Nitrogen source influences wild mustard growth and competitive effect on sweet corn

Author(s): Adam S. Davis and Matt Liebman
Source: Weed Science, 49(4):558-566.
Published By: Weed Science Society of America
https://doi.org/10.1614/0043-1745(2001)049[0558:NSIWMG]2.0.CO;2
URL: http://www.bioone.org/doi/full/10.1614/0043-1745%282001%29049%5B0558%3ANSIWMG%5D2.0.CO%3B2

Weed Science, 49:558–566. 2001

Nitrogen source influences wild mustard growth and competitive effect on sweet corn

Adam S. Davis
Corresponding author. Department of Plant, Soil, and Environmental Sciences, University of Maine, Orono, ME 04469-5722. Present address: Department of Agronomy, Iowa State University, Ames, IA 50011-1010; asdavis@iastate.edu

Matt Liebman
Department of Plant, Soil, and Environmental Sciences, University of Maine, Orono, ME 04469-5722. Current address: Department of Agronomy, Iowa State University, Ames, IA 50011-1010

Manipulations of the soil environment can affect the growth and competitive ability of annual weeds because of the large influence that soil conditions exert on seedlings early in the growing season. Our objective was to identify soil nitrogen (N) management systems with weed suppression potential. We hypothesized that competition from wild mustard against sweet corn would be weaker when N was supplied by organic sources (organic) or a split application of NH_4NO_3 fertilizer applied at planting and 4 wk thereafter (split) than when NH_4NO_3 fertilizer was applied in a single dose at planting (early). This hypothesis was tested in a 2-yr field experiment conducted in central Maine. Wild mustard's maximal relative growth rate (RGR) was 12% lower ($P < 0.05$) in 1997 and 1998, and the amount of time needed to achieve maximal RGR was delayed by 0.8 d ($P < 0.05$) in 1997 in the organic compared to the early treatment. The competitive effect of wild mustard on sweet corn yield was lower in the organic treatment than in the early and split treatments in 1 of 2 yr. In 1997, competition from wild mustard reduced marketable ear yields of sweet corn by 30%, but the magnitude of yield reduction did not differ between the three N addition treatments. In contrast, in 1998, sweet corn yield in the organic treatment was not reduced by weed competition, whereas yield loss in the early and split treatments was 20 and 35%, respectively. The mechanisms underlying selective suppression of weeds, but not crops, by organic N sources require further attention.

Nomenclature: Red clover, *Trifolium pratense* L., 'Mammoth'; spring wheat, *Triticum aestivum* L., 'Belvedere'; sweet corn, *Zea mays* L. 'Clockwork'; wild mustard, *Brassica kaber* (D.C.) L.C. Wheeler SINAR.

Key words: Allelopathy, compost, green manure, nutrient competition, phytotoxicity, soil organic amendments, weed competition.

In recent years, concerns over the environmental effects, economic costs, and long-term efficacy of conventional weed management systems have led a growing number of farmers and scientists to seek alternative systems that are less reliant on herbicides and more reliant on ecological processes. Research supporting the development of ecologically based weed management has been scarce over the past 50 yr (Benbrook 1996) but is now the highest scientific priority of farmers that do not use herbicides (Organic Farming Research Foundation 1998). One approach to improving weed management while reducing reliance on herbicide technology involves the integration of soil, crop, and weed management (Liebman and Davis 2000). Our overall objective in this study was to investigate whether variations in soil nitrogen (N) management could limit sweet corn yield reductions due to competition by wild mustard, a weed found commonly throughout the northern tier of states in the United States (Bridges and Anderson 1992).

Split application of N fertilizer may be a useful practice for managing weeds in sweet corn. Early-season soil N levels are kept intentionally low in a split application management system because sweet corn demand for N at this time is low, whereas the potential for loss of excess N from the system is high (Magdoff 1991). Several lines of research suggest that low early-season N levels could result in selective weed suppression (Liebman and Davis 2000). Small-seeded weeds are able to make up for their initial disadvantage in seedling size, compared to larger seeded crops because they are adapted for high relative growth rate (RGR) fueled by intensive nutrient uptake (Seibert and Pearce 1993). Grime (1977) suggested, however, that increased competitive ability conferred by a high maximal RGR (RGR_{max}) strategy comes at the cost of greater growth reductions in stressful environments. A study by Shipley and Keddy (1988) indicated that species with the highest RGR_{max} under optimal nutrient conditions suffered the largest declines in RGR_{max} under deficient nutrient conditions. This finding suggests that farming systems that minimize nutrient availability early in the growing season should limit the growth of small-seeded weeds without compromising the growth or yield of larger seeded, better provisioned crops. Previous studies of the effect of delayed nutrient availability on weed–crop competition have both corroborated (Alkämper et al. 1979; Angonin et al. 1996) and contradicted (Ball et al. 1996) this hypothesis.

Organic soil amendments, such as legume green manures, cover crops, animal manures, and composts, are fundamental components of low-external-input cropping systems that may also be valuable for weed management (Liebman and Davis 2000). Traditionally, one of the most common uses of organic soil amendments has been as a means of increasing soil fertility and improving soil physical characteristics (Pieters 1927). Organic amendments may also suppress weeds by releasing, during decomposition, phytotoxins such as phenolic compounds (Ohno et al. 2000) and short-chain fatty acids (Ozores-Hampton et al. 1999). These com-

TABLE 1. Summary of N source and timing of N fertilizer applications made to experimental plots in 1997 (rotation Cycle I) and 1998 (rotation Cycle II).[a]

N management treatment	Previous rotation crop[b]		NH_4NO_3 banded at planting		NH_4NO_3 banded at sweet corn V6 stage		N from red clover[c]		Supplemental N from compost[c]		Compost application rate[d]	
	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998
			kg N ha^{-1}								Mg ha^{-1}	
Control	W	W	0	0	0	0	0	0	0	0	0	0
Early	W	W	110	110	0	0	0	0	0	0	0	0
Organic	WC	WC	0	0	0	0	47	79	63	31	71	35
Split	W	W	20	20	90	90	0	0	0	0	0	0

[a] Red clover, *Trifolium pratense*; spring wheat, *Triticum aestivum*; sweet corn, *Zea mays*.
[b] Rotation crop abbreviations: W, wheat; WC, wheat + red clover.
[c] Availability of mineral N from red clover residues and compost during the first growing season after incorporation was assumed to be 70 and 20% of their total N content, respectively (Eghball and Power 1999; Fox and Piekielek 1988). See Table 2 for red clover biomass and total N content.
[d] Compost application rate was on a dry weight basis. Total N content of compost was 0.97% of dry weight in 1997 and 1.33% of dry weight in 1998.

pounds have been linked with allelopathic inhibition of weed growth (Liebman and Ohno 1998; Ohno et al. 2000) and increases in the pathogenicity of soil-borne diseases (Dabney et al. 1996; Toussoun and Patrick 1963). Dyck et al. (1995) found that the use of crimson clover (*Trifolium incarnatum* L.) green manure as an N source decreased common lambsquarters (*Chenopodium album* L.) biomass by 65% and increased sweet corn biomass by 131% compared to a treatment in which a similar amount of N was supplied in the form of NH_4NO_3 fertilizer applied at planting.

The work presented here examines weed competition within the context of varying N management systems to gain insight into how crop and soil factors might contribute to weed management. We assessed the effect of different N management systems on sweet corn yield loss due to wild mustard competition and used the functional approach to growth analysis (Hunt 1982) to derive crop and weed growth parameters from fitted curves to determine the effect of soil N management on crop and weed performance. Our specific objectives were to determine (1) whether delayed application of synthetic N fertilizer reduced weed competitive ability and (2) whether organic N sources reduced weed competitive ability compared to NH_4NO_3 fertilizer regardless of fertilizer application timing.

Materials and Methods

Field Procedures

Experimental work was conducted from 1996 to 1998 at the University of Maine Sustainable Agriculture Research Farm in Stillwater, ME (44°56′N, 68°42′W). Soil type was a Nicholville very fine sandy loam (coarse-silty, mixed, frigid, Aquic Haplorthods) (50% sand, 42% silt, and 8% clay) with 3.5% organic matter and pH 6.4. Two 2-yr rotation cycles were used, with Cycle I beginning in 1996 and Cycle II beginning in 1997. In year 1 of each rotation cycle, soft red spring wheat was grown either as the sole crop or as an intercrop with red clover. Wheat was drilled at 115 kg seeds ha^{-1} into rows spaced 17.5 cm apart, and red clover preinoculated with *Rhizobium* was broadcast with a hand-operated push-spreader at 17 kg seeds ha^{-1}. Red clover plants were left to overwinter within the wheat stubble after grain harvest. In year 2 of each rotation cycle, the wheat or wheat plus red clover residues from the previous year were incorporated into the soil and sweet corn was grown with or without wild mustard competition. Red clover spring regrowth was allowed to continue until 2 wk prior to the date of sweet corn planting. Two 0.125-m^2 quadrats were then sampled in each of the plots to assess above- and belowground biomass and N content. Plant tissue was dried, ground, and analyzed for total N content by Kjeldahl procedures. Following sampling, red clover and wheat residues plus supplemental compost broadcast on those plots that received N from organic sources (see below) were incorporated into the soil with a disk-harrow and power takeoff–driven rototiller. On June 16, 1997, and June 1, 1998, sweet corn was sown with a four-row planter at a density of 6 seeds m^{-2} (20.3-cm spacing within rows) with an 80-cm row spacing; plot size was 3.2 m wide by 8.3 m long. On these same dates, after sweet corn planting was completed, wild mustard was hand sown in rows offset 5 cm from sweet corn rows. Wild mustard was thinned once a week for the next 3 wk until a target density of 12 plants m^{-2} (10.1-cm spacing between plants within rows) was reached.

The experiment was conducted in a generalized randomized block design (Neter et al. 1996) with experimental units replicated three times within each of two blocks. The design consisted of a factorial of competition treatments, which determined whether sweet corn was weed-free or planted in mixture with wild mustard, with four N management treatments differing in timing of N fertilizer application and N source (Table 1). In two N management treatments, NH_4NO_3 fertilizer was used as an N source, following sole-cropped wheat. One of these, 'early', consisted of a single application of NH_4NO_3 fertilizer at the rate of 110 kg N ha^{-1} banded 7.5 cm from the sweet corn row at planting. The other, 'split', received a split application of NH_4NO_3, consisting of 20 kg N ha^{-1} banded at planting, with an additional 90 kg N ha^{-1} side-dressed at the sweet corn V6 stage of development (Hanway 1963). A third N management system, 'organic', followed a wheat plus red clover intercrop and relied on N mineralization from red clover residues (Table 2) and supplemental composted dairy manure to reach a predicted N fertilizer equivalency rate of 110 kg N ha^{-1}. The fourth N management treatment, 'control', did not receive synthetic N fertilizer, red clover residue, or compost, and followed sole-cropped wheat. Just prior to planting, P (in the form of triple superphosphate) and K (in the

TABLE 2. Wheat (*Triticum aestivum*) and red clover (*Trifolium pratense*) biomass and nitrogen content of rotation crops in field experiments in 1997 (rotation Cycle I) and 1998 (rotation Cycle II) in Stillwater, ME.[a]

	Wheat shoot residue		Red clover root + shoot residue		Red clover N content	
Rotation crop	1997	1998	1997	1998	1997	1998
	$\log_e$ kg ha^{-1}				$\log_e$ kg N ha^{-1}	
Wheat + red clover	7.60	7.14	7.30	8.01	4.23	4.74
	(2,001)	(1,770)	(1,494)	(3,079)	(72)	(115)
Wheat	7.54	7.35	1.57	0.68	0.33	0.15
	(1,936)	(1,384)	(65.8)	(7.4)	(0.29)	(0.28)
SE	0.12	0.11	0.14	0.12	0.1	0.1

[a] Analysis of variance was performed on $\log_e (x + 1)$-transformed values. Values in parentheses are means of raw data (kg ha^{-1}).

form of KCl) were applied at rates recommended by the University of Maine Soil Testing Service/Analytical Lab for sweet corn production.

Sampling Procedures

Aboveground biomass was determined over the course of the growing season through a combination of destructive harvests of shoot tissue and indirect estimations of shoot biomass. Shoot biomass per plant was recorded on a weekly basis for the first 4 (Cycle I) or 6 (Cycle II) wk after planting, followed by three midseason harvests at 2-wk intervals and a final harvest at crop maturity. Destructive sample areas were 1.5 m^2 for all harvest dates except the final harvest, for which the sample area was 4.3 m^2. Harvest subplots were separated by 1.5-m^2 buffer areas to prevent edge effects from the destructive sampling. Destructive harvests occurred within the same plots on weeks 1, 4, 8 (week 10 in Cycle II) and at crop maturity (week 12 in Cycles I and II); all other biomass measurements were nondestructive. Because of plot space limitations, shoot biomass was estimated nondestructively in time intervals between destructive harvests via allometric equations (Appendix) generated from data collected in additional replications of experimental plots interspersed randomly among plots from which we measured biomass and yield directly. The additional experimental plots were used for allometric purposes only and were not part of the experimental design. Thirty plants in 16 additional plots were measured for stem diameter and height and were harvested for determination of shoot dry mass. Stem diameter or height, or both, were regressed on shoot dry mass per plant using an adjusted R^2 criterion and inspection of residuals for model building (Neter et al. 1996). The R^2 values of allometric equations used to predict shoot biomass varied from 0.69 to 0.99. During the same time period, stem diameter and height were measured for plants in primary experimental plots, enabling prediction of shoot biomass. All measurements or indirect estimates of aboveground biomass included both vegetative and reproductive tissues.

Parameters measured during destructive harvests included soil NO_3-N and NH_4-N from 0 to 30 cm deep, sweet corn and wild mustard shoot biomass, stem diameter, height, and plant tissue N concentration. Fifteen soil cores per plot were taken from random locations and bulked to form a composite sample for each plot. A 5-g subsample was extracted for 1 h in 2 M KCl and analyzed for both NO_3-N and NH_4-N on an automated ion analyzer. Plant tissue was dried, ground, and analyzed for N content using Kjeldahl procedures. At crop maturity, marketable ear yield of sweet corn was measured as fresh mass of husked ears that were over 17.5 cm long from base to tip. Within replications of a N management treatment, percent yield loss was calculated as weed-free minus weedy marketable ear mass per hectare divided by weed-free marketable ear mass, multiplied by 100%.

Soil data for 1998 only are reported because of sampling bias in 1997 that excluded row areas where fertilizer was applied. Soil samples were collected in a fully randomized pattern in 1998, permitting unrestricted comparisons between banded and nonbanded N treatments (Mahler 1990).

Curve Fitting

The functional approach to growth analysis takes advantage of the statistical power conferred by the large number of data points used to develop plant growth curves (Hunt 1982). Furthermore, when growth parameters are derived from fitted curves and subjected to analysis of variance (ANOVA), the analysis tends to be more powerful than an analysis of raw data points because of the smaller standard errors associated with predicted values (Vernon and Allison 1963). The intensive biomass recording schedule described above allowed development of finely resolved plant growth curves. The growth curves comprised eight data points per replicate in Cycle I and 10 data points per replicate in Cycle II. Each data point represented the mean biomass of 90 sweet corn or wild mustard plants (15 plants per replicate times six replicates). All values were $\log_e$-transformed to maintain homogeneity of error variances throughout the growing season. Using the least squares curve-fitting subroutine of the KaleidaGraph® graphical software package,[1] followed by the NONLIN subroutine of SYSTAT v.5.2.1 (Wilkinson et al. 1992), two general classes of functions were fit to plant growth data for each replicate of the N management treatments. For growth curves that followed a sigmoidal pattern, including all sweet corn growth curves and those of wild mustard during Cycle I, the Gompertz exponential function (Hunt 1982) was used (Equation 1).

$$Y = \mathrm{a}e^{(-\mathrm{b}e^{(-\mathrm{k}T)})} \qquad [1]$$

For curves that followed a sigmoidal pattern until they reached their maximum and then declined, including wild

TABLE 3. Contrast statements (1 df) for a priori hypotheses of N source effects on sweet corn (*Zea mays*) and wild mustard (*Brassica kaber* SINAR) performance.

Hypothesis	Contrast: Sweet corn	Contrast: SINAR
N addition	(early + split + organic)/3 − control ≥ 0	(early + split ± organic)/3 − control ≥ 0
Delayed N	early − split ≤ 0	early − split ≥ 0
Amendment effect	early − organic ≤ 0	early − organic ≥ 0

mustard growth curves during Cycle II, a third-order polynomial function was used (Equation 2).

$$Y = a + bT + cT^2 + dT^3 \quad [2]$$

Y represents $\log_e$ biomass per plant; T represents time in days after planting (DAP); e represents the exponential constant 2.7471; and a, b, c, d, and k are parameters to be estimated. R^2 values of Gompertz fits varied from 0.98 to 0.99, and R^2 values of third-order polynomial fits varied from 0.97 to 0.99.

Three growth parameters were derived from fitted curves: (1) maximal shoot biomass per plant (W_{max}), (2) maximal relative growth rate (RGR_{max}), and (3) days after planting at which RGR_{max} occurred (T_{max}). To calculate W_{max}, the maxima of Equations 1 and 2 were determined. To obtain RGR_{max}, the first derivative of Equations 1 and 2 with respect to T was calculated to obtain, respectively,

$$Y' = RGR = abke^{(-kT - be^{(-kT)})} \quad [3]$$

$$Y' = RGR = b + 2cT + 3dT^2, \quad [4]$$

after which RGR_{max} was calculated as the maxima of Equations 3 and 4. Finally, to obtain T_{max}, Equations 3 and 4 were solved for T when Y' was set at the maximum.

Data Analysis

Biomass and N content of the wheat or wheat plus red clover rotation crops were analyzed by ANOVA to test for main effects (rotation cycle and rotation crop) and interactions using the MGLH subroutine of SYSTAT v.5.2.1 (Wilkinson et al. 1992). All other parameters were analyzed by ANOVA to test for main effects (rotation cycle, N management, wild mustard competition) and interactions, with further partitioning of the N management and competition by N management sums of squares into three one-sided contrasts (1 df) (Table 3). Contrasts were established a priori according to predictions made by the delayed nutrient availability hypothesis and results from field experiments with organic N sources by Dyck et al. (1995). The significance level for these analyses was set at $P < 0.05$. Significant rotation cycle by N management interactions led us to analyze sweet corn and wild mustard N uptake data separately for each rotation cycle. The modified Levene's test (Neter et al. 1996) was used to test growth analysis parameters and sweet corn yield data for homogeneity of error variances across rotation cycles. With the exception of wild mustard T_{max}, error variances for these data were constant, allowing them to be pooled across rotation Cycles I and II.

Maximal biomass, W_{max}, was derived from growth curves based on $\log_e$-transformed data; therefore, ANOVA was performed on $\log_e$-transformed data. Both $\log_e$-transformed ($\log_e$ kg ha^{-1}) and raw values for W_{max} are reported in tabular form, but raw values were used to calculate percentages reported in the Results and Discussion section.

At each date of indirect biomass estimation, allometric equations were subjected to analysis of covariance to determine if slope and intercept varied by N management treatment (Neter et al. 1996). When allometric relationships were not significantly different, data were pooled across N management treatments. Analysis of the residuals of directly measured and indirectly estimated data points for plant growth curves indicated that there was no difference in error variances between the two types of observations. All data points in plant growth curves were thus treated the same. Comparisons of derived growth analysis parameters used standard errors calculated from variation among replicates (Vernon and Allison 1963). In cases where a posteriori contrasts were necessary to clarify results, probability values reflected a Bonferroni adjustment for multiple comparisons (Neter et al. 1996).

Results and Discussion

N Sources

The primary objective of this study was to investigate the effect of N source on weed growth and competition with crops. Therefore it was important to compare the N-supplying capacity of the early, split, and organic N treatments with that of the zero-N control to determine if the N addition treatments resulted in greater inorganic N availability.

Both soil and plant N data suggest that mineral N availability was greater in the early, split, and organic treatments than in the control treatment. In Cycle II 9, 27, 57, and 70 DAP, soil inorganic N content was 69, 51, 43, and 13% lower, respectively, in control plots than in plots receiving some form of N fertilizer (Figure 1). Addition of N fertilizer, regardless of N source, increased sweet corn N content under weedy and weed-free conditions 59 DAP in Cycle I ($P < 0.05$) and 27 and 70 DAP in Cycle II ($P < 0.05$ and $P < 0.001$, respectively) (Table 4). Although there was not a statistically significant competition by N management interaction for sweet corn N content 59 DAP in Cycle I, it is apparent from examination of Table 4 that sweet corn N content was the same for the control, organic, and split treatments under weed-free conditions at this date. An a posteriori analysis revealed that the high sweet corn N content in the early/weed-free treatment 59 DAP in Cycle I accounted for the N addition main effect. Under weedy

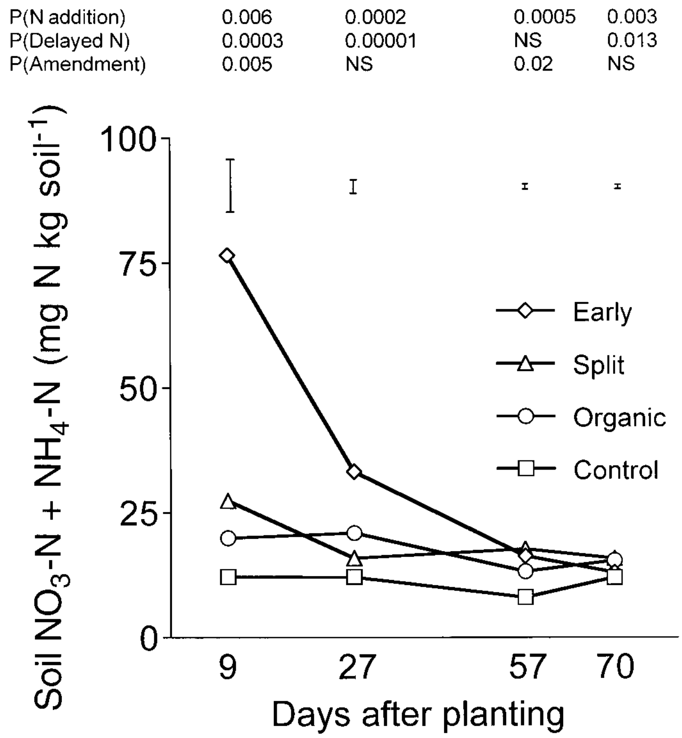

FIGURE 1. Soil total inorganic N to 30-cm deep averaged across competition treatments at four dates during Cycle II (1998). Plots in the control treatment received no N fertilizer. Plots in the early, split, and organic treatments received, respectively, 110 kg N ha^{-1} supplied from a single application of NH_4NO_3 fertilizer banded in the crop row at planting, a split application of 110 kg N ha^{-1} NH_4NO_3 fertilizer divided between planting and 4 wk thereafter, or soil-incorporated red clover residues supplemented with composted dairy manure to reach a predicted fertilizer equivalency value of 110 kg N ha^{-1}. P values represent the results of contrasts (1 df) at each of the four sampling dates. N addition = (early + split + organic)/3 − control, Delayed N = early − split. Amendment = early − organic. Error bars represent one standard error of the mean of six replicates.

conditions 59 DAP in Cycle I and under both weed-free and weedy conditions 27 and 70 DAP in Cycle II, sweet corn N content was greater for each of the N addition treatments than for the control treatment.

Wild mustard N content was not increased by N addition at any date in either rotation cycle (Table 5). High variability in wild mustard N content may have accounted for the lack of an 'N addition' effect. Another possibility is that

TABLE 5. Wild mustard (*Brassica kaber* SINAR) tissue N content as affected by N management and interference in field experiments in 1997 (rotation Cycle I) and 1998 (rotation Cycle II).

N management treatment	SINAR N content			
	1997		1998	
	27 DAP[a]	59 DAP	27 DAP	70 DAP
	kg N ha^{-1}			
Control	4.5	25	0.86	103
Early	5.2	37	0.83	92
Organic	3.1	36	0.78	88
Split	5.0	32	0.67	73
SE	0.75	4.6	0.14	15

[a] Abbreviation: DAP, days after planting.

addition of N fertilizer differentially affected N uptake capacity, promoting sweet corn N uptake more than wild mustard N uptake.

Alternative N Management Strategies

To assess the potential contribution that soil N management can make to integrated weed management systems, we examined crop and weed growth analysis parameters and tissue N under contrasting N management regimes. Tests of the 'delayed N' and 'amendment effect' hypotheses (Table 3) investigated the potential, respectively, for reduced wild mustard growth and competition with sweet corn in plots receiving the split or organic treatment compared to the early treatment.

Delayed application of synthetic N differentially affected the growth of sweet corn and wild mustard. Whereas sweet corn W_{max} was the same in the split and early treatments in Cycles I and II (Table 6), wild mustard W_{max} was 30% lower in the split treatment compared to the early treatment in Cycles I and II ($P < 0.05$) (Table 7). Sweet corn N content was 32% lower in the split treatment than in early treatment 59 DAP in Cycle I ($P < 0.01$) (Table 4), but sweet corn W_{max}, ear mass per hectare, and yield loss did not differ between the split and early treatments in Cycles I and II (Table 6; Figure 2). Therefore, it is possible that early-season soil N was in excess in the early treatment, pointing to a potential inefficiency of the early N management system.

TABLE 4. Sweet corn (*Zea mays*)[a] N content as affected by N management and interference in field experiments in 1997 (rotation Cycle I) and 1998 (rotation Cycle II).

N management treatment	Sweet corn N content							
	1997				1998			
	27 DAP[b]		59 DAP		27 DAP		70 DAP	
	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed
	kg N ha^{-1}							
Control	8.6	10.1	78	39	0.56	0.48	100	82
Early	9.9	12.2	115	81	0.73	1.15	177	151
Organic	9.4	10.1	77	73	0.86	0.83	210	154
Split	9.5	8.7	79	58	0.68	0.89	176	166
SE	1.1		8		0.11		15	

[a] Sweet corn was grown in plots that were either free of wild mustard (*Brassica kaber*) (− Weed) or in plots that contained wild mustard (+ Weed) thinned to a fixed density.
[b] Abbreviation: DAP, days after planting.

TABLE 6. Sweet corn (*Zea mays*)[a] maximal biomass (W_{max}), maximal relative growth rate (RGR_{max}), and days after planting (DAP) at which RGR_{max} was attained (T_{max}) in field experiments in 1997 (rotation Cycle I) and 1998 (rotation Cycle II).

N management treatment	Sweet corn W_{max}[b]				Sweet corn RGR_{max}				Sweet corn T_{max}			
	1997		1998		1997		1998		1997		1998	
	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed	− Weed	+ Weed
	$\log_e$ g plant^{-1}				mg g^{-1} d^{-1}				DAP			
Control	4.70 (114)	4.46 (79)	4.91 (114)	4.59 (85)	84	84	96	86	30.6	28.6	42.8	47.6
Early	4.95 (146)	4.65 (113)	5.19 (172)	5.08 (157)	80	89	78	78	29.6	29.0	43.7	43.5
Organic	4.78 (136)	4.73 (122)	5.29 (188)	5.12 (158)	81	84	81	81	29.6	29.1	44.0	43.1
Split	4.86 (137)	4.62 (106)	5.22 (170)	4.96 (138)	79	85	86	86	29.6	29.7	44.0	44.5
SE	0.10				3				0.84			

[a] Sweet corn was grown in plots that were either free of wild mustard (*Brassica kaber*) (− Weed) or in plots that contained wild mustard (+ Weed) thinned to a fixed density.

[b] Analysis of variance was performed on $\log_e (x + 1)$-transformed values. Values in parentheses are means of raw data (g plant^{-1}).

This was corroborated by early-season soil N levels in Cycle II that were higher in the early than in the split treatment by 64% 9 DAP and 48% 27 DAP (Figure 1) with no corresponding differences ($P > 0.1$) in sweet corn N content between the early and the split treatments at either 27 or 70 DAP (Table 4). Although soil N levels in Cycle II did not differ between the early and split treatments at either 57 or 70 DAP, this equality at later dates does not reduce potential losses of soil N to groundwater or to weeds during the early part of the growing season when the crop has not yet reached its full N uptake capacity (Magdoff 1991).

Our results provided only limited support for the delayed N availability hypothesis, because the split treatment did not reduce sweet corn yield loss due to wild mustard competition (Figure 2). The work of Alkämper et al. (1979) remains the most convincing evidence for differential crop/weed suppression by delayed soil nutrient availability. When sweet corn infested with common lambsquarters or wild mustard was treated with a split application of NPK fertilizer, sweet corn biomass increased by 70%, whereas common lambsquarters and wild mustard biomass decreased by up to 50% compared to treatments receiving the same amount of NPK fertilizer applied in a single dose at planting (Alkämper et al. 1979). Because the plants used by Alkämper and coworkers were grown in containers holding a peat-based potting mixture, it may have been easier to create truly nutrient-deficient early-season conditions than in the present study. Also, by delaying the availability of three macronutrients at once, Alkämper and coworkers may have created conditions more stressful for early seedling growth. Future field studies of the effects of delayed nutrient availability on weed competition might benefit from treatments that completely withhold N at planting or immobilize soil N early in the growing season, as well as treatments delaying N, P, and K availability simultaneously.

Weed growth was suppressed in the organic treatment compared to the early treatment. In Cycle I, wild mustard N content was 40% lower 27 DAP ($P < 0.05$) in the organic treatment than in the early treatment (Table 5). There was no difference in wild mustard N content between the organic and early treatments at other dates. Because soil N data are unavailable for Cycle I, it is unclear whether wild mustard N content was lower in the organic treatment because of reduced N availability in the soil or because the N uptake capacity of wild mustard was diminished. Wild mustard RGR_{max} was 12% lower ($P < 0.05$) in Cycles I and II and T_{max} was delayed by 0.8 d ($P < 0.05$) in Cycle I in the organic compared to the early treatment (Table 7). These results indicate that the efficiency with which wild mustard was producing biomass at the peak of its growth was lower and the time at which peak growth was attained was later in the organic treatment compared to the early treatment.

Compared to wild mustard, sweet corn experienced relatively little negative effect from the organic treatment but benefited from reduced wild mustard competition under the organic treatment compared to the early treatment. A significant N by competition interaction ($P < 0.05$) indicated that sweet corn N content in the organic treatment was 33%

TABLE 7. Wild mustard (*Brassica kaber* SINAR) maximal biomass (W_{max}), maximal relative growth rate (RGR_{max}), and days after planting (DAP) at which RGR_{max} was attained (T_{max}) in field experiments in 1997 (rotation Cycle I) and 1998 (rotation Cycle II).

N management treatment	SINAR					
	W_{max}[a]		RGR_{max}		T_{max}	
	1997	1998	1997	1998	1997	1998
	$\log_e$ g plant^{-1}		mg g^{-1} d^{-1}		DAP	
Control	2.53 (12.1)	2.61 (13.8)	110	83	30.5	49.0
Early	2.71 (15.4)	3.41 (30.4)	125	98	29.5	46.1
Organic	2.62 (13.5)	2.95 (19.6)	113	85	30.3	48.0
Split	2.63 (13.1)	2.88 (17.9)	116	98	30.4	44.8
SE	0.14		5		0.24[b]	1.20

[a] Analysis of variance was performed on $\log_e (x + 1)$-transformed values. Values in parentheses are means of raw data (g plant^{-1}).

[b] Due to nonhomogeneity of error variances, wild mustard T_{max} data were analyzed separately by rotation cycle.

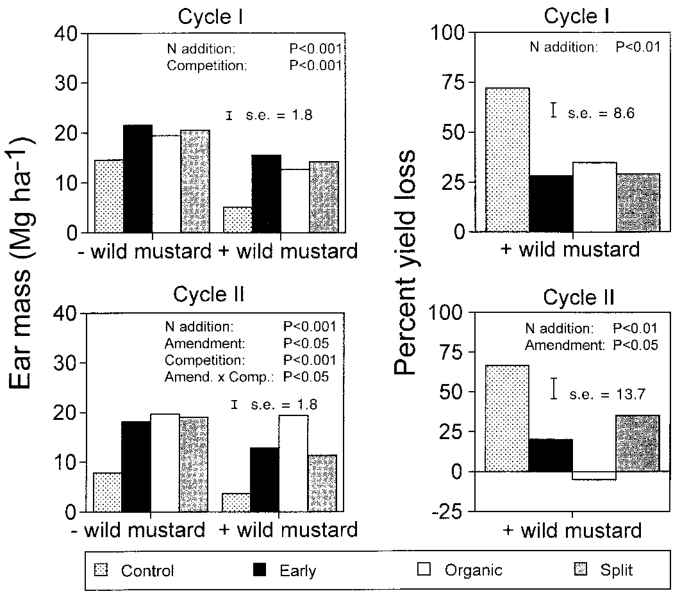

FIGURE 2. Sweet corn marketable ear mass per hectare and yield loss due to wild mustard competition in Cycle I (1997) and Cycle II (1998). Error bars represent one standard error of the mean of six replicates. Treatments and contrasts are explained in the caption for Figure 1.

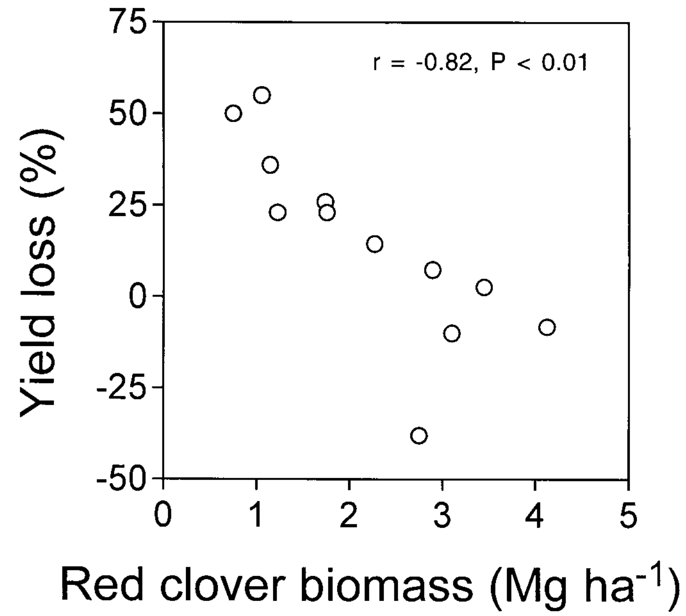

FIGURE 3. Percent loss of sweet corn ear mass due to wild mustard competition in Cycle I (1997) and Cycle II (1998) was negatively correlated with the amount of red clover biomass incorporated into the soil prior to planting. Measurements were made in plots receiving N from red clover residues supplemented with composted dairy manure to reach a predicted fertilizer equivalency value of 110 kg N ha^{-1}.

lower under weed-free conditions 59 DAP in Cycle I compared to the early treatment but that there was no difference, under weedy conditions, in sweet corn N content between the two N source treatments (Table 4). There was no difference ($P > 0.1$) in sweet corn N content between the early and organic treatments at other dates (Table 4), nor was there a difference in sweet corn W_{max}, RGR_{max}, or T_{max} between the organic and early treatments in either rotation cycle (Table 6). During Cycle I, sweet corn marketable ear mass per hectare and yield loss due to wild mustard competition did not differ between the organic and early treatments (Figure 2). In contrast, there was an amendment by competition interaction ($P < 0.05$) for sweet corn marketable ear mass per hectare in Cycle II. Sweet corn grown under the organic treatment in Cycle II yielded the same, regardless of whether wild mustard was present or absent, whereas sweet corn ear mass per hectare in the early treatment was decreased by 20% because of wild mustard competition. Because the reduction of sweet corn N content 59 DAP in Cycle I did not have an adverse effect on the marketable yield of sweet corn with respect to the early treatment, the potential of the organic treatment to exert a small negative effect on sweet corn does not appear to reduce the utility of the organic N management treatment. An a posteriori contrast ($P < 0.05$) indicated that the organic treatment was also more effective at limiting sweet corn yield loss due to wild mustard competition during Cycle II compared to the split treatment, in which there was 35% yield loss.

In both rotation cycles, wild mustard seedling emergence 7 DAP was 22% ($P < 0.05$) lower in the organic treatment compared to the early treatment and 34% ($P < 0.05$) lower in the organic treatment compared to the split treatment (data not presented). If wild mustard stands had not been held constant by subsequent hand thinning, differences in cropping system performance between the organic treatment and the synthetic N treatments might have been even greater than observed. In Cycle II, suppression of sweet corn seedling emergence 7 DAP in the organic treatment was also observed, but this did not translate into reductions in final sweet corn density.

Differences in the degree of weed suppression and sweet corn yield loss in the organic treatment between Cycles I and II may have resulted from the influence of contrasting temperature patterns in these 2 yr on rotation crop biomass and crop and weed growth. The majority of red clover spring regrowth took place during the month of May in each rotation cycle. Average air temperature in May 1998 was 9.8 C higher than the 30-yr mean (for the years 1967 to 1996), whereas May 1997 was 1.1 C cooler than the 30-yr mean. Twice as much red clover regrowth occurred in the wheat plus red clover intercrops during Cycle II as in Cycle I ($P < 0.05$) (Table 2). Within replications of the organic treatment across rotation cycles there was a strong negative correlation ($r = -0.82$, $P < 0.01$) between red clover biomass and sweet corn yield loss because of wild mustard competition (Figure 3). Incorporation of greater amounts of fresh red clover biomass into the soil may therefore have caused the greater reduction in wild mustard competition observed during Cycle II compared to Cycle I. Experimental manipulation of red clover biomass would be necessary, however, to establish a clear causal link between red clover biomass prior to soil incorporation and reduction of weed competition.

A second factor that may have contributed to differential weed suppression between rotation cycles was a delay in seedling development in Cycle II due to cool temperatures immediately after planting. In the 2-wk period subsequent to planting, 210 growing degree days (base 7.6 C) accumulated in Cycle I, whereas only 133 growing degree days accumulated in Cycle II. The slow growth of both the crop and weed during this time in Cycle II was reflected by a 2-

wk delay in T_{max} for both sweet corn and wild mustard in Cycle II compared to Cycle I ($P < 0.001$) (Tables 6 and 7). Sweet corn RGR_{max} was similar between Cycles I and II, but wild mustard RGR_{max} was reduced by 22% in Cycle II compared to Cycle I. We speculate that the drop in temperature following planting compounded the effects of greater red clover biomass in Cycle II by retarding seedling development, thus prolonging a growth stage during which plants are highly susceptible to unfavorable soil conditions (Harper 1977).

Although we did not directly address the underlying mechanism of weed suppression by the organic treatment in this study, we believe that the amendment effect was due to phytotoxicity from the organic N sources, rather than N-related effects. First, although reduction of wild mustard competition was associated with red clover biomass, there was no relationship between either sweet corn or wild mustard N content and red clover biomass in the preceding phase of the rotation. Second, sweet corn N content was not greater in the organic treatment than in either of the synthetic N treatments. Third, weed emergence was suppressed early in the season by the organic treatment, but not by the split treatment, although the soil N levels did not differ between those two treatments over the course of the growing season (Figure 1). Fourth, Ohno et al. (2000) found in bioassays that inhibition of wild mustard seedling growth by red clover–amended soil was due to phytotoxic effects of the red clover residues. Finally, Dyck and Liebman (1994) addressed the issue of whether delayed N availability from organic N sources contributed to weed suppression. Supplemental N fertilizer was added at planting to a sweet corn cropping system receiving its N from soil-incorporated crimson clover residues. This treatment did not reduce weed suppression by crimson clover residues compared to crimson clover receiving no additional synthetic N.

Perhaps the most important question arising from our study is how to account for the selective suppression of the weed, but not the crop, by the organic N sources. Mohler (1996) hypothesized that variations in seed size constitute the basis for selective suppression of weeds but not crops. Westoby et al. (1996) noted that seedlings arising from less massive seeds are more susceptible to early environmental stresses than seedlings arising from more massive seeds. In our experiment, seed mass differed 86-fold between sweet corn (189 mg $seed^{-1}$) and wild mustard (2.2 mg $seed^{-1}$). Similarly, in the experiment conducted by Dyck et al. (1995), in which differential susceptibility to crimson clover residue was observed, seed mass differed 230-fold between sweet corn and common lambsquarters (0.74 mg $seed^{-1}$). This pattern is not anomalous; many crops have seed mass between one and three orders of magnitude greater than the weeds with which they compete (Mohler 1996). The seed size hypothesis for differential suppression of crops and weeds by organic N sources needs to be tested with bioassays on a wide range of species with intra- and interspecific variations in seed size. Such work should provide insight as to what crop/weed species combinations may be managed with organic N sources as part of an integrated soil, crop, and weed management system.

Synergy between multiple weed control tactics is the cornerstone of integrated weed, crop, and soil management systems (Liebman and Davis 2000). The work presented here represents a small step in identifying weed-suppressive crop and soil management systems. Future experiments examining interactions between soil management and other weed management tactics will be necessary to increase the practical utility of integrated weed, crop, and soil management to producers.

Source of Materials

[1] KaleidaGraph curve fitting software, Macintosh version, Synergy Software, 2547 Perkiomen Avenue, Reading, PA 19606-2049.

Acknowledgments

We thank C. Berube, M. S. Erich, E. R. Gallandt, T. S. Griffin, W. A. Halteman, C. W. Honeycutt, and the staff of the University of Maine Sustainable Agriculture Farm for their hard work and insight. This is contribution 2485 of the Maine Agriculture and Forestry Experiment Station, Orono, ME 04469.

Literature Cited

Alkämper, J., E. Pessips, and D. V. Long. 1979. Einfluss der Düngung auf die Entwickelung und Nahrstoffnahme verschiedener Unkräuter in Mais. Pages 181–192 *in* Proceedings of the European Weed Research Society Symposium, Mainz, Germany. Paris: European Weed Research Society.

Angonin, C., J. P. Caussanel, and J. M. Meynard. 1996. Competition between winter wheat and *Veronica hederifolia*: influence of weed density and the amount and timing of nitrogen application. Weed Res. 36: 175–187.

Ball, D. A., D. J. Wynsocki, and T. G. Chastain. 1996. Nitrogen application timing effects on downy brome (*Bromus tectorum*) and winter wheat (*Triticum aestivum*) growth and yield. Weed Technol. 10:305–310.

Benbrook, C. M. 1996. Pest Management at the Crossroads. Yonkers, NY: Consumers Union. pp. 5–7.

Bridges, D. C. and R. L. Anderson. 1992. Crop losses to weeds in the United States by crop and region. Pages 61–74 *in* D. C. Bridges, ed. Crop Losses Due to Weeds in the United States, 1992. Champaign, IL: Weed Science Society of America.

Dabney, S. M., J. D. Schreiber, C. S. Rothrock, and J. R. Johnson. 1996. Cover crops affect sorghum seedling growth. Agron. J. 88:961–970.

Dyck, E. and M. Liebman. 1994. Soil fertility management as a factor in weed control: the effect of crimson clover residue, synthetic nitrogen fertilizer, and their interaction on emergence and early growth of lambsquarters and sweet corn. Plant Soil 167:227–237.

Dyck, E., M. Liebman, and M. S. Erich. 1995. Crop–weed interference as influenced by a leguminous or synthetic fertilizer source: I. Double-cropping experiments with crimson clover, field corn, and lambsquarters. Agric. Ecosyst. Environ. 56:93–108.

Eghball, B. and J. F. Power. 1999. Composted and noncomposted manure application to conventional and no-tillage systems: corn yield and nitrogen uptake. Agron. J. 91:819–825.

Fox, R. H. and W. P. Piekielek. 1988. Fertilizer N equivalence of alfalfa, birdsfoot trefoil, and red clover for succeeding corn crops. J. Prod. Agric. 1:313–317.

Grime, J. P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. Am. Nat. 111:1169–1193.

Hanway, J. J. 1963. Growth stages of corn. Agron. J. 55:487–492.

Harper, J. L. 1977. Population Biology of Plants. London: Academic Press. pp. 111–147.

Hunt, R. 1982. Plant Growth Curves: The Functional Approach to Growth Analysis. London: Edward Arnold. pp. 51–54, 128–135.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40: 27–47.

Liebman, M. and T. Ohno. 1998. Crop rotation and legume residue effects on weed emergence and growth: applications for weed management. Pages 181–210 *in* J. L. Hatfield, D. D. Buhler, and B. A. Stewart, eds. Integrated Soil and Weed Management. Chelsea, MI: Ann Arbor Press.

Magdoff, F. 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. J. Prod. Agric. 4:297–305.
Mahler, R. L. 1990. Soil sampling fields that have received banded fertilizer applications. Commun. Soil Sci. Plant Anal. 21:13–16.
Mohler, C. L. 1996. Ecological bases for the cultural control of weeds. J. Prod. Agric. 9:468–474.
Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman. 1996. Applied linear statistical models. Chicago: Irwin. pp.112–114, 230–231, 736–738, 1010–1013, 1106–1108.
Ohno, T., K. Doolan, L. M. Zibilske, M. Liebman, E. R. Gallandt, and C. Berube. 2000. Phytotoxic effects of red clover amended soils on wild mustard seedling growth. Agric. Ecosyst. Environ. 78:187–192.
Organic Farming Research Foundation. 1998. Third biennial national organic farmers' survey. Santa Cruz, CA: Organic Farming Research Foundation. p. 5.
Ozores-Hampton, M., P. J. Stoffella, T. A. Bewick, D. J. Cantliffe, and T. A. Obreza. 1999. Effect of age of composted MSW and biosolids on weed seed germination. Comp. Sci. Util. 7:51–57.
Pieters, A. J. 1927. Green Manuring: Principles and Practice. New York: J. Wiley. pp. 10–15.
Seibert, A. C. and R. B. Pearce. 1993. Growth analysis of weed and crop species with reference to seed weight. Weed Sci. 41:52–56.
Shipley, B. and P. A. Keddy. 1988. The relationship between relative growth rate and sensitivity to nutrient stress in twenty-eight species of emergent macrophytes. J. Ecol. 76:1101–1110.
Toussoun, T. A. and Z. A. Patrick. 1963. Effect of phytotoxic substances from decomposing plant residues on root rot of bean. Phytopathology 53:265–269.
Vernon, A. J. and J.C.S. Allison. 1963. A method of calculating net assimilation rate. Nature (London) 200:814.
Westoby, M., M. Leishman, and J. Lord. 1996. Comparative ecology of seed size and dispersal. Philos. Trans. R. Soc. Lond., B 351:1309–1318.
Wilkinson, L., M. Hill, S. Miceli, P. Howe, and E. Vang. 1992. SYSTAT for the Macintosh. Version 5.2. Evanston, IL: SYSTAT.

Received July 25, 2000, and approved March 12, 2001.

APPENDIX. Allometric equations used to estimate shoot biomass for sweet corn (*Zea mays*) and wild mustard (*Brassica kaber*) from stem diameter, height, or both.

Year	Species	Harvest	Allometric equation[a]	R^2
		WAP[b]		
1997	Sweet corn	2	$SB = -0.87 + 0.012 \times H$	0.94
		3	$SB = -0.996 + 0.178 \times SD$	0.99
		5	$SB^{0.5} = -1.35 + 0.050 \times H$	0.85
		6	$SB^{0.5} = -1.38 + 0.058 \times H$	0.84
	Wild mustard	2	$SB^{0.5} = -0.077 + 0.097 \times H^{0.5} + 0.054 \times SD^{0.5}$	0.69
		3	$SB^{0.5} = -0.696 + 0.096 \times H^{0.5} + 0.430 \times SD^{0.5}$	0.82
		5	$SB^{0.5} = -2.205 + 7.85 \times SD^{0.5}$	0.86
		6	$SB^{0.5} = -3.650 + 0.170 \times H^{0.5} + 1.64 \times SD^{0.5}$	0.84
1998	Sweet corn	2	$SB^{0.5} = 0.009 + 0.015 \times H$	0.83
		4	$SB^{0.5} = -0.386 + 0.036 \times H$	0.76
		5	$SB^{0.5} = -0.6999 + 0.021 \times H + 0.069 \times SD$	0.87
		6	$SB^{0.5} = -1.826 + 0.024 \times H + 0.126 \times SD$	0.93
		7	$SB^{0.5} = -2.505 + 0.036 \times H + 0.126 \times SD$	0.87
		9	$SB^{0.5} = -4.28 + 0.0402 \times H + 0.323 \times SD$	0.69
	Wild mustard	2	$SB^{0.5} = 0.034 + 0.027 \times H$	0.82
		4	$SB^{0.5} = -0.2403 + 0.2743 \times SD$	0.85
		5	$SB^{0.5} = -0.1834 + 0.2753 \times SD$	0.78
		6	$SB^{0.5} = 0.0427 + 0.3482 \times SD$	0.70
		7	$SB^{0.5} = -0.493 + 0.539 \times SD$	0.90
		9	$SB^{0.5} = -0.54 + 0.6754 \times SD$	0.73

[a] Abbreviations in allometric equations: SB, shoot biomass (g plant^{-1}); H, height (cm); SD, stem diameter (mm, measured at cotyledon scar for wild mustard or first leaf collar for sweet corn).
[b] Abbreviation: WAP, weeks after planting.