Tomato Responses to Preplant-incorporated or Fertigated Phosphorus on Soils Varying in Mehlich-1 Extractable Phosphorus

Osmar Alves Carrijo¹

Brazilian Agricultural Research Agency National Center for Vegetable Research (EMBRAPA-CNPH), Km 09 rod. BR 060, Cx. Postal 0218, 70059-970 Brasília-DF, Brazil

George Hochmuth²

Horticultural Sciences Department, North Florida Research and Education Center, University of Florida, 30 Research Road, Quincy, FL 32351

Additional index words. fertilizer, fertigation, drip irrigation, plateau models, soil-test calibration, fertilizer recommendation, *Lycopersicon esculentum*

Abstract. Experiments were conducted to evaluate the yield response of tomato (*Lycopersicon esculentum* Mill.) to P, either preplant-incorporated or injected through the drip irrigation system, on soils with low, high, or very high soil P content. Fertilization through the drip irrigation system (fertigation) was more efficient than preplant incorporation of P for soil that tested low in P (9 mg·kg⁻¹ Mehlich-1 P). On soil testing low in P, marketable yield response to preplant soil P application rates (0 to 100 kg·ha⁻¹) was maximum at 61 kg·ha⁻¹ P according to the linear-plateau model, but 37 kg·ha⁻¹ P according to the quadratic-plateau model. The lower value is about one-half the P recommended by Univ. of Florida for low-P soils. On soil testing high in P (48 mg·kg⁻¹ Mehlich-1 P) the linear-plateau model predicted a maximum yield of 72.8 t·ha⁻¹ with 25 kg·ha⁻¹ P. The Univ. of Florida recommended no P for that soil. On soil testing very high in P (85 mg·kg⁻¹ Mehlich-1 P), there was no yield improvement with P fertilization.

Tomato is the most important vegetable crop grown in Florida, with ≈18,400 ha/year producing an average yield of 34.1 t·ha⁻¹ (Florida Dept. of Agriculture, 1997). Growers in Florida use large amounts of fertilizer to produce high tomato yields. The average fertilizer applications for tomatoes in the early 1990s were 250 kg·ha⁻¹ N, 90 kg·ha⁻¹ P, and 360 kg·ha⁻¹ K (National Agricultural Statistics Service, 1990; Shuler and Hochmuth, 1995).

The Univ. of Florida Extension Soil Testing Laboratory (ESTL) uses the Mehlich-1 soil test extractant (Mehlich, 1953) calibrated for Florida sandy soils (Hochmuth and Hanlon, 1995; Shuler and Hochmuth, 1995). Most of these soils, used for continuous vegetable production, are very high in residual soil P and crops do not respond to P fertilization (Hochmuth et al., 1993a, 1993b; Locascio et al., 1996; Rhoads et al., 1990; Rhue and Everett, 1987; Shuler and Hochmuth, 1995). Although the Univ. of Florida Extension Service recommendations, and the above research reports,

support zero P application, growers still apply P to high-P soils.

Although soils might contain large amounts of P, the availability of P to plants depends on soil-fertilizer chemical reactions. Phosphorus reacts chemically in soils with Ca²⁺, Mg²⁺, Al³⁺, Fe³⁺, and Mn²⁺ to form compounds less available to plants (Burt et al., 1995). Therefore, P near the roots must be continually replenished or dissolved from these less available P fractions to support plant growth (Mikkelsen, 1989). A calibrated soil test should be able to predict relative availability of P to plants from the soil during the season.

Because of the low mobility of P in the soil, P fertilizer should be placed near the roots, using the most efficient methods of application. Banding the fertilizer in a concentrated zone near the plant roots should be more efficient than broadcasting (Barber and Kovar, 1985; Kovar and Barber, 1987; Randall and Hoelt, 1988). Although band placement of P is theoretically more efficient than broadcast application, experiments comparing band placement vs. broadcasting have occasionally given conflicting results (Lorenz and Vittum, 1980). In Israel, no difference was found between broadcast or drip irrigation injection of P for corn grown on a sandy soil (Bar-Yosef et al., 1995).

With P fertigation, only a small fraction of the root zone is exposed to P. Mikkelsen (1989) documented that nutrient application through drip irrigation was comparable with

application in an adjustable fertilizer band, where the nutrient applications can be exactly timed to meet plant needs during critical growth stages. Fertilization of P through a drip irrigation system has not been widely recommended; however, some reports indicate that this procedure can stimulate plant growth and yield (Mikkelsen, 1989; Rolston et al., 1981). These benefits are probably due to a “band-like” application of P by drip irrigation; nutrients are not widely mixed, avoiding P fixation (Hochmuth and Smajstrla, 1997; Mikkelsen, 1989; Rolston et al., 1981).

About 30% of the Florida tomato crop is grown with drip irrigation. Tomatoes are grown on polyethylene-mulched beds, and drip irrigation can improve production by efficiently applying both water and nutrients under the mulch (Smajstrla et al., 1995). Drip fertigation with N and K is a common practice in this system (Locascio et al., 1996). However, fertigation with P has not been widely used, mainly because emitters can be plugged by the formation of insoluble P precipitates with the calcium in the irrigation water, and because of the generally assumed restricted movement of P in the root zone (Rauschkolb et al., 1976). Use of acidic fertilizer sources such as phosphoric acid (H₃PO₄) and urea phosphate should minimize formation of insoluble P salts (Mikkelsen, 1989). More recently, the use of monopotassium phosphate-MKP (KH₂PO₄) in fertigation has been reported to be beneficial (Ankorian, 1995; Csiszinsky, 1996).

The objectives of this trial were to evaluate the yield response of tomato to P fertilization of soils testing low, high, or very high in P. In addition, the yield responses to the method of applying P, preplant-incorporated or injected through the drip irrigation system as monopotassium phosphate, were evaluated.

Materials and Methods

Three experiments were carried out in fields with soils containing three different concentrations of Mehlich-1 P (low, high, and very high) at the Univ. of Florida Horticultural Research Unit at Gainesville, Fla., during Spring 1997. The ESTL, using the Mehlich-1 extractant (Hanlon et al., 1994), evaluated the chemical properties of the soil samples. The soil in the high-P field used in this experiment was classified as Pelham sand (sandy, siliceous, thermic arenic Paleaquults). The soils in the low-P and very-high-P fields were classified as Pomona sand (sandy, siliceous, thermic ultic Alaquods) (Harris, personal communication; Thomas et al., 1984).

The low-P soil (9 mg·kg⁻¹ Mehlich-1 soil test P index) was low in K (23 mg·kg⁻¹), and Ca (98 mg·kg⁻¹), and high in Mg (49 mg·kg⁻¹). The soil classified initially as high in P (48 mg·kg⁻¹) was high in Ca (552 mg·kg⁻¹) and Mg (70 mg·kg⁻¹) and low in K (27 mg·kg⁻¹). This high-P field was reclassified as very high in P after liming (61 mg·kg⁻¹). This increase in extractable P was probably due to the effects of lime on P release from insoluble P salts present in the soil matrix, as Al, Fe, and Mn phosphates. Although this soil, after liming,

Received for publication 11 June 1998. Accepted for publication 3 Dec. 1998. Florida Agricultural Experiment Station Journal Series No. R-06393. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked advertisement solely to indicate this fact.

¹Visiting Research Scientist at Univ. of Florida. E-mail: carrijo@cnph.embrapa.br

²Professor.

was 1 index unit inside the very high classification, it will henceforth still be referred to as high-P soil. The soil classified as very high in P (85 mg·kg⁻¹) was also high in most of the other nutrients.

The low-P and high-P fields received 4.5 and 2 t·ha⁻¹ of dolomite lime, respectively, 45 d before planting. But even after liming, at 56 d after planting, the pH of the low-P field was still low (4.9). Liquid K₂CO₃ (0N-0P-24K) was applied in that field once a week for 3 weeks at 2.5 L·ha⁻¹. Injection of K₂CO₃ through the irrigation water increased soil pH from 4.9 to 5.4.

Randomized complete-block designs were used for the two factorial experiments conducted in the high- and low-P soils with treatments replicated four times. The treatments were defined by a factorial combination of four P rates (25, 50, 75, and 100 kg·ha⁻¹), and two methods of P application [preplant-incorporated or injected (fertigated) during the season through the drip irrigation system]. On the field with soil very high in P, only the four rates of preplant P were used in a randomized complete-block design. A check treatment with zero P was included in all three experiments.

Nitrogen (N), potassium (K), and lime were applied as recommended by the ESTL. Potassium fertilizer requirements were determined by the Mehlich-1 soil test made before soil preparation. Total seasonal amount of K applied therefore differed among experiments (fields). Twenty percent of the N and K were preplant-applied, and the remaining 80% was injected through the drip lines once per week (Table 1). The K sources were K₂SO₄ for preplant application, and KNO₃ for fertigation. The N sources were (NH₄)₂SO₄ for preplant application, and NH₄NO₃ for fertigation. Preplant P treatments consisted of 60% normal (single) superphosphate and 40% triple superphosphate. Monopotassium phosphate (MKP) was the source of P for fertigation, injected in equal, weekly amounts, according to treatment. The use of MKP resulted in variable amounts of injected K, but these were equalized by adjusting the amounts of fertigated KNO₃ and NH₄NO₃.

Soil was prepared by plowing and disking, and beds were formed on 1.2-m centers with preplant fertilizers incorporated in the soil bed. Beds were 0.15 m high and 0.75 m across the top surface. During bed preparation, the soil was fumigated with 400 kg·ha⁻¹ of a mixture of 98 methyl bromide : 2 chloropicrin (trichloro nitromethane), and covered with black polyethylene film.

Drip tubing for irrigation was placed in the center of the bed, buried 2 cm deep. The emitters were 30 cm apart with a 1.74 L·h⁻¹ discharge rate at 103.5-kPa pressure. Water was applied by drip irrigation to maintain soil moisture potential at -10 to -15 kPa at a 0.15-m depth as measured by tensiometers. The tomato transplants, cv. Agriset 761 (AgriSales, Ft. Myers, Fla.), were planted on 18 Mar. in single rows on the beds with 0.45 m between plants. The target plant density was 17,940 plants/ha. Each experimental plot had 20 plants

Table 1. Fertilizer application schedule for tomato.

After planting (weeks)	P soil test (experiment)					
	Low		High		Very high	
	K	N	K	N	K	N
	----- Injected nutrient rate (kg·ha ⁻¹ /day) ^z -----					
2	1.5	1.8	1.0	1.8	1.5	1.8
3	2.0	1.8	1.3	1.8	2.0	1.8
4	2.0	2.4	1.3	2.4	2.0	2.4
5 ^y	5.0	6.2	3.4	4.8	5.0	4.8
6 ^y	6.0	7.1	2.0	3.0	3.0	3.0
7	3.0	3.0	2.0	3.0	3.0	3.0
8	3.0	2.4	2.0	2.4	3.0	2.4
9	3.0	2.4	2.0	2.4	3.0	2.4
10	3.0	2.4	2.0	2.4	3.0	2.4
11	3.0	2.4	2.0	2.4	3.0	2.4
12	2.0	1.8	1.3	1.8	2.0	1.8
13	1.5	1.8	1.0	1.8	1.5	1.8
Preplant (kg·ha ⁻¹) ^x	56.0	52.3	37.9	52.3	56.0	52.3
Season total (kg·ha ⁻¹)	300.1	300.0	189.2	261.3	279.2	261.3

^zAdapted from Hochmuth and Smajstrla (1997) for 1.2-m beds.

^yFertigated twice in the week.

^x20% of total N and K requirements recommended were preplant applied.

Table 2. Effects of P fertilization rate and application method on tomato yield in soil testing high in P, and significance of treatment effects.

P rate (kg·ha ⁻¹) ^z	Yield		Avg marketable fruit wt (g)
	Extra-large	Total marketable	
	----- (t·ha ⁻¹) -----		
P preplant	44.5	72.3	194
P fertigated	46.9	76.7	191
0 (check)	32.9	61.0	177
P rate × method	NS	NS	NS
Method	NS	NS	NS
P rate ^y (0–100)	NS	L*	NS
P rate (25–100)	NS	NS	NS
0 vs. 25 kg·ha ⁻¹	*	*	*
No P vs. P	**	**	*

^zPrate calculated on basis of planting beds on 1.2-m centers but incorporated in the soil in the raised, mulched bed measuring 15 cm in height and 75 cm wide.

^yRegression model contained significant linear (L) term.

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

Table 3. Leaf tissue P concentration (g·kg⁻¹) of tomato growing in soils testing high and low in P at three sampling times and significance of treatment effects.

P rate (kg·ha ⁻¹) ^z	First flower cluster		65 d after planting		After second harvest	
	High P	Low P	High P	Low P	High P	Low P
0 (check)	4.8	3.3	2.9	2.9	1.9	1.6
25	4.9	4.8	3.0	3.2	1.9	2.3
50	5.4	5.8	3.4	4.2	2.1	3.0
75	5.6	6.5	4.0	5.2	2.4	3.9
100	6.0	6.8	4.5	5.5	2.5	4.5
P preplant	5.6	6.3	3.6	4.9	2.1	2.8
P fertigated	5.3	5.6	3.9	4.1	2.7	4.0
P rate × method	NS	NS	NS	NS	NS	*
Method	NS	**	NS	**	**	**
P rate (25–100)	NS	**	**	**	**	**
0 vs. 25	NS	**	NS	NS	NS	NS
No P vs. P ^y	NS	**	**	**	*	**

^zPrate calculated on basis of planting beds on 1.2-m centers but incorporated in the soil in the raised, mulched bed measuring 15 cm in height and 75 cm wide.

^yContrast (check vs. P rate) was done over average of P rates. Interaction of method and rate P was significant after second harvest for tomatoes growing in low-P soil. However, for comparison purposes, the contrast for this period was also done over averages.

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

and only the center 16 plants were harvested.

On 20 Nov. 1996 (before liming), on 10 Feb. 1997 (after liming and soil preparation but prior to fertilization), and on 13 June 1997 (after the second harvest), soil samples were taken from the bed to a depth of 0.15 m. To investigate P movement in the soil, additional sets of samples were taken to a depth of 0.20 m in 0.05-m increments on 14 Jun. 1997 (after the second harvest). These were taken at 0, 0.05, 0.10, 0.15, and 0.20 m from the emitter, both parallel with (data not shown) and perpendicular to the drip irrigation line. Samples of 10 recently matured leaves from shoots were taken for nutrient concentration determinations on 22 Apr. (when the first flower clusters appeared), on 13 May, and on 13 June, which were 35, 56, and 88 d after planting, respectively. Leaves were dried, ground, and digested in sulfuric acid/hydrogen peroxide, and analyzed for N by rapid-flow colorimetry and for P, K, and micronutrients by plasma emission spectroscopy (Hanlon et al., 1994).

Tomatoes were harvested three times from the fields with soils testing very high and high in P, and four times from the field with soil low in P. Fruits were harvested at the mature-green stage and graded into marketable and cull (undersized and misshapen) categories using a mechanical fruit sizer. Marketable fruits were further graded into size categories of extra-large, large, and medium (>70, 63.5 to 70, and 57 to 63.5 mm diameter, respectively) according to the Florida Tomato Marketing Order (Florida Tomato Committee, 1997). Fifteen fruits from the second harvest were chosen at random to evaluate postharvest fruit quality parameters. Soluble solids ($^{\circ}$ Brix), pH, and titratable acidity were evaluated after fruits had fully ripened in a ripening room in the dark at 20 $^{\circ}$ C. Soluble solids concentrations were measured using a digital refractometer ABBE type (model MARK II, Cambridge Instruments, Buffalo, N. Y.). The pH of the fruit juice was then determined. Titratable acidity was determined using 6 g of tomato juice centrifuged at 17.6 kg pressure (17,600 g_n) for 15 min and mixed with 50 mL of distilled water. Each sample was titrated with 0.1 N NaOH to pH 8.2 (end point) with an automatic titrimer. The titratable acidity was calculated using the following equation:

$$\% \text{ Acid} = \text{mL } 0.1 \text{ N NaOH} \times 0.064 \times 100 [1]$$

Yield data were analyzed by analysis of variance using the SAS GLM procedure (SAS Institute, 1995). There were unequal numbers of plants per plot due to the low occurrence of bacterial wilt. A covariance analysis was performed to minimize the effects of this inequality (different numbers of plants per plot). The number of plants per hectare was incorporated in the regression models. Orthogonal contrasts were made between treatments, including preplant P vs. zero P, fertigated P vs. zero P, 25 kg-ha $^{-1}$ P vs. zero P, and soil applied P vs. fertigated P. Regression lines were fitted to data by linear and nonlinear least square procedures.

Fig. 1. Effect of P application rates (soil applied and injected) on total marketable fruit yield on soil testing high in P. P is the P rate and NP is the actual average number of plants used to estimate the predicted yield.

Table 4. Effect of P fertilization rates and application methods on yields for tomato growing in a soil low in P, and significance of treatment effect.

Application method	P rate (kg-ha $^{-1}$) ²	Yield (t-ha $^{-1}$)		
		Extra-large	Medium plus large	Total marketable
Check	0	17.5	19.9	37.4
	25	26.1	28.3	54.4
	50	31.0	33.4	64.3
	75	28.1	38.6	66.6
	100	36.2	43.0	79.2
P fertigated	25	34.4	28.4	62.8
	50	33.6	29.2	62.8
	75	35.3	35.2	70.5
	100	25.1	38.0	63.1
P rate $\times$ method		*	**	*
P preplant vs. none		**	**	**
P fertigated vs. none		**	**	**
No P vs. 25		**	*	*
P preplant (0–100) ³		L*	L**	L**
P fertigated (0–100)		Q**	L**	Q**

²P rate calculated on basis of planting beds on 1.2-m centers but incorporated in the soil in the raised, mulched bed measuring 15 cm in height and 75 cm wide.

³Regression models contained significant linear (L) and quadratic (Q) terms.

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

Results and Discussion

Field with soil testing very high in P. Application of P (0 to 100 kg-ha $^{-1}$) had no significant effect on fruit production in the very-high-P field. Average yields were 64.6 t-ha $^{-1}$ of extra-large and 88.2 t-ha $^{-1}$ of marketable fruits. Average fruit weight decreased significantly from 216 to 204 g per fruit as P applica-

tion increased from 0 to 100 kg-ha $^{-1}$. Soils in Florida testing above 30 mg·kg $^{-1}$ Mehlich-1 P are not expected to respond to P fertilization (Hochmuth and Hanlon, 1995). These results were similar to the those reported by Rhue and Everett (1987) and Shuler and Hochmuth (1996) for Florida sandy soils testing very high in P. Yield of millet was not affected by P fertilization of soils in Colorado and Ne-

braska testing $>35 \text{ mg} \cdot \text{kg}^{-1}$ Mehlich-1 P (Rodriguez et al., 1989).

Field with soil testing high in P. There was no interaction of P rate and application method effects for fruit yield and P concentration in tomato leaves. P application method (preplant or fertigation) did not affect extra-large or total marketable yields, or fruit weight (Table 2). Fertilization method had no effect on tomato yield because all plants received ample P under either application method (Table 3).

Rate of P application did not affect yield of extra-large fruits (average = $45.6 \text{ t} \cdot \text{ha}^{-1}$), total marketable yield (average = $74.6 \text{ t} \cdot \text{ha}^{-1}$), or fruit weight (average = 193 g), although plants without P had lower yields than those with P (Table 2). Contrast between the check (zero P) and the $25 \text{ kg} \cdot \text{ha}^{-1}$ P rate was significant at the 5% level for extra-large and total marketable yield, and for average fruit weight. There was a slight beneficial effect on yield of applying P but no more than $25 \text{ kg} \cdot \text{ha}^{-1}$ P was required. A linear-plateau model (Dahnke, 1993; Dahnke and Olson, 1990) was fitted to total marketable yields using the NLIN SAS procedure (Fig. 1). Although P fertilization was not recommended for this soil, the linear-plateau model predicted maximum total marketable yield of $75.4 \text{ t} \cdot \text{ha}^{-1}$ with $25 \text{ kg} \cdot \text{ha}^{-1}$ P ($r^2 = 0.55$).

Neither rate nor method of application affected P concentrations in leaves at the first flower cluster stage (Table 3). These concentrations were higher than the reported sufficiency values (2 to $4 \text{ g} \cdot \text{kg}^{-1}$ at flowering stage) for tomato growing in the open field in Florida (Hochmuth et al., 1996). Method of P application did not affect leaf P concentration 65 d after planting, but application of P at rates greater than $25 \text{ kg} \cdot \text{ha}^{-1}$ increased it (Table 3). However, all leaf P concentrations were in the sufficiency range (Burt et al., 1995; Hochmuth et al., 1996; Reisenauer, 1983). Leaf P concentrations at second harvest were greater with fertigated than with preplant P (Table 3), although both concentrations were within sufficiency ranges (Burt et al., 1995; Hochmuth et al., 1996; Reisenauer, 1983). Application of P above $25 \text{ kg} \cdot \text{ha}^{-1}$ increased leaf P concentration at second harvest, and the concentrations with zero or $25 \text{ kg} \cdot \text{ha}^{-1}$ were near deficiency (Burt et al., 1995; Hochmuth et al., 1996; Reisenauer, 1983). This late-season deficiency in P probably was associated with the slight reductions in yield with less than $25 \text{ kg} \cdot \text{ha}^{-1}$ P. Leaf macronutrient concentrations were sufficient for N, Ca, and Mg (data not presented).

Neither rate or application method used affected the pH, soluble solids, or titratable acidity of tomato fruits, with grand means of 4.5, 3.8 °Brix, and 0.94%, respectively.

Field with soil testing low in P. The interactions between application methods and P rates for extra-large, medium-plus-large, and total marketable yield were significant for tomato from the low-P field (Table 4). When P was preplant-incorporated, the effects of P fertilization on extra-large, medium-plus-large, and total marketable yields were linear. There was a linear relationship between yield of medium-plus-large fruits and increasing fertigated P rates, and a quadratic effect of P

Fig. 2. Effect of preplant P application rates (soil applied) on marketable fruit yield for soil testing low in P. P is the P rate and NP is the actual number of plants used to estimate the predicted yield.

Fig. 3. Effect of fertigated P application rates on marketable fruit yield for soil testing low in P. P is the P rate and NP is the actual number of plants used to estimate the predicted yield.

rate for extra-large and total marketable yield. Average fruit weight (165 g/fruit) was not affected by P application method or P rate (data not presented).

Plants with preplant fertilization had higher leaf P concentration than did those under fertigation at flowering and fruiting stages, but the reverse was true at harvesting time (Table 3). Fertilization with P increased leaf P concentrations in all three growth stages. Although concentrations at first flowering and at 65 d after planting were increased by P fertilization, all values were within published sufficiency ranges. Leaf P at the second harvest had fallen to a deficient concentration with zero P and to near deficiency with 25 kg·ha⁻¹ P.

A preplant application of 72 kg·ha⁻¹ P was recommended by Univ. of Florida (Hochmuth and Hanlon, 1995) for producing tomatoes in a low-P soil (10 to 15 mg·kg⁻¹ Mehlich-1 P). This amount is slightly greater than the maximum preplant P response value obtained by linear-plateau fitting (61 kg·ha⁻¹) for total marketable yield of 71 t·ha⁻¹ (Fig. 2). The recommended P rate is considerably less than the preplant P requirement predicted by the quadratic-plateau model (142 kg·ha⁻¹) for a maximum marketable yield of 79 t·ha⁻¹. Cerrato and Blackmer (1990), and Hochmuth et al. (1993a) observed that quadratic models tend to overpredict responses to fertilization for other crops and nutrients.

The quadratic regression model and a quadratic-plateau model (linear-plateau was not significant) were applied to the total marketable yield in fertigated plots (Fig. 3). The P rate for maximum marketable yield was 68.3 kg·ha⁻¹ for the quadratic regression, and 36.6 kg·ha⁻¹ for the quadratic-plateau model, with maximum yields of 68.9 and 64.3 t·ha⁻¹, respectively. An unexpected decrease in yield of extra large fruits was observed when the highest rate (100 kg·ha⁻¹) of P was applied. Fertigation with P had no effect on yield of extra-large fruits for either plateau model. The quadratic regression model predicted 55.6 kg·ha⁻¹ of fertigated P for maximum extra-large yield of 36.1 t·ha⁻¹ (Fig. 4). The optimum fertigated P rate (37 kg·ha⁻¹) to maximize total marketable yield was smaller than those values predicted for preplant P (61, or 142 kg·ha⁻¹ P), indicating that P was more efficiently used following fertigation than following preplant soil incorporation. This increased efficiency in P utilization with fertigation was not observed for the tomatoes grown on the soil testing high in P. Effectiveness of fertigated P might differ with relative soil test P levels, as shown by Peterson et al. (1981) with wheat. In the wheat study, banding was three times as effective as broadcasting on low-P soils, but the methods of placement were equally effective when soil P was in the medium range.

Neither the P fertilization rate nor the method of P application affected any of the following fruit quality parameters on low-P soil: pH, soluble solids, or titratable acidity with overall averages of 4.5, 3.9 °Brix, and 1.1%, respectively.

Phosphorus movement away from the emitters was greater than 20 cm in depth and 10 to

Fig. 4. Effect of fertigated P application rates on extra-large fruit yield for soil testing low in P. P is the P rate and NP is the actual average number of plants in the fertigated P treatments in low P field used to estimate the predicted yield.

Fig. 5. Effects of soil depth and radial distance perpendicular to tube on change in Mehlich-1 extractable P (mg·kg⁻¹) on low-P soil, after drip application of 100 kg·ha⁻¹ P. Change in Mehlich-1 extractable P = postharvest soil Mehlich-1 extractable P index minus the preplant Mehlich-1 soil extractable P index.

15 cm in width (Fig. 5), sufficient to supply P to most of the root zone. Without added fertilizer, this soil contained 9 mg·kg⁻¹ Mehlich-1 P, and by the end of the season, concentrations >60 mg·kg⁻¹ P (very high) were found 20 cm under the drip tube emitter and up to 10 cm laterally from the emitter. Using several P fertilizer sources on sprinkler-irrigated sandy soils near Patterson, Wash., Lauer (1988) measured P movement to a depth of 10 cm. Our results showed that fertigation with acidic P fertilizers such as MKP can be used to place P in the root zone in these sandy soils.

In summary, the Univ. of Florida Extension Service, in 1997, recommended 72 kg·ha⁻¹ preplant-incorporated P for tomatoes to be grown on soil testing low in P, which is greater than the P rate predicted by the linear-plateau model (61 kg·ha⁻¹) to maximize marketable yield. University of Florida also recommended no P application for tomato production on very high and high-P soils. Results of these experiments showed no response on soil testing very high in P. However, there was a slight beneficial effect of a small amount of P on the high-P soil. The linear-plateau model predicted a maximum total marketable yield of 75.8 t·ha⁻¹ on high-P soil with a P application of 25 kg·ha⁻¹. A slight change in the Mehlich-1 P calibration might be warranted and more research is justified with soils in the range of 50 to 70 mg·kg⁻¹ Mehlich-1 P.

Our results also documented greater P fertilization efficiency with fertigation than with a broadcast preplant application of P to the soil. The Univ. of Florida recommendation of 72 kg·ha⁻¹ P was adequate for greatest yields when the P was broadcast and incorporated in the low-P soil. However, only one-half that amount of P was needed to achieve maximum yield when the P was applied by fertigation.

Literature Cited

- Ankorion, J. 1995. MKP—Monopotassium-phosphate—A new fertilizer for fertigation, p. 175–194. In: Proc. Dahlia Greidinger Intl. Symp. on Fertigation. Haifa, Israel.
- Barber, S.A. and J.L. Kovar. 1985. Principles of applying phosphorus fertilizer for greatest efficiency. *J. Fert. Issues* 2:91–94.
- Bar-Yosef, B., B. Sagiv, T. Markovitch, and I. Levkovich. 1995. Phosphorus placement effects on sweet corn growth, uptake, and yield, p. 141–154. In: Proc. Dahlia Greidinger Intl. Symp. on Fertigation. Haifa, Israel.
- Burt, C., K. O'Connor, and T. Ruehr. 1995. Fertigation. California Polytechnic State Univ. Irrigation Training and Res. Ctr., San Luis Obispo.
- Cerrato, M.E. and A.M. Blackmer. 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. *Agron. J.* 82:138–143.
- Csizinszky, A.A. 1996. Response of microirrigated bell pepper to phosphorus sources and rates. *Soil Crop Sci. Soc. Fla. Proc.* 56:20–24.
- Dahnke, W.C. 1993. Soil test interpretation. *Commun. Soil Sci. Plant Anal.* 24:11–27.
- Dahnke, W.C. and R.A. Olson. 1990. Soil test correlation, calibration, and recommendation. p. 45–71. In: R.L. Westerman (ed.). *Soil testing and plant analysis*, 3rd ed. Soil Sci. Soc. Amer., Madison, Wis.
- Florida Department of Agriculture and Consumer Services. 1997. Florida agricultural statistics. Florida Dept. of Agr. and Consumer Services. Vegetable summary 1995–96. Tallahassee, Fla.
- Florida Tomato Committee. 1997. Regulatory bulletin no. 1. Florida Tomato Committee, Orlando.
- Hanlon, E., J.G. Gonzales, and J.M. Bartos. 1994. IFAS Extension soil testing laboratory chemical procedures and training manual. Florida Coop. Ext. Serv. Circ. 812.
- Hochmuth, G.J. and E.A. Hanlon. 1995. IFAS standardized fertilization recommendations for vegetable crops. Florida Coop. Ext. Serv. Circ. 1152.
- Hochmuth, G.J., E.A. Hanlon, and J. Cornell. 1993a. Watermelon phosphorus requirements in soils with low Mehlich-1 extractable phosphorus. *HortScience* 28:630–632.
- Hochmuth, G.J., E. Hanlon, B. Hochmuth, G. Kidder, and D. Hensel. 1993b. Field fertility research with P and K for vegetable interpretations and recommendations. *Soil Crop Sci. Soc. Fla. Proc.* 52:95–101.
- Hochmuth, G.J., D.N. Maynard, C.S. Vavrina, W.M. Stall, T.A. Kucharek, F.A. Johnson, and T.G. Taylor. 1996. Tomato production in Florida, p. 305–316. In: G.J. Hochmuth and D.N. Maynard (eds.). *Vegetable production guide for Florida*. Florida Coop. Ext. Serv. Circ. 170.
- Hochmuth, G.J. and A.G. Smajstrla. 1997. Fertilizer application and management for micro (or drip) irrigated vegetables in Florida. Florida Coop. Ext. Serv. Circ. 1181.
- Kovar, J.L. and S.A. Barber. 1987. Placing phosphorus and potassium for greatest recovery. *J. Fert. Issues* 4:1–6.
- Lauer, D.A. 1988. Vertical distribution in soil of sprinkler-applied phosphorus. *Soil Sci. Soc. Amer. J.* 52:862–868.
- Locascio, S.J., A.G. Smajstrla, and M.R. Allgood. 1996. Nitrogen requirements of drip-irrigated tomato. *Proc. Fla. State Hort. Soc.* 109:146–149.
- Lorenz, O.A. and M.T. Vittum. 1980. Phosphorus nutrition of vegetable crops and sugar beets, p. 737–762. In: F.E. Khasawneh, E.C. Sample, and E. J. Kamprath (eds.). *The role of phosphorus in agriculture*. Amer. Soc. Agron. Madison, Wis.
- Mehlich, A. 1953. Determination of P, Ca, Mg, K, Na, and NH₄. North Carolina Soil Test Division (mimeo.). North Carolina Dept. Agr., Raleigh.
- Mikkelsen, R.L. 1989. Phosphorus fertilization through drip irrigation. *J. Prod. Agr.* 2(3):279–286.
- National Agriculture Statistics Service. 1990. Agricultural chemical usage. 1990. Vegetables Summary. U.S. Dept. Agr. Econ. Serv., Washington, D.C.
- Peterson, G.A., D.H. Sander, P.H. Grabouski, and M.L. Hooker. 1981. A new look at row and broadcast phosphate recommendations for winter wheat. *Agron. J.* 73:13–17.
- Randall, G.W. and R.G. Hoeft. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. *J. Prod. Agr.* 1:70–78.
- Rauschkolb, R.S., D.E. Rolston, R.J. Miller, A.B. Carlton, and G.G. Burau. 1976. Phosphorus fertilization with drip irrigation. *Soil Sci. Soc. Amer. J.* 40:68–72.
- Reisenauer, H.M. 1983. Soil and plant tissue testing in California. Univ. California, Div. Agr. Sci. Bul. 1879.
- Rhoads, F.M., E.A. Hanlon, S.M. Olson, and G.J. Hochmuth. 1990. Response of snapbean to N rates and soil-test P and K. *Soil Crop Sci. Soc. Florida. Proc.* 49:10–13.
- Rhue, R.D. and P.H. Everett. 1987. Response of tomatoes to lime and phosphorus on a sandy soil. *Agron. J.* 79:71–77.
- Rodriguez, J.B., G.A. Peterson, and D.G. Westfall. 1989. Calibration of nitrogen and phosphorus soil tests with yield of proso millet. *Soil Sci. Soc. Amer. J.* 53:1737–1741.
- Rolston, D.E., R.S. Rauschkolb, C.J. Phene, R.J. Miller, K. Urier, R.M. Carlson, and D.W. Henderson. 1981. Applying nutrients and other chemicals to trickle-irrigated crops. Univ. California Div. Agr. Sci. Bul. 1891.
- SAS Institute. 1985. SAS user's guide: Statistics. SAS Inst., Cary, N.C.
- Shuler, K. and G. Hochmuth. 1995. Field tests of phosphorus fertilization of tomato growing in high P soils in Palm Beach County, Florida. *Proc. Fla. State Hort. Soc.* 108:227–232.
- Smajstrla, A.G., W.B. Boggess, B.J. Boman, G.A. Clark, D.S. Haman, G.W. Knox, S.J. Locascio, T.A. Obreza, L.R. Parsons, F.M. Rhoads, T. Yeager, and F.S. Zazueta. 1995. Status and growth of microirrigation in Florida. p. 325–330. Proc. Fifth Intl. Microirrigation Congr., Orlando, Fla.
- Thomas, B.P., E. Cummings, and W.H. Wittstruck. 1984. Soil survey of Alachua County, Florida. Soil Conservation Serv., U.S. Dept. Agr.