Effects of Canopy and Micro-irrigation under the Trees on Spatial Variations of Soil Labile Phosphorus and Metals in a Citrus Grove*

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Abstract. To evaluate effects of canopy and micro-irrigation under trees on accumulation and leaching of phosphorus (P) and heavy metals in agricultural sand soils, the horizontal and vertical variations of soil P and metals in a 408-m² plot within a grove under grapefruit (*Citrus paradisi* Macf.) production near Fort Pierce, Fla., was examined. A high horizontal variation of labile soil P and metal concentrations was observed. Across the row, the highest values of pH, EC, water-soluble P, and all metals occurred in the soils under the canopies, and the lowest values occurred in the soils near the water furrow or the midway of the inter-row. Along the grapefruit row, the highest values of many measured variables occurred along the northern side of the citrus tree and close to the emitter. The downward movement of P, Cu, and Zn in the soils was more significant in the soils in open areas (near the water furrow and midway of inter-neighboring trees) than those under the canopies. The differences in labile P and metal spatial distributions in the soils were related to the location of emitter fertigation and differences in rainfall-induced leaching in the field. The results suggest that applying fertilizers to sites under the canopy rather than the spaces between the trees can minimize leaching losses of nutrients.

Sandy soils, which are the dominant soil type for citrus production in Florida, have the disadvantages that mobile nutrients are readily leached by heavy rain or over-irrigation and a very small amount of water can be retained. Therefore, fertilization and irrigation management are critical for commercial citrus production on these soils. Repeated applications of fertilizers or metals-containing pesticides often lead to elevated soil P and trace metals (Alva, 1992; Stanley et al., 1995). Phosphorus and trace metal losses in the surface and subsurface runoff from agriculture to surface waters or groundwater increase with increasing soil P and trace metal levels (Heckrath et al., 1995; Sharpley, 1995; Moore et al., 1998). The fate of the P and heavy metals also depends on water movement in soil. Plant cover could change the distribution of rain, and thus affect water movement in the soils. Plant canopy can effect the distribution of rainfall and soil moisture and soil properties (Challinor, 1968; Saffigna et al., 1976; Parker and Muller, 1982; Parkin and Codling, 1990; Moody and Jones, 2000). Citrus plant canopies intercept rain and alter the spatial distribution of water flux, thus

resulting in spatial variation of the nutrient and pesticide leaching potential (Alva et al., 1999). Fertilizers in citrus groves are commonly applied by a broadcast spreader or through emitter fertigation. The emitter fertigation was usually applied in a limited area. It was hypothesized that both canopy and emitter irrigation influence the accumulation and movement of P and metals in the soils. However, most studies of canopy effect on soil properties have been conducted on forest trees or field crops (Moody and Jones, 2000; Parker and Muller, 1982). In addition, the soil properties measured in these studies were primarily organic matter, biomass, moisture, nitrogen, and pH (Belsky et al., 1993; Berger and Glatzel, 1998; Callaway, 1990; Dolan et al., 2001; Hook et al., 1994; Moody and Jones, 2000; Ostertag, 1998). Minimal information exists regarding citrus canopy effects on the concentrations of P and heavy metals in soils within a citrus field. The objective of this study was to investigate the variability of soil labile P and metals in a citrus grove, which is important for assessing the leaching losses of P and heavy metals.

Materials and Methods

This study was conducted on a 408 m² (68 × 6 m) plot in a com-

mercial citrus grove in Fort Pierce, Fla., with 20-year-old white 'Marsh' grapefruit (*Citrus paradisi* MacFadyen.) trees that have a canopy diameter of ≈3.6 m. The trees were planted in north-south rows with a planting distance of 4 × 6 m² on double-row raised beds to facilitate drainage for the tree root system. Bed height was ≈40 to 50 cm above the bottom of the water furrow. The plot is nearly flat (<2% slope). The soil series was Wabasso sand (sandy, siliceous, hyperthermic alfic Alaquod). Mean clay and organic C were 41 and 4.7 g·kg⁻¹, respectively. Historically, annual amounts of N, P, and K application averaged 165, 37, and 95 kg·ha⁻¹, respectively. In October and February, 70% of the P was applied in the grove with dry broadcast; N, K and the remaining P were applied by emitter fertigation. Emitter spray reaches an area with a diameter of 2 m. Irrigation averaged 8 h/week at a rate of 37.8 L·h⁻¹ during the dry season. In addition to application of N, P, and K, both micronutrient fertilizers (annual foliar application of Cu and Zn ranged from 2.2 to 5.6 kg·ha⁻¹ as copper sulfate, 2.2 to 4.5 kg·ha⁻¹ as zinc sulfate, or 0.8 to 1.1 kg·ha⁻¹ as chelated zinc), and Cu- and Zn- containing pesticides/fungicides (such as copper hydroxide) were also routinely applied, which accelerate Cu and Zn accumulation in the soils. Mean annual rainfall in the grove is 1250 mm. Rainfall varied seasonally, and most of the rainfall occurred from May to October.

Soil samples were collected in September 2001 using a 5-cm-diameter cylindrical soil auger. Four sampling patterns were followed. 1) A transect along the direction of the citrus tree row: three surface soils (0 to 5 cm) were collected from each inter-tree space along a 68-m-long citrus tree row with a total of 51 samples collected. The interval of two neighboring sampling points was 1.33 m. The three samples for each inter-tree space were distributed respectively on the north side of the tree (position A, close to emitter), midway between two neighboring tree (position B), and on the south side of tree (position C) (Fig. 1). 2) Transects across the direction of the citrus row: eight 0-5 cm surface soils (L1, L2, L3, L4, L5, L6, L7, and L8, as

Fig. 1. Scheme of the soil sampling points (+ represents the emitter position).

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Table 1. The maximum, minimum, mean values, and coefficients of variation (cv) of pH, electrical conductivity (EC), water-soluble, and Mehlich-III extractable P and metals in the surface soils (n = 102).^a

Variable	Range	Mean	cv (%)
pH	6.18–8.04	7.20	5.4
EC ($\mu\text{S}\cdot\text{cm}^{-1}$)	49.4–511	159	58.4
Water-soluble			
P ($\text{mg}\cdot\text{kg}^{-1}$)	2.47–20.6	6.32	47.2
Ca ($\text{mg}\cdot\text{kg}^{-1}$)	1.84–84.8	13.6	95.4
Mg ($\text{mg}\cdot\text{kg}^{-1}$)	0.44–26.6	3.72	102
K ($\text{mg}\cdot\text{kg}^{-1}$)	0.80–25.3	2.83	103
Na ($\text{mg}\cdot\text{kg}^{-1}$)	2.92–16.3	6.01	39.6
Cu ($\text{mg}\cdot\text{kg}^{-1}$)	0.21–11.2	1.15	106
Zn ($\text{mg}\cdot\text{kg}^{-1}$)	0.18–1.37	0.40	52.5
Fe ($\text{mg}\cdot\text{kg}^{-1}$)	0.49–13.8	2.55	88.2
Mn ($\text{mg}\cdot\text{kg}^{-1}$)	0.02–2.71	0.79	99.2
Cr ($\mu\text{g}\cdot\text{kg}^{-1}$)	0–44.4	10.92	82.6
Ni ($\mu\text{g}\cdot\text{kg}^{-1}$)	0–57.4	8.48	102
Pb ($\mu\text{g}\cdot\text{kg}^{-1}$)	0–195	29.3	133
As ($\mu\text{g}\cdot\text{kg}^{-1}$)	0–137	12.7	152
Se ($\mu\text{g}\cdot\text{kg}^{-1}$)	0–50.2	13.4	114
Mehlich III-extractable			
P ($\text{mg}\cdot\text{kg}^{-1}$)	36.3–337	143	53.5
Cu ($\text{mg}\cdot\text{kg}^{-1}$)	23.9–156	70.8	45.3
Zn ($\text{mg}\cdot\text{kg}^{-1}$)	7.60–71.8	35.3	42.0
Pb ($\text{mg}\cdot\text{kg}^{-1}$)	1.06–7.49	2.86	44.4

^aSurface samples included samples from the first three sampling patterns.

shown in Fig. 1) were collected along a transect from water furrow to midway of the inter-row (perpendicular to the water furrow), with a 75-cm sampling interval. Position L4 was the nearest to the tree trunk. A total of four replicate transects were chosen. 3) A systematic sampling pattern near a emitter where two sets of 0 to 5 cm surface soils (each including 10 samples with interval of 10 cm) were collected at varying distances from the emitter along two directions (X, along the row; Y, perpendicular to the row, as shown in Fig. 1). 4) Duplicate profiles (PF1, PF2, and PF3, Fig. 1) were collected from near the water furrow, midway of the inter-neighboring tree, and under the canopy. Sampling depths were 0–5, 5–10, 10–20, 20–30, 30–40, 40–60, 60–80, and 80–100 cm from the surface.

All soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was measured in water at a soil:water ratio of 1:1 and electrical conductivity (EC) was measured in water at a 1 soil : 2 water ratio using a pH-ion conductivity meter (Accumet model 50; Fisher Scientific, Pittsburgh, Pa.). Surface soil samples were analyzed for labile P and metals by two different extraction methods. 1) Water-soluble P and metals (1:10 ratio of soil to deionized water; 120-min reaction time) (Kuo, 1996);

2) Mehlich 3-extractable P, Cu, Zn, and Pb (1:10 ratio of soil to Mehlich 3 extraction solution; 5-min reaction time) (Amacher, 1996; Mehlich, 1984). After each extraction, the suspension was centrifuged at 7500 g_n for 30 min and then the supernatant was passed through a 0.45- μm membrane filter. Phosphorus and metal concentrations in the extracts were determined by inductively coupled plasma atomic emission spectrometer (ICPAES, J-Y Emission Division Instruments SA, Inc., NJ). The detection limits of the ICP-AES are 2.54 (P), 1.55 (Ca), 5.52 (Mg), 3.85 (K), 10.5 (Na), 2.50 (Cu), 0.60 (Zn), 0.63 (Fe), 0.11 (Mn), 0.42 (Cr), 0.61 (Ni), 1.96 (Pb), 1.24 (As), and 2.73 (Se) $\mu\text{g}\cdot\text{L}^{-1}$. Total Cu, Zn, and P contents of soil profile samples were determined using the ICP-AES after digesting 1 g of soil with nitric acid and perchloric acid (Reed and Martens, 1996). Statistical differences in measured variables among the sampling positions were analyzed with the SAS linear regression model procedure (SAS, 1998).

Results and Discussion

Overall variation in the surface soils. The measured soil variables varied widely among

the 102 surface soil samples (Table 1). The pH values for all surface samples ranged from 6.18 to 8.04 with a coefficient of variation (cv) value of 5.4%. The EC values varied from 49.4 to 511 $\mu\text{S}\cdot\text{cm}^{-1}$, with the maximum value being about 10 fold of the minimum. The water-soluble P and metal concentrations also varied widely, with the CV values ranging from 39.6% to 152%. Among them, water-soluble Ca, Mg, K, Cu, Fe, Mn, Cr, Ni, Pb, As, and Se had CV values >80%. The CV values of Mehlich III-extractable P, Cu, Zn, and Pb were between 40% and 55%. High CV values of the water-soluble soil P and metal concentrations indicate a high spatial variability of the measured variables in the grove.

Correlations were significant ($p < 0.05$) for 82 of 120 soil attribute pairs (Table 2), indicating that most of the measured variables were strongly dependent. Significant correlations ($p < 0.01$) were found between EC and Ca, and Mg; between Ca and Cu, Mg, P, Zn; between Cr and Fe, Zn, As; between Cu and Mg, P, Zn; between Mg and P, Zn; between Ni and Zn; and between P and Mn. Water-soluble P was positively correlated with all other variables except for pH, water soluble Pb, and Se. All metals except for Fe, Pb, and Mn were positively correlated with the EC values. Water soluble Cu was significantly correlated with all the measured variables except for pH and Pb, whereas water-soluble Zn was significantly correlated with all measured variables except for pH and Na. The high correlations between nutrients and/or heavy metals suggest that the nutrients and/or metals accumulated in the soil had similar source (fertilizers, pesticides) and trends of accumulation and leaching in the soil.

Variations in the transect across the row. Significant variations of soil pH, EC, water-soluble P and metals, and Mehlich III-extractable P, Cu, Zn, and Pb were measured in the transect perpendicular to the water furrow (Tables 3 and 4). The highest values of pH, EC, water-soluble P, and all metals generally occurred in the soils under the canopies. The lowest values occurred in the soils near the water furrow (position L2) for EC, Ca, Mg, Na, K, P, As, and Se, and the midway of inter-row (position L8) for most of the heavy metals (Fe, Cr, Cu, Ni, Pb, Zn, and Mn). Except for water-soluble Ni, As, and Se, all the water-soluble

Table 2. Correlation coefficients (r) among pH, electrical conductivity (EC), and water-soluble P and metals (n = 102).

Variable	EC	Ca	Cr	Cu	Fe	K	Mg	Na	Ni	P	Pb	Zn	As	Mn	Se
pH	-0.36**	-0.27**	-0.06	-0.15	0.01	-0.13	-0.28**	0.34**	-0.10	-0.07	0.06	-0.18	-0.05	0.08	-0.04
EC		0.79**	0.29**	0.46**	0.08	0.44**	0.77**	0.30**	0.31**	0.64**	-0.21*	0.49**	0.21*	0.02	0.22*
Ca			0.56**	0.74**	0.35**	0.37**	0.98**	0.33**	0.43**	0.84**	-0.03	0.78**	0.41**	0.30**	0.36**
Cr				0.58**	0.89**	0.30**	0.55**	0.06	0.22*	0.53**	0.47**	0.78**	0.71**	0.61**	0.40**
Cu					0.45**	0.34**	0.74**	0.30**	0.45**	0.74**	0.17	0.81**	0.33**	0.47**	0.26**
Fe						0.19	0.36**	0.00	0.11	0.36**	0.53**	0.61**	0.76**	0.65**	0.30**
K							0.38**	0.15	0.16	0.54**	-0.15	0.33**	0.12	0.04	0.35**
Mg								0.29**	0.41**	0.82**	-0.08	0.74**	0.44**	0.23*	0.37**
Na									0.27**	0.39**	-0.04	0.19	-0.03	0.15	0.05
Ni										0.33**	0.09	0.39**	0.18	0.15	0.15
P											0.01	0.73**	0.29**	0.38**	0.33
Pb												0.37**	0.15	0.79**	0.04
Zn													0.47**	0.68**	0.36**
As														0.30**	0.40**
Mn															0.22*

*,**Significant at $p < 0.05$ or 0.01, respectively.

Table 3. Variations of pH, electrical conductivity (EC), and water-soluble P and metals in the surface soils across the citrus row (n = 4).

Position	pH	EC	Ca	Mg	Na	Fe	K	P
		($\mu\text{s}\cdot\text{cm}^{-1}$)	(mg·kg ⁻¹)					
L1	6.88 bc ^z	147 bc	11.6 bc	1.75 b	4.13 c	2.11 ab	2.29 bc	4.19 cd
L2	7.37 a	107 c	4.7 c	0.80 b	6.93 bc	2.43 ab	1.22 c	3.22 d
L3	7.36 a	146 bc	8.5 bc	1.68 b	7.35 ab	2.55 ab	1.92 c	5.17cd
L4	7.35 a	124 bc	9.1 bc	1.78 b	7.69 ab	3.00 a	1.76 c	6.62 bc
L5	7.18 ab	227 a	26.1 a	6.86 a	9.07 a	2.68ab	4.00 ab	10.38 a
L6	7.45 a	212 ab	21.4 ab	6.35 a	8.46 ab	2.07 ab	3.69 ab	8.06 ab
L7	6.72 c	164 bc	8.6 bc	2.64 b	4.61 bc	0.88 b	4.39 a	5.41 cd
L8	6.66 c	181 bc	10.9 bc	3.69 ab	4.21 c	0.98 b	3.28 ab	4.17 cd
	Mn	Cu	Zn	Pb	Ni	As	Se	Cr
	(mg·kg ⁻¹)			(μg·kg ⁻¹)				
L1	0.83 ab	1.21 bc	0.47 ab	24.4 ab	10.2 a	7.06 a	6.15 a	8.4 bc
L2	1.16 ab	1.17 bc	0.38 ab	57.8 a	10.7 a	3.37 a	6.61 a	8.4 bc
L3	1.06 ab	1.34 ab	0.42ab	67.1 a	11.6 a	1.11 a	2.72 a	11.6 ab
L4	1.27 ab	1.63 a	0.40 ab	71.7 a	14.1 a	7.67 a	10.45a	12.9 a
L5	1.32 a	1.49 a	0.52 a	27.0 ab	18.5 a	10.93 a	19.40 a	12.2 a
L6	0.83 ab	1.05 bc	0.51 a	26.6 ab	21.0 a	8.22 a	18.40 a	10.0 bc
L7	0.06 b	0.54 bc	0.28 b	1.32 b	12.9 a	9.98 a	12.50 a	5.0 bc
L8	0.09 b	0.47 c	0.26 b	2.29 b	9.9 a	8.02 a	8.91 a	4.8 c

²Mean values for each variable with the same letter (s) are not different at $p = 0.05$.

Table 4. Variations of Mehlich III-extractable Cu, P, Pb, and Zn in the surface soils across the citrus row (n = 4).

Position	Mean concn (mg·kg ⁻¹)			
	Cu	P	Pb	Zn
L1	55.9 bc ^z	81.2 c	2.53 bc	36.8 bc
L2	109.7 a	67.1 c	3.92 ab	35.5 bc
L3	111.1 a	86.5 c	4.38 a	39.5 ab
L4	115.1 a	173.4 b	4.51 a	34.4 bc
L5	110.6 a	300.6 a	2.87 bc	52.3 a
L6	62.6 b	189.8 b	3.26 bc	47.1 ab
L7	44.7 bc	85.7 c	1.71 c	44.7 ab
L8	28.6 c	58.6 c	1.71 c	22.4 c

^zMean values for each variable with the same letter (s) are not different at $p = 0.05$.

Table 5. Variations of pH, electrical conductivity (EC), and water-soluble P and metals in the surface soils along the citrus row (n=17).

Position	pH	EC	Ca	Mg	Na	Fe	K	P
		($\mu\text{S}\cdot\text{cm}^{-1}$)	(mg·kg ⁻¹)					
A	7.36 a ²	209 a	22.5 a	6.10 a	6.52 a	2.74 a	4.35 a	9.22 a
B	7.34 a	115 b	9.7 b	2.95 b	5.92 a	3.52 a	1.65 b	4.88 b
C	7.08 b	104 b	6.8 b	1.90 b	4.51 b	2.70 a	1.90 ab	4.75 b
	Mn	Cu	Zn	Pb	Ni	As	Se	Cr
	(mg·kg ⁻¹)			(μg·kg ⁻¹)				
A	0.96 a	2.04 a	0.54 a	14.7 a	6.32 a	17.02 a	10.78 a	13.5 a
B	0.95 a	0.78 b	0.35 b	45.0 a	5.38 a	21.32 a	13.22 a	12.0 a
C	0.74 a	0.74 b	0.31 b	36.8 a	3.32 a	8.09 a	10.12 a	8.7 a

^zMean values for each variable with the same letter (s) are not different at $p = 0.05$.

Table 6. Variations of Mehlich III-extractable Cu, P, Pb, and Zn in the surface soils along the citrus row (n=17).

Position	Mean concn (mg·kg ⁻¹)			
	Cu	P	Pb	Zn
A	82.5 a ^z	208.8 a	2.45 a	48.3 a
B	54.4 b	97.9 b	3.26 a	24.8 b
C	56.8 b	111.3 b	3.31 a	20.0 b

^zMean values for each variable with the same letter (s) are not different at $p = 0.05$.

components were significantly different among the eight sampling positions (L1, L2, L3, L4, L5, L6, L7, and L8). In addition, the highest values of Mehlich III-extractable Cu, P, Pb, and Zn also occurred in the soils under the canopies (L3, L4, L5; Table 4), whereas the lowest values generally occurred at the midway of the inter-row (position L8). Higher concentrations of water-soluble and Mehlich III extractable P and

heavy metals in the soil under the canopies than open areas (near the water furrow or midway of inter-neighboring trees) were probably related to interception of rain by citrus plant canopies and thus weakened leaching of P and metals from the soils. For the mature citrus trees with a dense canopy, the precipitation at the spaces between trees was greater than that under the tree canopy. The citrus canopy intercepted a

considerable portion of the rainfall, and thus reduced rain dropping on the soil under the canopy. Therefore, leaching of P and metals from soil-applied fertilizers under the canopy was less pronounced than for the other spaces. A study by Alva et al. (1999) using 25-year-old Valencia orange (*Citrus sinensis* L. Osbeck) showed that the amounts of precipitation under the canopy were 47% to 94% of the incident rainfall. Parkin and Codling (1990) also observed that corn plants could intercept and channel 19% to 42% of the total rainfall during a storm event, which could reduce the leaching of fertilizer under the canopy to groundwater. In addition, the higher concentrations of P and heavy metals under the canopy could be also due to increased leaf litters under the canopy. Tree can acquire nutrients from the spaces between the trees, and then concentrate the nutrients under the canopy (Davenport et al., 1996; McDaniel and Graham, 1992). The organic materials often contained more P and heavy metals than inorganic components, and would reduce metal leaching from the sandy soils. The application of partial P through the emitters was also partially responsible for the higher P concentration under the canopy.

The decreased water-soluble Ca, Mg, Na, K, and P concentrations in the soil near the water furrow were probably due to the stronger surface runoff near the water furrow. Lower water-soluble heavy metals in the soil in the midway of inter-row were due to great leaching and low input of the metals. Since micronutrients were applied by foliar spray, potential foliar runoff of heavy metals induced by foliar application of micronutrients was a possible factor for concentrations of heavy metals under the canopy.

Variations along the row. pH, EC, and water-soluble Ca, P, Cu, and Zn concentrations of 51 surface soils were measured every 1.33 m along a 68-m-long citrus row. All the measured variables varied over a short distance. The difference in pH values between maximum and minimum along the row was ≈ 1.5 units. The maximum values of EC, and water-soluble Ca, P, Cu, and Zn were 9.1, 46.1, 8.3, 53.2, and 7.6-fold, respectively, of their minimum values (data not shown). The variation of EC, and water-soluble Ca and Cu were greater than that of water-soluble P and Zn.

Tables 5 and 6 show statistical results of pH, EC, water-soluble P and metals, and Mehlich III-extractable P, Cu, Zn, and Pb when all the 51 surface soil samples were categorized into three groups (positions A, B, and C) based on their sampling positions. The differences in the pH, EC, water-soluble Ca, Mg, Na, K, P, Cu, and Zn, and Mehlich III extractable Zn, P, and Cu were significant among the three positions. The highest values of all measured variables except for water-soluble Fe, Pb, As, and Se, and Mehlich III extractable Pb occurred at position A. This position was located at the north side of the citrus tree, close to the emitter, whereas the lowest values for most of the measured variables, including pH, EC, water-soluble Ca, Mg, Na, K, P, Cr, Cu, Ni, Zn, As, Mn, and Mehlich III extractable Cu and Zn occurred at position C. Significant higher values of the EC,

Fig. 2. Variations of Mehlich III-extractable P, Zn, and Cu and pH in the soils near the emitter as a function of distance (X = along the row, Y = perpendicular to the row).

and water-soluble Ca, Mg, Na, P, Cu, and Zn probably resulted from a long-term fertigation that supplied and increased the metals in the soils around the position A.

Small-scale variations near emitter. High variability of selected variables occurred near an emitter (Fig. 2). The variations of Mehlich III extractable P, Cu, and Zn were greater than

variation of pH. Higher Mehlich III extractable P, Cu, and Zn occurred in the soils within 0 to 20 cm distance from the emitter. The variations were probably due to uneven distribution of irrigation by the emitter. The soil in the area within 0 to 20 cm distance from the emitter, receiving more irrigation water than outside with distance of 20 to 90 cm from the emitter, had more P accumulation. In addition, being closer to citrus tree trunk, the soil in the area within 0 to 20 cm distance from the emitter also received more heavy metals from trunk flow than other areas.

Vertical distribution of phosphorus, copper, and zinc. Profile distributions of contaminants in soils can trace migration of the contaminants (Cassagne et al., 2000; Maskall et al., 1996). Significant variations of total P, Cu, and Zn concentrations occurred among the three sampling locations. Generally, total P, Cu and Zn were the highest in the surface soils (0 to 5 cm) and decreased gradually downward (Fig. 3). Total P, Cu, and Zn concentrations in the soils of 0 to 10 cm depth were higher in the PF3 than the PF1 and PF2. In contrast, for the soils at the 20 to 100 cm depth, the total P, Cu, and Zn concentrations were higher in PF1 and PF2 than PF3, indicating that P, Cu, and Zn downward movement in the soils near the water furrow or midway of inter-neighboring trees was more significant than those under the canopies. The extent of P, Cu, and Zn downward movement was in the order of PF1 > PF2 > PF3. These results suggest that application of fertilizers to site under the canopy rather than the spaces between the trees could minimize leaching losses of P and metals.

Conclusions

Labile P and metals in the soil under citrus production were characterized by a high spatial variability, even within a very short distance, as indicated by high cv values. Across the row, the values of pH, EC, water-soluble P, and all metals were the highest in the soils under the canopies, and the lowest in the soils near the water furrow or the midway of inter-row.

Fig. 3. Vertical variations of total P, Cu, and Zn in the soil profiles collected from different positions. PF1 = near the water furrow, PF2 = midway of the inter-neighboring tree, PF3 = under the canopy.

Along the row, the highest values of most measured variables occurred at the location close to the emitter where P and metals were partially supplied by the fertigation. Most of the measured variables were strongly spatially dependent. Phosphorus, Cu, and Zn downward movement in the soil was more significant near the water furrow or midway of inter-neighboring trees than under the canopies. The downward movement of P, Cu, and Zn in the soils was more significant in the soils in open areas (near the water furrow and midway of inter-neighboring trees) than those under the canopies. The spatial variation of soil labile P and metals is a reflection of spatial variation in both fertigation and rain-induced leachings and merits great attention in the sampling and interpretation of soil analysis data for citrus production systems. These results also suggest that application of fertilizers to site under the canopy rather than the spaces between the trees could minimize leaching losses of P and metals.

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