Large Single-head Broccoli Yield as Affected by Plant Density, Nitrogen, and Cultivar in a Plasticulture System

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SUMMARY. An open-market window has been identified in Virginia for fall broccoli (*Brassica oleracea* var. *italica*). Vegetable producers using plasticulture systems can capitalize on this opportunity by growing broccoli as a second crop after summer vegetables. The objective of this project was to evaluate suitability of two broccoli cultivars, Everest and Gypsy, for the fall production of large single-heads (>6 inches in diameter) for the fresh market. Planting density and rate of nitrogen (N) fertilizer (25, 60, and 100 lb/acre N) effects on yield characteristics were evaluated in a plasticulture system during a 3-year study (2003–05) conducted with broccoli transplants at the Virginia Polytechnic Institute and State University Kentland Agricultural Research Farm near Blacksburg, VA. The percentage of large heads was cultivar, plant density, and N rate dependent. The midseason ‘Gypsy’ produced significantly higher total yield and head weight compared with the early-season ‘Everest’. The optimum density to maximize floret production per area was 12,500 plants/acre and a supplemental N rate of 100 lb/acre. This N rate significantly ($P < 0.002$) improved marketable yield, large head yield, and leaf N accumulation compared with the lower rates. The data indicate that the feasibility of growing fall broccoli using a plasticulture system depends on the number of large heads produced for the fresh market. This in turn will depend on the choice of cultivar, stand establishment, and the requirement for supplemental N fertilizer over the residual level available in the soil after the first crop.

In Virginia, past research has identified an open-market window for fall broccoli (Sterrett et al., 1990). Because earlier studies demonstrated the feasibility of multicroping broccoli on plastic mulches (Burnette et al., 1993; Clough et al., 1990; Coffey and Ramsey, 1987), growers that invest in a plasticulture system can capitalize on this market opportunity by producing broccoli after summer vegetables. Due to seasonal production schedules, the use of transplants is recommended for uniform stand establishment (Elson et al., 1992; Sterrett et al., 1991). Furthermore, transplants allow for the production of large single-heads (>6 inches diameter) preferred by consumers (Jett et al., 1995; Relf

et al., 1990). As a result, growers supply a high-value fall product and use plastic and residual N fertilizer from summer production.

The feasibility of producing vegetable crops using new cultural practices requires an examination of basic production components. Broccoli cultivar selection can significantly impact yield, quality, and production schedule (Cutcliffe, 1975; Damato, 2000). Multicroping changes the grower approach to N management, which affects broccoli yield, leaf N accumulation, and N recovery (Sanders et al., 1993; Zebarth et al., 1995).

Furthermore, plant density impacts the quantity of marketable head and broccoli head-size (Chung, 1985; Jett et al., 1995). We conducted a 3-year study to identify practices that maximize large, single-head broccoli production.

Materials and methods

Experiments were conducted in 2003, 2004, and 2005 at the Virginia Polytechnic Institute and State University, Kentland Agricultural Research Farm, near Blacksburg, VA, at elevation ≈2000 ft on a Hayter loam soil (fine-loamy mixed, mesic Ultic Hapludaf, pH 6.8).

During 2003 and 2004, five transplant densities were tested using two broccoli cultivars, Everest (early, 49 d from transplanting) and Gypsy (midseason, 59 d), (Seedway Seed, Elizabethtown, PA). The 2005 experiment evaluated the interaction between planting density and nitrogen of ‘Gypsy’. ‘Gypsy’ was chosen for the 2005 experiment based on its enhanced postharvest attributes (Reddy, 2004).

In 2003 and 2004, plant densities were 19,425; 14,570; 11,735; 9715; and 8095 plants/acre, and in 2005, a low density of 7285 plants/acre was added. In-row plant spacing was 9, 12, 15, 18, 21, and 24 inches, respectively, using twin rows spaced 12 inches on the plasticulture bed. A split-block design was used with cultivar in 2003 and 2004, and nitrogen rate in 2005 as a main plot factors, and density as a subplot factor.

In the fall, a winter rye (*Secale cereale* ‘Abruzzi’) cover crop (Southern States, Richmond, VA) was established and grown through the spring. The cover crop was killed ≈8 weeks before planting using paraquat (Gramoxone™; Syngenta, Greensboro, NC) at 0.06 gal/acre. Experimental

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
2.2417	ton/acre	Mg·ha ⁻¹	0.4461
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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sites were first disked to incorporate cover crop residues, left for 2 to 3 weeks, and then chisel plowed and disked again.

Before planting, soil samples were taken to determine pH and residual fertility. In 2003 and 2004, a bulk blend urea, diammonium phosphate, and potash (Southern States, Richmond, VA) amounting to 50 lb/acre N, 75 lb/acre phosphorus (P), and 200 lb/acre potassium (K) in 2003 and 150 lb/acre K in 2004 was broadcast and incorporated by a tractor-mounted rototiller before bed formation. In 2005, 60 lb/acre P triple superphosphate and 175 lb/acre K potash (Southern States) was applied and all N was injected through the drip system after planting to simulate conditions of succession planting where preplant N application was not feasible. Raised beds 2.5 ft wide by 7 inches high were formed on 3-ft centers. Embossed black plastic (1.25 mil thickness) was laid over the bed with a single drip line (0.45 gal/min, 1-ft emitter spacing) installed 1 inch deep in the center of the bed.

Seeds were planted in 72 cell trays (1.5 × 1.5 × 2.0 inches) containing a peat-based media (Superfine Germination Mix; Fafard, Concord, MA). Plants were grown 6 to 7 weeks under day temperatures of 25 to 30 °C and 20 °C night and were acclimated for 7 d in a sheltered outdoor area before planting. Planting dates were 28 Aug. 2003, 29 July 2004, and 4 Aug. 2005. Adverse weather conditions delayed the planting date in 2003. To ensure adequate stand establishment, any wilted or dead plants were replaced for up to 4 d after planting. However,

due to extreme heat in 2005 and transplant loss, plants were replaced for up to 9 d. A twin guard row was established on the outside of the plot area.

A single drip line, set between the twin rows, was used for irrigation and fertilizer delivery. Beginning 2 weeks after transplanting in 2003 and 2004, supplemental fertilizer (20N–8.7P–16.7K, Millers Soluble; Miller Chemical and Fertilizer, Hanover, PA) was injected five times resulting in a supplemental N application of 50 lb/acre N. In 2005, three N rates (25, 60, and 100 lb/acre) of the same source were split into seven weekly applications beginning 1 week after transplanting. Disease, insects, and weeds were controlled following standard pest management recommendations (Bratsch et al., 2003).

Harvest began 10 weeks after planting and continued for 2 to 3 weeks, totaling eight to nine harvests. Head maturity and uniformity were the primary selection criteria for harvest. Leaves were removed and heads were cut to uniform lengths of 8 inches. Individual heads were sorted into marketable and cull yield. Culls included damaged heads and heads less than 3 inches in diameter. The marketable heads were further separated into large head category (>6 inches in diameter). All marketable heads were cut and checked for hollow stem. In 2003 and 2004, effects on maturity by cultivar were evaluated using the percentage of heads harvested during the first harvest. Treatment effects on maturity were not evaluated in 2005 because of variable stand establishment and delayed replacements.

In 2005, 10 whole leaves were sampled from each treatment during early heading to compare N uptake under the N regimes. Leaves were dried at 80 °C and analyzed for percentage of N (A&L Eastern Agricultural Laboratories, Richmond, VA).

Analyses of variance for yield data were completed with PROC GLM of SAS (SAS Institute, Cary, NC). Results are reported as significant when $P \leq 0.05$ for the least significant difference test.

Results and discussion

CULTIVAR EFFECTS. In 2003, the heads were smaller and had less stem hollowness (Table 1). The later planting date in 2003 and cooler temperatures during the growth period likely slowed the rate of head development and affected its size and quality, similar to the experiment conducted by Cutcliffe (1972). In 2004, the average head diameter of cultivars Gypsy and Everest were close to the targeted size of 6 inches.

In 2003 and 2004, ‘Gypsy’ produced higher average head weights, but also had significantly greater stem hollowness than ‘Everest’. However, in 2003, significant interactions between cultivar and plant density were observed for head weight ($P = 0.0043$) and stem hollowness ($P = 0.0077$). ‘Gypsy’ at the lowest density had the highest head weight and stem hollowness (data not shown). A correlation between head weight and hollowness has long been documented (Zink, 1968). No such interactions occurred in 2004.

When selecting a cultivar, growers consider maximizing yield and

Table 1. Broccoli yield and stem hollowness, as affected by cultivar during 2003 and 2004 growing seasons at Blacksburg, VA.

Cultivar	Total yield (tons/acre) ^z	Marketable yield ^y (tons/acre)	Large yield ^x (tons/acre)	Avg head wt (lb) ^z	Avg head diam (inches) ^z	Hollow stem (%)
2003						
Everest	4.8	4.3	3.1 a ^w	0.80 b	2.8 b	0 b
Gypsy	4.9	4.6	2.8 b	0.86 a	3.0 a	5 a
P value	0.460	0.860	0.025	0.008	0.004	<0.001
2004						
Everest	4.6 b ^w	4.4 b	2.9	0.75 b	5.9	14 b
Gypsy	5.4 a	5.0 a	3.2	0.95 a	5.9	60 a
P value	0.002	0.013	0.130	<0.001	0.86	<0.001

^z1 ton/acre = 2.2417 Mg·ha⁻¹, 1 lb = 0.4536 kg, 1 inch = 2.54 cm.

^yHeads > 3 inches diameter.

^xHeads > 6 inches diameter.

^wMeans within a column follow by different letters are significantly different at the 5% level according to the least significant difference test.

Table 2. Broccoli yield and stem hollowness as affected by density, averaged across cultivars and 2003 and 2004 growing seasons at Blacksburg, VA.

Density (plants/acre) ^z	Total yield (tons/acre) ^z	Market yield ^y (tons/acre)	Large yield ^x (tons/acre)	Avg head wt ^w (lb) ^z	Avg head diam (inches) ^z	Hollow stem ^w (%)
19,425	7.5 a ^v	2.8 a	0.9	0.62 d	4.3 c	5
14,570	7.0 ab	2.0 b	1.1	0.76 c	4.4 bc	9
11,735	6.4 bc	1.5 c	1.1	0.87 bc	4.6 abc	17
9,715	6.0 c	1.2 d	1.0	0.94 b	4.8 a	14
8,095	5.6 c	0.9 e	0.8	1.06 a	4.7 a	23
P value	0.002	0.001	NS	0.001	0.001	NS

^z 1 plant/acre = 2.4711 plants/ha, 1 ton/acre = 2.2417 Mg·ha⁻¹, 1 lb = 0.4536 kg, 1 inch = 2.54 cm.

^y Heads > 3 inches diameter.

^x Heads > 6 inches diameter.

^w Significant interaction occurred between cultivar and density in single year (2003) analysis.

^v Means within a column follow by different letters are significantly different at the 5% level according to the least significant difference test.

Fig. 1. Quadratic response of large broccoli head yield to plant density in 2003 and 2004 at Blacksburg, VA. The regression model was $Y = 1253 + 1.01X - 4.08 \times 10^{-5} X^2$ ($R^2 = 0.98$) where “Y” is number of large heads per acre and “X” is broccoli density. The maximum yield of 7500 large head per acre is obtained at $\approx 12,500$ plants/acre (1 plant or head per acre = 2.4711 plants or heads per hectare).

marketability. In both years, the trend for early maturity of ‘Everest’ was evident (Table 1). With succession cropping, planting date can be variable, and cultivar maturity should be considered in relation to market timing and adverse fall growing temperatures. Earliness is often a sought after trait for marketability, however, studies in Virginia have shown a later market window has better prices (Sterrett et al., 1990). Furthermore, in a related study to test modified-atmosphere packaging, ‘Gypsy’ displayed superior storage longevity and color retention (Reddy, 2004). Due to increased yield potential, marketability, and postharvest quality, despite increased stem hollowness, this study indicates ‘Gypsy’ as the preferred cultivar for fall broccoli production in plasticulture systems.

Table 3. Fall broccoli total yield and stem hollowness as affected by plant density and supplemental nitrogen (N) at Blacksburg, VA, during the 2005 growing season.

Density (plants/acre) ^z	Total yield (tons/acre) ^z			Hollow stem (%)		
	N rate (lb/acre): ^z			25	60	100
19,425	3.2 ^y	3.4	4.4 ab	8 c	11 d	29 d
14,570	3.0	4.0	5.0 a	13 c	40 c	50 c
11,735	3.2	3.9	4.1 ab	39 b	49 bc	59 bc
9,715	3.0	3.7	3.7 b	42 b	53 b	70 ab
8,095	2.8	3.6	4.1 ab	49 b	78 a	79 ab
7,285	3.2	3.2	3.8 b	73 a	72 a	83 a
P value	NS	NS	0.0198	<0.001	<0.001	<0.001

^z 1 plant/acre = 2.4711 plants/ha, 1 lb/acre = 1.1209 kg·ha⁻¹, 1 ton/acre = 2.2417 Mg·ha⁻¹.

^y Means within a column follow by different letters are significantly different at the 5% level according to the least significant difference test.

DENSITY EFFECTS. In 2003 and 2004, total yield was higher under higher densities (Table 2). Other studies confirm our results; higher yield with higher densities but with a trend for smaller heads (Chung, 1985; Palevitch, 1970; Zink and Akana, 1951). In addition, average head weight, average head diameter, and stem hollowness increased under the lower plant densities (Table 2). Under conditions of lower competition, faster plant growth and stem and head expansion rates have been speculated as reasons for increased hollowness (Cutcliffe, 1972). Stem hollowness appears to be a quality tradeoff for larger head development.

Recommendations for planting densities must achieve an efficient use of space. As a result, the primary objective of our study was to optimize the number of large heads of broccoli in a plasticulture system. Planting density determines plant populations, thus impacting the amount of space available for plant development. In 2003 and 2004, the combined result

of 7,500 large heads/acre peaked at $\approx 12,500$ plants/acre when analyzed with regression analysis (Fig. 1). On raised open soil beds, Jett et al. (1995) reported highest single-head broccoli yields under at 14,570 plants/acre.

NITROGEN EFFECTS. Although numerous N fertility trials have been reported on broccoli, comparison, interpretation, and extrapolation of the results can be difficult due to different geographic locations, soil, weather, and crop management systems (Kowalenko and Hall, 1987). Significant interactions between density and N were observed for total yield ($P = 0.0260$) and stem hollowness ($P = 0.0330$). At low and middle N rates, there was no difference between total yield under the density gradient. However, the highest N rate appeared to have increased total yield under increasing density and stem hollowness increased under high N and low plant densities (Table 3). Increased N fertility has been shown to moderate the reduction of head weight

Table 4. Fall broccoli yield, quality, and leaf nitrogen as affected by applied nitrogen (N) at Blacksburg, VA, during 2005 growing season.

N rate (lb/acre) ^z	Marketable yield ^y (tons/acre) ^z	Large yield ^x (tons/acre)	Avg head wt (lb) ^z	Avg head diam (inches) ^z	Leaf nitrogen (%)
25	2.8 b ^w	0.7 c	0.59 c	5.3 b	3.5 b
60	3.3 b	1.2 b	0.70 b	5.6 ab	4.2 a
100	4.1 a	2.0 a	0.79 a	5.7 a	4.4 a
P value	0.002	0.002	0.003	0.030	0.002

^z1 lb/acre = 1.1209 kg·ha⁻¹, 1 ton/acre = 2.2417 Mg·ha⁻¹, 1 lb = 0.4536 kg, 1 inch = 2.54 cm.

^yHeads > 3 inches diameter.

^xHeads > 6 inches diameter.

^wMeans within a column follow by different letters are significantly different at the 5% level according to the least significant difference test.

associated with high plant populations (Dufault and Waters, 1985).

In 2005, higher supplemental N rates increased marketable and large head yield. Average head weight and diameter were increased with higher N rates (Table 4). These results are consistent with other studies that reported that N had the most marked effect on marketable yield (Cutcliffe, 1971; Kahn et al., 1991; Zink and Akana, 1951) and stem hollowiness (Hipp, 1974; Tremblay, 1989). The improved yield parameters associated with higher N rates are supported by the higher percentage of N accumulation in leaf tissue (Table 4). Nitrogen accumulation in the above-ground portion of the plant increases with increasing rate of N fertilizer (Everaarts and De Willigen, 1999; Zebarth et al., 1995). In a study by Kowalenko and Hall (1987), high N rates significantly increased N in the leaf tissue and broccoli head without stimulation of the vegetative growth.

Data from 2003 and 2004 identify that a plant density of 12,500 plants/acre produces 7,500 large single-heads/acre in a twin-row plasticulture system. In addition, conditions for maximizing large head development also promote stem hollowiness. In 2005, the lower-than-expected yields were a result of simulating a multi-cropping environment where broadcast preplant N application is prohibitive. Further research is needed to refine N inputs and predict yield response of broccoli at the recommended densities following various seasonal fertility regimes in selected summer vegetables.

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