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Greenhouse Tomato Limited Cluster Production Systems: Crop Management Practices Affect Yield

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Abstract. **Limited-cluster production systems may be a useful strategy to increase crop production and profitability for the greenhouse tomato (*Lycopersicon esculentum* Mill). In this study, using an ebb-and-flood hydroponics system, we modified plant architecture and spacing and determined the effects on fruit yield and harvest index at two light levels. Single-cluster plants pruned to allow two leaves above the cluster had 25% higher fruit yields than did plants pruned directly above the cluster; this was due to an increase in fruit weight, not fruit number. Both fruit yield and harvest index were greater for all single-cluster plants at the higher light level because of increases in both fruit weight and fruit number. Fruit yield for two-cluster plants was 30% to 40% higher than for single-cluster plants, and there was little difference in the dates or length of the harvest period. Fruit yield for three-cluster plants was not significantly different from that of two-cluster plants; moreover, the harvest period was delayed by 5 days. Plant density (5.5, 7.4, 9.2 plants/m^2) affected fruit yield/plant, but not fruit yield/unit area. Given the higher costs for materials and labor associated with higher plant densities, a two-cluster crop at 5.5 plants/m^2 with two leaves above the cluster was the best of the production system strategies tested.**

The greenhouse tomato grower in the northeastern United States and other similar regions is faced with many challenges, including: high heating and electrical expenses; competition from domestic and foreign growers; unstable market prices; and above average labor costs (Bartok, 1994; Welwitta and Govindasamy, 1996). Research on alternative production systems that may increase yield and reduce operating expenses is clearly warranted.

The single-cluster hydroponic tomato production system was designed for continuous year-round production, with as many as five crops per year (Giniger et al., 1988; Janes and McAvoy, 1989). Growers using this system can capitalize on the premium paid for dependability and continuity of supply, especially during the midwinter period (McAvoy and Janes, 1989), compared with the traditional two-crop system with harvests in the fall and spring. Some additional benefits of the single-cluster system are: easier accessibility for handling plants during pruning; pollinating, spraying, and harvesting (Fisher et al., 1990; Logendra and Janes, 1999); better utilization of natural and supplemental light (Janes and McAvoy, 1991; McAvoy et al., 1989); improved labor efficiency via automation of some cultural practices (Giacomelli et al., 1994a; Janes and McAvoy, 1991); and better space utilization, since plants grow in transportable benches (Giacomelli et al., 1994b; McAvoy and Janes, 1988).

The major drawback of single-cluster tomato production is the poor use of vertical space in the greenhouse, since the whole plant, with only one cluster, is removed after harvest. As a result, the potential value of the materials (seed, rock wool, fertilizer, etc.), labor, and energy expended to bring the plant into production are not fully realized. Moreover, once the plant is established for the production of one cluster, any accidental damage to that cluster during pollination, side shoot removal, or other cultural practice will result in a plant with no fruit. In addition, since crops at different stages of development occupy the greenhouse at the same time, crop management is more complicated.

Many components of the production system, such as variety selection, plant density, plant architecture, fertilizer application, supplemental lighting, and enrichment of the greenhouse environment with CO_2, could be manipulated to increase the yield per unit area. In this study, we modified plant architecture and spacing, and determined the effects on fruit yield and harvest index for the greenhouse tomato cultivated using an ebb-and-flood hydroponics system.

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Materials and Methods

Seeds (cv. Laura) were sown singly in rock wool (RW) plugs (2.5 × 2.5 × 3.8 cm) and kept moist until germination at 25 °C. Seedlings were fertilized daily with 1 Hydrosol (E.C. Geiger, Harleysville, Pa.) : 1Ca(NO3)$_2$ solution (1.0 mS·cm^{-1}). After 2 weeks, the seedlings in RW plugs were placed in the center of RW blocks (7.6 × 7.6 × 6.3 cm) that had a hole cut large enough to accommodate the plug. Seedlings were irrigated daily with 1 Hydrosol : 1 Ca(NO3)$_2$ solution (2.3 mS·cm^{-1}) and spaced at 20 × 20 cm. The irrigation cycle was increased to twice per day after 4 weeks. At 5 weeks, plants were moved to ebb-and-flood aluminum benches (1.4 × 5.0 m), and placed on a thin sheet of rayon-polyester material that lined the bench (Logendra and Janes, 1999), at a spacing of 30 × 30 cm, unless specified otherwise, and irrigated six times per day with nutrient solution. The aerial portion of the plant was supported with two horizontal layers of galvanized wire mesh netting (12 gauge, with 15 × 20-cm grids) mounted on the benches at 30, and at either 60 or 90 cm above the benchtop. Plants were topped by pinching the terminal bud of the main stem, leaving two leaves above the first, second, or third flower cluster, depending on the experiment, when the uppermost leaf was 5 cm in length. Side shoots were manually pruned when required. Pollination was accomplished by vibrating the flower clusters daily with a leaf-blower during the flowering period. Fruits were harvested at the firm red stage. The crop was removed after 80% to 85% of the fruit were harvested, and the remaining fruit were stored ≈1 week at room temperature until ripe. Total side shoot number and weight, days to anthesis of the first flower of the first cluster, total fruit number and weight, plant shoot fresh weight, harvest date, plant height at 35 d, plant height at harvest, and harvest index (fresh weight basis) were determined. If the outside natural light intensity was <800 μmol·m^{-2}·s^{-1}, supplemental lighting was provided from high-pressure sodium lamps at an intensity of 80 μmol·m^{-2}·s^{-1} for 16 h from 0500 to 2100 HR. Light integral measurements were recorded with LI-COR, LI 1000 data-logger (LI-COR, Lincoln, Nebr.) with quantum sensors located 1 m above the benchtop. The greenhouse was maintained at 24 °C day/20 °C night air temperature. All data were subjected to analysis of variance for a randomized complete-block experiment. Means were separated by LSD test.

Expt. 1. Effect of number of leaves above the fruit cluster in single-cluster plants. Plants were pinched at 50 d so that there were zero, one, or two leaves above the first cluster (Table 1). The experimental design was a randomized complete-block with three treatments (two plants/treatment per block) and eight blocks. The experiment was conducted under typical winter lighting conditions, with a measured average daily light integral of 10.6 mol·m^{-2}·d^{-1}, and under typical spring lighting conditions with a measured average daily light integral of 25.1 mol·m^{-2}·d^{-1}.

Expt. 2. Effect of number of clusters/plant. Experiments with multiple clusters were conducted to determine if better use could be made of greenhouse vertical space without significantly increasing crop production time or reducing the number of crops per year. The first study compared single and two-cluster production systems in a randomized complete-block design with two treatments (nine plants/treatment per block) and two blocks (Table 2). The second study compared single, two-, and three-cluster systems in a randomized complete-block design with three treatments (four plants/treatment per block) and two blocks (Table 3). Plants were pinched at two leaves above the final cluster. This study was repeated twice with similar results.

Expt. 3. Effect of plant density. To improve utilization of bench space, plant density experiments were conducted using the two-cluster system. All of the plant spacings tested would be considered high density compared with the conventional spacing of 2.5–3.6 plants/m^2. Two-cluster tomato plants were grown at three densities: 30×30, 30×45, and 30×60 cm (9.2, 7.4, and 5.5 plants/m^2) in a randomized complete-block design with three treatments (four plants/treatment per block) and two blocks (Table 4). Plants were pinched at the shoot apex, leaving two leaves above the second cluster. The experiment was conducted under typical winter lighting conditions with a measured average daily light integral of 7.0 mol·m^{-2}·d^{-1}, and under typical spring lighting conditions with a measured average daily light integral of 17.2 mol·m^{-2}·d^{-1}. This study was repeated twice with similar results.

Results and Discussion

Expt. 1. Effect of number of leaves above the cluster in single-cluster plants. Yield in tomato is a product of fruit number and fruit weight. Leaving two leaves above the fruiting cluster significantly increased fruit yield/plant by ≈25% for both the winter and spring experiments compared with no leaves above the cluster (Table 1); 9 or 10 leaves remained below the cluster to provide assimilate to the developing fruit. In the spring experiment, the increase in yield for the two-leaf treatment resulted from an increase in fruit weight, rather than fruit number.

In tomato, the fruiting cluster imports carbohydrate from leaves above and below through the external and internal phloem, respectively (Ho and Hewitt, 1986), although a greater percentage of assimilates are typically supplied by the two (Bonnemain, 1965) or three (Shishido and Hori, 1977) leaves subtending the cluster. Leaves above the cluster typically supply the apical meristem, and the young leaves and flower clusters, whereas the lowest leaves on the stem supply the root system (Khan and Sagar, 1967). It was therefore surprising that additional leaves above the fruiting cluster had such a significant effect on fruit yield. However, for single-cluster plants in which the apical bud had been removed, yield was correlated with total leaf dry weight regardless of the relative position of the cluster on the stem (Fisher, 1975). Moreover, in our experiments with an ebb-and- flood hydroponic system, the root system was greatly reduced, minimizing its importance as a carbohydrate sink. Without significant competition for assimilates from the apical bud and the roots, the fruiting cluster was the predominant sink for carbohydrate and could be supplied by leaves both below and above it. This may also account for the high harvest index measured in these experiments (>60%, Table 1), compared with only 50% for three-cluster plants (Tanaka et al., 1974) or 36% for single-cluster plants (Yoshioka and Takahashi, 1979) grown in other cultural systems.

Light has long been considered to be the limiting factor in greenhouse tomato production in northern latitudes (Cooper, 1961; Craig, 1959). This is also true in limited-cluster systems. While the average air temperature was about the same in the winter and spring experiments, average total light integral/d differed considerably. As a result of higher light levels, fruit yield was higher in the spring experiments due to increases in both fruit number and fruit weight (Table 1). Photosynthetic activity of source leaves probably increased in the spring, but given the difference in harvest index between winter and spring experiments, increased sink strength of the flowers and fruit probably also contributed to increased yield. There may, therefore, be an additional direct effect of light on fruit set and early development. For example, in tomato, and in many other plants, low light intensity inhibits pollen development and reduces the size of the ovary (Picken, 1984) leading to floral abortion and fruit abscission (Kinet, 1977). In soybean [*Glycine max* (L.) Merrill], providing light directly and exclusively to the flowers increased pod set, perhaps by stimulating the mobilization of assimilates to the flowers and young fruit (Myers et al., 1987). High light intensity, therefore, can increase both the assimilate supply and sink strength of flowers and young fruit, leading to an increase in fruit number and fruit size. Increasing the number of leaves also increases assimilate supply, but does not affect sink strength of the flowers and fruits. This results in an increase in fruit weight, but not fruit number (Table 1).

Expt. 2. Effect of number of clusters/plant. When single and two-cluster plants were compared, two-cluster plants were taller and yielded 30% to 40% more because of increased numbers of fruits (Table 2). Since there is considerable overlap in the develop-

Table 1. Effects of pruning to 0, 1, or 2 leaves above the fruiting cluster on vegetative and reproductive growth in a single-cluster greenhouse tomato crop grown hydroponically under winter (10.6 mol·m^{-2}·d^{-1}) and spring (25.1 mol·m^{-2}·d^{-1}) lighting conditions.

No. of leaves	Side shoots		Plant ht. at	Shoot	Fruit			Harvest
above cluster	No./plant	Fresh wt (g)	harvest (cm)	fresh wt (g)	Wt/plant (g)	No./plant	Avg wt (g)	index
				Winter				
0	4.4 a[z]	18.0 a	61.9 c	358 b	697 b	4.1 a	173 a	0.66 a
1	4.7 a	22.0 a	64.9 b	404 a	807 ab	4.3 a	188 a	0.67 a
2	5.3 a	24.3 a	69.8 a	452 a	892 a	4.8 a	193 a	0.66 a
				Spring				
0	3.1 a	22.0 b	57.6 c	493 b	1236 b	5.7 a	220 b	0.71 a
1	3.4 a	38.3 ab	61.5 b	548 b	1323 b	5.9 a	227 b	0.71 a
2	3.5 a	50.0 a	65.0 a	608 a	1506 a	6.0 a	252 a	0.71 a
				Winter vs. Spring				
	**	**	*	***	***	***	*	**

[z]Mean separation within columns and seasons by LSD, $P \leq 0.05$.
*, **, ***Significant at $P \leq 0.05$, 0.01, or 0.001 respectively.

Table 2. Vegetative and reproductive growth of one- vs. two-cluster plants in a hydroponically-grown greenhouse tomato crop.

No.	Plant ht (cm)		Time of anthesis	Fruit			Harvest
clusters/plant	At 35 DAS[z]	At harvest	of the 1st flower (d)	No./plant	Wt/plant (g)	Avg wt (g)	interval (DAS)
1	22.6	70.9	47.8	5.1	726	165	93–104
2	22.4	96.8	47.7	8.4	1094	127	93–106
Significance	NS	***	NS	*	**	NS	

[z]DAS: days after sowing.
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

ment of the fruit on the first two clusters, there was essentially no difference in the harvest period and it only took an additional 2 d to harvest the remaining fruit from the second cluster on two-cluster plants. When a third cluster was left (Table 3), plants were significantly taller and had more leaves, but fruit yield was not significantly greater than for two clusters. Moreover, the harvest period was delayed 3 d and not completed until 110 d after seeding, 5 d after the harvest of two-cluster plants. Fruit set on the third cluster was very low (data not shown). Given the considerably reduced root systems of the plants, there may be inadequate levels of root-derived hormones for fruit set and development on a third cluster, or a third cluster may be unable to compete with older clusters that have higher sink strength.

Expt. 3. Effect of plant density. Under the higher light conditions of spring (17.2 $mol\cdot m^{-2}\cdot d^{-1}$), fruit yield/plant and fruit weight were greater for the lower density treatments, but fruit yield was not significantly affected by plant spacing arrangements when calculated on a unit area basis (Table 4). Under the lower light conditions in winter (7.0 $mol\cdot m^{-2}\cdot d^{-1}$), spacing affected neither yield/plant nor yield/unit area; plants at the highest density were significantly taller, whereas at higher light levels, plant density did not affect height. Plant spacing had no effect on harvest index within seasons, although, as in Expt. 1, harvest index and fruit yield were greater under the higher light conditions. Given the greater costs of materials, such as fertilizer, seed, and rock wool, and the increased labor costs for pruning, harvesting, and pest control, there seems to be little advantage to increasing plant densities above 5.5 plants/m^2, particularly at higher light levels, because crop yield per unit area is not significantly increased. Moreover, fruit weight was largest at the lowest density. In many studies in both field- and greenhouse-grown tomato crops, as plant density increased, yield/plant decreased, but yield/m^2 increased, although fruit weight eventually declined at extremely high densities (>5.5 plants/m^2) reducing yield/m^2 (Fery and Janick, 1970; Papadopoulos and Ormrod, 1988,1990; Rodriguez and Lambeth, 1975). Declining plant yield is likely to result from inter- and intra-plant competition for light (Fery and Janick, 1970). However, at lower plant densities under high light conditions, yield may be greater because of increased light penetration to lower leaves in the canopy (Papadopoulos and Ormrod, 1988).

For the limited-cluster production system, using ebb-and-flood benches with supplemental light, a two-cluster plant with two leaves above the second cluster, spaced at 5.5 plants/m^2, was the most cost-effective of the cropping designs that were tested. Moreover, a 29% increase in fruit yield was obtained with the two-cluster system (five crops per year) compared with the traditional production system (two crops per year in the spring and fall) (unpublished data). Using plant growth regulators to increase fruit set, or to advance and synchronize fruit ripening in the limited cluster production system, and these experiments will be the subject of future investigations.

Table 3. Vegetative and reproductive growth of single, two- vs. three-cluster tomato plants grown hydroponically in a greenhouse.

	No. clusters/plant		
Observation	1	2	3
Plant height (cm)			
35 d after sowing (DAS)[z]	24.6 a[y]	26.4 a	25.2 a
At harvest	72.8 c	94.8 b	117.9 a
Side shoot			
No./plant	11.1 a	13.2 a	13.8 a
Wt/plant (g)	31.0 a	48.3 a	86.8 a
Shoot fresh wt. (g)	554 a	600 a	690 a
No. leaves/plant	12.0 c	14.9 b	18.4 a
Fruit no./plant	6.2 b	10.1 a	11.1 a
Weight of fruit (g)			
Per plant	1351 b	1771 a	1692 a
Per fruit	216 a	172 a	149 a
Per leaf	112 a	119 a	92 a
Harvest Index	0.69 a	0.72 a	0.67 a
Harvest interval (DAS)	89–103	89–105	92–110

[z]DAS: days after sowing.
[y]Mean separation within rows by LSD, $P \leq 0.05$.

Table 4. Vegetative and reproductive growth of two-cluster tomato plants at three plant spacings grown under winter (7.0 $mol\cdot m^{-2}\cdot d^{-1}$) and spring (17.2 $mol\cdot m^{-2}\cdot d^{-1}$) lighting conditions.

Spacing (cm)	Plant ht at harvest (cm)	Time of anthesis of the 1st cluster (d)	Shoot fresh wt (g)	Fruit No./plant	Fruit Wt/plant (g)	Fruit Wt/m^2 (kg)	Fruit Avg wt (g)	Harvest index
				Winter				
30 × 30	121 a[z]	47.0 a	518 a	6.6 a	893 a	7.6 a	136 a	0.61 a
30 × 45	108 b	47.5 a	606 a	7.6 a	1141 a	7.9 a	151 a	0.62 a
30 × 60	105 b	47.3 a	640 a	8.5 a	1264 a	6.5 a	151 a	0.61 a
				Spring				
30 × 30	84 a	43.4 a	454 b	7.1 a	1167 c	10.0 a	158 b	0.69 a
30 × 45	76 a	43.0 a	542 ab	8.0 a	1489 b	10.2 a	183 b	0.71 a
30 × 60	77 a	44.9 a	658 a	9.5 a	2058 a	10.6 a	221 a	0.74 a
				Winter vs. Spring				
	***	***	NS	*	*	*	*	**

[z]Mean separation within columns and seasons by LSD, $P \leq 0.05$.
[NS, *, **, ***]Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

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