2006

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Darren C. Barker
Pioneer Hi-Bred International

Stevan Z. Knezevic
University of Nebraska-Lincoln, sknezevic2@unl.edu

Alex R. Martin
University of Nebraska-Lincoln

Daniel T. Walters
University of Nebraska-Lincoln

John L. Lindquist
University of Nebraska-Lincoln, jlindquist1@unl.edu

Barker, Darren C.; Knezevic, Stevan Z.; Martin, Alex R.; Walters, Daniel T.; and Lindquist, John L., "Effect of nitrogen addition on the comparative productivity of corn and velvetleaf (Abutilon theophrasti)" (2006). *Agronomy & Horticulture -- Faculty Publications*. 418.
http://digitalcommons.unl.edu/agronomyfacpub/418

Weed Science, 54:354–363. 2006

Effect of nitrogen addition on the comparative productivity of corn and velvetleaf (*Abutilon theophrasti*)

Darren C. Barker
Pioneer Hi-Bred International, Inc., York, NE 68467

Stevan Z. Knezevic
Haskell Agricultural Laboratory, University of Nebraska, Concord, NE 68728

Alex R. Martin
Daniel T. Walters
Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68583-0915

John L. Lindquist
Corresponding Author. Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68583-0915; jlindquist1@unl.edu

Weeds that respond more to nitrogen fertilizer than crops may be more competitive under high nitrogen (N) conditions. Therefore, understanding the effects of nitrogen on crop and weed growth and competition is critical. Field experiments were conducted at two locations in 1999 and 2000 to determine the influence of varying levels of N addition on corn and velvetleaf height, leaf area, biomass accumulation, and yield. Nitrogen addition increased corn and velvetleaf height by a maximum of 15 and 68%, respectively. N addition increased corn and velvetleaf maximum leaf area index (LAI) by up to 51 and 90%. Corn and velvetleaf maximum biomass increased by up to 68 and 89% with N addition. Competition from corn had the greatest effect on velvetleaf growth, reducing its biomass by up to 90% compared with monoculture velvetleaf. Corn response to N addition was less than that of velvetleaf, indicating that velvetleaf may be most competitive at high levels of nitrogen and least competitive when nitrogen levels are low. Corn yield declined with increasing velvetleaf interference at all levels of N addition. However, corn yield loss due to velvetleaf interference was similar across N treatments except in one site–year, where yield loss increased with increasing N addition. Corn yield loss due to velvetleaf interference may increase with increasing N supply when velvetleaf emergence and early season growth are similar to that of corn.

Nomenclature: Velvetleaf, *Abutilon theophrasti* Medic. ABUTH; corn, *Zea mays* L. 'Pioneer 33A14'.

Key words: Functional growth analysis, functional equilibrium, leaf area index, optimal partitioning, nitrogen use efficiency.

The canopy architecture of velvetleaf makes it a strong competitor for light (Lindquist and Mortensen 1999). However, velvetleaf growth, reproductive output, and competitiveness are all sensitive to nutrient supply (Parrish and Bazzaz 1982a, 1982b), timing of nutrient addition (Benner and Bazzaz 1985, 1987; Harbur and Owen 2004), and maternal nutrient regime (Wulff and Bazzaz 1992) but not the spatial heterogeneity of nutrient availability within the rhizosphere (Casper and Cahill 1996). Velvetleaf growth was most sensitive to nutrient supply at planting (Benner and Bazzaz 1987). Understanding the influence of nutrients, especially nitrogen (N), on crop–weed competition is important because it may be possible to use nitrogen management in an integrated weed management program.

Most C_4 species use N more efficiently than C_3 species (Nieto and Staniforth 1961; Okafor and DeDatta 1976; Tollenaar et al. 1994). Because corn is a C_4 and velvetleaf, a C_3 species, it is expected that corn will be the more efficient user of N, especially when N supply is limiting (Harbur and Owen 2004; Lindquist 2001). High levels of nutrient application do not always favor the crop over the weed (Qasem 1992). Carlson and Hill (1985) showed that wheat yield loss resulting from wild oat competition increased with increasing nitrogen application. High nutrient supply often favors weed vegetative growth and may provide little added benefit in crop yield (DiTomaso 1995). The increased crop loss from weed competition at high fertility may be due to the greater plasticity of weeds in responding to available resources.

Plants typically partition a greater proportion of new growth to roots under conditions of limited nitrogen supply (Agren and Ingestad 1987; Bonifas et al. 2005; Perez-Leroux and Long 1994). This provides the plants with greater root mass and volume so that more nitrogen can be acquired and N concentration in new leaves can be optimized. However, the greater investment in roots comes at the expense of leaf growth (Bonifas and Lindquist 2006), which subsequently limits potential growth rate. Because corn is a more efficient user of nitrogen, velvetleaf must partition a relatively greater proportion of new growth to roots under low N, resulting in a greater reduction in leaf area growth compared with corn (Bonifas et al. 2005). However, when nitrogen is nonlimiting, velvetleaf will partition most of its growth into leaves and stems. The plant is taller and has a greater leaf area, making it more competitive with corn for light than when nitrogen is limiting. Therefore, we hypothesize that velvetleaf height, leaf area, and biomass accumulation will have a greater response to nitrogen addition than corn. As a result of the different growth response of the two species, we also hypothesize that corn yield loss due to velvetleaf competition will increase with increasing nitrogen supply. The objectives of this research were to determine the influence of variable nitrogen addition on corn and velvetleaf height, leaf area, and aboveground biomass accumulation, and corn yield and yield loss in mixtures.

Materials and Methods

Field Experiments

Field experiments were conducted at the Agricultural Research and Development Center near Mead, NE

Table 1. Monthly rainfall and irrigation amounts and minimum, maximum, and mean average daily temperatures for the months of May, June, July, August, and September in 1999 and 2000. Thirty-year average precipitation and temperatures for these months are included for reference.

			Water supply		Temperature			30-yr average	
Site[a]	Year	Month	Rainfall	Irrigation	Min	Max	Mean	Rainfall	Temp
			mm		C			mm	C
ARDC	1999	May	149	0	10	22	16	109	17
		June	128	0	15	26	21	107	22
		July	56	0	20	32	26	83	25
		Aug	80	0	16	28	22	86	23
		Sept	69	0	10	25	18	88	18
	2000	May	74	51	11	26	19	109	17
		June	152	51	15	29	22	107	22
		July	88	51	18	29	24	83	25
		Aug	30	51	19	31	25	86	23
		Sept	16	0	11	28	20	88	18
NEREC	1999	May	87	0	10	22	16	98	16
		June	181	0	15	25	20	106	22
		July	40	0	19	30	25	79	24
		Aug	24	0	15	28	22	74	23
		Sept	2	0	9	24	16	67	17
	2000	May	139	0	10	24	17	98	16
		June	157	0	13	26	20	106	22
		July	45	51	18	28	23	79	24
		Aug	31	76	17	29	23	74	23
		Sept	8	25	10	26	18	67	17

[a] Abbreviations: ARDC, Agricultural Research and Development Center near Mead, NE; NEREC, Northeast Research and Extension Center near Concord, NE.

(ARDC) and at the Northeast Research and Extension Center near Concord, NE (NEREC) in 1999 and 2000.

Agricultural Research and Development Center

Soil type at the site was a Sharpsburg silty clay loam (fine, smectitic, mesic, Typic Argiudoll) with a pH of 6.7 to 6.8 and 3.3% soil organic carbon (SOC). Phosphorus (P) was broadcast-applied as 0–46–0 at a rate of 48 kg P ha^{-1} in 1999, based on soil test. No phosphorus was required in 2000.

The experiment was designed as a randomized complete block with 16 plots and four replications. Treatments included four rates of nitrogen application and four corn–velvetleaf plots (one corn and one velvetleaf monoculture and two corn–velvetleaf mixture plots). The highest nitrogen application rate was determined based on a 12.5 Mg ha^{-1} corn yield goal and residual soil nitrogen as determined by soil tests. Nitrogen was applied at rates of 0, 45, 90, and 180 kg N ha^{-1} and 0, 60, 120, and 240 kg N ha^{-1} in 1999 and 2000, respectively. Mixture treatments included corn and velvetleaf in mixture with 65,800 corn plants ha^{-1} and velvetleaf at 26,300 plants ha^{-1} (2 plants m^{-1} of corn row) or 131,600 plants ha^{-1} (10 plants m^{-1} of corn row). Each experimental unit (EU) was 6 by 9 m in 1999, although velvetleaf monoculture plots were split to obtain two velvetleaf monoculture density treatments (i.e., EU was 3 by 9 m). Each EU was increased to 6 by 10.5 m in 2000.

The field was previously cropped with corn and disked twice in spring followed by field cultivation in 1999. The 2000 field was moldboard-plowed in the fall of 1999, then disked and field cultivated in spring for seedbed preparation. Corn (‘Pioneer 33A14’) was seeded in rows spaced 0.76 m apart on May 3 in both 1999 and 2000. Tefluthrin was applied at a rate of 0.15 kg ai ha^{-1} at planting for early season insect control. Untreated velvetleaf seeds (100 times the desired density) were seeded directly into the corn rows at a depth of 1 cm using a hand-push planter immediately after corn seeding. Corn and velvetleaf reached 50% emergence on May 16 and 18, 1999, and on May 9 and 11, 2000, respectively. Nitrogen was applied as ammonium nitrate granules using a calibrated wheel-driven fertilizer spreader on May 3, 1999, and May 2, 2000.

Velvetleaf treatment densities were established by hand-thinning to the appropriate weed density beginning May 25, 1999, and May 23, 2000. Weeds other than velvetleaf were removed by hand as needed and by interrow cultivation on June 15, 1999. No cultivation was done in 2000. Corn began anthesis on July 21, 1999 (774 growing degree days [gdd]), and July 11, 2000 (713 gdd), and physiological maturity was reached on September 9 (1,445 gdd), and August 30 (1,416 gdd), in 1999 and 2000, respectively. Irrigation was not available in 1999, and was provided throughout the growing season in 2000, with approximately 51 mm of water applied once every 2 to 3 wk (Table 1).

Northeast Research and Extension Center

Soil in 1999 was a Kennebec silt loam, 0 to 2% slope (Fine-silty, mixed, superactive, mesic Cumulic Hapludoll) with a pH of 6.5 and 2.8% SOC. The soil in 2000 was a Moody silt loam, 0 to 2% slope (Fine-silty, mixed, mesic Udic Haplustolls) with a pH of 6.6 and 3.0% SOC.

TABLE 2. Corn maximum height (HT_{max}) and thermal time of maximum absolute growth rate (a/b from Equation 1 fitted to HT on growing degree days [gdd]) as influenced by nitrogen supply and mixture treatments in 1999 and 2000. Within columns and years, means followed by different letters are different at $P < 0.05$.[a,b]

Year	Velvetleaf density	N_{trt}	HT_{max}	a	b	a/b	rmse	$\sim r^2$
		kg N ha^{-1}	cm			gdd		
1999		0	224 b	2.96	0.0057	519 a	233.5	0.96
		45	238 ab	2.94	0.0063	467 b	218.2	0.97
		90	250 a	2.88	0.0062	465 b	246.7	0.97
		180	257 a	3.05	0.0066	462 b	200.7	0.98
2000		0	282 c	3.85	0.0075	513 a	140.2	0.99
		60	287 b	3.88	0.0076	511 a	89.6	0.99
		120	291 a	3.98	0.0077	517 a	74.9	0.99
		240	290 ab	4.02	0.0078	515 a	127.1	0.99
	0		284 b	3.93	0.0077	510 b	97.5	0.99
	2		290 a	4.00	0.0077	519 a	104.0	0.99
	10		287 ab	3.89	0.0075	519 a	130.8	0.99

[a] Corn height was affected by nitrogen (N) application treatment in both years and by velvetleaf density treatment in 2000. There was no interaction between N application and velvetleaf density in either year.

[b] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

The experiment was designed as a split plot with 12 treatments and four replications. Main plot treatments included four rates of N application, and subplots included three corn–velvetleaf densities. The highest nitrogen application rate was determined at the ARDC as described above. Nitrogen was applied at rates of 0, 45, 90, and 180 kg N ha^{-1} and 0, 60, 120, and 240 kg N ha^{-1}, in 1999 and 2000, respectively. Mixture treatments included corn in monoculture and in mixture with velvetleaf at densities of 26,300 plants ha^{-1} (2 plants m^{-1} of corn row) and 131,600 plants ha^{-1} (10 plants m^{-1} of corn row). Each experimental unit was 4.5 by 10.5 m in both 1999 and 2000.

Fields were previously cropped with corn and disked twice followed by field cultivation for seedbed preparation. Corn (Pioneer) was seeded in rows spaced 0.76 m apart to achieve 65,800 plants ha^{-1} on May 14, 1999, and May 11, 2000. Tefluthrin insecticide was applied at 0.15 kg ha^{-1} at planting for early season insect control. Untreated velvetleaf seeds were seeded directly into the corn row using a hand-push planter immediately after corn seeding. Corn and velvetleaf reached 50% emergence on May 24 and 26 in 1999, and on May 20 and 21 in 2000, respectively. Nitrogen was applied as ammonium nitrate granules using a calibrated wheel-driven fertilizer spreader on May 14, 1999, and May 11, 2000.

Velvetleaf densities were established by hand-thinning to the appropriate weed density beginning on June 25, 1999, and June 16, 2000. Weeds other than velvetleaf were removed by hand as needed and by interrow cultivation on June 25, 1999, and June 16, 2000. Corn began anthesis on July 31, 1999 (786 gdd), and July 26, 2000 (768 gdd), and physiological maturity was reached on September 29 (1,357 gdd), and 14 (1,477), in 1999 and 2000, respectively. Irrigation was not available in 1999 but was applied with a lateral-move irrigation system in 2000 (Table 1).

Data Collection (ARDC site only)

Destructive plant samples were periodically taken in each experimental unit at the ARDC site to quantify crop and weed growth and canopy dynamics. The first sample was taken on May 24, 1999 (76 gdd after crop emergence), and May 15, 2000 (48 gdd). Sampling continued weekly for the next 10 wk and, thereafter, every-other week, when samples were alternated among treatments (the high and low N application treatments were taken one week and the two middle N treatments the next). Plants within a 1-m section of row were sampled from the second, third, sixth, or seventh row of each experimental unit of the corn or mixture treatments, or from the second, third, or fourth row of each velvetleaf monoculture treatment. At least 1 m of row and the adjacent row were left intact between each sample area to ensure no edge effects of sampling. Plant height was determined for each plant within the sampled area before clipping plants at the soil surface. Before the sixth-leaf stage, corn height was measured to the extended tip of the tallest leaf. After a distinct bend was observed in corn leaves, height was measured to the tallest point on the undisturbed plant. After tassel emergence, height was measured to the top of the tassel. Velvetleaf height was measured at the tallest point on the plant throughout the season. Plants were then separated into stems, leaves, dead leaves, and reproductive tissues, and green leaf area was determined using an area meter.[1] Young leaves were unfurled for this measurement, and dead leaf material was removed. Tissues were then dried at 60 C to constant weight.

Grain Yield (ARDC and NEREC)

Plots at both ARDC and NEREC were hand-harvested for grain yield at the end of each growing season. At ARDC, 15 m of row was harvested within rows four and five of each EU. At NEREC, 15 m of row were harvested from rows three and four of each EU. Measurements of grain weight and moisture were obtained after grain was shelled. Grain yield is reported in units of kg grain ha^{-1} corrected to 15.5% moisture.

Weather Data

Daily weather data were obtained through the High Plains Climate Center from an automated weather station

Table 3. Velvetleaf maximum height (HT_{max}) and thermal time of maximum absolute growth rate (*a*/*b* from Equation 1 fitted to HT on growing day degrees [gdd]) as influenced by nitrogen (N) supply and mixture treatments in 1999 and 2000. Within columns, years, and velvetleaf density treatments (Vd), means followed by different letters are different at $P < 0.05$.[a]

			Monoculture						Mixture					
Year	Vd	N_{trt}	HT_{max}	*a*	*b*	*a*/*b*	rmse[a]	$\sim r^2$	HT_{max}	*a*	*b*	*a*/*b*	rmse[a]	$\sim r^2$
	Plants m^{-1} of row	kg N ha^{-1}	cm			gdd			cm			gdd		
1999	2	0	185 b	4.17	0.0047	883 a	163	0.94	81 c	3.86	0.0058	666 a	341	0.71
	2	45	206 a	4.38	0.0052	837 a	148	0.97	119 ab	3.69	0.0059	616 b	866	0.70
	2	90	208 a	4.12	0.0049	846 a	347	0.93	136 a	4.42	0.0076	582 b	1446	0.67
	2	180	195 ab	4.45	0.0059	753 b	210	0.96	106 b	3.41	0.0058	593 b	539	0.74
	10	0	145 b	4.84	0.0063	765 a	63	0.97	100 ab	3.48	0.0047	739 a	300	0.78
	10	45	162 ab	3.87	0.0052	739 a	324	0.91	105 ab	3.26	0.0054	603 b	583	0.71
	10	90	156 ab	4.04	0.0059	682 a	353	0.91	91 b	3.24	0.0062	526 b	298	0.80
	10	180	169 a	4.04	0.0058	698 a	301	0.93	123 a	3.57	0.0056	633 ab	675	0.74
2000	2	0	189 b	5.32	0.0072	743 b	135	0.97	125 b	4.61	0.0074	627 a	336	0.88
	2	60	209 a	5.51	0.0066	837 a	446	0.91	167 a	4.36	0.0063	688 a	445	0.89
	2	120	198 ab	4.79	0.0066	726 b	282	0.95	158 a	4.66	0.0073	635 a	634	0.85
	2	240	210 a	5.18	0.0069	747 b	336	0.95	175 a	4.31	0.0065	664 a	678	0.87
	10	0	161 b	4.95	0.0068	725 a	517	0.88	90 b	3.94	0.0069	574 a	182	0.87
	10	60	166 b	5.51	0.0082	671 a	267	0.94	91 b	3.98	0.0070	571 a	205	0.85
	10	120	199 a	4.40	0.0062	706 a	219	0.96	91 b	4.51	0.0085	528 a	256	0.84
	10	240	195 a	4.41	0.0059	746 a	478	0.91	102 a	3.96	0.0068	580 a	179	0.89

[a] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

approximately 0.5 km from the experimental fields (Table 1). Thermal units (gdd) accumulated from corn emergence were calculated using gdd = $\Sigma\min([\{T_{max} + T_{min}\}/2] - T_b, 20)$, where T_{max} and T_{min} are maximum and minimum daily air temperatures and T_b is the base temperature for development (10 C was used for both corn and velvetleaf).

Models, Calculations and Assumptions

Corn and velvetleaf growth in canopy height (HT), leaf area index (LAI), and biomass per unit area as a function of thermal time (gdd) were determined for each species within each EU. Leaf area index was determined from leaf area of harvested plants and plant density. To quantify growth over time as influenced by N application and mixture treatment, data were regressed on thermal units (gdd) accumulated from emergence using the Richard's function (Hunt 1982):

$$Y = \frac{Y_{max}}{1 + \exp(a - b\,gdd)^{1/c}} \qquad [1]$$

where Y_{max} represents maximum HT, LAI, or biomass and *a*, *b*, and *c* are shape coefficients. The combination $b/(c + 1)$ represents a weighted mean relative growth rate and $Y_{max}b/(2[c + 2])$ is a weighted mean absolute growth rate over the entire growth period (Hunt 1982). Note that when $c = 1$, Equation 1 simplifies to the logistic function, which is symmetric around the inflection point. The ratio a/b defines the thermal time at which the inflection point occurs (when $c = 1$), which is also the thermal time from emergence when maximum absolute growth rate occurs. Some caution is needed when interpreting this ratio because its value also is highly correlated with Y_{max} (i.e., taller plants will reach a/b later). Only LAI from emergence to the beginning of senescence were used in the analysis of LAI. Corn yield loss in mixture treatments was calculated as $100(1 - [\text{weedy yield/mean weed-free yield}])$.

Statistical Analysis

To evaluate the effects of nitrogen supply and mixture treatment on height, LAI, and biomass growth, Equation 1 was fitted to these data for each experimental unit using PROC NLIN (SAS 1990). Preliminary analyses indicated that the *c* parameter in Equation 1 did not differ from 1 in the majority of these regressions, so the simpler logistic function was used for all analyses discussed hereafter. Parameter estimates obtained for each EU were then subjected to ANOVA to determine treatment effects. Within a treatment, or where treatments did not differ, data were pooled and Equation 1 was fit to the pooled data. Approximate r^2 values were calculated as 1 − (residual sums of squares/corrected total sums of squares). The effect of N application and velvetleaf density treatment on corn grain yield was tested using ANOVA. ANOVA was conducted using the PROC MIXED procedure in SAS[2] (Littell et al. 1996) to compute least-squares means, standard errors, and the difference between least-squared means using an LSD-like, pair-wise *t* test to test for treatment differences at the $\alpha = 0.05$ level.

TABLE 4. Corn maximum leaf area index (LAI_{max}) and thermal time of maximum absolute growth rate of LAI (a/b from Equation 1 fitted to LAI on growing degree days [gdd]) as influenced by nitrogen (N) supply and mixture treatments in 1999 and 2000. Within columns, years and velvetleaf density treatment means followed by different letters are different at $P < 0.05$.[a,b]

Year	Velvetleaf density	N_{trt}	LAI_{max}	a	b	a/b	rmse	$\sim r^2$
		kg N ha^{-1}	m^2 m^{-2}			gdd		
1999		0	2.43 d	6.25	0.0141	443 a	0.13	0.89
		45	2.85 c	7.16	0.0177	405 b	0.15	0.91
		90	3.23 b	6.51	0.0158	412 b	0.15	0.93
		180	3.68 a	6.41	0.0154	416 b	0.15	0.94
	0		3.85 b	6.78	0.0147	461 a	0.07	0.98
	2		3.94 a	6.64	0.0141	471 a	0.08	0.97
	10		3.83 b	6.94	0.0146	475 a	0.09	0.97
2000		0	3.64 c	6.33	0.0137	462 a	0.082	0.97
		60	3.84 bc	6.90	0.0149	463 a	0.051	0.98
		120	3.94 ab	6.98	0.0148	472 a	0.067	0.98
		240	4.07 a	6.93	0.0145	478 a	0.085	0.97

[a] Corn height was affected by N application treatment in both years and by velvetleaf density treatment in 1999. There was no interaction between N application and velvetleaf density in either year.

[b] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

Results and Discussion

Rainfall and Thermal Units

Soil temperature at planting was 16 C in 1999 and 20 C in 2000 at ARDC. Soil temperature at planting was unavailable for NEREC in 1999 and 18 C in 2000. Monthly average daily air temperature was generally cooler at ARDC in 1999, except in June, which was 1 C warmer than the 30-yr average (Table 1). Monthly average temperatures at NEREC were 0.8 C and 0.2 C cooler than the normal during the 1999 and 2000 growing seasons, respectively. May and June 1999 were wetter than the 30-yr average at both ARDC and NEREC. However, July, August, and September 1999 monthly precipitation averages were 17 mm and 50 mm below the normal at ARDC and NEREC, respectively. May 2000 was dryer than the average at both ARDC and NEREC, but timely precipitation and irrigation resulted in above-average water deposition for the remainder of the season at both locations (Table 1).

Canopy Height

Equation 1 explained at least 96% of the variance in corn height in relation to thermal time from emergence (Table 2). Corn generally reached a greater height (HT_{max}) and had greater season-long, relative-height growth rate ($b/2$) in 2000 than in 1999. Corn height growth was affected by N addition but not velvetleaf density treatment in 1999. Both N addition and velvetleaf density treatments, but not their interaction, affected corn height growth in 2000. Addition of nitrogen generally increased corn height in both years and resulted in an earlier time of maximum height growth rate in 1999.

Corn reached a maximum height of 257 cm in the 180 N application treatment in 1999 and 290 cm in the equivalent treatment in 2000. Corn HT_{max} was reduced by 13 and 3% in the 0 N compared with the highest N treatment in 1999 and 2000, respectively (Table 2). Thermal time of maximum corn height growth rate (a/b) was an average of 10% greater (54 gdd, or approximately 3 d later) in the zero N treatment compared with other N treatments in 1999, whereas no differences in time of maximum height growth rate occurred across any N treatments in 2000. Competition from velvetleaf at 2 plants m^{-1} row increased corn HT_{max} by 2%, and a/b occurred 9 gdd later compared with corn monoculture in 2000.

Equation 1 explained at least 67% of the variance in velvetleaf height in relation to thermal time from emergence (Table 3). As expected given its greater genetic diversity and phenotypic plasticity, velvetleaf height growth is more variable than that of corn, especially when grown in competition with corn. Nitrogen addition, velvetleaf density, crop presence or absence, and their interactions all affected velvetleaf height growth in both years.

Corn presence had the strongest negative effect on velvetleaf height growth, reducing estimated velvetleaf HT_{max} by 40 and 35% (from 180 and 190 cm) across all other treatments in 1999 and 2000, respectively. Velvetleaf reached an HT_{max} that was 15 and 24% shorter in the 10 compared with the 2 plants m^{-1} row density treatments in 1999 and 2000, respectively. Because the velvetleaf was taller, thermal time of maximum-height growth rate was 9 (67 gdd) and 8% (60 gdd) later in the 2 compared with the 10 plants m^{-1} row treatment. Velvetleaf HT_{max} was 19 and 16% smaller in the 0 compared with all other N treatments in 1999 and 2000, respectively (main effect results not shown).

Estimated velvetleaf maximum height (HT_{max}) in monoculture at 2 plants m^{-1} row reached 208 and 210 cm in 1999 and 2000, respectively, and was reduced (by 11 and 10%) only in the 0 N treatment in both years (Table 3). Thermal time of maximum velvetleaf height growth rate occurred 15% earlier (130 gdd, or about 7 d) in the 180 N compared with the 0 N treatment in 1999. Although the estimated maximum velvetleaf height in the 60-kg N ha^{-1} treatment reached 209 cm in 2000, time of maximum-height growth rate in that treatment occurred 100 gdd (ca. 5 d) later, indicating that overall height growth was delayed at low N. Monoculture-grown velvetleaf at 10 plants m^{-1} of row grew 14 and 17% taller

TABLE 5. Velvetleaf maximum leaf area index (LAI_{max}) and thermal time of maximum absolute growth rate of LAI (*a*/*b* from Equation 1 fitted to LAI on growing degree days [gdd]) as influenced by nitrogen (N) supply and mixture treatments in 1999 and 2000. Within columns, years and velvetleaf density treatment (Vd) means followed by different letters are different at $P < 0.05$.[a]

			Monoculture						Mixture					
Year	Vd	Ntrt	LAI_{max}	*a*	*b*	*a*/*b*	rmse	$\sim r^2$	LAI_{max}	*a*	*b*	*a*/*b*	rmse	$\sim r^2$
	Plants m^{-1} of row	kg N ha^{-1}	m^2 m^{-2}			gdd			m^2 m^{-2}			gdd		
1999	2	0	1.43 b	149	0.1942	768 a	0.243	0.53	0.08 b	159	0.3457	460 b	0.011	0.12
	2	45	3.02 a	7.77	0.0103	754 a	0.093	0.92	0.17 b	4.22	0.0085	495 b	0.010	0.32
	2	90	2.39 a	6.94	0.0102	680 ab	0.573	0.58	0.18 b	7.93	0.0185	429 b	0.007	0.47
	2	180	2.58 a	7.81	0.0127	615 b	0.145	0.88	0.77 a	3.98	0.0035	1154 a	0.690	0.45
	10	0	2.35 b	6.94	0.0080	846 a	0.129	0.74	0.31 c	5.27	0.0115	458 ab	0.022	0.44
	10	45	3.59 a	23.8	0.0400	598 b	0.374	0.87	0.45 b	5.43	0.0137	396 b	0.037	0.50
	10	90	2.62 b	6.27	0.0079	796 a	0.126	0.84	0.49 b	9.23	0.0242	381 b	0.031	0.61
	10	180	3.67 a	7.58	0.0123	616 b	0.315	0.87	0.97 a	4.72	0.0084	563 a	0.059	0.70
2000	2	0	2.40 b	8.82	0.0128	689 a	0.250	0.77	0.16 d	5.46	0.0091	602 b	0.003	0.57
	2	60	2.04 b	7.96	0.0105	758 a	0.223	0.63	0.72 a	4.61	0.0045	1015 a	0.002	0.80
	2	120	2.68 b	10.7	0.0160	675 a	0.228	0.84	0.26 c	8.16	0.0155	526 b	0.003	0.80
	2	240	3.73 a	12.4	0.0178	697 a	0.489	0.82	0.37 b	6.38	0.0109	585 b	0.012	0.65
	10	0	4.12 b	5.91	0.0079	749 b	0.389	0.81	0.54 c	4.35	0.0074	590 b	0.017	0.68
	10	60	3.47 b	6.37	0.0097	657 b	0.276	0.85	0.56 c	8.14	0.0153	532 b	0.028	0.67
	10	120	3.23 b	6.54	0.0111	589 b	0.164	0.91	0.76 b	5.46	0.0096	566 b	0.019	0.82
	10	240	8.38 a	5.32	0.0063	850 a	0.730	0.85	1.43 a	4.75	0.0064	746 a	0.067	0.72

[a] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

in the higher N treatments in 1999 and 2000, respectively.

Estimated velvetleaf maximum height (HT_{max}) in mixture at 2 plants m^{-1} row reached 136 and 175 cm in 1999 and 2000, respectively, and was reduced (by 24 and 29%) in the 0 N treatment (Table 3). Thermal time of maximum velvetleaf height growth rate occurred 12% later (73 gdd, or about 4 d) in the 0 N compared with the N addition treatments in 1999. Mixture-grown velvetleaf at 10 plants m^{-1} of row grew 19 and 12% taller in the higher N treatments in 1999 and 2000, respectively.

Results show that competition from corn strongly reduces velvetleaf height, but velvetleaf only reduced corn height by up to 2%. Velvetleaf intraspecific competition also slowed velvetleaf height development and reduced maximum height. Nitrogen addition had a positive effect on both corn and velvetleaf height growth. The effect was similar among species in monoculture, but velvetleaf in mixture with corn was more affected by N addition than corn or velvetleaf growing alone.

Canopy Leaf Area Index

Equation 1 explained at least 89% of the variance in corn LAI in relation to thermal time from emergence (Table 4). Corn generally reached a greater LAI (LAI_{max}) in 2000 than in 1999. Corn LAI was affected by N addition and velvetleaf density treatments, but not their interaction, in 1999, but only by N addition in 2000. Addition of nitrogen generally increased corn LAI and resulted in an earlier time of maximum leaf area growth rate.

Corn reached a maximum LAI of 3.68 in the 180 N treatment in 1999 and 4.07 in the equivalent treatment in 2000. Estimated corn LAI_{max} was reduced by 34 and 11% in the 0 compared with the highest N treatment in 1999 and 2000, respectively (Table 4). Thermal time of maximum corn LAI growth rate (*a*/*b*) was 6% greater in the 0 N treatment compared with other N treatments in 1999, whereas no differences in *a*/*b* occurred across N treatments in 2000. Competition from velvetleaf at 2 plants m^{-1} of row increased corn LAI_{max} by 2% compared with weed-free corn or corn in mixture with velvetleaf at 10 plants m^{-1} of row in 1999, but no effect of weed density was observed in 2000.

Equation 1 explained an average of 79 and 58% of the variation in LAI of velvetleaf grown in monoculture and mixture, respectively (Table 5). As with height growth, velvetleaf LAI is more variable than that of corn, especially in mixture. Nitrogen addition, velvetleaf density, crop presence or absence, and their interactions all affected velvetleaf LAI in both years.

Corn presence had the strongest negative effect on velvetleaf LAI growth, reducing estimated velvetleaf LAI_{max} by 87% (from 2.67 and 4.09 m^2 m^{-2}) across all other treatments in both 1999 and 2000. Velvetleaf reached an LAI_{max} that was 30 and 96% greater in the 10 compared with the 2 plants m^{-1} of row density treatments in 1999 and 2000, respectively. Although velvetleaf LAI was greater in the 10 plants m^{-1} row treatment, thermal time of maximum LAI growth rate was 11% (79 gdd) earlier in 1999 and 8% (53 gdd) later in 2000 (Table 5). Velvetleaf LAI_{max} was 53 and 44% smaller in the 0 compared with

TABLE 6. Corn maximum aboveground biomass ($Bio_{\max}$) and thermal time of maximum absolute growth rate of biomass (a/b from Equation 1 fitted to biomass on growing degree days [gdd]) as influenced by nitrogen (N) supply and mixture treatments in 1999 and 2000. Within columns, years and velvetleaf density treatment means followed by different letters are different at $P < 0.05$.[a]

Year[b]	Velvetleaf density	N_{trt}	$Bio_{\max}$	a	b	a/b	rmse	$\sim r^2$
		kg N ha^{-1}	g m^{-2}			gdd		
1999		0	883 c	4.57	0.0060	762 a	14,302	0.87
		45	1,199 b	4.17	0.0054	772 a	31,343	0.85
		90	1,248 b	4.63	0.0065	712 b	26,120	0.90
		180	1,487 a	4.49	0.0060	748 a	22,060	0.93
	0		1,369 a	4.43	0.0058	764 a	50,147	0.86
	2		1,115 b	4.61	0.0064	720 b	46,769	0.83
	10		1,139 b	4.29	0.0056	766 a	41,666	0.84
2000		0	1,843 c	4.94	.0058	858 a	12,116	0.97
		60	1,991 b	4.76	.0054	881 a	8,303	0.98
		120	2,023 b	4.94	.0056	876 a	15,355	0.96
		240	2,169 a	4.76	.0053	898 a	9,046	0.98

[a] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

[b] Corn height was affected by N application treatment in both years and by velvetleaf density treatment in 1999. There was no interaction between N application and velvetleaf density in either year.

high N treatments in 1999 and 2000, respectively (main effect results not shown).

Estimated maximum velvetleaf LAI ($\mathrm{LAI}_{\max}$) in monocultures at 2 plants m^{-1} of row reached 3.02 and 3.73 in 1999 and 2000, respectively, and was reduced by 46 and 36% in the 0 N compared with high N treatments (Table 5). This reduction was 90 and 57% in the presence of corn. Velvetleaf $\mathrm{LAI}_{\max}$ in monoculture was reduced only in the 0 N treatment in 1999 but was greater only in the 240 N treatment in 2000. N addition had a greater relative affect on velvetleaf $\mathrm{LAI}_{\max}$ in mixture. Thermal time of maximum velvetleaf LAI growth rate occurred 20 and 27% earlier in the highest N compared with the 0 N treatments in 1999 and 2000, respectively. Monoculture-grown velvetleaf at 10 plants m^{-1} of row grew 36 and 55% less LAI in the 0 N compared with high N treatments in 1999 and 2000, whereas this difference was 68 and 62% in mixture.

The greater reduction in velvetleaf $\mathrm{LAI}_{\max}$ grown in mixture indicates that competition from corn has more influence on velvetleaf leaf area growth than intraspecific competition with velvetleaf. The greater reduction in velvetleaf $\mathrm{LAI}_{\max}$ at low N compared with corn indicates that N influences velvetleaf leaf area to a greater degree than it does to corn. Radin (1983) found that leaf area growth of dicotyledonous plants was inhibited to a greater degree than C_4 cereal grains when nitrogen supply was limited. This increases the advantage in light competition for corn compared with velvetleaf at lower levels of N. The greater influence of N on velvetleaf LAI compared with corn may be associated with its pattern of leaf senescence or differences among species in N use efficiency (Hikosaka 2005). Velvetleaf plants in the greater N application treatments may be able to support more leaves for longer periods of time before senescence occurs.

Biomass

Equation 1 explained at least 83% of the variance in corn aboveground biomass in relation to thermal time from emergence (Table 6). Corn generally achieved greater biomass in 2000 than 1999. Corn biomass was affected by N addition and velvetleaf density treatment in 1999 but only N addition in 2000. Competition from velvetleaf reduced maximum corn biomass ($Bio_{\max}$) in 1999. Nitrogen addition generally increased corn biomass in both years.

Corn reached a maximum biomass of 1,487 g m^{-2} in the 180 N treatment in 1999 and 2,169 g m^{-2} in the equivalent treatment in 2000. Corn $Bio_{\max}$ was reduced by 41 and 15% in the 0 N compared with the highest N treatment in 1999 and 2000, respectively (Table 6). Competition from velvetleaf reduced corn $Bio_{\max}$ by 17%, regardless of density, in 1999.

Equation 1 explained an average of 76 and 50% of the variation in biomass of velvetleaf grown in monoculture and mixture, respectively (Table 6). As with height and LAI growth, velvetleaf aboveground biomass is more variable than that of corn, especially in mixture. Nitrogen addition, velvetleaf density, crop presence or absence, and their interactions all affected velvetleaf biomass accumulation in both years.

Corn presence had the strongest negative effect on velvetleaf aboveground biomass, reducing estimated velvetleaf $Bio_{\max}$ by 90 and 87% (from 738 and 816 g m^{-2}) across all other treatments in 1999 and 2000, respectively. Velvetleaf reached a $Bio_{\max}$ that was 50 and 98% greater in the 10 compared with the 2 plants m^{-1} of row density treatments in 1999 and 2000, respectively. Although velvetleaf biomass was greater in the 10 plants m^{-1} of row treatment, thermal time of maximum biomass growth rate was 12% (128 gdd) earlier in 1999 and 7% (66 gdd) later in 2000 (Table 7). Velvetleaf $Bio_{\max}$ was 57 and 34% smaller in the 0 compared with the highest N treatments in 1999 and 2000, respectively (main effect results not shown).

Estimated maximum velvetleaf biomass ($Bio_{\max}$) in monoculture at 2 plants m^{-1} of row reached 2,053 and 1,539 in 1999 and 2000, respectively. The extremely large number in 1999 was offset by a long delayed time of maximum growth rate (a/b) so that predicted biomass at

TABLE 7. Velvetleaf maximum aboveground biomass (Bio_{max}) and thermal time of maximum absolute growth rate of biomass (a/b from Equation 1 fitted to biomass on growing degree days [gdd]) as influenced by nitrogen (N) supply and mixture treatments in 1999 and 2000. Within columns, years and velvetleaf density treatment (Vd) means followed by different letters are different at $P < 0.05$.[a]

			Monoculture						Mixture					
Year	Vd	N_{trt}	Bio_{max}	a	b	a/b	rmse	$\sim r^2$	Bio_{max}	a	b	a/b	rmse	$\sim r^2$
	Plants m^{-1} of row	kg N ha^{-1}	g m^{-2}			gdd			g m^{-2}			gdd		
1999	2	0	2,053 a	6.72	0.00405	1,667 a	3,457	0.78	14.5 c	10.94	0.0122	893 b	58	0.30
	2	45	595 c	8.54	0.0084	1,019 b	8,464	0.83	41.9 b	3.98	0.0044	905 b	362	0.32
	2	90	590 c	7.03	0.0069	1,026 b	10,285	0.78	44.5 b	5.28	0.0072	738 c	370	0.44
	2	180	707 b	6.19	0.0060	1,026 b	7,195	0.85	128 a	5.11	0.0036	1,408 a	256	0.52
	10	0	660 c	6.94	0.0070	964 b	4,722	0.88	86.6 b	4.52	0.0049	922 b	546	0.55
	10	45	740 bc	5.73	0.0064	902 b	23,125	0.75	106 b	4.07	0.0054	748 c	1,803	0.45
	10	90	843 b	5.37	0.0064	840 b	28,930	0.77	99.1 b	7.92	0.0119	666 c	3,217	0.35
	10	180	1,539 a	4.75	0.0042	1,419 a	35,528	0.76	451 a	4.44	0.0033	1,341 a	3,516	0.57
2000	2	0	512 b	7.60	0.0085	898 a	6,565	0.84	23.6 c	5.58	0.0071	791 c	85	0.48
	2	60	478 b	12.8	0.0139	921 a	10,188	0.73	43.6 b	8.02	0.0095	845 bc	99	0.70
	2	120	526 b	7.01	0.0819	856 a	6,688	0.84	60.2 b	7.09	0.0081	880 b	398	0.50
	2	240	694 a	7.82	0.0087	898 a	9,824	0.87	92.1 a	6.68	0.0066	1,020 a	1,043	0.50
	10	0	911 b	5.53	0.0056	986 a	23,685	0.77	70.1 c	4.64	0.0057	817 b	586	0.51
	10	60	867 b	6.17	0.0068	903 a	11,815	0.87	308 a	4.73	0.0033	1,425 a	113	0.95
	10	120	1,398 a	5.86	0.0057	1,026 a	18,913	0.87	90.7 c	4.53	0.0057	792 b	2,636	0.30
	10	240	1,279 a	6.56	0.0068	962 a	16,171	0.92	145 b	4.78	0.0054	882 b	1,555	0.60

[a] Abbreviations: N_{trt}, N treatment; rmse, residual mean square error.

the time of corn maturity (1,445 gdd from emergence) was 568 g m^{-2}, which is lower than any other estimated Bio_{max}. Using 568 g m^{-2} as the estimated final biomass for the 0 N treatment, Bio_{max} was reduced by 20 and 26% in the 0 N compared with high N treatments (Table 7). This reduction was 88 and 74% in the presence of corn. Monoculture grown velvetleaf at 10 plants m^{-1} of row grew 57 and 29% less biomass in the 0 N compared with high N treatments in 1999 and 2000, whereas this difference was 81 and 52% in mixture.

Warmer growing conditions at planting in 2000 allowed for an earlier and more even plant emergence, which usually leads to increases in corn biomass production (Graven and Carter 1991). Experiments were irrigated in 2000, but not in 1999, and irrigation is known to cause an increase in total corn biomass production compared with nonirrigated conditions (Wienhold et. al. 1995). The difference in final corn biomass was smaller between N treatments in 2000. Nitrogen was likely more available in 2000 because of increases in soil mineralization due to the greater soil moisture and because nitrogen is a mobile nutrient and its availability is influenced by soil water content (Barber and Cushman 1981).

Total aboveground biomass of monoculture-grown velvetleaf increased with increasing nitrogen application. Measured corn biomass in the zero N treatment at maturity was 56 to 96% of that in the highest N levels, whereas measured velvetleaf biomass in the zero N treatment was only 41 to 53% that in the highest N treatment (data not shown). The decrease in total velvetleaf plant biomass in 0 compared with high N levels was greater in mixture than in monoculture in both years. Therefore, nitrogen has a greater influence on velvetleaf biomass production than it has on corn, especially in mixture.

Corn Yield and Yield Loss

Corn yield was lower at NEREC than ARDC in both years (Table 8), so locations were not combined for analysis. Differences between locations are most likely due to environmental and management differences. Based on average weather data, growing season length is expected to be 100 gdd shorter at NEREC than ARDC. Actual growing season was shorter at NEREC in 1999 but not in 2000. The lower corn population density at NEREC may have contributed to the lower yields at that site. Corn yield at both locations was lower in 1999 than 2000. Both locations experienced dryer conditions during July and August 1999. Water stress during anthesis and grain fill is known to cause early senescence (Claassen and Shaw 1970a; Jurgens et al. 1978) and reduced yields (Claussen and Shaw 1970b; Denmead and Shaw 1960; Downey 1971).

Over the past 40 to 50 yr, increases in corn yield have been closely associated with increases in the amounts of applied nitrogen (Sinclair and Muchow 1995). Monoculture corn yield increased with increasing N supply in all site–years (Table 8). However, the effect of competition from velvetleaf at low (2 plants m^{-1}) and high densities (10 plants m^{-1}) varied with nitrogen application treatment. With the exception of the 45 and 60 N treatments in 1999 and 2000 at ARDC, yield generally decreased as weed density increased (Table 8). Mean yields were ac-

TABLE 8. Mean corn grain yield and yield loss as influenced by nitrogen (N) and velvetleaf density treatments at Agricultural Research and Development Center (ARDC) near Mead, NE, and the Northeast Research and Extension Center (NEREC) near Concord, NE, in 1999 and 2000. Within locations and years, means followed by different letters are different at $P < 0.05$ (letters in parentheses signify differences among velvetleaf density treatments). An asterisk indicates that yield loss differs among density treatments within an N treatment at $P < 0.05$.

Location	Year	N treatment	Corn yield (kg ha^{-1})			Yield loss[a] (%)	
			Velvetleaf density (plants m^{-1} of row)			Velvetleaf density (plants m^{-1} row)	
		kg ha^{-1}	0	2	10	2	10
ARDC	1999	0	7,807 c(a)	7,822 b(a)	6,592 c(a)	−1.9 b	15.6 b*
		45	8,429 b(a)	10,016 a(a)	8,618 b(a)	−18.8 c	−2.2 c*
		90	12,035 a(a)	10,563 a(a)	8,561 b(b)	12.2 a	28.9 a*
		180	11,786 a(a)	11,308 a(a)	10,987 a(a)	4.1 b	6.8 b*
	2000	0	13,336 b(a)	12,586 a(ab)	11,507 a(b)	5.6 a	13.7 a
		60	12,934 b(a)	13,116 a(a)	13,899 a(a)	−1.4 b	−7.5 b
		120	14,450 a(a)	13,573 a(a)	13,312 a(a)	6.1 a	7.9 a
		240	14,080 a(a)	12,975 a(ab)	12,254 a(b)	7.9 a	13.0 a
NEREC	1999	0	6,566 b(a)	6,184 a(a)	6,175 a(a)	5.8 b	6.0 b
		45	7,180 ab(a)	6,895 a(a)	5,160 b(b)	4.0 b	28.1 a*
		90	7,685 a(a)	6,797 a(ab)	6,004 ab(b)	11.6 a	21.9 a*
		180	7,254 ab(a)	7,013 a(ab)	6,232 a(b)	3.3 b	14.1 b*
	2000	0	9,061 b(a)	6,962 a(b)	6,548 a(b)	23.2 b	27.7 b*
		60	9,687 ab(a)	8,087 a(b)	6,198 a(c)	16.5 b	36.0 b*
		120	10,169 ab(a)	7,587 a(b)	6,449 a(b)	25.4 ab	36.6 ab*
		240	10,599 a(a)	7,126 a(b)	6,181 a(b)	32.8 a	41.7 a*

[a] Corn yield loss was calculated as 100(1 − [weedy yield/mean weed-free yield]).

tually larger for corn grown with velvetleaf than for corn grown in monoculture in the 45 and 60 N application treatments. These results imply that low levels of nitrogen addition may have a slight negative impact on corn yield in monoculture, though it is not clear why. Similar trends in yield were not observed at NEREC, indicating that environmental factors may play a role in these interactions.

Corn yield loss was greater at NEREC than ARDC in both years (Table 8). Velvetleaf emergence at NEREC in 2000 was only 11 gdd (1 d) behind that of corn, the shortest thermal time difference in corn and velvetleaf emergence. Thinning of weeds at NEREC was done after initial thinning at ARDC was completed, and initial weed populations at NEREC in both years were higher than that of ARDC. Although detailed biomass measurements were only taken at ARDC, velvetleaf was generally observed to be taller and leafier at NEREC in both years. Earlier weed emergence, delay of thinning, and lower corn population may have led to increased growth and competition from velvetleaf at earlier stages of corn development, which may have contributed to the greater yield loss at NEREC.

Nitrogen addition and velvetleaf density, but not their interaction, affected yield loss at ARDC in 1999, but only N treatment affected yield loss in 2000. Nitrogen and velvetleaf density treatments affected yield loss at NEREC in both years, and their interaction was significant in 2000. Corn yield loss increased with increasing velvetleaf density at ARDC in 1999. Corn yield loss was smallest in the 45 and 60 N treatments at ARDC in 1999 and 2000, respectively. Corn yield loss at NEREC was greatest in the 90 N treatment in the low velvetleaf density mixtures in 1999. However, in the 10 velvetleaf plants m^{-1} of row treatment, yield loss was lowest in the zero N treatment, greatest in the 45 N treatment, and declined with further increases of N in 1999. Corn yield loss increased with increasing N application at NEREC in 2000 (Table 8).

Velvetleaf height, LAI, and biomass accumulation responded more to N addition than corn, supporting our initial hypothesis. However, corn yield loss due to velvetleaf competition did not consistently increase with increasing N addition. The stronger competitive effects of corn on velvetleaf at ARDC diluted the N response of velvetleaf and its subsequent effect on corn yield loss. However, corn and velvetleaf emergence dates were similar and weed pressure was greater at NEREC than at ARDC. Therefore, corn did not have as great a competitive effect on velvetleaf at NEREC compared with ARDC, and the N response of velvetleaf gave it more of a competitive advantage at this location. Results of this research indicate that when velvetleaf emerges with the crop, its competitive effects on corn yield may increase with increasing N supply and as corn population density decreases. To minimize the positive effects of N application on velvetleaf growth and competitiveness, the management implications from this study suggest planting corn at the greatest density appropriate for a given environment and ensuring that velvetleaf emerges at least 2 d after corn emergence.

Sources of Materials

[1] LI-3000 area meter, LiCor, 4421 Superior Street, Lincoln, NE 68504-0425.

[2] SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414.

Acknowledgments

A contribution of the University of Nebraska Agricultural Research Division, Lincoln, NE. Journal Series No. 14671. This research was supported in part by funds provided by the Hatch Act and by the State of Nebraska.

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Received September 9, 2005, and approved December 12, 2005.