den 'Redmond' and silver linden 'Sterling' required the fewest hours of chilling to produce measurable foliar budbreak.

Following termination of the greenhouse portion of this study, all trees were moved back to the growing area outdoors to allow observation of subsequent growth. By the end of the growing season in Fall 2000, differences observed in initial budbreak were magnified. Trees within each cultivar that had received greater amounts of chilling were larger than trees receiving less chilling. Furthermore, the overall growth was greater on 'Sterling' than the other cultivars, with the least overall growth occurring for 'Redmond'.

This study provides an indication of the need to carefully select lindens suitable for the region in which they will be grown, whether in field or container production or in the landscape. Based on the results of this study, considering the parameters evaluated for these four linden cultivars, 'Sterling' appears to be the most suitable linden for landscape use in similar climate regions to Auburn, Ala.

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Production of High-quality Tomato Transplants with a Novel Buffered Fertilizer

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ADDITIONAL INDEX WORDS. *Lycopersicon esculentum*, **phosphorus, root development, runoff**

SUMMARY. 'FTE 30' tomato (*Lycopersicon esculentum*) transplants were produced in Florida under standard commercial conditions and supplied with one of six treatments: zero, low (20% of the control rate), or high (control) super-phosphate (SP) fertilizer, or 0.5%, 1%, or 2% buffered-phosphorous fertilizer (Al-P). Growth characteristics were evaluated for four sets of transplants, produced in January, April, May, and August. Two sets of transplants were grown in the field in Florida (started in January and August) and one set was grown in Pennsylvania during the summer (started in May). Phosphorus concentration in leachate was measured weekly from one crop. Plants grown with Al-P showed a 72% to 88% reduction in P released in leachate compared with the high SP control. Transplants produced with 1% or 2% Al-P were of equal size and quality compared with transplants produced with conventional (high SP) fertilization, and had greater total root length and specific root length (length per unit root weight). Transplants grown with 0.5% Al-P were sometimes smaller than other fertilized treatments, while no-P plants were very small and grew slowly after transplanting. There were no significant differences in growth, yield, or fruit quality of plants from

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transplants grown with 1% or 2% Al-P or high SP at either site. Therefore high quality tomato transplants can be produced using buffered-P fertilizer, while reducing P leaching from the containers.

Production of quality crops from transplants requires the use of uniform, high quality transplants. Many factors determine transplant quality, including leaf area, root to shoot ratio, root volume, fertilization, height, transplant age and shipping and storage conditions and duration (Cantliffe, 1993). High quality transplants are tolerant of shipping and transplanting stresses and are capable of rapid establishment in the field, leading to earlier and often greater yield (Orzolek, 1991, 1996; Vavrina and Orzolek, 1993). Transplants should be compact and short for efficient planting with mechanized planters. Shoot growth is currently regulated by plant age (Vavrina and Orzolek, 1993). Growth retardants are effective for height control, but have not been labeled for use on vegetable crops (Orzolek, 1986). Water restriction, nutrient stress (especially low P), and other treatments may be used to control height but these may have negative effects on subsequent field establishment and yield (Cantliffe, 1993; Latimer, 1991). Mechanical conditioning, such as brushing or shaking, works well, but development of mechanized equipment has so far been a limitation (Latimer, 1991).

It has been suggested that lower P availability could be used to restrict shoot growth as a method of growth retardation (Sheldrake, 1991). The reduced leaf area and the increased root to shoot ratio associated with lower P availability would be expected to improve resistance to transplant shock, especially under dry conditions (Watts et al., 1981). However, it is difficult to reduce P to an extent necessary to produce desirable growth retardation without risking P deficiency, because P availability is difficult to control in horticultural media. Media used for production of transplants and many other horticultural crops are typically based on peat and other materials which lack the ability to bind and buffer P. Thus, any P added to the medium which is not immediately used by the plant would be leached out in the next irrigation (Yeager and Barrett, 1986). Growers must therefore add excess P to ensure an adequate supply at all times. Concentrations of P typically used in transplant production are in the range of 150 to 500 μM (1.5 to 4.6 ppm) while fertile soils contain only 1 to 5 μM (0.03 to 0.15 ppm) P in solution (Reisenaur, 1964).

Excessive P use in horticultural production systems is wasteful and can create significant environmental problems when P enters the environment. This is a recognized problem in the transplant production areas of Florida, a major producer of vegetable transplants for the eastern U.S. (Vavrina and Summerhill, 1992). Transplant production in Florida is concentrated in regions adjacent to the Everglades, which is ecologically sensitive to P in agricultural runoff. Fertilization technologies such as buffered P that reduce P leaching from container grown plants might help alleviate this problem.

Alumina-buffered P (Al-P) is a novel method for supplying a lower but constant concentration of P in the medium (Elliott et al., 1983; Lin et al., 1996; Lynch et al., 1990). The buffering ability of alumina mimics the complex chemical and biological buffering of solution P that occurs in natural soil (Comerford, 1998). Use of Al-P rather than conventional soluble or slow-release fertilizer has been shown to greatly reduce P concentration in leachate from various containerized crops (Borch et al., 1998; Brown et al., 1999; Lin et al., 1996). Marigold (*Tagetes patula*) and impatiens (*Impatiens wallerana*) plants grown with Al-P had better post-production quality and wilted more slowly when irrigation was withheld than plants grown with conventional soluble P fertilizer (Borch et al., 1998). Differences in drought tolerance were attributed to better root development and smaller leaves.

The effects of Al-P on root morphology and architecture could be important for quality and establishment of vegetable plants, which are typically produced as plugs and transplanted into the field. Rapid root proliferation after transplanting may be an important factor determining establishment and early yield (Leskovar and Stofella, 1995; NeSmith, 1999). Buffered P fertilizers may therefore be useful in reducing P leaching from transplant production areas, and in producing transplants with better rooting, and therefore better resistance to the stresses of shipping and transplanting operations. The objective of this study was to evaluate Al-P fertilizer for the production of tomato transplants in Florida, including evaluation of field performance of the transplants in both Florida and Pennsylvania.

Materials and methods

Tomato transplants were produced in Immokalee, Fla., in Speedling (Plant City, Fla.) Styrofoam plug trays with 10×20 cells, 26 cm^3 (1.6 inch^3) each, which were sterilized by dipping in a 0.3% sodium hypochlorite solution and then rinsing in water. Before seeding, Verlite Vegetable Plug Mix A (Verlite, Tampa, Fla.) medium with no starter fertilizer was mixed with one of the following P treatments: no P = plain Verlite, high SP = 1.48 g·L^{-1} (2.5 lb/yard^3) super-phosphate [0.13 g·L^{-1} (130 ppm) elemental P], low SP = 20% of control [0.297 g·L^{-1} (0.5 lb/yard^3) super-phosphate [0.026 g·L^{-1} (26 ppm) elemental P], 0.5% Al-P = 5 g·L^{-1} (8.4 lb/yard^3) Al-P; 1% Al-P = 10 g·L^{-1} (16.8 lb/ yard^3) Al-P, or 2% Al-P = 20 g·L^{-1} (33.7 lb/ yard^3) Al-P. The Al-P was produced with a desorbing concentration of 200 μM (6.2 ppm) P after the first rinse (Lynch et al., 1990). Previous work had shown that Al-P at 1% to 2% provides adequate P for plant production (Borch et al., 1998; Lin et al., 1996). Tomato seeds of 'FTE 30' (Petoseed, Seminis Inc., Oxnard, Ca-

Table 1. Dates and locations of transplant production and planting in field sites. All transplants were started in Immokalee, Fla., and one set was planted in Rock Springs, Pa.

Transplants started	Season designation	Planted in field	
		Site	Date
28 Jan.	Winter	Immokalee	14 Mar.
9 Apr.	Spring	Not planted	---
24 Apr.	Summer	Rock Springs	10 June
12 Aug.	Fall	Immokalee	15 Sept.

lif.) were planted in the trays, which were watered daily with a 1/4-strength Hoagland's solution modified to contain no P (Lorenz and Maynard, 1988). The N concentration was 56.25 μM (45 ppm) from ammonium nitrate (NH_4NO_3). Transplants were grown in a greenhouse with a clear plastic cover and sides that were lowered during the day. There were four blocks per treatment, each block consisting of one-half tray (100 plants).

Tomato transplants were started 28 Jan. (winter), 9 Apr. (spring), 24 Apr. (summer), and 12 Aug. (fall) and sampled after 5 weeks for transplant quality (Table 1). The following measurements were made on transplants from all four crops in Florida: stem length and diameter, fresh weight of roots and shoots, leaf area, dry weight of leaves, stems, roots, and shoots, true leaf number, and chlorophyll content, measured as absorption of green light (calculated from differences in optical density at about 650 and 940 nm) with a chlorophyll meter (SPAD 502; Minolta, Ramsey, N.J.). There were five plants sampled from each of four blocks. Transplants from the winter, summer, and fall experiments were also sent to Pennsylvania and the following characteristics were evaluated on one plant from each of the four blocks: root length, root, shoot, and leaf dry weight, and P content of leaves, roots, and stems. For root length determination, whole root systems were scanned using a flat bed scanner (Scanjet IIC; Hewlett Packard, Palo Alto, Calif.). Root length was estimated using image analysis software (Delta-T SCAN; Delta-T Devices LTD, Burwell, Cambridge, England). Specific root length was calculated by dividing the total root length per plant by the dry weight of the roots. Root to shoot ratio was calculated from the dry weight of the roots and shoots. Dry weights used in these calculations were from the samples processed at Pennsylvania State University, i.e., the same samples as used for root length. The P content of dried plant tissues was measured by the method of Murphy and Riley (1962).

For measurements of P in leachate, plants started in January were evaluated weekly. Twenty cell subunits were cut from the experimental flats for the leachate collection. These subunits were placed atop plastic boxes on the days when all leachate was collected (once per week). To create leachate, two applications of 100 mL (3.38 oz) water each were applied via graduated cylinder (taking care not to spill over) over the individual subunits at each collection time. Water in and water out was measured. On days when leachate was not collected (i.e., irrigation for transpirational replacement only) plants were irrigated manually with minimal water, so as not to create runoff. Minimal or no leaching occurred on those days. The P concentration was measured by the method of Murphy and Riley (1962).

Three of the transplant crops were planted in the field to evaluate field establishment and yield, two in Florida and one in Pennsylvania. Winter and fall transplants were planted in Immokalee fine sand (sandy, silicaceous, hyperthermic, Arenic Haplaquod) in Immokalee on 5 Mar. 1997 and 15 Sept. 1997, respectively. Beds in the fall were fumigated with methyl bromide and fertilized in a combination broadcast/banded application with 224 kg·ha^{-1} (200 lb/acre) nitrogen (N), 56 kg·ha^{-1} (52.6 lb/a) P, and 291 kg·ha^{-1} (260 lb/acre) potassium (K). For the spring experiment, beds from the previous fall were reused, and N and K rates similar to those used in the fall were side dressed in three separate applications (i.e., 1/3 of the total rate each) by introducing into holes 30.4 cm (12 inches) from the center of the bed on each side of the plants in February, March and April. No additional P was supplemented in the spring. Plants were spaced 61 cm (24 inches) (spring) or 46 cm (18 inches) (fall) apart under white plastic in beds spaced 1.83 m (6 ft) apart (center to center). Plants from different P regimes were arranged in a randomized complete block design with six blocks each containing 16 (winter) or 14 (fall) plants for each P treatment. Seepage irrigation was used to water tomato plants when required. Plants were staked, pruned, and tied. Plant establishment was evaluated by clipping plants at ground level at 30 and 45 d after transplanting for determination of shoot fresh weight and the number and weight of green fruit. There were six samples per treatment in the winter experiment and three samples per treatment in the fall experiment. Fruit were harvested 11 and 12 weeks after transplanting for the spring experiment and 11, 12, and 13 weeks after transplanting for the fall experiment. Fruit were separated into size and color (red or green) classes, counted, and weighed. Size grades were determined by fruit diameter classes as follows: extra-large, >7.14 cm (2 25/32 inches); large, 6.51 to 7.14 cm (2 17/32 to 2 27/32 inches); medium, 5.79 to 6.51 cm (2 9/32 to 2 19/32 inches); cull, <5.79 cm (2 9/32 inches).

Transplants started on 24 Apr. were shipped to Pennsylvania 2 June and arrived 3 June. They were stored in a cold room [5 °C (41 °F)] in the dark for 2 d and then in a cold frame for 5 d before planting. Preplant fertilizer (12N–21P–6.6K) was applied to the plots at 44.8 kg·ha^{-1} (40 lb/acre) N. Transplants were planted through black plastic mulch by hand on 10 June in Rock Springs, Pa. Replications of 15 plants per treatment were arranged in a randomized complete-block design within six rows, each 148 m (485.6 ft) long. The center four rows, each with six replications, were the experimental plants, and these were surrounded by border plantings of 15 plants each. Plants were spaced 0.8 m (2.62 ft) apart. Six adjacent plants were left in the center of each replication for yield evaluation, and other plants, not adjacent to those used for yield, were sampled during the season for assessment of plant establishment. Irrigation was provided by drip tape and standard production practices for tomato were used (Orzolek et al, 1997). Plant establishment was evaluated by measuring plant height, width, leaf number, shoot dry weight and root dry weight at 2 and 4 weeks after planting, and shoot dry weight, root dry weight and green fruit number 8 weeks after planting. Breaker, turning, and pink fruit were harvested at 16 and 17 weeks after planting, passed through a size grader, counted and weighed. Size ranges for fruit diameter in each grade were extra-large, greater than 7.0 cm (2 3/4 inches); large, 6.5 to 7.0 cm (2 9/16 to 2 3/4 inches); medium 5.7 to 6.5 cm (2 1/4 to 2 9/16 inches), and cull (not included in yield) <5.7 cm (2 1/4 inches). Defective and fully ripe fruit were not included in yield data.

The effects of P treatments and season of production were analyzed using analysis of variance (ANOVA), and mean comparisons were done by Fisher's protected least significant dif-

Table 2. Analysis of variance results for the effect of P and season of transplant production (S) on various measures of transplant growth. F ratio values are shown; ^{NS,*,**,***}Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively. Degrees of freedom for analyses of Florida (FL) data were 5 (P), 3 (S), 15 (P×S), and 69 (residual), and for Pennsylvania (PA) they were 5 (P), 2 (S), 10 (P×S) and 54 (residual) because PA did not collect data for the spring transplants.

Variable	Site evaluated	P	S	P × S
Total dry weight	FL	33.5***	32.0***	2.1***
Shoot dry weight	FL	37.7***	31.6***	2.5**
Leaf number	FL	10.8***	29.9***	0.7^{NS}
Leaf area	FL	45.8***	8.6***	2.9**
Stem length	FL	44.3***	2.4^{NS}	1.3^{NS}
Leaf chlorophyll	FL	14.6***	11.1***	3.8***
Root dry weight	PA	67.2***	228.1***	12.3***
Root length	PA	30.7***	47.7***	8.9***
Specific root length	PA	11.2***	4.5*	9.3***
Root to shoot ratio	PA	14.0***	128.4***	2.8**
P content of leaves	PA	171.5***	38.1***	11.9***

ference (PLSD) (StatView, SAS Institute, Cary, N.C.). Means of subsamples within blocks were used in ANOVA and standard error (SE) calculations. Where significant mean comparisons are given in the text, the F ratio was significant at $P < 0.05$ and means were compared with Fisher's PLSD.

Results

Growth. Transplant growth—measured as total dry weight, shoot dry weight, root dry weight, and leaf number or area—was significantly affected by P treatment and season of transplant production (Table 2). However, as expected, the largest differences were found between the no-P treatment and the other treatments. When comparing the treatments other than no-P, there were only small or insignificant differences which varied with the season of production. Low Al-P transplants had smaller dry weights than transplants grown with P treatments other than no-P in the summer and fall experiments, but low SP treatments, which were provided only 20% of the recommended rate of P, were not significantly different from high SP, medium Al-P or high Al-P treatments (Fig. 1). Similar patterns were observed for leaf area, fresh and dry weights of leaves and shoots, and stem length (not shown). Leaf number was less affected by P treatment than was shoot fresh or dry weight. For example, shoot dry weight was reduced by 52% in no-P transplants compared to high SP transplants in the summer experiment, while leaf number was reduced by only 21% (data not shown). There were no significant differences in leaf number among treatments that received P fertilizer.

Chlorophyll readings were significantly affected by season and P treatment (Table 2). Except in the spring, when all values were equal except no-P, the Al-P and low SP treatments had higher chlorophyll values compared with the high SP control (Fig. 2).

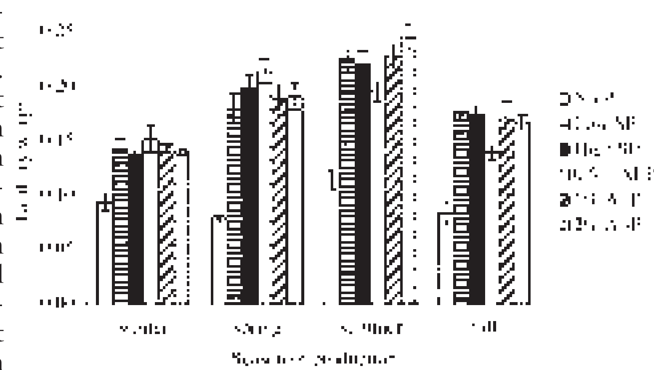
Root fresh and dry weights showed a response to P treatment and season similar to total dry weight (Fig. 1). However, the differences in root growth were less pronounced than those in shoot growth, resulting in higher root to shoot dry weight ratio in some of the lower P treatments (Figs. 1 and 3, Table 2). Despite the higher root to shoot ratios of the no-P and low SP treatments, there was only a weak negative correlation between total transplant dry weight and root to shoot ratio ($r^2 = 0.39$). Root to shoot ratios of transplants grown with 1% or 2% Al-P were not significantly different from the high SP control.

P treatment and season of transplant production significantly affected root length (Table 2, Fig. 4). Overall, root lengths were higher in transplants produced in summer and in transplants produced with Al-P or low SP. Mean comparisons over all seasons showed significantly greater root lengths for Al-P grown transplants compared with the high SP control ($P < 0.0001$). Root length was also significantly increased by the low SP treatment compared with the high SP control ($P < 0.001$), but root length was reduced when no P fertilizer was added ($P < 0.0001$).

Differences among treatments in root length were larger than differences in root dry weight or root to shoot ratio, especially when high SP and Al-P treatments were compared. This could be explained by the specific root length (root length per unit dry weight) (Fig. 5). Over all seasons, specific root length was greater in all Al-P treatments than in the high SP control or in the no-P treatment, while Al-P treatments were not significantly different from each other or from the low SP treatment. Specific root length was particularly extreme in the fall experiment, when high SP plants had very low values, while the other treatments had greater values than in the other seasons. This was due to differences in length, not dry weight, since high SP transplants had slightly greater root dry weight than the Al-P and low SP transplants (data not shown).

P content of transplant tissues. The P treatment significantly affected P content in plant tissues (Table 2, Fig. 6). Patterns of P accumulation among treatments in roots and stems were similar to those in leaves (data not shown). As expected, transplants which received no P fertilization had very low P content. Gener-

Fig. 1. Total dry weight (roots + shoots) of 5-week-old tomato transplants produced with six different phosphorous (P) fertilization regimes at four times of year. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE; 1.00 g = 0.0353 oz.



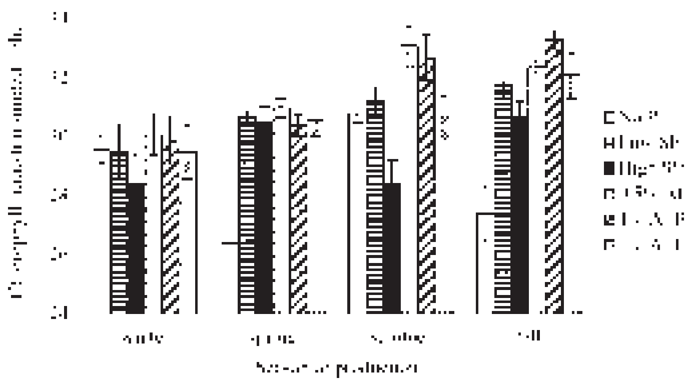


Fig. 2. Chlorophyll content of leaves from 5-week-old tomato transplants, as optical density ratio of transmitted light. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE.

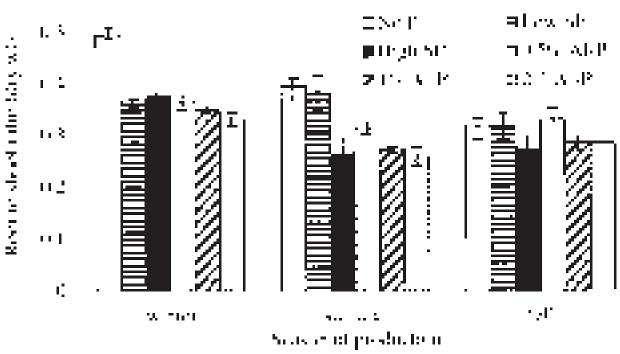


Fig. 3. Root:shoot dry weight ratios of 5-week-old tomato transplants. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE.

ally, transplants fertilized with Al-P had lower leaf P than high SP transplants, but in the summer season, 2% Al-P transplants had a slightly higher leaf P content than the high SP treatment (Fig. 6). There was a relatively small difference between high SP and 2% Al-P treatments over all seasons [mean difference = 2 $mg \cdot g^{-1}$ (0.2%), a 20% reduction]. Transplants grown with 0.5% Al-P and 1% Al-P had a 34% and 39% reduction, respectively, in P content compared with high SP controls. Low SP and 0.5% Al-P transplants were not significantly different in P content. Transplants produced in the spring had higher P content than transplants produced in summer or fall.

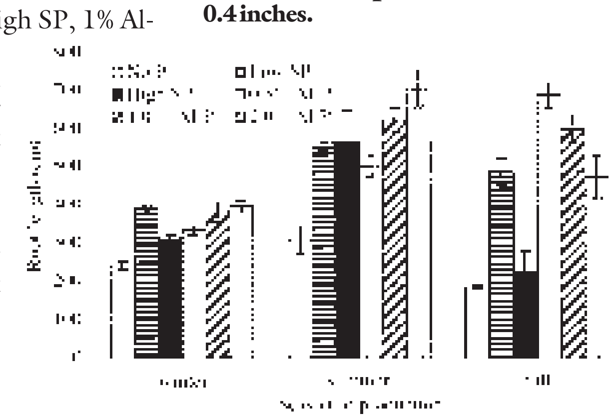
P CONTENT OF LEACHATE. As expected, plants fertilized with SP (low SP and high SP treatments) showed much higher concentrations of P in leachate (Fig. 7). Over the 5-week production period, leachate reductions compared to high SP controls were 72%, 81%, and 88% for 0.5%, 1% and 2% Al-P incorporation rates, respectively. Plants fertilized with 1% or 2% Al-P showed remarkably consistent levels of P in leachate, while those fertilized with 0.5% Al-P dropped over the course of the experiment. The P in leachate dropped drastically in containers fertilized with SP. With low SP fertilization, final levels were lower than for any of the Al-P treatments. Thus the P supply was inconsistent, and highest during the earliest part of growth.

EARLY GROWTH OF TRANSPLANTS IN THE FIELD. The P treatment significantly affected growth of summer transplants in the field in Pennsylvania (Table 3, Fig. 8). Differences among treatments for root and shoot dry weight (not shown) were similar to those shown for total dry weight (Fig. 8), and there was no significant effect of P treatment on root to shoot ratio (Table 3). Transplants fertilized with 2% Al-P were taller than other treatments at 2 weeks, but at 4 weeks high SP, 1% Al-P and 2% Al-P treatments were all the same and taller than the other treatments (data not shown). Canopy volume (height × width1 × width2) was not significantly different among fertilized treatments, but was significantly less at 2 weeks for no-P transplants (not shown). Transplants grown without P had lower root and shoot dry weight and were shorter than other treatments at 2 and 4 weeks after planting (not shown). At 8 weeks we measured dry weight of roots and shoots, and found no significant effects of P treatment on root dry weight, shoot dry weight or root to shoot dry weight ratio (data not shown).

Transplants from the winter and fall experiments planted in the field in Florida showed a significant difference in shoot dry weight among P treatments at 30 d after transplanting (Table 3, Fig. 9). There were no significant differences among fertilized plants during the winter, but in fall the Al-P plants had gained more dry weight than the high SP fertilized plants. Low P had no detrimental effect on shoot dry weight accumulation after planting, but transplants fertilized with no P gained weight more slowly in the field. By 45 d after transplanting, there were no significant effects of P treatment on shoot dry weight (data not shown).

FRUIT YIELD AND QUALITY. Transplants from the winter and fall experiments grown in Florida showed no significant differences among P treatments in final yield (as fruit weight or number) or yield of premium fruit (extra large, mature green) (data not shown). Yields of all categories of red fruit and of green extra-large fruit were significantly less in the fall experiment than in the spring experiment [extra-large green fruit yield was 32,280 $kg \cdot ha^{-1}$ (28,800 lb/acre) in

Fig. 4. Total root length of 5-week-old tomato transplants produced with various P fertilization regimes at three times of year. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE; 1 cm = 0.4 inches.



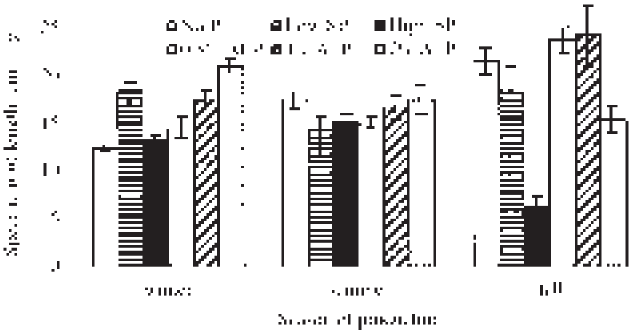


Fig. 5. Specific root length, in cm root length per mg root dry weight, of 5-week-old tomato transplants produced with various P fertilization regimes at 3 times of year. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE; 1 cm·mg^{-1} = 932 ft/oz.

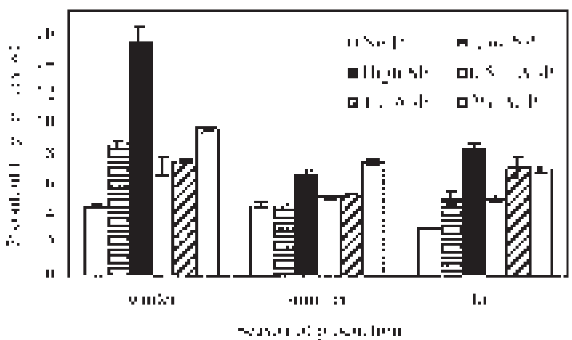


Fig. 6. The P content of leaves from 5-week-old tomato transplants produced with various P fertilization regimes at three times of year. Treatments were no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of 4 replications + SE; 1 mg·g^{-1} = 0.1%.

spring and 24,748 kg·ha^{-1} (22,080 lb/acre) in fall, with different spacing]. Traditionally, yields are lower in the fall in Florida due predominantly to heat stress related flower abortion (C. Vavrina, personal communication).

In Pennsylvania, fruit from summer transplants were grown in the field and harvested on two dates, 16 and 17 weeks after transplanting. Yield, expressed as fruit weight, fruit number, or weight, number, or percent of fruit in the largest fruit class, was not significantly different among P treatments (data not shown). The average yield of extra-large fruit over all treatments was 15,931 kg·ha^{-1} (14,506 lb/acre).

Discussion

Tomato transplants produced with 1% or 2% Al-P were of equal size and equal or better quality compared with those produced with conventional fertilization (high SP). Despite the variations in transplant growth during different seasons, dry weight accumulation, leaf area, and leaf number were comparable among these treatments (Fig. 1). Chlorophyll ratings were significantly higher in Al-P treatments compared with high SP controls in all seasons except spring (Fig. 2). Plants grown with low SP showed similarly elevated chlorophyll readings. Excess P availability reduces leaf chlorophyll content (Marschner, 1995). Higher leaf chlorophyll content may benefit transplants by increasing light capture prior to full canopy development. Neither low SP nor Al-P were effective for reducing height of young transplants, however. Only the no-P treatment had this effect.

In summer and fall, the transplants grown with 0.5% Al-P were smaller than those grown with higher Al-P concentrations (Fig. 1) and had substantially reduced P content of their leaves (Fig. 6). Plants fertilized with 0.5% Al-P during production were not significantly different from higher Al-P treatments in growth in the field in either Pennsylvania (Fig. 8) or Florida (Fig. 9). This treatment therefore may have been borderline in its ability to supply adequate P for optimal growth. The rate at which the amendment is incorporated affects two aspects of P nutrition. The first is the total amount of P in the medium, including Al-bound and free forms. Although we have shown that Al-P amendments provided adequate P to growing plants over periods exceeding a year (Brown et al., unpublished data), these plants were grown in larger containers which had a greater volume of medium, and therefore a larger amount of Al-P. In the very small containers used for plug production, the volume of medium relative to root length and plant size is very low, and therefore contains less Al-P, which could be a significant limitation. The second effect of the incorporation rate is to determine the mean distance between Al-P particles, which in turn determines the distance roots must grow to gain access to the P supply. This distance is greater when the incorporation rate is lower.

Reducing the rate of conventional P fertilizer by 80% (low SP treatment) produced transplants equal in dry weight to the high SP and Al-P treatments (Fig. 1). Although these plants were 5 to 6 cm shorter than the high SP and 1% or 2% Al-P treatments at 4 weeks after transplanting (Fig. 8), they were not significantly different in root or shoot dry weight or canopy volume at that time (data not shown). The low SP treatment therefore had surprisingly few negative effects on plant growth. This suggests that it may be possible to substantially reduce P fertilization during transplant production without compromising performance. This strategy would have less benefit than use of Al-P in terms of

Fig. 7. The P content of leachate from tomato transplants during one 5-week production cycle. Treatments were: no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. Values shown are means of four replications + SE. Analysis of variance indicated significant main effects and interaction of P treatment and time (*P* < 0.001); 100 μM = 3.1 ppm.

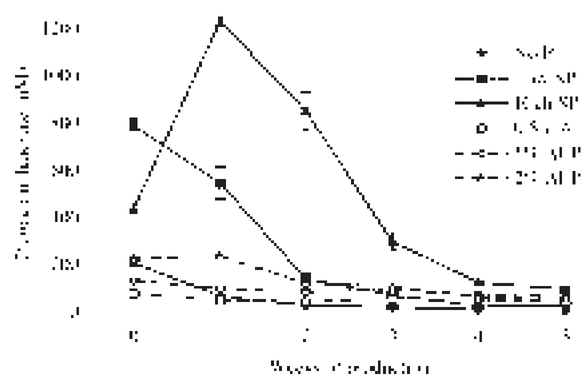


Table 3. Analysis of variance results for growth of transplants in the field in Florida (FL) during the spring and fall seasons and in Pennsylvania (PA) during the summer. Season significantly affected dry weight of the shoots on both dates in FL ($P < 0.001$), but there was no significant interaction between P treatment and season for plant growth at the FL site. F ratio values are shown; ^{NS,**,***}Nonsignificant or significant at $P < 0.01$ or 0.001, respectively.

Site	Variable	Assessment time	
		2 weeks	4 weeks
PA	Total dry wt	11.6^{***}	11.2^{***}
	Shoot dry wt	11.8^{***}	11.2^{***}
	Root dry wt	6.1^{**}	7.6^{***}
	Root:shoot ratio	1.7^{NS}	1.2^{NS}
	Plant height	15.1^{***}	23.9^{***}
	Canopy volume	8.9^{***}	1.2^{NS}
FL	Variable	30 d	45 d
	Shoot dry wt	4.0^{**}	1.3^{NS}

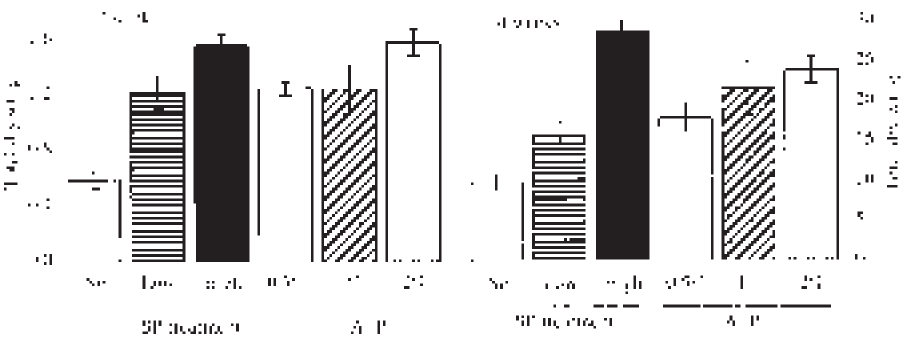


Fig. 8. Total dry weight (shoot + root) of summer transplants 2 and 4 weeks after planting to a field in Pennsylvania (PA). Treatments during transplant production were: no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. All plants received equal and adequate fertilization in the field. Values shown are means of four replications + SE. Note the difference in scales on y-axes; 1.0 g = 0.035 oz.

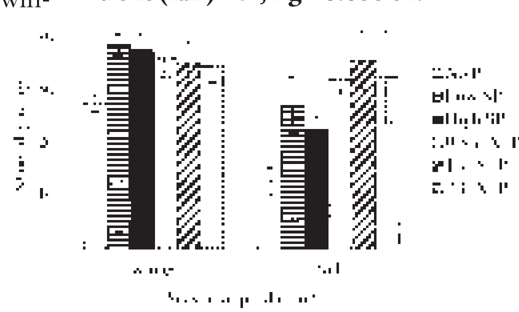
effects on P leaching, but the reduction in P in leachate is still substantial (Fig. 7).

The P content of the low SP and 0.5% Al-P leaves were similar, and intermediate between the no P and high SP or higher Al-P treatments (Fig. 6). Leaf P content has been shown to be associated with total yield in tomato, with yield reductions occurring when leaves sampled 21 d after transplanting had below 3 to 4 $mg \cdot g^{-1}$ (0.3% to 0.4%) P (Grubinger et al., 1993), which was the approximate P content of leaves in the 5-week-old no-P transplants in our experiment (Fig. 6). Low-P and 0.5% Al-P transplants had leaf P contents ranging from 4.5 $mg \cdot g^{-1}$ (0.45%) (summer) to 8.6 $mg \cdot g^{-1}$ (0.86%) (spring), above the suggested minimum, but plants grown with 0.5% Al-P still showed some growth reduction (Fig. 1), suggesting borderline P status. The minimum leaf P content for optimal yield may be higher when leaves of younger plants are sampled.

Plants under very low P availability typically display increased root to shoot ratio (Broschat and Klock-Moore, 2000; Jeschke et al., 1996). We observed this effect in some of our treatments. During the summer production season, when leaf P content was lowest (Fig. 6), the root to shoot dry weight ratio of low SP plants was similar to that of no-P transplants, and both were significantly higher than the other treatments (Fig. 3). In the winter season, only no-P transplants had elevated root to shoot ratio (Fig. 3). In previous work with Al-P, we showed that root to shoot ratio was doubled in P-deficient [1 μM (0.03 ppm) P] compared with P-sufficient [50 μM (1.5 ppm) P] bean (*Phaseolus vulgaris*) plants (Borch et al., 1999). However, when adequate P was supplied to marigolds with 2% to 8% Al-P, the root to shoot ratio was unaffected or reduced, depending on cultivar, compared to the soluble-fertilizer controls (Lin et al., 1996). Likewise, in these experiments we found no significant difference among 1% Al-P, 2% Al-P, and high SP treatments in root to shoot dry weight ratio (Fig. 3). Only the treatments which reduced P content (Fig. 6) produced a significant increase in root to shoot dry weight ratio (Fig. 3).

Root length was significantly increased in Al-P and low SP treatments (Fig. 4). The specific root length was also increased (Fig. 5), suggesting that the roots produced in Al-P or low SP were of smaller diameter or lower density. Visual examination of these roots suggests that Al-P and low SP plants had more fine roots, which would increase nutrient uptake during transplant production and after planting in the field. Work with bell peppers (*Capsicum anuum*) showed that direct-seeded plants had more than three times greater proportion of total root dry mass as lateral roots (which tend to be fine) and greater root growth rates than transplants (Leskovar and Cantliffe, 1993). An increased development of fine roots might therefore be important for transplant establishment. Al-P transplants grown in the field in Florida in the fall experiment did produce more shoot dry weight than high SP controls by 30 d after transplanting (Fig. 9). Although we

Fig. 9. Shoot dry weight of tomato plants grown in the field in Florida (FL), measured 30 d after transplanting. Treatments during transplant production were: no P fertilizer, conventional P fertilizer [superphosphate (SP) at low SP (20% of normal rate) or high SP (normal rate)], and alumina-buffered phosphorus (Al-P) at 0.5%, 1%, or 2%. All plants received equal and adequate fertilization in the field. Values shown are means of six replications (spring) or four replications (fall) + SE; 1 g = 0.035 oz.



could not detect differences in yield in these experiments, improved root development could improve plant performance in seasons with greater stresses.

Confirming previous work (Borch et al., 1998; Brown et al., 1999; Lin et al., 1996), we have shown that use of buffered-P fertilizer (Al-P) substantially reduces leaching of P from transplant trays during production (Fig. 7). If 1% Al-P is used, the reduction is more than 80% compared with conventional fertilization. Given the size of the vegetable transplant production industry (1.2 billion plants in Florida in 1992 (Vavrina and Summerhill, 1992)), substantial reductions in release of P into the environment could be realized by adoption of this technology.

We conclude that tomato transplants can be successfully produced with lower P supplied by conventional fertilizer or Al-P, reducing nutrient runoff from transplant production facilities. Transplants produced with lower P had equal or greater quality than plants fertilized with high P as in current practice.

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