Proc. Fla. State Hort. Soc. 123:67–73. 2010.

Estimating Relative Nutrient Uptake by Mature Citrus Trees in Field Conditions

Kirandeep K. Mann*, Laura J. Waldo, Kevin Hostler, Rajinder S. Mann, and Arnold W. Schumann

University of Florida, IFAS, Citrus Research and Education Center, Lake Alfred, FL 33850

Additional index words. Advanced Citrus Production System (ACPS), Open Hydroponics System (OHS), frequent fertigation, nutrient depletion method

Knowledge of nutrient uptake rates by tree roots is of fundamental importance to develop a citrus fertilization program. However, measuring the nutrient uptake by mature trees in field conditions is difficult. Nutrient uptake by intact roots of mature citrus trees was estimated using the nutrient depletion method, wherein intact roots were separated from the soil and placed in a nutrient solution of known composition. Thereafter, the nutrient concentrations of the solution were measured at a series of time intervals (0, 4, 8, 12, 24, 48, 72, 96, 120, and 144 h) to determine the nutrient depletion curve. The solution volume was maintained with deionized water using constant head Mariotte tubes. Our results showed that the diurnal and seasonal changes in soil temperature and evapotranspiration were responsible for the corresponding variations in nutrient uptake. The time periods, determined by inflection points, beyond which further nutrient uptake was negligible were very low (12–51 h) for different months, revealing that the nutrient uptake by roots is very fast for the first few hours and is negligible after a certain level of depletion is reached. These results suggested the need of frequent small fertigations to supply the tree roots with a continuous source of nutrients to sustain high uptake rates, to prevent nutrient losses to the environment, and to increase nutrient use efficiency. Relative uptake of different nutrient ions also varied across different months. Collectively, our results provide a basis for the development of guidelines for fertigation in an Advanced Citrus Production System and fertilizer formulations to meet the plant's requirements.

Estimation of nutrient uptake by roots of mature citrus trees is important to develop a fertilization program to match crop needs. Seedling studies are generally used to evaluate nutrient uptake by tree roots, but the results from these studies can not be applied to mature trees, because nutrient uptake requirements may change as trees mature (Eissenstat and Achor, 1999; Wells and Eissenstat, 2003). The variations in nutrient uptake between seedlings and mature trees can be due to the differences in their root anatomy, respiration, and hydraulic conductivity (Wells and Eissenstat, 2003) as well as the absence or presence of a fruit crop. In addition, roots may also show differential nutrient uptake in solution and in soil media (Skene et al. 1998). Consequently, results of the seedlings or young plants can not be extrapolated to mature trees in field conditions. However, measuring nutrient uptake by roots of mature trees in field conditions is not easy. This can be primarily due to a larger tree's root system size and difficulty to access roots from the soil.

Nutrient uptake for mature trees has been accomplished either by using excised or intact roots (Lucash et al., 2007). In the first method, roots are excavated from the soil, excised, and sealed inside bags, which are placed in an aerated nutrient solution. Alternatively, in the intact root method, roots of mature trees are excavated without detaching them from the tree and placed in an aerated nutrient solution in-situ (Lucash et al., 2005). The most significant advantage of intact root methods is that the roots are still attached to the tree and can continue to transport carbon, water, and nutrients. The nutrient depletion method is generally used to measure nutrient depletion at a series of time intervals from an initial solution of known concentration (Claassen and Barber, 1974). Nutrient uptake for intact roots using the nutrient depletion method has been widely used for forest trees (Escamilla and Comerford, 1998; McFarlane and Yanai, 2006).

Nutrient uptake by citrus trees is generally evaluated using young plants, and there is little information for the uptake by mature trees in field conditions. Citrus trees under managed orchards are subjected to seasonal fertilizer applications. However, infrequent high doses of seasonal fertilizer applications reduce fertilizer uptake efficiency (nutrient recovered/nutrient applied) due to increased nutrient losses. These losses may include increased adsorption to the soil, leaching, precipitation, volatilization, and immobilization. Nutrient losses to the environment can be prevented by adopting Best Management Practices (BMPs), which should focus on limited and timely efficient application of fertilizers.

The Advanced Citrus Production System (ACPS) is a new and promising technique for intensive, efficient and economic citrus production (Morgan et al., 2009; Roka et al., 2009; Stover et al., 2008). The ACPS aims to enhance bloom and fruit set, maximizing fruit quality, and increasing nutrient and water use efficiencies using the Open Hydroponics system (OHS). An OHS is a method of supplying a crop's nutrient and water needs continuously with intensive fertigation and irrigation. Small and frequent fertigations allow limited fertilizer-soil contact, make nutrients readily available to the roots, and prevent adsorption and leaching losses. Consequently, the OHS can conserve fertilizer as compared with the conventional infrequent fertilizer application (Schumann et al.,

*Corresponding author; phone: (863) 956-1151, ext. 1200, 1235; email: mannkk@crec.ifas.ufl.edu

2009). Besides conserving the fertilizer, this system also has the potential of increasing photosynthesis, transpiration, and citrus tree growth as compared to the conventional methods of fertilizer and irrigation application (Schumann et al., 2009). The OHS reduces nutrient leaching and hence ground water contamination by precisely managing the applied nutrients within the tree root zone (Schumann et al., 2010).

However, further refinement of fertigation recipes, frequency, and time of application in the OHS is required for enhancing nutrient use efficiencies. Knowledge of the seasonal patterns of nutrient uptake by roots is also an important component of fertilizer management as related to physiological events like fruit production and can be used to increase nutrient use efficiency by matching fertilizer applications with the periods of high nutrient uptake capacity. Yet, this system has to be closely monitored for nutrient depletion patterns in order to maintain sufficient nutrient levels in the root zone and prevent nutrient losses. Hence, our objectives were to 1) estimate the nutrient uptake rates by mature citrus trees in field conditions using the nutrient depletion method, and 2) evaluate the diurnal and seasonal changes in the nutrient uptake rates.

Materials and Methods

Experimental approach. To estimate nutrient uptake with the nutrient depletion method, a mature 'Hamlin' orange tree [*Citrus sinensis* (L.) Osb.] on Swingle citrumelo [*Citrus paradisi* Macf. × *Poncirus trifoliata* (L.) Raf.] rootstock growing in a grove at the Citrus Research and Education Center (CREC), Lake Alfred, FL, was used. The soil series in the study is a Candler fine sand (hyperthermic, coated Typic Quartzipsamments). Two intact fibrous roots were separated carefully from the wall of a shallow access pit dug in the soil and washed with deionized water to remove any soil particles attached to them. These roots were each trained into separate 1-L plastic root boxes containing an aerated Hoagland's nutrient solution of known composition. Roots were trained and conditioned for 4–5 d before starting the actual experiment to allow them to recover from physical manipulation and to adjust to the liquid medium. The modified Hoagland's nutrient solution consisted of 269 $mg \cdot L^{-1}$ NO_3-nitrogen (N), 62 $mg \cdot L^{-1}$ phosphorus (P), 430 $mg \cdot L^{-1}$ potassium (K), 281 $mg \cdot L^{-1}$ calcium (Ca), 49 $mg \cdot L^{-1}$ magnesium (Mg), 124 $mg \cdot L^{-1}$ sulfur (S), 3 $mg \cdot L^{-1}$ boron (B), 1 $mg \cdot L^{-1}$ zinc (Zn), 3 $mg \cdot L^{-1}$ manganese (Mn), 6 $mg \cdot L^{-1}$ iron (Fe), 0.1 $mg \cdot L^{-1}$ copper (Cu), and 0.1 $mg \cdot L^{-1}$ molybdenum (Mo). The nutrient solution in the two replicated root boxes was continuously aerated using an aquarium air pump and flexible PVC tubing inserted to the bottom of the containers. A constant head Mariotte tube system was assembled for each root container to maintain the solution volume with deionized water. The experiment was started at 7 AM by filling the root containers to a known volume (900 mL) with Hoagland's nutrient solution. Thereafter, 15-mL solution samples were collected to measure the pH, electrical conductivity, and nutrient concentrations of the solution at a series of time intervals (0, 4, 8, 12, 24, 48, 72, 96, 120, and 144 h) to describe a complete depletion curve. A correction calculation for nutrient remaining was used to account for the 15-mL aliquot samples being removed. The control experiment consisted of a similar setup, but without roots in order to quantify nutrient concentration changes due to volatilization, precipitation, or diffusion into the Mariotte tube reservoir. The experiment was repeated every month to explore the seasonal difference in nutrient uptake patterns.

Data analysis. Nutrient concentrations left in the solution were plotted against time to describe nutrient depletion curves. Nutrient uptake rates were expressed per unit time for the experiment duration each month. Relative nutrient uptake was expressed as the uptake ratio of various nutrients. The patterns of nutrient uptake rates were plotted against time to test for diurnal and seasonal changes. Daily and hourly weather data were downloaded from the Florida Automated Weather Network (FAWN) website (http://fawn.ifas.ufl.edu/) for the weather station located at Lake Alfred. Hourly evapotranspiration (ETo) was predicted from the Penman-Monteith equation (Allen et al., 1998) using the hourly mean temperature, wind speed, relative humidity, and solar radiation. Cumulative heat units at different times were calculated from hourly temperature readings obtained from FAWN. Heat accumulated each day was determined by adding together the maximum and minimum temperatures and dividing the total by two to obtain a daily average. The crop threshold for citrus of 13 °C was then subtracted from this average, and final values were used to represent the daily heat units for citrus (Hardy and Khurshid, 2007). To relate the nutrient uptake rates with weather conditions, regression analysis was performed using PROC REG with SAS software (SAS Ver. 9.1 SAS Institute, Inc., 2003).

Results and Discussion

Diurnal changes in nutrient uptake. Daily variations of N, P and K uptake followed the patterns of soil temperature and ETo (Fig. 1). In Dec. 2009, soil temperatures were high for the first 8 h and decreased thereafter until 48 h, after which the patterns of day and night were noticeable. The ETo also varied in a similar pattern throughout the experiment duration. An increase in soil temperatures and ETo up to 8 h increased the nutrient uptake correspondingly; however, N, P, and K uptake was negligible after this period. The patterns of N, P, and K uptake over the course of the experiment in May 2010 showed distinct diurnal variations and these variations followed the variations in soil temperature and ETo up to 48 h, and showed very low uptake after that. Nutrient uptake in the months of January, February, March, and April also varied with the diurnal variations in weather conditions. Nutrient uptake for Ca, Mg, S, B, Fe, and Mn also followed similar patterns for each month (data not shown). These diurnal trends revealed the important role of soil temperature and ETo in nutrient uptake by tree roots. High soil temperatures and ETo increase uptake by enhancing the nutrient translocation to shoots (Silberbush and Asher, 2001). These daily variations in the nutrient uptake can also be due to the corresponding variations in the transport of photosynthates to the roots, because diurnal variations in temperature affect photosynthesis and gas exchange of citrus trees (Jifon and Syvertsen, 2003; Robeiro et al., 2009). Air temperatures also influence both soil and nutrient solution temperatures affecting the nutrient uptake, because uptake increases linearly with an increase in root zone temperature (Stoltzfus et al., 1998). Diurnal patterns of increased nutrient uptake during specific hours of the day were also observed in our study. These patterns would assist in planning hourly fertigation according to the uptake capacity of tree roots to increase fertilizer use efficiency. Therefore, frequent fertigations in the OHS should be monitored, controlled, and manipulated in order to apply the fertilizer in the root zone during the high uptake hours of the day.

Seasonal changes in nutrient uptake. The variations in average weather conditions during the experiment for different months (Table 1) showed about a 4× increase in solar radiation, a

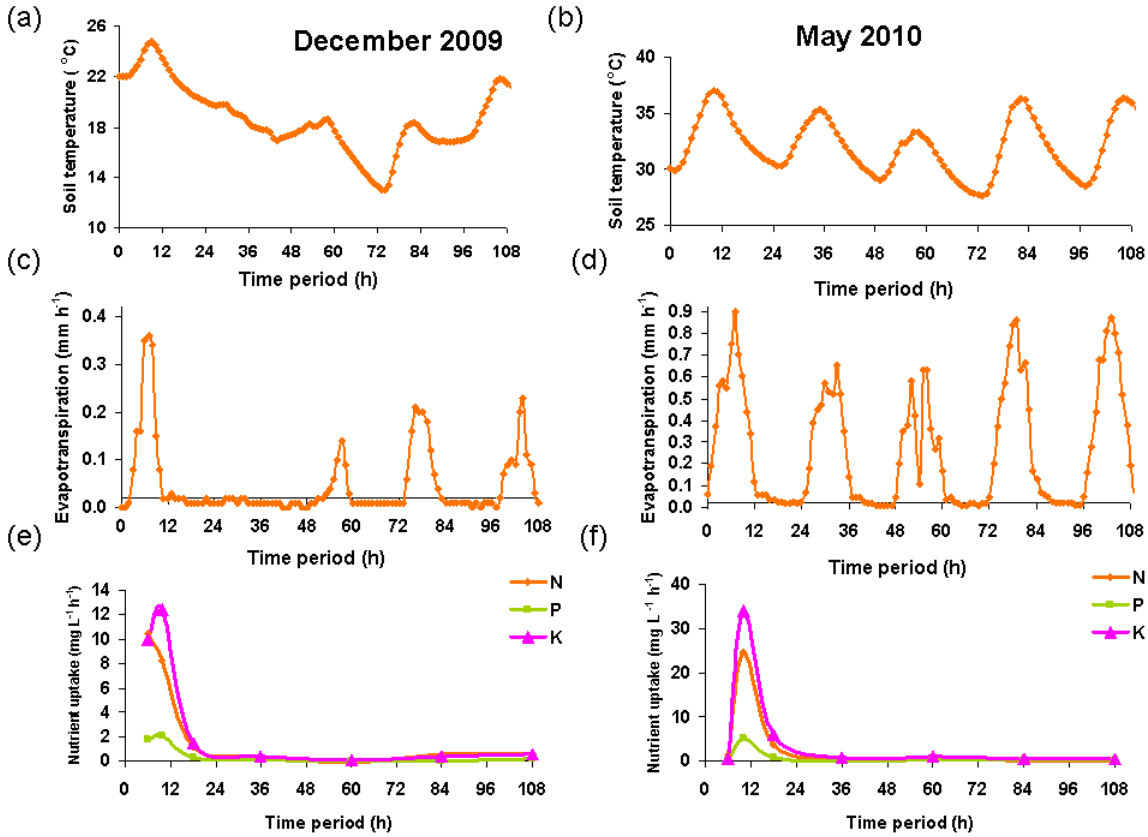

Fig. 1. Diurnal variation in (**a, b**) soil temperature, (**c, d**) evapotranspiration and (**e, f**) nutrient uptake for Dec. 2009 and May 2010.

2x increase in air and soil temperatures, and about an 8× increase in ETo from Dec. 2009 to May 2010. Soil temperatures during uptake periods ranged from about 15 to 32 °C and ETo from 0.03 to 0.24 mm·d^{-1}. This large increase in temperatures and ETo throughout these months combined with the active spring growth period of the tree increased the nutrient uptake to a large extent. Comparing the nutrient uptake from Dec. 2009 to May 2010 (Fig. 1) there was an approximately 2–3× increase in the uptake rates of N, P, and K. The increase in nutrient uptake with increasing temperatures and ETo could be either due to their direct effect on nutrient uptake kinetics or an indirect effect of temperature on plant growth. These seasonal variations could also be due to variations in photosynthetic activity, because photosynthetic activity for citrus plants is higher in the summer as compared to that in winter (Riberro et al., 2009). Another possibility for the variable seasonal uptake rates could be the effect of soil temperature on root growth and activiy. The amount of citrus root growth has been positively correlated with soil temperature throughout the year showing maximum root activity in summer and fall (Bevington and Castle, 1986). They correlated the total monthly root growth and monthly mean soil temperature for rough lemon (*Citrus jambhiri* Lush) with r = 0.85 and Carrizo citrange [*C. sinensis* (L.) Osb. × *Poncirus trifoliata* Raf.] with r= 0.73, and found more intense root growth when soil temperatures were above 27 °C. Increasing soil temperatures up to 30 °C also increase the number of fine roots in citrus (Poerwanto et al., 1989). The increased number of fine roots may increase root surface area leading to more root-soil contact for enhanced nutrient and water absorption at higher temperatures.

Cumulative heat units for different time intervals within each experiment for all the months (Table 2) also increased by about 3–5× from Dec. 2009 to May 2010. The values ranged from 0–32

Table 1. Average weather conditions during the course of the experiment for each month.

Month and year	Solar radiation (W·m^{-2})	Temp (°C) Air	Temp (°C) Soil	Rainfall (cm)	ETo (mm·d^{-1})
Dec. 2009	68.9	17.6	19.4	0.032	0.03
Jan. 2010	129.2	15.4	15.0	0.007	0.09
Feb. 2010	144.9	13.0	16.4	0.014	0.09
Mar. 2010	235.3	18.7	24.2	0.011	0.17
Apr. 2010	284.0	23.1	27.8	0.045	0.24
May 2010	266.0	27.0	32.0	0.001	0.23

Table 2. Cumulative heat units for each month at different time periods of the experiment duration.

Duration of experiment (h)	Dec.	Jan.	Feb.	Mar.	Apr.	May
24	9.3	0.0	7.7	6.7	24.2	31.8
48	9.3	3.7	9.3	11.4	36.4	45.4
72	8.9	10.4	9.3	18.9	47.2	60.5
96	16.8	16.9	11.8	26.7	57.1	74.7
120	27.8	18.2	11.8	33.2	63.6	88.0
144	36.6	18.2	11.8	38.2	64.0	94.8

Table 3. Regression analysis between cumulative nutrient uptake and cumulative heat units for each month.

	Dec.	Jan.	Feb.	Mar.	Apr.	May
N	0.87**	0.87**	0.40^{NS}	0.87**	0.86**	0.72*
P	0.93**	0.86**	0.46^{NS}	0.97**	0.88**	0.84*
K	0.93**	0.87**	0.60^{NS}	0.92**	0.78*	0.76*
Ca	0.60^{NS}	0.86**	0.43^{NS}	0.89**	0.90**	0.83*
Mg	0.61^{NS}	0.86**	0.44^{NS}	0.91**	0.85**	0.86**
S	0.23^{NS}	0.85**	0.45^{NS}	0.91**	0.86**	0.81*
B	0.59^{NS}	0.86**	0.44^{NS}	0.91**	0.87**	0.55^{NS}
Fe	0.64^{NS}	0.73*	0.50^{NS}	0.72*	0.94**	0.80*
Mn	0.60^{NS}	0.87**	0.43^{NS}	0.96***	0.70*	0.87**
Zn	0.58^{NS}	0.95**	0.07^{NS}	0.83*	0.74*	0.64^{NS}

$^{NS, *, **, ***}$Nonsignificant or significant at $P < 0.05$, 0.01, and 0.001, respectively.

at the 48th hour and 12–95 at the 144th hour of the experiment. Relationships between cumulative heat units and cumulative nutrient uptake (Table 3) were linear and strong for most of the nutrients for each month except December and February. The strong relationships between cumulative heat units and uptake are commonly used to model or predict the effect of temperature on nutrient uptake (Scholberg et al., 2002; Unruh and Silvertooth, 1996). These variations in nutrient uptake across different months can be driven by variable weather conditions, nutrient availability and demand, and the root's ability to absorb nutrients that changes with the tree growth stage. Seasonal variations in nutrient uptake by tree roots affect specific physiological stages, export of nutrients, and fertilizer use efficiency (Lucash et al., 2005). Thus, understanding the timing of nutrients being taken up by roots is an important aspect in planning fertilizer applications to coincide with these periods of high nutrient uptake. The key would be to develop a fertilization program to match crop needs and nutrient uptake, reduce leaching, and to maximize fertilizer use efficiency. This information could be beneficial when making best management decisions concerning the application of fertigation in an ACPS.

Nutrient removal with time. To measure how fast the nutrients are depleted from the initial solution we used the inflection point times and concentrations of different nutrients for each month. This inflection point time was defined as the breakthrough point in the nutrient depletion curve beyond which there was negligible nutrient uptake. For example, they were 24 h for Ca uptake in May 2010 (Fig. 2 a and b). These inflection points were the same for nutrient uptake of all the other nutrients for the same month (Table 4). The inflection point time periods for different months varied from about 12 to 51 h, and were less than 24 h for all the months except January and February. The concentrations corresponding to the inflection point time periods (Table 5) showed seasonal variations. The threshold concentrations beyond which the nutrient uptake was negligible were higher in December through February and started decreasing after March, suggesting increasing nutrient uptake efficiency by the roots during the spring months. The threshold concentrations of macro nutrients were 2–4× lower in May as compared to those in December due to the increased nutrient uptake by the roots with the increased temperatures (Scholberg et al., 2002) and tree growth. However, the concentrations of the micro nutrients did not vary much through different months except for Fe (decreased) and Zn (increased) in May. The concentrations were higher in February, possibly due to the after-effects of a severe January freeze. These critical threshold nutrient concentrations across different months would assist in developing fertigation recipes and ideal dilution ratios by fertilizer injection in an ACPS.

We compared nutrient depletion as a fraction of the initial

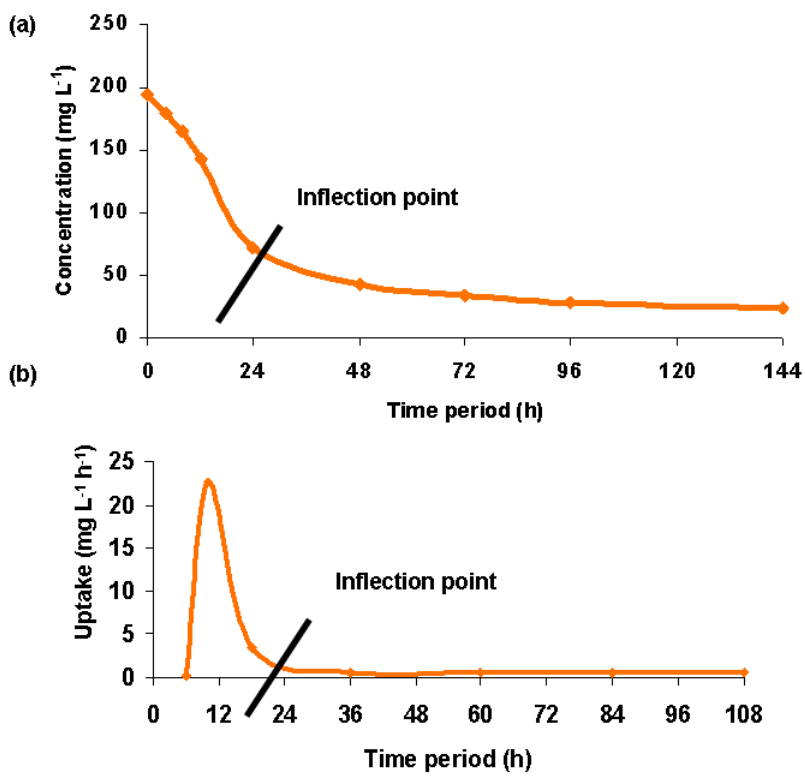

Fig. 2. The (**a**) depletion curve and (**b**) uptake rate of Ca for May 2010 showing the inflection point time period and concentration.

Table 4. The inflection point time periods of all the nutrients for each month.

	Inflection point time period (h)					
Nutrient	Dec.	Jan.	Feb.	Mar.	Apr.	May
N	17	36	39	24	20	24
P	18	36	39	24	20	24
K	18	36	51	24	20	24
Ca	18	36	39	24	20	24
Mg	18	36	39	24	20	24
S	18	36	39	24	20	24
B	18	36	30	24	24	24
Fe	18	30	51	36	12	24
Mn	18	12	51	24	48	24
Zn	18	42	51	48	48	24

Table 5. The inflection point concentrations of all the nutrients for each month.

	Initial concn	Inflection point concn (mg·L^{-1})					
Nutrient	(mg·L^{-1})	Dec.	Jan.	Feb.	Mar.	Apr.	May
N	269	199	224	239	169	100	70
P	62	41	46	49	34	33	19
K	430	257	354	302	229	155	126
Ca	281	178	195	205	155	143	71
Mg	49	33	35	37	28	25	13
S	124	77	84	89	69	62	36
B	2.5	1.6	1.7	1.8	1.8	1.2	1.8
Fe	6.3	1.9	2.2	1.1	1.4	1.2	1.1
Mn	2.5	1.6	1.7	2.2	1.4	1.2	1.8
Zn	0.9	0.6	0.7	0.6	0.7	0.5	0.4

solution concentration, which was expressed as percentage for different time periods (Table 6). In general, uptake was relatively high in December and January, but decreased in February. However, rising temperatures from March to May increased nutrient uptake continuously. There was more than 70% depletion of N, P, and K after 72 h of starting the experiment in May 2010. The percent uptake relative to the initial concentration was high for Ca, Mg, and S in December, January, April, and May. However in December, S showed the fastest depletion (75%) relative to the initial solution concentration. Among micronutrients, Fe was depleted at a faster rate throughout all the months. However, most of the nutrients were depleted by more than 80% at the 144th hour of the experiment.

Inflection point time periods, concentrations, and nutrient depletion with time indicated that nutrient uptake by roots is very fast for the first few hours when nutrient concentrations in solution are still high, after which there is negligible uptake. Based on these observations we can expect that in the real field conditions, nutrients supplied continuously in small amounts are rapidly taken up by the trees within the first few hours of fertilizer application. Rapid nutrient uptake from the soil solution would be desirable because losses to the environment by leaching, precipitation, adsorption, immobilization or volatilization would thus be minimized. After the rapid uptake of nutrients depletes the soil solution in the root zone to suboptimal concentrations for further uptake, a steady stream of nutrients will be released from soil surfaces having reversible nutrient holding sites (cation and anion exchange capacity) until they too are depleted. Frequent

Table 6. Nutrient taken up at 72 h as a percentage of the initial concentration for each month.

Nutrient	Dec.	Jan.	Feb.	Mar.	Apr.	May
N	48.0	58.7	38.8	51.8	65.0	77.2
P	47.1	58.6	38.8	34.2	51.3	73.2
K	44.0	61.8	36.8	45.1	56.0	73.0
Ca	48.3	58.4	38.2	37.9	49.7	72.9
Mg	44.8	56.0	36.9	34.1	48.5	69.4
S	74.0	57.1	38.5	36.0	49.0	69.9
Fe	74.9	66.6	57.7	74.1	48.8	73.0
B	45.8	57.0	37.9	34.47	80.7	85.8
Mn	43.9	55.3	36.6	33.9	58.7	70.8

Table 7. Uptake ratios of nutrients for each month for the whole experiment duration of 144 h.

Uptake ratio	Dec. 2009	Jan. 2010	Feb. 2010	Mar. 2010	Apr. 2010	May 2010
N/K	0.84	0.6	0.8	1.7	0.9	1.0
N/Ca	1.1	1.1	1.4	1.3	1.7	1.7
K/Ca	1.3	1.9	1.1	1.4	1.2	3.2
Ca/Mg	5.9	6.0	9.5	6.9	5.8	5.0
N/S	2.5	2.5	3.0	3.8	2.8	2.7
N/B	201.4	125.8	107.9	63.7	142.8	241.6

fertigation essentially substitutes for the less predictable nutrient storage capacity of soil and compensates for low storage capacities of very sandy soils such as those in Florida. Frequent fertigations with small doses as in ACPS would provide a continuous source of nutrients and prevent leaching below the root zone in highly leached Florida sandy soils and increase nutrient use efficiency. Increased nutrient use efficiency with decreased nutrient levels in the root zone has been observed in other studies (Campbell et al., 1993; Jiang and Hull, 1998). Scholberg et al. (2002) found that more frequent application of dilute N solution (N at 7 mg·L^{-1}) doubled nutrient use efficiency (NUE) compared with less frequent application of more concentrated N solution (N at 70 mg·L^{-1}) for Swingle citrumelo [*Citrus paradisi* Macf. × *Poncirus trifoliata* (L.) Raf. var. Swingle] and Volkamer lemon (*C. volkameriana* Ten & Pasq.) seedlings.

Relative nutrient uptake. Uptake ratios of various nutrients (Table 7) indicated the variations in relative nutrient uptake across different months. Uptake of K was higher than N from December to February, after which N uptake started increasing and N:K ratio was close to 1. The balance between N and K is important for flowering, fruit set, and vegetative canopy development. For example, N increases juice volume, total soluble solids (TSS), and acid concentration, but decreases fruit size and weight. In contrast, K increases fruit size, and weight, however decreases juice content, TSS, and TSS/acid ratio (Obreza et al., 2008). Therefore, N and K fertilizers are recommended at equal rates under normal growing conditions (Obreza et al., 2008). Uptake ratios for N:Ca were lower before March (1.1 to 1.4), which coincides with the period of flower and leaf initiation than after Mar. (1.7), when relative Ca uptake decreased. Among uptake of cations, K:Ca ratios varied from 1.1 to 1.9 until April, after which this ratio increased to more than 3. Conversely, the ratios for Ca:Mg were high from January through March due to more Ca uptake during cell differentiation and division. Among anions, the N:S ratios increased from February onwards probably due

to the higher demand of N for flowering and fruit set in spring. In contrast, the N:B ratio was approximately 200 in December; however, this ratio decreased during February and March, indicating more B uptake during flowering. Deficiency of boron leads to reduced flowering and fruit set, low sugar content, gumming, and fruit drop in citrus (Obreza et al., 2008; Smith and Reuther, 1949). Variable nutrient uptake across the seasons suggests that the application and availability of various nutrients with respect to each other could affect tree growth, fruit production, and quality. As suggested by the nutrient uptake ratios, the key would be to identify the role each nutrient plays in tree growth, fruit production and quality, and time the application of a nutrient element to stimulate a specific physiological process. Further nutrient interactions and their role in citrus production will be explored by comparing various nutrients ratios to the established norms in further studies using the Diagnosis and Recommendation Integrated System (DRIS) (Walworth and Sumner, 1975). The DRIS identifies nutrient imbalances, deficiencies and excesses in nutrient solution (Schumann and Sumner, 2004) or leaves (Campion and Scholes, 2007; Schumann and Sumner, 1999) and ranks them in order of importance. After diagnosing the nutrient status, linear programming could be used to adjust the fertilizer solutions to match the plant's requirements.

Conclusions

The diurnal and seasonal changes in soil temperature, ETo, and concomitant growth differences were the likely causes for the corresponding variations in total nutrient uptake. These diurnal and seasonal trends of nutrient uptake would assist in planning fertigation during the active nutrient uptake periods to increase the fertilizer use efficiency. The inflection point time periods beyond which further nutrient uptake was negligible were very low (12–51 h) for different months indicating very fast nutrient uptake for the first few hours which become negligible at low remaining nutrient concentrations. The threshold nutrient concentrations corresponding to the inflection point time periods varied seasonally and were 2–4× lower in May as compared to those in Dec. The variable threshold concentrations across different months would assist in developing fertigation recipes. The small (12–51 h) inflection points suggested the need of frequent fertigations to supply the tree roots with a continuous nutrient source, to prevent nutrient losses to the environment, and to increase nutrient use efficiency. Uptake ratios of different nutrients in different months suggested the importance of timely application of specific nutrient elements to stimulate a specific physiological process. It seems evident from the results that the nutritional solution composition in fertigation should be designed according to crop needs. Based on these investigations, guidelines for the development of recipes and frequency of fertigations can be established to meet the plant's requirements and our objectives in ACPS.

Literature Cited

Allen, R.G., L.S.Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements Food and Agriculture Organization of the United Nations, Rome.

Bevington, K.B. and W.S. Castle. 1986. Root growth studies on citrus. Acta Hort. 175:63–66.

Campbell, C.A., F. Selles, R.P. Zentner, and B.G. McConkey. 1998. Nitrogen management for zero-till spring wheat: Disposition in plant and utilization efficiency. Commun. Soil Sci. Plant Anal. 24:2223–2239.

Campion, J.M. and M.C. Scholes. 2007. Diagnosing foliar nutrient dynamics of *Eucalyptus grandis* in KwaZulu-Natal, South Africa, using optimal element ratios and the diagnosis and recommendation integrated system (DRIS). Southern Hemisphere For. J. 69:137–150.

Claassen N. and S.A. Barber. 1974. A method for characterizing the relation between nutrient concentration and flux into roots of intact plants. Plant Physiol. 54:564–568.

Escamilla, J.A. and N.B. Comerford. 1998. A method for measuring nutrient depletion by roots of mature trees in the field. Soil Sci. Soc. Amer. J. 62:797–804.

Eissenstat D.M. and D.S. Anchor. 1999. Anatomical characteristics of roots of citrus rootstocks that vary in specific root length. New Phytol. 141:309–321.

Florida Automated Weather Network (FAWN). University of Florida IFAS Ext. <http://fawn.ifas.ufl.edu/>.

Hardy, S. and T. Khurshid. 2007. Calculating heat units for citrus. Profitable and sustainable primary industries. Primefact 749.

Jiang, Z. and R.J. Hull. 1998. Interrelationships of nitrate uptake, the low N concentrations of reclaimed water are not nitrate reductase, and nitrogen use efficiency in selected Kentucky bluegrass cultivars. Crop Sci. 38:1623–1632.

Jifon, J.L. and J.P. Syvertsen. 2003. Moderate shade can increase net gas exchange and reduce photoinhibition in citrus leaves. Tree Physiol. 23:119–127.

Lucash M.S., J.D. Joslin, and R.D. Yanai 2005. Temporal variation in nutrient uptake capacity by intact roots of mature loblolly pine. Plant Soil 272:253–262.

Lucash, M.S., D.M. Eissenstat, J.D. Joslin, K.J. McFarlane, and R.D. Yanai. 2007. Estimating nutrient uptake by mature tree roots under field conditions: challenges and opportunities. Trees 21:593–603.

McFarlane, K.J. and R.D. Yanai. 2006. Measuring nitrogen and phosphorus uptake by intact roots of mature *Acer saccharum* Marsh., *Pinus resinosa* Ait., and *Picea abies* (L.) Karst. Plant Soil. 279:163–172.

Morgan, K., D. Kadyampakeni, A. Schumann, W. Castle, E. Stover, P. Spyke, F. Roka, F.R. Muraro, and A. Morris. 2009. Citrus production systems to survive greening—Horticultural practices. Proc. Fla. State Hort. Soc. 122:114–121.

Obreza, T.A., M. Zekri, and H.F. Stephen. 2008. General soil fertility and citrus tree nutrition, p. 16–22. In: T.A. Obreza and K.L. Morgan (eds.). Nutrition of Florida citrus trees, 2nd Ed. Fla. Coop. Ext. Serv. SL253. 16 Feb. 2009. <edis.ifas.ufl.edu/SS478>. Univ. of Fla. Inst. Food and Agr. Sci., Gainesville.

Poerwanto, R., H. Inoue, and I. Kataoka. 1989. Effects of temperature on the morphology and physiology of the roots of trifoliate orange budded with Satsuma mandarin. J. Jpn. Soc. Hort. Sci. 58:267–274.

Ribeiro R.V., E.C. Machado, M.G. Santos, and R.F. Oliveira. 2009. Seasonal and diurnal changes in photosynthetic limitation of young sweet orange trees. Environ. Expt. Bot. 66:203–211.

Roka, F., R. Muraro, A. Morris, P. Spyke, K. Morgan, A. Schumann, W. Castle, and E. Stover. 2009. Citrus production systems to survive greening—Economic thresholds. Proc. Fla. State Hort. Soc. 122:122–126.

Scholberg, J.M.S, L.R. Parsons, T.A. Wheaton, K.T. Morgan, and B.L. McNeal. 2002. Soil temperature, N concentration, and residence time affect nitrogen uptake efficiency of citrus. J. Environ. Qual. 31:759–768.

Schumann, A.W., K. Hostler, K.K. Mann, and L. Waldo. 2009. Advanced citrus production systems: managing for productivity. Citrus Ind. 90:7–9.

Schumann A.W., K. Hostler, W. Waldo, and K.K. Mann. 2010. Update on advanced citrus production system research in Florida. Citrus Ind. 91:6–11.

Schumann, A.W. and M.E. Sumner. 1999. Plant nutrient availability from mixtures of fly ashes and biosolids. J. Environ. Quality 28:1651–1657.

Schumann, A.W. and M.E. Sumner. 2004. Formulation of environmentally sound waste mixtures for land application. Water, Air, Soil Pollut .152:195–217.

Silberbush, M. and J. Ben-Asher. 2001. Simulation study of nutrient uptake by plants from soilless cultures as affected by salinity buildup and transpiration. Plant Soil 233:59–69.

Skene, K.R., J.A. Raven, and J.I. Sprent. 1998. Cluster root development in *Grevillea robusta* (Proteaceae) I. Xylem, pericycle, cortex, and epidermis development in a determinate root. New Phytol. 138:725–732.

Smith, P.F. and W. Reuther. 1949. Observations on boron deficiency in citrus. Proc. Fla. State Hort. Soc. 62:31–37.

Statistical Analysis System Institute. 2003. SAS/STAT guide for personal computers. Version 9.1. SAS Inst., Cary, NC.

Stoltzfus, R.M.B., H.G. Taber, and A.S. Aiello. 1998. Effect of increasing root-zone temperature on growth and nutrient uptake by 'Gold Star' muskmelon plants. J. Plant Nutr. 21:321–328.

Stover, E., W.S. Castle, and P. Spyke. 2008. The citrus grove of the future and its implications for huanglongbing management. Proc. Fla. State Hort. Soc. 121:155–159.

Unruh, B.L. and J.C. Silvertooth. 1996. Comparisons between an upland and a pima cotton cultivar: II.Nutrient uptake and partitioning. Agron. J. 122:589–595.

Walworth, J.L. and M.E. Sumner. 1975. The Diagnosis and Recommendation Integrated System (DRIS), p. 149–188. In: B.A. Stewart (ed.). Advances in soil science, Vol. VI. Springer-Verlag, New York.

Wells, C.E. and D.M. Eissenstat. 2003. Moving beyond the roots of young seedling: The influence of age and branching order on root functions. J. Plant Growth Regul. 21:324–334.