Yield, Dry Matter Partitioning, and Storage Quality of Hardneck Garlic as Affected by Soil Amendments and Scape Removal

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Additional index words. *Allium sativum*, nitrogen, manure compost, flower stalk

Abstract Two on-farm field studies were conducted in 1996 and repeated in 1997 to determine the effects of soil amendments and scape (flower stalk) removal on yield, dry matter partitioning, and storage quality of hardneck garlic (*Allium sativum* L.). One study site was on a loamy sand soil with low organic matter and fertility and the other site was on a sandy loam soil with high organic matter and fertility. Soil amendment treatments tested at both sites were: 1) no amendment, 2) composted manure, and 3) inorganic fertilizer according to soil test recommendations. A fourth treatment, dried, composted turkey-manure-based fertilizer, was included at the low organic matter site. Scares were removed at the curled stage from plants in half of the harvest rows. Scares from the remainder of the harvest row plants were allowed to mature until harvest. In 1997, bulbs from each treatment were stored at 0 to 3 °C or 19 to 21 °C for 6 months. Soil amendment treatments had no effect on total garlic bulb yield, dry mass partitioning, or stored bulb weight loss at the sandy loam, high organic matter site. Manure compost, fertilizer, and composted turkey manure soil amendments reduced the yield of smaller bulbs compared with the control at the loamy sand, low organic matter site. The proportion of bulbs >5 cm was highest with the manure compost treatment. At the low organic matter site, scape removal resulted in a 15% increase in bulb yield and an increase in bulb size compared with leaving scares on until harvest ($P = 0.05$). At the high organic matter site, scape removal increased bulb yield by 5% ($P = 0.10$). Scape removal increased dry matter partitioning to the bulbs, but had no effect on total (scape + shoot + bulb) aboveground dry matter production. The increase in bulb dry mass when scares were removed was offset by an increase in scape dry mass when scares were left on. Bulb weight loss in storage was less at 0 to 3 °C than 19 to 21 °C. Soil amendments only affected bulb storage quality at the loamy sand, low soil organic matter site. The effect of scape removal on bulb weight loss was nonsignificant at either location.

Garlic (*Allium sativum* L.), a member of the onion family, has been cultivated for thousands of years and is widely used for culinary and medicinal purposes (Hahn, 1996a). Popularity of this crop has recently increased in the United States, in part because of the many health benefits attributed to garlic consumption.

Despite the fact that commercially grown garlic is sterile, many cultivars differing in phenotypic characteristics exist. Most garlic in the United States is grown in the mild climates of California. Cultivars grown in California typically do not produce a flower

stalk or scape and are termed “softneck” or “nonbolting types.” In contrast to softneck cultivars, many of the cultivars adapted to colder climates produce a scape and are termed “hardneck” or “bolting types” (Hahn, 1996b). Temperature and photoperiod can influence the extent of bolting, and in many cases dictate adaptability of the garlic cultivar to a particular area (Takagi, 1990). Softneck cultivars are usually preferred commercially because of higher yield potential, presumably due to lack of a scape. However, hardneck cultivars have been selected that grow well in cold climates and can be preferred in taste tests over softneck cultivars grown in mild climates (Engeland, 1991).

Recent demand for high-quality garlic has prompted interest in garlic production for niche markets in the Upper Midwest. Most research on garlic production has been conducted on improving production of softneck cultivars in mild climates (Brewster and Rabinowitch, 1990), with only minimal efforts on hardneck

cultivars. The suggested fertilizer requirement for garlic varies widely with growing locality and with other factors affecting yield potential, such as plant population. Buwalda (1986b) reported that 120 kg-ha⁻¹ N was optimum for growing softneck garlic in New Zealand, with higher rates of N causing a higher incidence of “daughter” bulbs, which reduced marketability. However, storage quality (weight loss and percent decay) at ambient temperatures after 6 months was not affected by N rate. Rates of 80 to 170 kg-ha⁻¹ N are recommended for the various regions in California, depending on previous crop and fertilization, soil type, and water management (Sims et al., 1976).

For hardneck garlic, the option for scape removal needs to be considered. Some garlic production guides recommend removal of scares to increase bulb yield (Bodner et al., 1997; Oregon State Univ. Extension Service, 2000). Orlowski et al. (1994) reported significant yield increases when scares were removed compared with leaving scares on until harvest. There is circumstantial evidence, however, to suggest that bulbs store better if the scape is left on until harvest or removed only a few days before harvest (Engeland, 1991). If soil nutrients and water are not limiting, the effects of scape removal on bulb yield may be minimal. Removal of scares involves extra labor, which may be offset if a market for the scares can be developed and yield is increased. Quantitative effects of scape removal on hardneck garlic production and storage in the literature could not be found. The overall objective of this research was to determine the effects of various soil amendments and scape removal on garlic yield, dry mass partitioning, and storage quality for garlic grown in two soil types.

Materials and Methods

Site selection and description. Field plots were established at two on-farm locations during the 1995–96 and 1996–97 growing seasons. For each growing season, garlic was planted in different but adjacent areas within each location. One site was located in Gutches Grove in central Minnesota on a Kandota sandy loam (fine-loamy, mixed Mollic Eutroboralfs). Average soil test values for the 0–15 cm depth over the 2 years prior to planting were as follows: pH (water 1:1), 6.7; organic matter, 4.5%; 2 N KCl extractable nitrate-N, 14 mg·kg⁻¹; Bray 1 phosphorus, 130 mg·kg⁻¹; ammonium acetate extractable potassium, 207 mg·kg⁻¹; and hot water extractable boron, 1 mg·kg⁻¹. This site was in grass-legume cover for 5 years prior to the study. During the summers of 1995 and 1996, buckwheat was planted as a green manure and plowed in at the end of August.

The other site was located in Cannon Falls in southeastern Minnesota on a Sparta loamy fine sand (sandy, mixed, mesic Entic Hapludolls). Average soil test values over the 2 years prior to planting for the 0–15 cm depth were as follows: pH (water 1:1), 6.8; organic matter, 1.4%; 2 N KCl extractable nitrate-N, 7 mg·kg⁻¹; Bray 1 phosphorus, 48 mg·kg⁻¹; am-

Received for publication 30 Oct. 2000. Accepted for publication 14 Apr. 2001. This research was supported by the Minnesota Agricultural Experiment Station and a grant from the Minnesota Dept. of Agriculture Sustainable Agriculture Program. We thank Joel Girardin and Phillip Arnold for assistance in plot maintenance.

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monium acetate extractable potassium, 80 mg·kg⁻¹; and hot water extractable boron, 0.4 mg·kg⁻¹. This site was in a grass cover for 5 years prior to the initiation of the study. During summer 1995, snap beans were planted and harvested, followed by a green manure of buckwheat. The buckwheat was incorporated with a rototiller in the middle of September. In 1996, peppers and cucumbers were grown, and residues were incorporated after harvest with a rototiller prior to planting the garlic.

Soil amendment treatments. Three treatments were tested at the Gutches Grove site and four treatments were tested at the Cannon Falls site during each growing season. Three treatments common to each site were: 1) non-amended control, 2) composted animal manure, and 3) inorganic fertilizer based on soil test recommendations (Rosen and Eliason, 1996).

The composted manure was produced at the Univ. of Minnesota animal operations and was a mixture of cow, sheep, and hog manure along with bedding used within the animal facilities. The bedding consisted of woodchips and straw. The manure and bedding were composted for 12 to 14 months before use. The C:N ratio of the compost just before application averaged 19 and the total N concentration averaged 1.25% on a dry weight basis. Application of the compost was based on an assumed N availability of 30% during the year of application. The actual N availability was not known and the 30% value may be an overestimation based on values for composted manure reported by Hartz et al. (2000).

At the Gutches Grove site, soil test P and K were in the high range; therefore, the inorganic fertilizer treatment was only fertilizer N applied at the rate of 90 kg·ha⁻¹. At Cannon Falls, the inorganic fertilizer treatment included fertilizer N applied at the rate of 134 kg·ha⁻¹. The N at each site was split in two applications with 56 kg·ha⁻¹ incorporated at planting as ammonium sulfate and 34 kg·ha⁻¹ at Gutches Grove and 78 kg·ha⁻¹ at Cannon Falls topdressed as ammonium nitrate in the spring after mulch removal. Because of lower soil test values at Cannon Falls, P as triple superphosphate (12 kg·ha⁻¹ P), K as potassium chloride (115 kg·ha⁻¹ K), and B applied as borax (1 kg·ha⁻¹ B) were broadcast and incorporated at planting each fall. The composted manure was applied at a rate of 22 Mg·ha⁻¹ dry weight at Gutches Grove and 34 Mg·ha⁻¹ dry weight at Cannon Falls in the fall prior to planting. Because of lower soil organic matter at Cannon Falls, the composted manure application was 12 Mg·ha⁻¹ higher and N application was 44 kg·ha⁻¹ higher than at Gutches Grove. At the Cannon Falls site, an additional manure treatment, Sustane (Sustane Corp., Cannon Falls, Minn.), was evaluated. The Sustane product is a dried turkey manure compost base supplemented with feather meal and had a nutrient analysis of 4N-3P-3K. Sustane was applied based on its N content and an assumption of 80% availability the first year (Sustane Corp., personal communication). The rate of product applied on a dry weight basis was 4.2 Mg·ha⁻¹ (1.4 Mg·ha⁻¹ before planting and 2.8

Mg·ha⁻¹ after mulch removal in the spring). All treatments were applied by hand at each site. Those applied in the fall were incorporated to a depth of 15 cm with a rototiller just prior to planting. Spring-applied treatments were topdressed over the row.

Scape removal treatment. One of the two harvest rows in each plot was selected for scape removal. Scapes in the other harvest row were allowed to mature until harvest. Scapes were removed by hand with a sharp knife on 27 June 1996 and 26 June 1997 at Cannon Falls and 10 July 1996 and 2 July 1997 at Gutches Grove. Dates of removal corresponded to when the scapes were curled. Scapes were cut just below the curl, then dried and weighed for dry matter and N determination.

Experimental design and cultural procedures. At each site, a split plot design with three replications was used. Main plots were soil amendment treatment and subplots were scape treatment. Each four-row main plot was 3 m wide and 6 m long. Spacing was 15 cm within rows and 76 cm between rows and the middle two rows were the harvest rows. This spacing resulted in plant populations that were lower than those used for most commercial softneck garlic fields in western United States, but simulated populations used on small farms in the Upper Midwest. The reason for using wider spacing between rows was to allow for mechanical cultivation. The garlic cultivar grown was 'Merrifield Rocambole', a hardneck type purchased from Merrifield Farms in Auburn, N.Y. Garlic cloves were planted by hand on 27 Sept. 1995 and 2 Oct. 1996 at Gutches Grove and 11 Oct. 1995 and 3 Oct. 1996 at Cannon Falls.

After planting, plots were mulched with 7 to 8 cm of straw to prevent winter damage. The straw mulch was removed on 10 Apr. 1996 and 3 Apr. 1997 at Cannon Falls and 18 Apr. 1996 and 17 Apr. 1997 at Gutches Grove. Following mulch removal, soil was allowed to warm for 1 month, plots were mechanically weeded, and then the straw mulch was placed back between each row for additional weed control. Garlic at each site was grown under non-irrigated conditions.

Harvest measurements. On 29 July 1996 and 29 July 1997 at Cannon Falls and 30 July 1996 and 28 July 1997 at Gutches Grove, garlic was harvested by hand from 3 m of the middle two rows from each main plot. About 50% of the leaves were senesced at the time of harvest. Garlic in the Upper Midwest is typically harvested between the second and fourth week in July. Scapes (from the scapes not removed treatment) were cut after the plants were pulled and then dried at 60 °C for subsequent dry matter and N determination. The garlic plants (bulb and shoots) were bunched in groups of 10 and allowed to cure in well-ventilated barns for 3 to 4 weeks. After curing, roots were trimmed and shoot mass, bulb yield, and graded quality recorded. Because harvested roots represented a small fraction of the dry mass (<1%), they were ignored in the dry mass and tissue N measurements. Bulbs were graded by shape and size. Misshapen bulbs and bulbs <3.8 cm were classified as

culls and the size grades were: 3.8 to 5.0 cm diameter, 5.1 to 6.4 cm diameter, and >6.4 cm diameter. Bulbs >3.8 cm diameter are considered "U.S. #1." Subsamples of shoots and bulbs were dried and weighed for dry matter and N determination.

Tissue nitrogen determination. Scape, shoot, and bulb tissue were dried at 70 °C and then ground with a Wiley mill to pass through a 1-mm screen. Following salicylic Kjeldahl digestion (Association of Official Analytical Chemists, 1970), total N in the tissues was determined using conductimetric procedures (Carlson, 1978). Nitrogen uptake by the crop was calculated by multiplying tissue N concentration × tissue dry mass.

Storage treatments. Five uniform bulbs (≥5 cm in diameter) from each treatment within each site from the 1997 growing season were placed in a mesh bag and stored at 0 to 3 °C or 19 to 21 °C, and 56% to 75% relative humidity for 6 months. Each bulb was weighed once a month, and cumulative percent fresh weight loss was calculated.

Data analysis. Within each site, data were compared by analysis of variance procedures over years. Amendment treatment means were separated using the Waller-Duncan Bayesian mean separation procedure with a k-ratio set at 100. This k-ratio approximates the 5% probability level (Steele and Torrie, 1980). Storage measurements were made only in the second year of the study and analyses are based on 1 year. Data analyses were performed using the general linear model procedure (SAS Institute, 1986).

Results and Discussion

Rainfall during the time from mulch removal to harvest was 24.8 and 45.7 cm in Cannon Falls for 1996 and 1997, respectively. During this same time period, rainfall in Gutches Groves was 28.9 and 22.1 cm for 1996 and 1997, respectively. Based on the previous 30 years, the average rainfall in Cannon Falls for this period is 35.5 cm, while in Gutches Grove the average rainfall is 33.7 cm. The 45.7 cm rainfall in Cannon Falls during 1997 is somewhat misleading because 14.5 cm occurred during the 5 d before harvest. In general, rainfall both years and at both sites was below the 30-year averages during the bulbing stage (June to early July). In 1997, spring temperatures were below average during the first week in April. A low temperature of -15 °C recorded after the mulch had been removed at Cannon Falls resulted in some freeze damage (malformed bulbs) at this site. A similar low temperature at Gutches Grove was recorded, but mulch had not yet been removed and there was no evidence of freeze damage.

Garlic yield and dry matter partitioning. Total yield at Cannon Falls was higher in 1997 compared with 1996; however, because of freeze damage due to early mulch removal, a larger proportion of the total yield in 1997 was in the cull category compared with that in 1996 (Table 1). Yield of smaller-sized (3.8 to 5.0 cm) bulbs was highest in the control plots

Table 1. Effect of soil amendments and scape removal on garlic bulb fresh yield and quality and plant dry matter partitioning at two Minnesota locations, (**top**) Cannon Falls and (**below**) Gutches Grove.

Source of variation	Cannon Falls									
	Garlic bulb fresh yield by diameter (Mg·ha ⁻¹)					Bulbs > 5 cm (%)	Garlic plant dry matter (Mg·ha ⁻¹)			
	Culls	3.8–5 cm	5–6.4 cm	>6.4 cm	Total		Scape	Shoot	Bulb	Total
Year										
1995–96	0.32	0.91	2.83	0.81	4.87	71.4	0.35	0.31	2.57	3.23
1996–97	1.26	0.51	3.00	1.43	5.51	74.9	0.17	0.28	2.62	3.07
Significance	**	NS	NS	NS	NS	NS	**	NS	NS	NS
Amendment										
Control	0.41 bc ^z	1.14 a	2.50 a	0.54 a	4.59 a	62.6 b	0.27 a	0.29 b	2.37 a	2.93 a
Compost	0.17 c	0.53 b	3.28 a	1.71 a	5.69 a	84.5 a	0.27 a	0.34 a	2.80 a	3.41 a
Fertilizer	0.85 a	0.62 b	2.85 a	0.62 a	4.93 a	68.7 ab	0.21 b	0.27 b	2.48 a	2.97 a
Sustane ^y	0.66 ab	0.55 b	3.06 a	1.30 a	5.57 a	76.9 ab	0.27 a	0.29 b	2.72 a	3.28 a
Scape										
Removed	0.58	0.58	3.07	1.38	5.62	76.9	0.15	0.29	2.76	3.19
Not removed	0.46	0.84	2.77	0.71	4.77	69.4	0.38	0.30	2.42	3.10
Significance	NS	*	NS	*	**	NS	**	NS	**	NS
Interactions										
Year (Y) × amendment (A)	NS	NS	NS	NS	NS	NS	**	**	NS	NS
Y × scape (S)	NS	NS	NS	NS	NS	NS	**	NS	NS	NS
A × S	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × A × S	*	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zMeans within the same column followed by the same letter are not significantly different according to the Waller–Duncan Bayesian k-ratio *t* test for minimum significant difference, k = 100.

^ySustane (dried turkey manure) was only tested at the Cannon Falls location.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

Table 1 (Continued).

Source of variation	Gutches Grove									
	Garlic bulb fresh yield by diameter (Mg·ha ⁻¹)					Bulbs > 5 cm (%)	Garlic plant dry matter (Mg·ha ⁻¹)			
	Culls	3.8–5 cm	5–6.4cm	>6.4cm	Total		Scape	Shoot	Bulb	Total
Year										
1995–96	0.64	0.05	2.46	4.39	7.53	91.0	0.50	0.41	3.69	4.60
1996–97	0.47	0.16	2.85	3.82	7.28	91.2	0.27	0.38	3.21	3.86
Significance	NS	NS	**	NS	NS	NS	*	NS	*	**
Amendment										
Control	0.59 a ^z	0.09 a	2.70 a	4.03 a	7.43 a	90.8 a	0.39 a	0.40 a	3.48 a	4.60 a
Compost	0.40 a	0.06 a	3.21 a	3.75 a	7.43 a	93.9 a	0.39 a	0.39 a	3.44 a	4.22 a
Fertilizer	0.66 a	0.16 a	2.03 b	4.51 a	7.36 a	88.7 a	0.38 a	0.39 a	3.41 a	4.18 a
Sustane ^y										
Scape										
Removed	0.64	0.06	2.53	4.37	7.60	90.9	0.25	0.40	3.54	4.19
Not removed	0.47	0.15	2.77	3.83	7.22	91.4	0.51	0.40	3.34	4.25
Significance	NS	NS	NS	NS	NS	NS	**	NS	NS	NS
Interactions										
Year (Y) × amendment (A)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × scape (S)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
A × S	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y × A × S	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zMeans within the same column followed by the same letter are not significantly different according to the Waller–Duncan Bayesian k-ratio *t* test for minimum significant difference, k = 100.

^ySustane (dried turkey manure) was only tested at the Cannon Falls location.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

compared with those plots receiving soil amendments. The proportion of bulbs >5 cm was significantly higher in the manure compost treatment compared with the control. The Sustane and fertilizer treatments also tended to increase bulb size compared with the control, but the effects were nonsignificant at $P = 0.05$. Three-way interactions (soil amendment × scape × year) were significant for the cull and 3.8 to 5.0 cm bulb category and were related to variability in cold damage in 1997 (data not presented). At Gutches Grove, total bulb yield in 1996 was similar to that in 1997 (Table 1). Due to the high fertility and soil organic matter

and finer soil texture of the Gutches Grove site, soil amendment treatments had minimal effects on bulb yield. The only significant, but not easily explainable, amendment effect was a lower yield of bulbs in the 5 to 6.4 cm category with the fertilizer treatment compared with the control and compost treatments.

Overall yields at Gutches Grove were ≈30% higher than at Cannon Falls. While climatic factors are confounded with soil factors, some of the differences in yield between the two sites can likely be attributed to soil. Differences in yield were perhaps due in part to differences in water-holding capacity of the

soils and potential water stress. The Cannon Falls soil was coarser and had lower organic matter compared with the Gutches Grove soil. The lack of irrigation capabilities and low rainfall during bulbing both years may have caused some drought stress. The effect would be more pronounced in a coarse-textured soil with low organic matter compared with a finer textured soil with high organic matter. The water limitations at Cannon Falls may have also masked a yield response to the soil amendments. Garlic yields at both sites were lower than those reported for softneck cultivars in other studies (Buwalda, 1986a; Sims et al.,

1976; Zink, 1963). In addition to possible water stress, the lower yields can, in part, be attributed to the lower plant populations used in this study compared with commercial fields (Brewster and Rabinowitch, 1990; Minard, 1978). Typical plant populations for commercial garlic are usually 2 to 3 times those used in this study. However, as mentioned above, the lower plant populations were used to simplify mechanical cultivation operations.

At Cannon Falls, total bulb yield increased by $0.85 \text{ Mg} \cdot \text{ha}^{-1}$ when scapes were removed at curling compared with leaving the scapes on until harvest. This corresponds to an average of a 15% yield increase with scape removal. Bulb size also tended to be larger when scapes were removed. These results are similar to those reported by Orlowski et al. (1994). The effects of scape removal at Gutches Grove were less obvious, but trends were similar to those at Cannon Falls. Scape removal tended to increase total bulb yield by $0.54 \text{ Mg} \cdot \text{ha}^{-1}$ (5% yield increase) and decrease the proportion of smaller-sized bulbs (3.8 to 5.0 cm) compared with leaving scapes on until harvest. These effects were significant at the 10% probability level, but not at the 5% level. At both sites, the scape $\times$ soil amendment interaction was nonsignificant, which indicates that the increase in yield due to scape removal was similar across all soil amendments. This finding was unexpected, especially at the Cannon Falls site, since reducing nutrient stress with the soil amendments was hypothesized to minimize the effect of not removing scapes. Even though the treatments used within each site did not offset the effect of leaving scapes on, there were clear differences between sites. Scape removal had more of an effect at Cannon Falls (low fertility and low water-holding capacity site) than at Gutches Grove (high fertility and high water-holding capacity site), suggesting that the effect of scape removal can be mini-

mized to some extent by reducing stress (either water or nutrient) during growth. At the Cannon Falls site, even though soil amendments provided adequate nutrients, water was probably the most limiting factor and likely had an overriding effect on yield response.

The decision to remove the scapes must be made in terms of a marketing and economics context. If there is a market for the bulbils from mature scapes, then it may be beneficial to sacrifice bulb yield. On the other hand, the bulb yield increase and potential market for immature scapes as a specialty vegetable may more than offset labor costs for early scape removal. A limited market for both bulbils and scapes has been reported by organic growers in the Upper Midwest (Rosen, personal communication).

At Cannon Falls, shoot dry mass increased with compost amendment compared with the control and other amendments, but the effect depended on year (Table 1). Shoot dry mass with compost was significantly higher in 1997 but not in 1996. The trends, however, in 1996 for compost effects were similar to those in 1997 (data not presented). Bulb dry mass and total dry mass were not affected by soil amendments. Scape dry mass was lowest with the fertilizer treatment each year; however, the magnitude of differences in comparison with the other treatments varied with year (year $\times$ amendment interaction, data not presented). Soil amendment treatments at Gutches Grove did not significantly affect scape, shoot, bulb, or total dry mass production. At both locations, scape dry mass production was affected by year and scape removal. Lower scape dry mass in 1997 was due to a slightly earlier date of removal. Scape dry mass at harvest was 2 to 2.5 times greater compared with that when removed at curling. The significant scape $\times$ year interaction for scape dry mass at Cannon Falls was due to a difference in magnitude of

response, not direction; that is, in both years dry mass of scapes at harvest was significantly greater than when removed at curling (data not presented). Shoot dry mass was not affected by scape removal at either site; however, bulb dry mass was significantly higher when scapes were removed compared with scapes not removed. The scape removal effect on bulb dry mass at the Cannon Falls site was highly significant, but at Gutches Grove, the effect was significant only at the 10% probability level. Total dry mass was not significantly affected by scape removal at either site. The increase in bulb dry mass when scapes were removed was offset by an increase in scape dry mass when scapes were left on. This response may be comparable to removal of pods from pigeon pea and soybean, which has been shown to increase vegetative development and shoot dry matter accumulation, presumably due to diversion of assimilates that would otherwise be transported to pods (Tayo, 1977, 1980).

Nitrogen concentration and uptake. At Cannon Falls, N concentrations of scape, shoot, and bulb tissue were higher with fertilizer and Sustane treatments compared with the control and compost treatments (Table 2). The fertilizer treatment at Gutches Grove also increased scape and bulb tissue N compared with the compost treatment. All significant year $\times$ soil amendment interactions and year $\times$ scape interactions were due to differences in magnitude of response rather than direction of response (data not presented). Concentrations of N in the bulb tissue are within ranges (1.9% to 2.3%) reported for bulb tissue associated with maximum yield by Minard (1978).

Total plant N uptake ranged from 52.5 to $89.1 \text{ kg} \cdot \text{ha}^{-1}$ at the Cannon Falls site and 80.8 to $89.1 \text{ kg} \cdot \text{ha}^{-1}$ at the Gutches Grove site (Table 2). Soil amendment treatments did not significantly affect N uptake, although at the Cannon Falls site, N uptake in the control treatment

Table 2. Effect of soil amendments and scape removal on scape, shoot, and bulb N concentrations and plant N uptake at two Minnesota locations.

Source of variation	Cannon Falls								Gutches Grove							
	N concn (%)			N uptake ($\text{kg} \cdot \text{ha}^{-1}$)					N concn (%)			N uptake ($\text{kg} \cdot \text{ha}^{-1}$)				
	Scape	Shoot	Bulb	Scape	Shoot	Bulb	Total		Scape	Shoot	Bulb	Scape	Shoot	Bulb	Total	
Year																
1995–96	1.20	0.56	2.17	4.4	1.8	55.4	60.4		1.20	0.94	2.08	6.0	3.9	76.4	86.4	
1996–97	1.19	0.75	2.07	2.0	2.1	54.1	58.2		1.59	1.00	2.35	3.9	3.8	75.4	83.1	
Significance	NS	*	NS	**	NS	NS	NS		**	NS	**	*	NS	NS	NS	
Amendment																
Control	1.13 b ^z	0.58 c	2.00 b	3.1 a	1.7 b	47.9 a	52.5 a		1.38 ab	0.99 a	2.22 ab	4.9 a	3.9 a	75.5 a	84.3 a	
Compost	1.13 b	0.57 c	2.02 ab	3.3 a	1.9 ab	57.7 a	62.9 a		1.35 b	0.89 a	2.11 b	5.0 a	3.5 a	72.3 a	80.8 a	
Fertilizer	1.29 a	0.79 a	2.21 a	2.8 a	2.1 a	55.2 a	60.1 a		1.44 a	1.02 a	2.32 a	5.0 a	4.1 a	80.0 a	89.1 a	
Sustane ^y	1.24 a	0.69 b	2.24 a	3.6 a	2.0 ab	61.0 a	66.6 a									
Scape																
Removed	1.10	0.69	2.15	1.6	2.0	59.6	63.1		1.53	0.95	2.18	3.5	3.8	76.7	84.0	
Not removed	1.29	0.63	2.08	4.9	1.9	50.0	55.4		1.26	0.98	2.26	6.4	3.9	75.1	85.4	
Significance	**	NS	NS	**	NS	**	NS		**	NS	NS	**	NS	NS	NS	
Interactions																
Year (Y) $\times$ amendment (A)	NS	NS	NS	*	*	NS	NS		*	NS	NS	NS	NS	NS	NS	
Y $\times$ scape (S)	**	*	NS	**	NS	NS	NS		**	*	NS	**	*	NS	NS	
A $\times$ S	NS	NS	NS	NS	NS	NS	NS		NS	NS	NS	NS	NS	NS	NS	
Y $\times$ A $\times$ S	NS	NS	NS	NS	NS	NS	NS		NS	NS	NS	NS	NS	NS	NS	

^zMeans within the same column followed by the same letter are not significantly different according to the Waller–Duncan Bayesian k-ratio *t* test for minimum significant difference, $k = 100$.

^ySustane (dried turkey manure) was only tested at the Cannon Falls location.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01 , respectively.

was numerically lower than that in the other treatments both years. The amount of N taken up in the bulb tissue was higher when scapes were removed compared with when scapes were left on until harvest at the Cannon Falls site. At Gutches Grove, scape removal did not significantly affect total N accumulation in the bulb. Scapes left on until harvest accumulated 2 to 3 times more N than scapes that were removed at curling. Mature scapes accumulated $\approx 8\%$ of the total N taken up by the plant. As with dry matter accumulation, N uptake by bulbs in this study was less than that reported in other studies with softneck garlic (Minard, 1978; Zink, 1963). The lower amount of N uptake was in part due to the lower plant population in this study compared with previous studies. Higher plant populations with higher yield potentials generally require higher rates of fertilizer application (Zink, 1963).

Storage effects. Although fresh weight loss was recorded monthly, treatment effects on loss were similar throughout the storage period (data not presented), so only cumulative loss after 6 months is reported. Storage effects on bulb fresh weight loss were more evident for bulbs grown at Cannon Falls than at Gutches Grove. Soil amendment and scape removal did not affect bulb weight loss at Gutches Grove (data not presented); however, bulbs stored at 0 to 3 °C lost less weight (16.5%) than those stored at 19 to 21 °C (27.5%). A similar storage temperature effect was significant at Cannon Falls, but because of temperature $\times$ soil amendment and temperature $\times$ scape in-

teractions, weight loss within each temperature regime is presented (Table 3). Bulbs grown at Cannon Falls with manure compost lost more weight than those grown with no soil amendment, regardless of storage temperature. This is significant because bulbs selected going into storage from each treatment were generally uniform in mass. Scape removal did not significantly affect weight loss at either storage temperature. Published recommendations for long-term garlic storage are 0 °C, and 65% to 70% relative humidity (Hardenburg et al., 1986); our data support these recommendations for hardneck garlic.

Conclusions. The results clearly show that scape removal had a significant effect on garlic bulb production and dry matter partitioning. Removal of scapes increased bulb yield and was particularly noticeable at the sandy, low organic matter site where plants were more likely stressed for water. Unless a market is available for bulbils produced on mature scapes, scape removal at the curled stage is indicated for optimum production of hardneck garlic. Soil amendment treatments had no effect on garlic yields or dry mass partitioning at the high organic matter site. Soil amendments tended to reduce the yield of smaller-sized bulbs and increase the proportion of larger-sized bulbs compared with the control at the low organic matter site. As found in previous studies, optimum long-term storage of hardneck garlic for consumption was found to be 0 to 3 °C. Scape removal did not significantly affect garlic storage quality at either location; however, at the low organic matter site, bulbs from nonfertilized plots tended to store better than those receiving soil amendments. Further studies to determine the effects of preharvest production practices on garlic yields and storage at higher plant populations than those used in this study are warranted.

Table 3. Effect of soil amendment and scape removal on percent fresh weight loss of bulbs from Cannon Falls, Minn., after 6 months of storage at two temperatures in 1997.

Source of variation	Fresh wt loss (%)	
	Storage temp	
	0 to 3 °C	19 to 21 °C
Amendment (A)		
Control	12.8 b ²	31.0 b
Compost	14.7 a	41.6 a
Fertilizer	13.1 ab	39.3 ab
Sustane	13.6 ab	37.4 ab
Scape (S)		
Removed	13.3	40.0
Not removed	13.8	34.6
Significance	NS	NS
Interactions		
A $\times$ S	NS	NS

²Means within the same column followed by the same letter are not significantly different, according to the Waller-Duncan Bayesian k-ratio *t* test for minimum significant difference, *k* = 100.

^{NS}Nonsignificant.

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