) ranged from 1.5 to 2.3 m wide and 4.9 to 6.1 m long. Whole plots (insecticide treated or untreated) ranged from 21 to 32 m wide and 4.9 to 6.1 m long. Seed quantity of the glandular-haired cultivars was low, which limited the subplot size. Whole-plot treatments were separated by at least 3 m, and a minimum of 1.5 m of PLH-susceptible alfalfa bordered all sides of each whole plot. Weeds were controlled with herbicides as needed: At Indiana, benefin (*N*-butyl-*N*-ethyl-α,α,α,trifluoro-2,6-dinitro-*p*-toludine) was applied preplant incorporated at 1.5 kg a.i. ha^{-1}, and 2,4-DB [4-(2,4-dichlorophenoxy) butanoic acid] was applied postemergence at 0.6 kg a.i. ha^{-1}; at Ohio, imazethapyr {(±)-2-[4,5-dihydro-4-methyl-4-1(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} was applied postemergence at 0.07 kg a.i. ha^{-1}; at Wisconsin, sethoxydim {2-[1-(ethoxy-imino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} at 0.21 kg a.i. ha^{-1} and imazethapyr at 0.07 kg a.i. ha^{-1} were applied postemergence; and at Minnesota, trifluralin [2,6-dinitro-*N*, *N*-dipropyl-4-(trifluoromethyl) benzenamine] was applied preplant at 1.0 kg a.i. ha^{-1}. Alfalfa weevil (*Hypera postica* Gyll.) was controlled in early May 1997 and 1998 at Indiana with carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranylmethyl carbamate) at 0.56 kg a.i. ha^{-1}. Alfalfa weevil populations were low at the other locations, and insecticide treatment for their control was unnecessary.

The experiment was harvested twice during the seeding year at all locations, with the first harvest taken 68 to 80 d after seeding and the second harvest taken ≈35 d after the first. In subsequent years, three harvests were taken at Minnesota and Wisconsin and four at Indiana and Ohio (Table 1). The first harvest at all locations was taken when alfalfa reached early flowering stage (late May to the first week of June). Summer harvests were taken at ≈35-d intervals at Indiana and Ohio and at 40- to 47-d intervals at Minnesota and Wisconsin. Forage yield data were recorded for all 10 harvests at Indiana and Ohio from 1996 to 1998. Yield data were not recorded at the first harvest in 1996 at Minnesota because of variability in the rate of establishment and presence of annual weeds. Yield data were recorded for the remaining seven harvests taken from 1996 to 1998 at Minnesota. Forage yield data were collected from all five harvests taken at Wisconsin from 1996 to 1997 (the experiment was discontinued after 1997). Forage was removed to a 6-cm stubble height from each subplot (4.7–5.9 m^2) with either a flail or sickle-bar harvester. Fresh weight in each subplot was recorded, and samples (300–500 g of fresh forage) were weighed and then dried at 60°C for 48 h to determine dry matter content, which was used to convert subplot fresh weight to dry matter yield.

Subplots were visually rated for PLH damage at each harvest using the following scale: 1 = no apparent damage, 2 = hopperburn symptoms on <20% of leaf area, 3 = hopperburn on 21 to 30% of leaf area, 4 = slight stunting with hopperburn on 31 to 40% of leaf area, 5 = moderate stunting with hopperburn on 41 to 50% of leaf area, 6 = significant stunting with hopperburn on 51 to 60% of leaf area, 7 = severe stunting with hopperburn on 61 to 70% of leaf area, 8 = severe stunting with hopperburn on 71 to 80% of leaf area, and 9 = extreme stunting with hopperburn on >80% of leaf area. The average of two or three canopy height measurements was recorded for each subplot at harvest. At the end of the experiment (October 1998) at Minnesota, Indiana, and Ohio, the final alfalfa plant density was determined in each subplot by digging and counting plants in an area ranging from 0.31 to 0.46 m^2. Plant counts were not made at Wisconsin.

Populations of PLH were monitored at all locations on a weekly basis beginning in June to provide a measure of the general PLH density in susceptible alfalfa borders within the experiment. Four samples were collected from the PLH-susceptible alfalfa borders surrounding the whole plots that had not been treated with insecticide. After insecticide treatment, four additional samples were collected from the treated alfalfa borders to ensure that PLH remained well below the economic injury level in treated plots. For each sample, 10 pendulum sweeps were made through the alfalfa canopy using an insect net with a 38-cm diam. The total number of PLH adults and nymphs was recorded along with the average canopy height in the border areas. The PLH density and canopy height data were related to economic thresholds. As a general rule, the economic threshold level was reached when the number of PLH adults plus nymphs collected per 10 sweeps of a sweepnet was numerically greater than the stem height of alfalfa expressed in inches (Willson et al., 2000).

Detailed monitoring of PLH nymph populations within individual subplots was performed in three of four states. At Indiana, PLH nymphs were counted in each subplot on a weekly basis during the second, third, and fourth growth cycles in 1996, 1997, and 1998. Nymphs were collected by sweeping polyethylene pans (25 by 34 by 4.4 cm) through the top half of the alfalfa canopy. Three pan sweeps were made in each subplot, and average number of nymphs per sweep was calculated. In 1996, the standard sweepnet procedure (described above for insect collection in border areas) was used at Ohio and Wisconsin to count PLH adults and nymphs in every subplot on one date during each of the two growth cycles. Pan sweeps were made periodically in each subplot during the summer in 1997 and 1998 at Ohio and in 1997 at Wisconsin.

Data Analysis

Mixed-model methodology, as implemented in SAS PROC MIXED (Littell et al., 1996), was used to analyze the response data from this trial. Insecticide treatment, cultivar group (see Table 2), and their interaction were considered fixed effects, whereas replicates, main-plot error, and experimental error

Table 3. Average potato leafhopper (PLH) density in untreated susceptible alfalfa border areas within the experiments during each growth interval at four locations.

Growth interval	Ohio			Indiana			Wisconsin			Minnesota		
	Adults	Nymphs	ETL†	Adults	Nymphs	ETL	Adults	Nymphs	ETL	Adults	Nymphs	ETL
	— no. sweep^{-1} —			— no. sweep^{-1} —			— no. sweep^{-1} —			— no. sweep^{-1} —		
1996												
1st	2.5	1.1	Yes	‡	16.1	Yes	0.2	0	No	‡	‡	
2nd	3.4	2.3	Yes	‡	1.7	Yes	1.7	1.0	Yes	‡	‡	
1997												
1st	0	0	No	<1	0	No	0	0	No	0	0	No
2nd	2.3	8	Yes	4.5	4	Yes	0.7	0.7	Yes	0.8	1.3	Yes
3rd	6	5.1	Yes	1.4	0.6	Yes	‡	‡	No	0.6	0	No
4th	0.5	0.6	Yes	0.3	0	No	‡	‡		‡	‡	
1998												
1st	0	0	No	0	0	No	‡	‡		0	0	No
2nd	8.1	2.3	Yes	1.4	5.2	Yes	‡	‡		2.9	2.4	Yes
3rd	5.5	4.7	Yes	2.1	1.4	Yes	‡	‡		0.5	0.1	No
4th	0.9	0.5	Yes	1.3	0.6	Yes	‡	‡		‡	‡	

† Indicates whether economic threshold level (ETL) for PLH was exceeded during growth interval. The ETL is defined as when the number of PLH adults plus nymphs collected per 10 sweeps of a sweepnet is numerically greater than the stem height of alfalfa, expressed in inches (Willson et al., 2000).

‡ Data not collected.

were considered to be random effects. We used a higher Type I error rate ($P = 0.15$) for interaction terms, extending the ideas of Carmer (1976) and Carmer and Walker (1988) regarding risk assessment for mean comparisons in crop performance trials. Least square means and associated standard errors were also calculated when appropriate. Cultivar groups were compared using preplanned contrasts. Cultivar group means for cumulative dry matter yield (dependent variable) were regressed on sequential harvest number (independent variable) to evaluate the yield response over time. Those regressions were forced through zero (no intercept model) to reflect no yield at establishment of the stand. Linear regressions were also used to describe the relationships between the following variables: PLH damage (hopperburn) scores vs. plant height and dry matter yield; plant height vs. yield; and PLH nymph density (at sampling date closest to harvest) vs. PLH damage score, plant height, and yield. The numerical differences between least squares means due to insecticide treatment (no-insecticide control mean − insecticide-treated mean) were used for all variables in those regressions. The regressions were forced through zero (no-intercept model) on the theoretical grounds that in the absence of PLH, there should be no difference between the control and insecticide-treated means. Nymph density was not recorded at Minnesota so that location was not represented in the regressions involving PLH density. All regression analyses were performed using StatView (SAS Inst., Cary, NC).

RESULTS AND DISCUSSION

Potato Leafhopper Density

Potato leafhopper density in untreated border areas planted to a conventional non-glandular-haired cultivar, as expected, varied considerably among locations (Table 3). In general, the farther south the location, the higher was the PLH pressure. In the seeding year (1996), the greatest injury (plant stunting, injury scores, and yield loss) from PLH feeding occurred at Ohio. At that location, the combination of late planting (20 May) and high PLH numbers resulted in severe stunting of the young seedlings beginning in early to mid-June. In subsequent years at Ohio and Indiana, economic thresholds were reached for the last three growth intervals, except for the fourth growth interval at Indiana in 1997. In contrast, economic thresholds were reached only in the second growth interval of the year at Wisconsin and Minnesota. Insecticide applications effectively controlled PLH in treated plots. Whenever detailed PLH counts were taken, insecticide applications reduced PLH populations to <15% of the population levels for the corresponding untreated cultivar group. In most cases, the reduction exceeded 96%, which was far below the economic threshold (data not shown).

Cumulative Dry Matter Yield and Final Stand Counts

Insecticide applications increased cumulative multiyear dry matter yields at all locations (Table 4). Average yield increases ranged from 0.4 to 5.2 Mg ha^{-1} at Minnesota and Ohio, respectively. The yield advantage of insecticide applications declined with increasing latitude (yield advantage = 32.7 − 0.72 × latitude; $r^2 = 0.86$, $P = 0.05$) and is likely related to differences in PLH density. The treatment × cultivar group interaction was significant only for the two southernmost locations, Indiana ($P = 0.12$) and Ohio ($P = 0.01$). At those locations, the yield advantage of insecticide application was greatest for the NR cultivar group and smallest for GR cultivars. Depending on location, total yield loss from PLH due to no insecticide application ranged from 5 to 23% for the NR group and 1 to 10% for the GR group.

The GR cultivars showed no yield advantage over NR cultivars at Minnesota and Wisconsin; however, at the two southern locations, the yield advantage of the GR group over the NR and GN groups was clearly evident when insecticide was not used (Table 4). When insecticide was applied, the cultivar groups were similar in yield at all locations, except at Indiana where GR yielded more than GN. This was noteworthy because the glandular-haired cultivars were slower to regrow after harvest and slower to initiate growth in early spring than NR cultivars (data not shown). Although the glandular-haired cultivars were similar in yield to NR cultivars, they were tested using Syn$_1$ or Syn$_2$ seed, whereas the NR cultivars were tested using seed of a later genera-

Table 4. Total accumulated forage yield and final stand density of three alfalfa cultivar groups grown without (control) and with (treated) insecticide for control of potato leafhopper (PLH).

Location and cultivar group†	Total dry matter yield				Final stand density			
	Control	Treated	Difference	SED‡	Control	Treated	Difference	SED
	Mg ha^{-1}				plants m^{-2}			
Minnesota								
GN	20.4	20.3	−0.1NS§	1.5	91	89	−2.2NS	9.7
GR	20.9	21.2	0.4NS	1.4	91	105	14.0*	8.1
NR	20.9	22.0	1.1NS	1.4	114	116	1.9NS	8.5
Contrasts								
GR vs. GN	NS	NS			NS	*		
GR vs. NR	NS	NS			**	NS		
Wisconsin								
GN	16.7	18.3	1.6**	0.6	¶	¶		
GR	16.3	18.0	1.7**	0.5	¶	¶		
NR	16.8	18.4	1.6**	0.5	¶	¶		
Contrasts								
GR vs. GN	NS	NS						
GR vs. NR	NS	NS						
Indiana								
GN	29.7	33.1	3.4**	0.9	102	91	−10.8*	5.2
GR	32.6	34.4	1.8**	0.8	85	99	13.4NS	3.9
NR	29.7	34.1	4.4**	0.8	116	108	−8.3*	4.2
Contrasts								
GR vs. GN	**	*			**	NS		
GR vs. NR	**	NS			**	*		
Ohio								
GN	25.3	30.5	5.2**	1.0	66	61	−5.8NS	4.5
GR	28.2	31.4	3.1**	0.9	64	65	0.8NS	4.2
NR	24.6	31.9	7.3**	0.9	73	66	−6.5NS	4.2
Contrasts								
GR vs. GN	**	NS			NS	NS		
GR vs. NR	**	NS			**	NS		

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† GN, glandular-haired, not commercially released; GR, glandular-haired, commercially released; and NR, non-glandular-haired, commercially released.
‡ Standard error of the difference.
§ NS, not significant ($P > 0.05$).
¶ Final stand counts were not taken at Wisconsin because the trial was terminated at the end of the second year.

tion. There is evidence in the literature that vigor and yield can decline with advancing generations in synthetic lines (Rumbaugh et al., 1988).

The effect of insecticide treatment on final stand count was small and inconsistent across locations (Table 4). Despite being more susceptible to PLH, the NR cultivar group had higher stand counts than the GR cultivars at all locations in the control plots. The lowest plant counts were observed at Ohio; however, stand densities there and at the other locations were within the range considered to be adequate for alfalfa production (Sheaffer et al., 1988).

Annual Yield Response to Insecticide

While the main variable of interest is the total cumulative yield over the duration of the trial, performance in individual years is important for evaluating consistency in the overall yield differences observed. Response to insecticide varied with location, year, and cultivar group; however, the general trend was for greater annual yield with insecticide treatment for all cultivar groups (Table 5). This trend was most consistent in Ohio where insecticide significantly increased yield in eight of nine comparisons. At both Indiana and Ohio, the yield response to insecticide treatment was usually greatest for the susceptible NR group (significant in five of six comparisons), intermediate for the GN group (significant in four of six comparisons), and least for the GR cultivar group (significant in only two of six comparisons).

In summary, application of insecticide generally increased both annual and multiyear cumulative yield at

Table 5. Total annual dry matter yield advantage for insecticide-treated vs. untreated controls for three alfalfa cultivar groups.

Location and cultivar group†	1996	1997	1998	SED‡
	Mg ha^{-1}			
Minnesota				
GN	−0.3	0.2	−0.1	0.68
GR	0.0	0.4	0.1	0.67
NR	0.1	0.6	0.6	0.67
Wisconsin				
GN	0.5	1.1*	§	0.35
GR	0.7	1.0*	§	0.31
NR	0.7	1.0*	§	0.31
Indiana				
GN	0.7	1.8**	0.9	0.35
GR	0.5	0.5	0.8	0.31
NR	1.1*	2.7**	0.6	0.32
Ohio				
GN	2.1**	1.7*	1.4*	0.41
GR	1.1*	1.4*	0.7	0.37
NR	3.6**	2.4**	1.4*	0.38

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† GN, glandular-haired, not commercially released; GR, glandular-haired, commercially released; and NR, non-glandular-haired, commercially released.
‡ Standard error of the difference.
§ Trial was terminated at the end of the second year in Wisconsin.

Table 6. Regression coefficients (±1 SE) for the regression of mean cumulative dry matter yield (Mg ha^{-1}) on sequential harvest number (1 to n) of three alfalfa cultivar groups grown without (control) or with (treated) insecticide for control of potato leafhopper (PLH). The intercept was forced through zero. For all regressions, $r^2 \geq 0.97$ and $P < 0.001$.

Location and cultivar group†	Control	Treated	Difference
Minnesota (n = 7)‡			
GN	3.19 ± 0.061	3.17 ± 0.067	−0.02NS
GR	3.22 ± 0.069	3.24 ± 0.072	0.02NS
NR	3.24 ± 0.072	3.41 ± 0.070	0.17NS
Contrasts			
GR vs. GN	NS§	NS	
GR vs. NR	NS	NS	
Wisconsin (n = 5)			
GN	3.37 ± 0.081	3.68 ± 0.087	0.31NS
GR	3.25 ± 0.092	3.60 ± 0.091	0.35NS
NR	3.34 ± 0.088	3.67 ± 0.096	0.33NS
Contrasts			
GR vs. GN	NS	NS	
GR vs. NR	NS	NS	
Indiana (n = 10)			
GN	3.09 ± 0.063	3.45 ± 0.061	0.36*
GR	3.40 ± 0.061	3.57 ± 0.059	0.17NS
NR	3.02 ± 0.063	3.54 ± 0.059	0.52*
Contrasts			
GR vs. GN	*	NS	
GR vs. NR	*	NS	
Ohio (n = 10)			
GN	2.54 ± 0.065	3.11 ± 0.047	0.57*
GR	2.86 ± 0.059	3.20 ± 0.048	0.34*
NR	2.42 ± 0.082	3.27 ± 0.044	0.85*
Contrasts			
GR vs. GN	*	NS	
GR vs. NR	*	NS	

* Significant at the 0.05 probability level.

† GN, glandular-haired, not commercially released; GR, glandular-haired, commercially released; and NR, non-glandular-haired, commercially released.

‡ n = total number of harvests for a particular location.

§ NS, not significant ($P > 0.05$).

all locations and for all cultivar groups. Differences between treated and control plots increased from north to south. The superiority of the GR cultivars was most apparent in the absence of insecticide treatment at Ohio and Indiana where PLH pressures were greatest. The yield rankings of the cultivar groups also demonstrate that the decision not to release the GN group of cultivars seems to have been appropriate because those experimental populations appeared to have lower resistance to PLH than their GR counterparts.

Yield at Individual Harvests

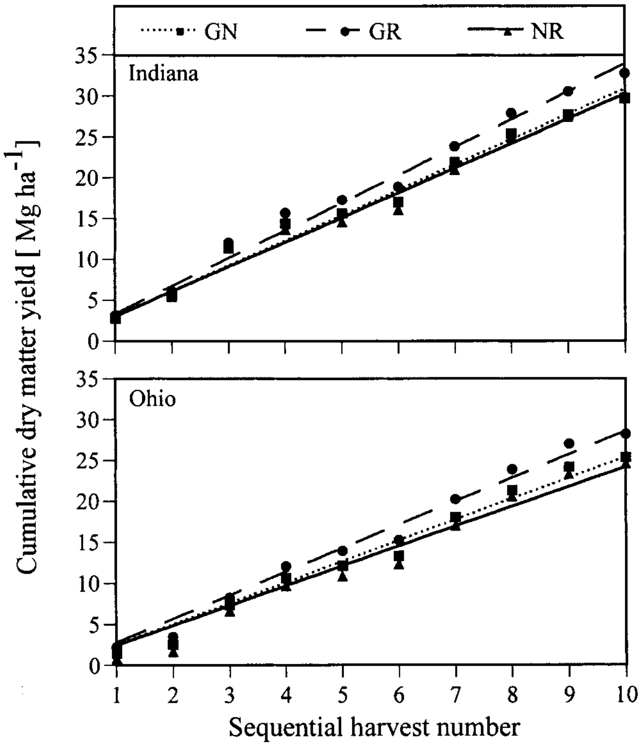

Fig. 1. Mean cumulative dry matter yield for glandular-haired alfalfa cultivars not commercially released (GN); glandular-haired, commercially released alfalfa cultivars (GR); and non-glandular-haired, commercially released alfalfa cultivars (NR) as a function of sequential harvest number. Data are for the control (no insecticide) treatment at Indiana and Ohio from 1996 to 1998. Regression statistics are presented in Table 6.

We expected that differences among cultivar groups would be greatest during the summer months (second and third growth cycles) when high PLH populations are most likely to occur. Generally, this hypothesis proved to be true. In 23 of 32 harvests of untreated plots across locations, the GR group yielded numerically more than the NR group (data not shown); in 8 of those 32 cases, this difference was significant at $P < 0.05$, and in 11 cases, it was significant at $P < 0.15$. At the southernmost location (Ohio), the GR group yielded numerically more than NR in 7 of 10 harvests; significant ($P \leq 0.01$) differences were observed at the first harvest (Aug. 5) of 1996 (1390 kg ha^{-1}), the second and third harvest dates in 1997 (total difference of 1370 kg ha^{-1}), and the third harvest date in 1998 (400 kg ha^{-1}). At Indiana, the GR group yielded numerically more than the NR group for all growth cycles, and significant ($P \leq 0.05$) differences were observed in the last three harvests of 1997 (total difference of 2150 kg ha^{-1}). The GR group yielded more ($P \leq 0.05$) than NR at Wisconsin during two harvests although the differences were extremely small (<50 kg ha^{-1}). The third harvest at Wisconsin for 1997 was the only case in the entire experiment where NR yielded significantly ($P \leq 0.05$) more (234 kg ha^{-1}) than GR in control plots. At the northernmost location (Minnesota), GR yielded significantly ($P \leq 0.05$) more (207 kg ha^{-1}) than NR only at the second harvest of 1997.

These results differ from those reported by Lefko et al. (2000a), who found that glandular-haired cultivars never produced significantly more dry matter than traditional non-glandular cultivars. They did, however, report that glandular-haired cultivars had more nodes, longer internodes, longer stems, and less hopperburn, with a trend of numerically more dry matter produced than a standard susceptible cultivar during growth cycles when PLH densities were high. In their experiments, estimates of dry matter were based on very small sampling units (0.1–1.4 m^2), and the authors concluded that their dry matter results should not be used to extrapolate estimates of alfalfa yield to large production areas. In our studies, we used subplot sizes that are commonly

Table 7. Linear regression of numerical differences due to insecticide treatment (no insecticide control vs. insecticide treated) to describe the relationships among the variables measured for three alfalfa cultivar groups. The intercept was forced through zero. Differences in slope estimates among cultivar groups were similar based on overlapping 95% confidence intervals.

Independent variable and maximum difference	Dependent variable and cultivar group†	Slope	SE	*n*	r^2	*P*
Damage score						
Maximum	Plant height, cm					
2.92	GN	−7.62	1.01	22	0.73	0.001
1.13	GR	−10.26	2.08	22	0.54	0.001
5.65	NR	−5.01	0.61	22	0.77	0.001
	Yield, kg ha^{-1}					
2.92	GN	−257	47	25	0.53	0.001
1.13	GR	−284	69	25	0.27	0.066
5.65	NR	−185	33	25	0.59	0.001
Plant height, cm						
Maximum	Yield, kg ha^{-1}					
−24.6	GN	34	5	22	0.69	0.001
−14.8	GR	30	5	22	0.60	0.001
−29.2	NR	35	6	22	0.60	0.001
PLH‡ nymph density, no. sweep^{-1}						
Maximum	Damage score					
40.8	GN	0.07	0.09	18	0.25	0.030
19.8	GR	0.03	0.02	17	0.10	0.241
70.3	NR	0.12	0.03	18	0.46	0.061
	Plant height, cm					
40.8	GN	−1.25	0.38	15	0.44	0.005
19.8	GR	−1.41	0.50	14	0.39	0.013
70.3	NR	−1.41	0.27	15	0.56	0.009
	Yield, kg ha^{-1}					
40.8	GN	−16	11	18	0.13	0.125
19.8	GR	−10	13	17	0.03	0.254
70.3	NR	−16	9	18	0.14	0.190

† GN, glandular-haired, not commercially released; GR, glandular-haired, commercially released; and NR, non-glandular-haired, commercially released.
‡ PLH, potato leafhopper.

used in alfalfa cultivar yield comparisons (Sheaffer et al., 1998). Thus, we were able to obtain meaningful yield estimates of cultivars under a wide range of naturally occurring PLH densities.

Cumulative Yield by Harvest

The continuous yield advantage of the GR group over the NR group in the absence of insecticide treatment is clearly demonstrated at the two southern locations by regressing cumulative harvest yield means on sequential harvest number (Table 6; Fig. 1). The intercept was forced through zero to reflect no yield at establishment of the stand. The coefficient of determination exceeded 0.97 in every case (data not shown), indicating an excellent fit. For control plots that did not receive insecticide applications, the GR group had the largest estimate for slope at Indiana and Ohio. Without insecticide applications, the yield advantage for this group ranged from 310 to 440 kg ha^{-1} harvest^{-1} at those two locations. The slope estimate for treated plots exceeded the corresponding estimate for the no-insecticide control plots, except for the GR group at Indiana. The improvement in cumulative yield due to insecticide application thus holds true across all harvests at Indiana and Ohio. The difference in slope between treated and control plots at those locations was greatest for the NR group and smallest for the GR group, again illustrating the progress of breeding for PLH resistance using the glandular-haired germplasm.

Potato Leafhopper Damage Score, Plant Height, and Potato Leafhopper Counts

Mean PLH damage scores (hopperburn) were consistently lowest for GR, intermediate for GN, and highest for NR, especially when PLH populations were high (data not shown). There was a significant negative relationship between PLH damage-score differences (untreated control − insecticide treated) and differences for plant height and dry matter yield (untreated control − insecticide treated) (Table 7). In other words, as damage score increased in untreated plots, plant height and yield decreased relative to treated plots. Although slope estimates of these relationships were similar for all cultivar groups, it is noteworthy that the maximal difference due to insecticide treatment for the independent variable (damage score) was lowest for GR, intermediate for GN, and highest for NR. The predicted yield losses and degree of plant stunting rank in that same order. Selection for tolerance to hopperburn has not been effective in developing resistance to yield loss caused by PLH (McCaslin, 1994); however, these glandular-haired cultivars exhibit both reduced hopperburn symptoms and improved resistance to stunting and yield loss. Lefko et al. (2000a) also reported lower hopperburn scores and less stunting in glandular-haired alfalfa than in susceptible alfalfa when PLH populations were high.

Plant height and yield differences due to insecticide treatment were positively related (Table 7). In other words, as reductions in plant height became greater in

Table 8. Density of potato leafhopper (PLH) nymphs in no-insecticide control plots of three alfalfa cultivar groups at three locations. Actual mean densities (±1 SE) are given for the NR group, whereas data for the GR and GN groups are expressed as a percentage of the NR group mean.

	Date				Cultivar group†		
Loc.	Sampling	Harvest	Growth interval	Sampling method	NR	GR	GN
					nymphs sweep^{-1}	%	
WI	15 Aug. 1996	21 Aug. 1996	2	sweepnet	1.6 ± 0.14	80	75
WI	11 July 1997	16 July 1997	2	pan	6.5 ± 0.32	59	80
WI	16 July 1997	16 July 1997	2	pan	13.6 ± 0.85	53	94
IN	19 June 1996	3 July 1996	1	pan	5.5 ± 1.39	28	47
IN	25 June 1996	3 July 1996	1	pan	26.7 ± 2.63	49	84
IN	10 July 1996	7 Aug. 1996	2	pan	2.4 ± 0.47	35	48
IN	18 July 1996	7 Aug. 1996	2	pan	0.5 ± 0.07	23	85
IN	23 July 1996	7 Aug. 1996	2	pan	2.2 ± 0.34	22	62
IN	1 Aug. 1996	7 Aug. 1996	2	pan	18.9 ± 0.53	14	37
IN	6 Aug. 1996	7 Aug. 1996	2	pan	33.3 ± 1.56	16	42
IN	21 Aug. 1996	‡	3	pan	12.9 ± 1.26	24	44
IN	29 Aug. 1996	‡	3	pan	3.4 ± 0.58	59	116
IN	6 Sept. 1996	‡	3	pan	2.1 ± 0.31	108	157
IN	1 July 1997	10 July 1997	2	pan	28.2 ± 1.87	5	36
IN	6 July 1997	10 July 1997	2	pan	56.9 ± 1.18	6	52
IN	14 July 1997	8 Aug. 1997	3	pan	2.4 ± 0.25	41	73
IN	21 July 1997	8 Aug. 1997	3	pan	2.6 ± 0.26	16	49
IN	30 July 1997	8 Aug. 1997	3	pan	1.0 ± 0.17	44	37
IN	4 Aug. 1997	8 Aug. 1997	3	pan	7.8 ± 0.38	19	47
IN	22 Aug. 1997	16 Sept. 1997	4	pan	1.2 ± 0.57	29	110
IN	29 Aug. 1997	16 Sept. 1997	4	pan	0.8 ± 0.20	13	30
IN	5 Sept. 1997	16 Sept. 1997	4	pan	0.3 ± 0.06	23	37
IN	19 June 1998	1 July 1998	2	pan	2.5 ± 0.22	34	45
IN	26 June 1998	1 July 1998	2	pan	18.1 ± 0.73	22	46
IN	2 July 1998	28 July 1998	3	pan	1.0 ± 0.15	86	59
IN	27 July 1998	28 July 1998	3	pan	3.4 ± 0.29	17	73
IN	11 Aug. 1998	9 Sept. 1998	4	pan	0.3 ± 0.10	73	83
IN	17 Aug. 1998	9 Sept. 1998	4	pan	0.2 ± 0.06	22	188
IN	3 Sept. 1998	9 Sept. 1998	4	pan	1.2 ± 0.44	81	72
OH	25 July 1996	5 Aug. 1996	1	sweepnet	1.1 ± 0.14	46	74
OH	20 Aug. 1996	11 Sept. 1996	2	sweepnet	3.0 ± 0.31	26	64
OH	7 July 1997	8 July 1997	2	pan	70.9 ± 4.87	15	58
OH	1 Aug. 1997	12 Aug. 1997	3	pan	8.7 ± 0.80	8	36
OH	11 Aug. 1997	12 Aug. 1997	3	pan	18.7 ± 1.32	11	48
OH	29 July 1998	29 July 1998	3	pan	10.8 ± 1.40	21	63

† GN, glandular-haired, not commercially released; GR, glandular-haired, commercially released; and NR, non-glandular-haired, commercially released.
‡ Only two harvests were taken during the seeding year.

untreated plots, yield losses also became greater. The slope estimates were similar among cultivar groups, but the maximal plant-height difference (and thus the maximal predicted yield difference) was lowest for the GR group, again indicating its superiority in resisting stunting and other damage caused by PLH.

The relationships between differences for PLH nymph density and damage score for the GN and NR cultivar groups were more pronounced than for the GR group (Table 7). Changes in nymph density and plant height were negatively related for all cultivar groups. In other words, as the numerical difference (untreated − insecticide treated) in nymph density became more positive, the height difference (untreated − insecticide treated) became more negative. The relationships between nymph density and dry matter yield differences were not significant ($P > 0.05$). Nevertheless, the maximal nymph density difference was greatest for the NR group, intermediate for GN, and least for GR. Cultivar group rankings for nymph density were consistent throughout the summer growth cycles. Whenever PLH nymphs were present, the densities were almost always lower in the GR and GN cultivars than in the NR cultivars (Table 8). The GR cultivar group had the lowest nymph counts, with few exceptions.

The large reductions in PLH nymph densities in glandular-haired cultivars that we observed are in sharp contrast to the findings of Lefko et al. (2000b). They found no evidence that glandular-haired alfalfa had a negative effect on PLH population growth, based on the number of nymphs developing from adults caged on field-grown alfalfa. In plot studies under natural infestations, Lefko et al. (2000a) found few differences in adult densities among cultivars; in only 2 of 60 comparisons did one or more glandular-haired cultivar have lower adult PLH densities than a non-glandular-haired cultivar (Lefko et al., 2000a). The few times that we collected PLH samples from subplots using sweepnets, large differences in nymph densities were observed (Table 8), but differences in adult densities were small and inconsistent among cultivar groups (data not shown). It is not clear why our findings on nymph density in glandular-haired cultivars were so different from those of Lefko et al. (2000b). The mechanism responsible for the lower nymph populations in glandular-haired alfalfa cannot be ascertained from this study. Antixenosis may have played a role in reducing oviposition in GR and GN cultivars, or antibiosis may have limited survival of nymphs. Both antibiosis and antixenosis have been implicated in controlled environment studies of glandular-haired alfalfa clones (Brewer et al., 1986; Elden and McCaslin, 1997; Shade et al., 1979). The dynamics of naturally occurring PLH populations in modern glandular-haired alfalfa cultivars need further investigation.

CONCLUSIONS

The six GR cultivars that we tested were not immune to PLH damage; however, they showed less hopperburn and plant stunting than standard, susceptible cultivars. More importantly, yield loss due to PLH in the glandular-haired cultivars was less than half of that observed in standard cultivars in Indiana and Ohio, environments where PLH density was high. In the absence of insecticide at those two locations, the GR yielded 1.0 to 1.2 Mg ha^{-1} yr^{-1} more dry matter on average than the standard cultivars.

In this study, the glandular-haired cultivars showed no advantage or disadvantage compared with standard cultivars when insecticide was applied to control PLH or in environments where PLH densities were low (Minnesota and Wisconsin). Our data also demonstrated that glandular-haired cultivars are likely to suffer significant yield losses if PLH densities are well over the established economic thresholds. Under such conditions, they showed no advantage over standard cultivars treated with insecticides in a timely manner. Based on the results of this experiment, the glandular-haired cultivars are likely to be of most benefit to growers who do not apply insecticides in timely fashion when needed, especially those in the lower Midwestern states where PLH densities frequently reach damaging levels.

These data demonstrate that glandular-haired cultivars may enable producers to reduce insecticide use in alfalfa production. Future progress is likely as plant breeding efforts continue to increase the level of resistance to PLH in new glandular-haired cultivars. As this occurs, these cultivars will likely have an increasing role in integrated pest management strategies to control this important alfalfa pest.

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PRODUCTION AGRICULTURE

Economic Analysis of Conservation and Conventional Tillage Cropping Systems on Clayey Soil in Eastern Arkansas

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ABSTRACT

Conservation tillage offers an alternative approach for managing clayey soils in the midsouthern United States. This study compared conservation tillage seedbed preparation vs. conventional tillage main plots with subplots of (i) nonirrigated soybean (*Glycine max* L. Merr.), (ii) irrigated soybean, (iii) irrigated grain sorghum (*Sorghum vulgare* L.), (iv) irrigated soybean followed by irrigated grain sorghum, (v) irrigated soybean followed by irrigated corn (*Zea mays* L.), and (vi) continuous irrigated cotton (*Gossypium hirsutum* L.) for the years 1986 to 1991 at Keiser, AR. Cropping practices were similar to those used by producers in the area. Grain sorghum yielded better in a soybean rotation than in monoculture and also in conventionally tilled seedbed than in conservation tillage. For other crops, yield did not differ significantly by tillage. Except for cotton, conventional tillage resulted in higher average net returns (NR) than conservation tillage. Although the most profitable system was continuous cotton with conservation tillage, NR varied widely across years, and there were fewer observations for cotton than for other systems in the study. Among conventional tillage seedbed preparation, nonirrigated continuous soybean was more profitable than any of the irrigated systems, including irrigated soybean. However, irrigated soybean resulted in NR that were less variable than nonirrigated soybean. The study confirmed the increased variable costs and decreased equipment costs that accompany conservation tillage systems. Even with the dramatic changes in burndown herbicide costs that have occurred since the study was conducted, the rankings of the cropping systems for profitability would not change.

Over the past decade, use of conservation tillage by farmers in the USA has increased. Nationally, the percentage of area planted using conservation tillage increased from 5.1% in 1989 to 16.3% in 1998 (Conserv. Technol. Inf. Cent., 1999). During this same period, conservation tillage in the Mississippi embayment—including the Delta region of eastern Arkansas—has also increased from 2.4% in 1989 to 10.7% in 1998. This increase is attributed to the nonclodding properties of the difficult-to-manage clay soils that are found in this area. Improvements in no-till farm machinery have also assisted in the adoption of this practice by enabling later planting into drier, harder soils, and thus extending the planting period. This suggests that Midsouth producers—who adopted conservation tillage more slowly than their Midwest counterparts—have become less hesitant in using this technology. In contrast, a reversal of this trend may be occurring in some areas. In very recent years, the percentage of no-till area in Iowa, e.g., has shown a decrease from 20.4% in 1994 to 16.2% in 1998.

For a cropping practice to be sustainable, it must also be profitable. One factor that contributes to the profitability of a conservation tillage system is that crop yield must compare favorably to that of a conventional system. Yield differences between conservation tillage and conventional tillage were examined by Hairston et al. (1990), who compared yield of soybean using no-till and conventional tillage on three Mississippi soils. Yields were similar between tillage systems on sandy soils for all 3 yr of the study. However, on silt loam and clayey soils, yield under conventional tillage exceeded no-till performance during most years. This yield reduction on finer textured soils was also noted in earlier studies by Hairston et al. (1984) and Dick et al. (1986a,b)

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Abbreviations: ACES, Arkansas Cooperative Extension Service; MSBG, Mississippi State Budget Generator; NR, net returns; TC, total costs; TFC, total fixed costs; TVC, total variable costs.