Nutrient Cycling in Agroecosystems **66:** 221–232, 2003.

Response to fertilization and nutrient deficiency diagnostics in peach palm in Central Amazonia

A. Ares[1,*], N. Falcao[2], K. Yuyama[2], R.S. Yost[1] and C.R. Clement[2]
*[1]Department of Tropical Plant & Soil Sciences, University of Hawaii at Manoa, 3190 Maile Way, Honolulu, HI 96822, USA; [2]Instituto Nacional de Pesquisas da Amazônia, Av. André Araújo 2936, Manaus, Amazonas 69083-000, Brazil; *Author for correspondence (e-mail: adrian@hawaii.edu)*

Received 19 November 2001; accepted in revised form 12 April 2002

Key words: Foliar nutrients, Soil nutrients, Tree crops

Abstract

Peach palm (*Bactris gasipaes* Kunth) is increasingly grown in the tropics for its heart-of-palm and fruit. Determining fertilization response and diagnosing nutrient status in peach palm may require methods that consider the particularities in nutrient acquisition and recycling of perennial crops. Responses to nutrient additions, and the diagnostic value of soil and foliar analyses were examined in three field experiments with three-year old peach palm stands on Oxisols in Central Amazonia. To diagnose P-deficiency levels in soils, samples from 0–5 cm and 5–20 cm depth were analyzed for available P by different methods (Mehlich-1, Mehlich-3 and Modified Olsen). The second and fifth leaves were analyzed to assess N, P and K deficiencies. Field experiments involved several combinations of N (from 0 to 225 kg ha^{-1} yr^{-1}), K (from 0 to 225 kg ha^{-1} yr^{-1}) and P (from 0 to 59 kg ha^{-1} yr^{-1}). Palms on control plots (unfertilized) and those receiving 225 kg ha^{-1} yr^{-1} N and 2 Mg ha^{-1} of lime yielded between 4 and 19% of the maximum growth which was obtained with N, P and K applications. In one of the experiments, yield of heart-of-palm was positively related to N additions at the lowest levels of P (8.6 kg ha^{-1} yr^{-1}) and K (60 kg ha^{-1} yr^{-1}) additions. In one experiment, critical leaf N level was 2.5% for the second leaf and 2.2% for the fifth leaf. Some growth responses to P additions at constant N and K levels were observed (e.g., 797 kg ha^{-1} yr^{-1} of heart-of-palm with 39.3 kg ha^{-1} yr^{-1} of applied P, and 632 kg ha^{-1} yr^{-1} of heart-of-palm with 10.9 kg ha^{-1} yr^{-1} of applied P in one experiment, and 2334 kg ha^{-1} yr^{-1} of heart-of-palm with 39.3 kg ha^{-1} yr^{-1} of P and 1257 kg ha^{-1} yr^{-1} of heart-of-palm with 19.7 kg ha^{-1} yr^{-1} of P in another trial). In the experiment for fruit production from peach palm, total plant height did not respond to P additions between 19.7 and 59 kg ha^{-1} yr^{-1} and K additions between 75 and 225 kg ha^{-1} yr^{-1}. Leaf P levels were found to be above the proposed critical levels of 0.23% for the third leaf and 0.16% for the fifth leaf. Plants in this experiment, however, showed evident symptoms of Mg deficiency, which was associated with a steep gradient of increasing Mg concentration from the fifth leaf to the second leaf. Standard leaf diagnostic methods in most cases proved less useful to show plant N and P status and growth responses to N and P additions. Soil P determined by common extractions was in general too variable for prediction of growth.

Introduction

Plant species evolved in the tropics are generally tolerant to some of the chief constraints to plant growth in tropical soils: low P supply, reduced N availability and high acidity. Nevertheless, fertilization is necessary to achieve and sustain commercial crop production. This situation applies to peach palm (*Bactris gasipaes* Kunth), a perennial crop increasingly grown for heart-of-palm (i.e., the unexpanded leaves within the tender petiole sheath of the spear leaf) and fruit production in the tropics (Mora Urpí et al. 1997). Although peach palm is adapted to infertile soils (Clement 1989), heart-of-palm plantations are regularly fertilized in the main cropping regions of Costa Rica (Molina 1999) and Brazil (Yuyama 1997;

Bovi 1998; Bovi et al. 2000). There is relatively little information, however, on rate of fertilization of peach palm for heart-of-palm production on nutrient-poor soils of the Amazon region. Research on nutrient requirements for fruit production in peach palm has been even more limited, and recommendations have been adapted from other palm fruit crops such as coconut and oil palm (N. Falcao, personal observation).

An important distinction should be made between the two main cropping systems under which peach palm is grown – for fruit and for heart-of-palm. In the system for fruit production, shoots are not regularly harvested (except perhaps for some initial pruning to retain a single stem) and commercial fruit production starts at 3–5 years. Peach palm leaves reach senescence on the plant in the fruit system and within-plant nutrient retranslocation is likely to be greater than in plants grown for heart-of-palm. Litter in the fruit system is low in nutrients and may decompose at a relatively slower pace (McGrath et al. 2000) than litter from heart-of-palm systems. When peach palm is grown for heart-of-palm production, shoots are cut twice or three times a year from each plant to obtain the heart-of-palm. Only the palm hearts and sheaths are thereafter exported from the field and a nutrient-rich residue is left to decompose on the ground. Peach palms in fruit systems would initially require less fertilization than heart-of-palm crops, although high demand for nutrients in the latter can be in part compensated by a faster nutrient cycling.

Successful detection of nutrient deficiencies is crucial to anticipate nutrient management problems, determine correction measures and prevent economic losses. One important characteristic of diagnostic procedures is ‘sensitivity’, which indicates if (and how rapidly) a given diagnostic measurement such as foliar nutrient concentration detects changes in the examined property (e.g., plant growth) (Meynard et al. 1997). Sensitivity of nutrient analysis to detect growth responses is considered lower in perennial crops than in annual crops, because the former may require a long time to react to nutrient additions (Yost et al. 1999). A heterogeneous spatial distribution of roots and nutrients in soils is an additional complicating factor for nutrient analysis in perennial crops. In these crops, foliar analysis may be more suitable for diagnosis than soil tests (Novais 2000). Foliar analysis, however, has not always been useful in predicting perennial crop responses to fertilization, because nutrient concentrations are affected by factors such as leaf position within the crown, sample position within the leaf, stand and foliage age, nutrient interactions, and climatic variations (Deenik et al. 2000). Therefore, diagnosing nutrient status in peach palm may require methods that are designed to reflect the particular characteristics of perennial plants in nutrient acquisition and recycling.

To address these concerns and determine responses of peach palm to fertilization, we analyzed soils and plant tissue from existing experiments in the Amazon region. The objectives of this study were: (i) to examine growth responses of peach palm to N, P and K additions in Central Amazonia, (ii) to determine nutrient concentrations in young (leaf 2) and relatively old (leaf 5) leaves to diagnose nutrient deficiency/sufficiency, and (iii) to examine the value of soil P extracted by different methods in order to diagnose P deficiency/sufficiency. It is important to note that the qualification about young and old leaves refers to peach palm for heart-of-palm only; in fruiting trees the fifth leaf is still young, as a healthy plant may have up to 23 leaves.

Materials and methods

Three experiments dealing with mineral nutrition of peach palm were initiated in Central Amazonia in 1996 on ‘terra firme’ soils classified as clayey, kaolinitic Oxisols (Soil Survey Staff 1999), and locally named ‘Latosolos amarelos’. These soils are low in organic matter, effective cation exchange capacity, P, K, Ca, Mg and some micronutrients. The sequence of horizons is, in general, A (approximately 0–20 cm), AB (20–40 cm) and B (40–60 cm). Mean annual temperature is 26 °C and annual rainfall is about 2450 mm. The dry season extends from July to October.

Two trials were located at Yuricam farm, on highway AM 010, km 100, municipality of Rio Preto da Eva, east–northeast of Manaus. The area had been deforested and used for cattle and fruit crop production for several years. The stand for heart-of-palm had 5000 plants ha^{-1} at 2 m by 1 m spacing. Initial soil available nutrients extracted by the Mehlich-1 method for 0–5 cm soil were (in mg kg^{-1}): 2.1 for P, 19.5 for K, 128 for Fe, 0.7 for Zn, 1.7 for Mn and 0.2 for Cu. Organic C was 1.4% and textural fractions were: 19% for sand, 1.5% for silt and 79.5% for clay. The study plots were arranged in a completely randomized block design with four replicates. Each plot contained 30 plants, with 12 measurable plants. The fertilizer treatments were (in kg ha^{-1} yr^{-1}): 0 N-0 P-0 K, 225 N-10.9 P-150 K, and 225 N-39.3 P-150 K.

In the fruit orchard experiment, initial plant density was 400 plants ha^{-1}. Soil available nutrients at 0–5 cm depth were (in mg kg^{-1}): 0.8 for P, 11.7 for K, 97 for Fe, 0.6 for Zn, 4.0 for Mn and 0.4 for Cu. Fertilizer treatments were factorial combinations of three P levels (19.7, 39.3, and 59.0 kg ha^{-1} yr^{-1}) and three K levels (75, 150 and 225 kg ha^{-1} yr^{-1}) with a 0 P-0 K treatment, in a completely randomized design with three replicates. Two tons/ha of dolomitic lime with 6.6% of Mg were split into two applications during the first year. All plots received a basal application of 225 kg N ha^{-1} yr^{-1}.

The third experiment was for heart-of-palm production and located at Rieda farm, on highway BR 174, km 17, municipality of Manaus. The site was previously occupied by a secondary forest of approximately 12 years of age. The initial density was 5000 plants ha^{-1}. Soil available nutrients at 0–5 cm depth were (in mg kg^{-1}): 12.0 for P, 39.1 for K, 113 for Fe, 1.3 for Zn, 2.8 for Mn and 0.4 for Cu. Organic C was 1.8% and textural fractions were: 42.5% for sand, 9.1% for silt and 48.4% for clay. The plots were arranged in a completely randomized design with three replicates. Fertilizer treatments were factorial combinations of three N levels (41.5, 83.0 and 124.5 kg ha^{-1} yr^{-1}), two P levels (8.6 and 17.3 kg ha^{-1} yr^{-1}), two K levels (60 and 120 kg ha^{-1} yr^{-1}), and a 0 N-0 P-0 K treatment.

The fertilizers (urea, triple superphosphate, and potassium chloride) were applied by hand in circles around the plants. N and K were applied in three equal allocations in January, February and March of each year, while the total amount of P was applied in February of each year.

At three years of age, plots within two blocks of each experiment were sampled. By convention, the spear (youngest) leaf of peach palm is numbered as zero. Plants grown for heart-of-palm usually have 6–8 leaves. The second and fifth leaves down the plant on five plants per plot were sampled in March 1999, and a composite sample of the middle third of each leaf (including rachis and leaflets) was taken to the laboratory for analysis. These leaves have ceased growing but were not yet senescent. Samples were dried at 75 °C to constant weight, ground to pass a 0.40-mm sieve, and analyzed for total N by a micro-Kjeldahl procedure (Nelson and Sommers 1972), and for Ca, Mg, K, Fe, Mn, Cu and Zn by atomic absorption spectrophotometry. Phosphorus was determined with UV spectrophotometry after stannous chloride reduction of the phospho-molybdate complex (Chapman and Pratt 1973). As an index of internal nutrient retranslocation, the fraction of nutrient retranslocated (FNR) was calculated as

$$\mathrm{FNR} = 1 - \frac{\mathrm{nutrient}_{\mathrm{leaf5}}/\mathrm{Ca}_{\mathrm{leaf5}}}{\mathrm{nutrient}_{\mathrm{leaf2}}/\mathrm{Ca}_{\mathrm{leaf2}}}$$

where nutrient and Ca indicate concentration (in %) in leaves 5 and 2. The purpose of this index is to compare nutrient concentration against a relatively stable nutrient such as Ca.

Soils were sampled within each plot at 0–5 cm and 5–20 cm depths from 10 positions at about 50 cm from plants. Soils were dried at 60 °C and ground to pass a 2 mm sieve. Total N was analyzed by a micro-Kjeldahl procedure, and P was extracted by the Mehlich-1 (Mehlich 1953), Mehlich-3 (Mehlich 1984) and modified Olsen (Diaz Romeu and Hunter 1978) methods, and determined by the colorimetric Murphy and Riley procedure (Murphy and Riley 1962). In the Mehlich-1 or double acid method, which is the most common test for determining P availability in the Amazon region, P is extracted with H_2SO_4 0.0125 N and HCl 0.050 N. In the Mehlich-3 method, CH_3COOH 0.2 N, NH_4NO_3 0.025 N, NH_4F 0.015 N, HNO_3 0.013 N and EDTA 0.001 N are used to extract P. In addition to P, this procedure allows to extract simultaneously K, Ca, Mg, Na, B, Cu, Fe, Mn and Zn. In the modified Olsen method, P is extracted with $NaHCO_3$ 0.5 M, EDTA 0.01 M and Superfloc 127.

In the heart-of-palm experiments, yield of high-grade (for export) heart-of-palm was recorded since plants reached the harvestable size in 1998 and, in the fruit orchard, plant height was measured as a growth index because the plants had not yet reached the fruit production stage. Plant height was a good index of growth response to fertilization in a previous trial with peach palm for fruit production (Pérez et al. 1993). Differences in cumulative (i.e., sum of yields from the first to the last harvest) yield, and in concentrations of soil and foliar nutrients were tested by analysis of variance or regression analysis in the case of continuous variables with at least three treatments levels. Correlation analysis (Pearson) was used to examine relationships between available soil P concentrations obtained with different methods. A paired-t test was used to compare nutrient retranslocation rates for different treatments. All statistical analyses were performed with the SAS package (SAS Institute Inc. 1989).

Results

Heart-of-palm yield increased with increasing nutrient additions in the experiment at Yurican farm. Maximum yield was found in the treatment receiving 225 kg N ha^{-1} yr^{-1}, 150 kg K ha^{-1} yr^{-1} and 39.3 kg P ha^{-1} yr^{-1}, and was about 33-fold greater than the yield in the unfertilized treatment (Table 1). Yield in the 39.3 kg P ha^{-1} yr^{-1} treatment was 26% higher than that in the 10.9 kg P ha^{-1} yr^{-1} treatment. Despite the positive response to P additions, neither P concentration in the second and fifth leaves, nor available soil P values determined by the different methods at two depths were correlated to the positive growth response.

Foliar P and K concentrations in the second leaf were below proposed critical levels (i.e., 0.23% for P and 1.0% for K as in Molina 1999) except for K in the 225:39.3:150 treatment (Table 1).

At 0–5 cm depth, Modified-Olsen P was positively related to Mehlich-3 P ($P = 0.02$), while Mehlich-1 P and Mehlich-3 P were correlated at 5–20 cm depth ($P = 0.05$). Available P at either 0–5 or 5–20 cm depth did not correlate to added P, although it was higher in the fertilized plots than in the control ($P = 0.03$).

In the experiment for heart-of-palm production at Rieda, maximum yield was 21-fold higher than the yields for the unfertilized treatments (Table 2). For the treatments in which it was possible to compare continuous nutrient addition effects, there was a significant yield response to N ($P = 0.01$) at the lowest levels of P (8.6 kg ha^{-1} yr^{-1}) and K (60 kg ha^{-1} yr^{-1}). Critical foliar N levels (i.e., the nutrient concentrations to reach 90% of maximum yield) were 2.2% for the fifth leaf, and about 2.5% for the second leaf.

Phosphorus additions increased heart-of-palm yields both at 42.5 and 124.5 kg ha^{-1} yr^{-1} of added N, and 60 kg ha^{-1} yr^{-1} of added K ($P = 0.05$ and 0.01, respectively). There were some significant differences in P concentrations in leaf five among treatments, but these differences did not correspond in direction to P doses. Again, foliar and soil P concentrations did not follow the growth response.

All measures of available soil P at both sampling depths were highly correlated ($P < 0.0001$). There was a positive correlation between added P and Mehlich-1 P ($P < 0.001$) and Mehlich-3 P (0.001) at 0–5 cm depth, but available P at 5–20 cm did not correlate to added P. There was no response to K in the 60 to 120 kg ha^{-1} yr^{-1} range of added K.

In both experiments for heart-of-palm, concentrations of Ca, Fe, Zn and Cu in the second leaf were, in general, above proposed sufficiency levels, while Mg and Mn concentrations appeared marginally deficient (Table 3).

In the fruit orchard experiment, maximum plant height in the fertilized treatments was more than five times the height in the control (Table 4). Height growth, however, did not increase with P additions between 19.7 and 59 kg ha^{-1} yr^{-1} and K doses between 75 and 225 kg ha^{-1} yr^{-1}. Foliar P levels were above the proposed critical levels of 0.23% for the third leaf and 0.16% for the fifth leaf in most treatments, except the control in which they were marginally deficient. Relatively high foliar N concentrations were congruent with the blanket application of N. Concentrations of Ca, Fe, Zn and Cu in the second leaf were, in general, above proposed sufficiency levels, while Mg and Mn concentrations were deficient (Table 5).

Plants in the fruit orchard showed marked symptoms of Mg deficiency, characterized by yellowing of the old leaves starting from the apical margins. Foliar Mg concentrations were extremely low, especially in leaf 5 (Table 5). Retranslocation rates for Mg were higher than those for N, P and K ($P < 0.001$) (Table 6). In the heart-of-palm experiment at Yuricam, there was no difference in retranslocation rates among elements, while at Rieda, Mg retranslocation differed from N and P rates, but these differences were less marked than in the fruit production study. In the fruit orchard experiment, foliar K concentration was inversely correlated to foliar Mg concentration ($P = 0.03$), but the relationship was not significant when the data for the control treatment were omitted, suggesting that antagonistic uptake of K was not the cause of low Mg concentrations.

All measures of available P at 0–5 cm were highly correlated among themselves ($P < 0.0001$), but only Mehlich-1 P values were correlated with those of Mehlich-3 P at 5–20 cm depth ($P < 0.0000$). Available P at the 0–5 and 5–20 cm depths was not correlated to added P.

Discussion

This study provides additional evidence that nutrient additions are needed to sustain peach palm production in nutrient-poor soils of Central Amazonia. Production of peach palm in the Amazon region has been very

Table 1. Cumulative heart-of-palm yield, foliar N, P and K concentrations, and available soil P at 0–5 cm and 5–20 cm depth in peach palm at Yuricam farm, Central Amazonia. Values are means ± one standard error.

Annual NPK rate			Yield	Leaf 2			Leaf 5			PM1	PM3	PMO	PM1	PM3	PMO
N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	(kg ha^{-1})	N	P (%)	K	N	P (%)	K	(mg kg^{-1})	0–5 cm (mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	5–20 cm (mg kg^{-1})	(mg kg^{-1})
0	0	0	24±24	3.6±0.1	0.12±0.00	0.43±0.02	2.9±0.3	0.11±0.01	0.29±0.01	2.1±0.1	0.7±0.2	0.6±0.1	1.0±0.2	0.4±0.1	0.6±0.2
225	10.9	150	632±39	2.0±0.2	0.19±0.01	0.91±0.02	1.9±0.2	0.14±0.01	0.57±0.14	24.8±17.4	21.8±4.6	7.2±1.0	1.7±0.2	0.6±0.2	0.6±0.1
225	39.3	150	797±9	2.5±0.1	0.18±0.01	1.05±0.05	2.1±0.2	0.14±0.01	0.90±0.17	9.2±0.4	6.3±0.8	2.9±0.8	1.5±0.2	0.7±0.1	1.3±0.7
Sufficiency levels*				2.50	0.23	1.00	2.20	0.16	0.80			10			

PM1 = Mehlich-1 soil P, PM3 = Mehlich-3 soil P, PMO = Modified Olsen soil P. *From Molina (1999).

Table 2. Cumulative heart-of-palm yield, foliar N, P and K concentration, and soil P concentration at 0–5 cm and 5–20 cm depth in peach palm at Rieda farm, Central Amazonia. Values are means ± one standard error.

Annual NPK rate			Yield	Leaf 2			Leaf 5			PM1	PM3	PMO	PM1	PM3	PMO
N	P	K		N	P	K	N	P	K		0–5 cm			5–20 cm	
(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})		(%)			(%)		(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
0	0	0	134±134	2.5±0.4	0.22±0.01	1.4±0.1	2.0±0.3	0.21±0.03	0.9±0.3	12.7±0.9	8.5±4.5	3.0±0.1	1.2±0.1	.0.8±0.1	0.7±0.1
41.0	8.6	60	1257±67	2.4±0.1	0.23±0.01	1.0±0.2	1.9±0.1	0.19±0.01	1.1±0.1	32.6±26.8	30.5±25.0	6.2±3.4	2.7±1.2	2.4±1.2	1.9±0.4
41.0	17.3	60	2334±250	2.4±0.1	0.24±0.01	1.0±0.2	2.2±0.1	0.19±0.02	0.6±0.1	33.5±5.2	33.6±6.0	10.2±2.1	4.0±0.1	5.8±2.3	3.0±0.3
83.0	8.6	60	1625±259	2.8±0.1	0.22 —	1.0±0.1	2.3±0.1	0.19 —	0.9±0.2	77.3±34.4	62.5±26.5	15.5±7.5	5.0±3.3	6.3±2.1	3.2±1.3
83.0	17.3	60	1623±1161	2.6±0.1	0.25±0.01	0.9±0.1	2.2±0.2	0.23±0.02	1.1±0.1	27.7±1.7	32.0±11.3	8.2±2.2	2.7±0.9	3.7±2.4	2.0±1.1
124.5	8.6	60	2041±43	2.8±0.0	0.24±0.01	1.0±0.0	2.9±0.2	0.29±0.01	1.0±0.0	32.3±16.4	32.6±9.2	8.4±1.2	4.6±1.8	5.2±0.1	3.9±1.5
124.5	17.3	60	2866±45	2.9±0.3	0.26±0.01	1.2±0.1	2.4±0.1	0.23±0.01	0.9±0.2	50.4±21.1	50.5±14.5	6.3±2.9	6.6±4.5	9.0±4.7	3.1±1.2
41.0	8.6	120	1643±245	2.6±0.5	0.22±0.01	1.1±0.1	1.8±0.0	0.20±0.01	0.9±0.2	13.8±10.5	11.9±9.1	7.0±4.7	6.1±4.6	11.3±10.2	3.0±0.0
41.0	17.3	120	1603±2	2.4±0.4	0.21±0.01	1.4±0.4	1.9±0.3	0.19±0.06	1.7±0.4	36.4±6.8	34.3±18.6	10.9±0.1	4.3±0.5	6.1±3.4	2.3±0.6
83.0	8.6	120	—	2.5±0.0	0.21 —	1.1±0.0	2.2±0.0	0.19 —	1.2±0.0	7.5± —	14.7± —	2.7± —	1.7± —	1.2± —	10.3± —
83.0	17.3	120	1432±147	2.7±0.2	0.24±0.01	1.1±0.1	1.8±0.0	0.21±0.01	0.9±0.2	12.0± 2.3	16.7±4.2	5.1±1.1	3.2± 2.0	2.9±0.2	5.6±3.5
124.5	8.6	120	1581±262	2.5±0.2	0.23±0.02	1.2±0.1	2.1±0.1	0.19±0.02	0.9±0.1	11.0±4.6	14.3±7.2	4.6±1.4	2.6± 0.9	3.1±1.4	4.2±2.9
124.5	17.3	120	1944±775	3.0±0.2	0.22±0.01	0.9±0.4	2.2±0.0	0.18±0.01	0.9±0.2	39.9±—	46.5±—	9.7±—	17.9± 8.3	25.5±22.5	7.9±6.9
Sufficiency levels*				2.50	0.23	1.0	2.2	0.16	0.8			10			10

PM1 = Mehlich-1 soil P, PM3 = Mehlich-3 soil P, PMO = Modified Olsen soil P. *From Molina (1999).

Table 3. Foliar Ca, Mg, Fe, Zn, Mn and Cu concentrations in peach palm for heart-of-palm at Yuricam and Rieda farms, Central Amazonia. Values are mean ± one standard error.

Annual NPK rates			Leaf 2						Leaf 5					
N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca	Mg	Fe	Zn	Mn	Cu	Ca	Mg	Fe	Zn	Mn	Cu
			(%)			(mg ha^{-1})			(%)			(mg ha^{-1})		
					Yuricam for heart-of-palm									
0	0	0	0.30±0.02	0.18±0.01	103±18	39±1	39±3	6±0	0.23±0.01	0.13±0.02	110±3	37±1	45±8	4±0
225	10.9	150	0.50±0.01	0.14±0.04	98±6	34±4	26±4	6±0	0.89±0.01	0.09±0.01	83±3	28±10	40±12	4±0
225	39.3	150	0.38	0.21	116	32	32	6	0.48	0.18	118	20	40	6
					Rieda for heart-of-palm									
0	0	0	0.54±0.12	0.20±0.06	111±20	38±3	53±2	8±0	74±0.06	0.15±0.06	98±17	31±3	59±2	6±0
41.5	8.6	60	0.46±0.02	0.24±0.01	75±2	38±1	60±13	8±0	0.69±0.06	0.24±0.01	83±1	26±0	59±15	6±0
41.5	17.3	60	0.29±0.01	0.11±0.09	77±11	42±0	60±1	7±1	0.50±0.05	0.11±0.01	102±18	32±4	66±8	6±0
83.0	8.6	60	0.46±0.06	0.16±0.05	144±48	63±13	57±3	9±1	0.82±0.16	0.16±0.06	97±1	43±3	66±4	7±1
83.0	17.3	60	0.47±0.06	0.18±0.02	96±28	43±1	61±11	9±1	0.72±0.08	0.17±0.02	102±23	39±1	64±12	6±0
124.5	8.6	60	0.49±0.02	0.17±0.02	137±7	39±3	74±14	9±1	0.92±0.09	0.19±0.02	109±11	31±1	79±11	7±1
124.5	17.3	60	0.42±0.06	0.20±0.09	88±16	38±2	61±12	9±1	0.71±0.12	0.21±0.01	96±14	33±7	69±9	8±0
41.5	8.6	120	0.45±0.10	0.17±0.06	75±5	38±3	57±12	8±0	0.82±0.28	0.17±0.12	121±12	46±8	78±8	7±1
41.5	17.3	120	0.45±0.03	0.21±0.03	106±24	37±2	71±12	8±0	0.74±0.05	0.26±0.01	82±1	29±2	69±6	6±2
83.0	8.6	120	0.40	0.21	82	38	72	8	0.37	0.20	98	34	60	6
83.0	17.3	120	0.54±0.05	0.21±0.02	91±12	35±5	66±7	7±1	0.55±0.06	0.22±0.06	104±18	42±0	71±8	8±0
124.5	8.6	120	0.47±0.05	0.21±0.01	77±3	43±3	55±8	10±0	0.65±0.12	0.19±0.03	83±1	35±2	56±8	7±1
124.5	17.3	120	0.53±0.03	0.21±0.03	87±1	34±3	58±13	9±1	0.66±0.00	0.21±0.01	103±3	24±1	60±13	7±1
Sufficiency levels*			0.40	0.25	50	15	60	5						

*From Molina (1999).

low without fertilization (Moreira Gomes et al. 1987). Control plots, either unfertilized or only receiving N and lime, yielded between 4 and 19% of the maximum yield obtained with N, P and K applications. It was difficult, however, to determine the effect of individual nutrients on yield because of limitations in the design of the experiments (i.e., lack of true controls) and, probably, because of the presence of multiple nutrient limitations.

In the experiment with varied N applications, growth responses of peach palm to N were observed only for the lowest levels of added P and K. This was rather unexpected, as responses of peach palm to N have been consistently observed in stands for heart-of-palm production (Guzmán 1985; Bovi et al. 2000), fruit production (Pérez et al. 1993), and in early stages prior to harvest (Jongschaap 1993; Lopes Reis 1997). In some cases, addition of N induced exponential growth responses (Pérez et al. 1993).

The limited response to P additions was consistent with previous research. A review of fertilization studies listed responses to P additions in only two out of six field experiments, with all responses occurring during early growth stages (Deenik et al. 2000).

Lack of response to K above levels of 60 and 75 kg ha^{-1} yr^{-1} of added K suggested that these amounts can supply peach palm requirements at least in the relatively short term. In the long term, it is possible that additional K will be needed because kaolinitic Oxisols under the trials can be rapidly depleted of K (Cravo and Smyth 1997).

Standard diagnostic methods did not seem to reflect peach palm responses to N and P additions in most cases. In the case of foliar analysis, results concurred with previous studies in which N and P concentrations in peach palm leaves did not change significantly with increasing fertilization rates, despite a positive growth response to nutrient additions (Guzmán 1985; Pérez et al. 1993). In only one experiment, critical foliar N levels of 2.50% for the second leaf and 2.20% for the fifth leaf were achieved. These critical levels are similar to estimated levels in Molina (1999).

A severe Mg deficiency in the experiment for fruit production at Yuricam may have affected growth responses to other nutrients in the fertilization treatments. Foliar Mg levels were well below proposed deficiency levels (i.e., 0.25% given by Molina (1999); and 0.24% by Gama Pacheco et al. (1997), although the latter is for seedlings). The modest addition of two tons of dolomitic lime per ha seemed not enough to satisfy plant Mg requirements over time. Magnesium concentration decreased steeply between leaf 5 and leaf 2, indicating high internal retranslocation. A previous study presented two opposite patterns of

Table 4. Rates of fertilizer applied, plant height, foliar N, P and K concentrations, and soil P concentrations at 0–5 cm and 5–20 cm depth in peach palm for fruit production at Yuricam farm. Values are means ± one standard error.

Annual rate		Height	Leaf 2			Leaf 5			PM1	PM3	PMO	PM1	PM3	PMO
P (kg ha^{-1})	K (kg ha^{-1})	(cm)	N	P (%)	K	N	P (%)	K	(mg kg^{-1})	0–5 cm (mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	5–20 cm (mg kg^{-1})	(mg kg^{-1})
0	0	75±4	3.1±0.2	0.18±0.05	0.8±0.2	2.6±0.5	0.16±0.02	0.5±0.2	0.8±0.1	1.1±0.9	1.8±0.6	0.6±0.1	0.4±0.1	2.6±0.9
19.7	75	348±45	2.7±0.1	0.23±0.01	1.1±0.1	2.3±0.1	0.22±0.02	1.7±0.2	6.7±5.5	2.9±2.4	5.1±1.9	1.3±0.4	0.3±0.1	3.1±1.2
39.3	75	340±72	2.5±0.3	0.26±0.01	1.2±0.1	2.1±0.2	0.21±0.01	1.2±0.6	2.4±0.2	0.8±0.1	5.0±0.2	1.3±0.8	0.5±0.1	1.7±0.7
59.0	75	357±43	2.7±0.3	0.26±0.1	1.0±0.0	3.1±0.8	0.28±0.014	1.0±0.1	2.8±0.6	1.6±0.3	3.0±1.6	1.3±0.4	0.4±0.2	1.6±0.7
19.7	150	396±8	2.3±0.1	0.22±0.01	1.2±0.2	2.3±0.4	0.19±0.02	1.3±0.1	45.0±42.3	31.7±30	20.3±15.5	2.1±0.1	0.7±0.2	4.6±0.6
39.3	150	355±43	2.8±0.2	0.25±0.01	1.5±0.1	2.2±0.3	0.20±0.01	1.5±0.2	76.3±72.0	41.4±38.5	36.0±33.3	2.9±1.0	1.0±0.5	3.9±3.0
59.0	150	351±21	2.6±0.0	0.26±0.01	1.3±0.1	2.1±0.1	0.28±0.02	1.5±0.1	15.2±11.2	2.3±0.3	5.3±3.2	2.1±0.3	0.6±0.1	2.2±1.4
19.7	225	397±8	2.5±0.1	0.26±0.01	1.6±0.1	2.47±0.1	0.20±0.01	1.5±0.4	21.8±17.3	9.6±6.8	13.6±7.4	1.0±0.1	0.4±0.1	3.8±2.0
39.3	225	342±24	3.1±0.1	0.25±0.01	1.4±0.1	2.1±0.2	0.22±0.03	1.6±0.1	49±1.9	3.3±0.7	3.6±2.3	2.3±1.1	0.4±0.1	2.0±0.7
59.0	225	376±30	3.2±0.1	0.26±0.01	1.3±0.0	2.3±0.2	0.21±0.01	1.4±0.1	6.1±4.0	12.8±0.5	8.9±2.1	2.1±0.1	1.0±0.2	3.6±2.6
Sufficiency levels*			2.50	0.23	1.00	2.20	0.16	0.80			10			10

PM1 = Mehlich-1 soil P, PM3 = Mehlich-3 soil P, PMO = Modified Olsen soil P. *From Molina (1999).

Table 5. Foliar Ca, Mg, Fe, Zn, Mn and Cu concentrations in peach palm for fruit at Yuricam farm, Central Amazonia. Values are mean ± one standard error.

Annual NPK rate			Leaf 2						Leaf 5					
N	P	K	Ca	Mg	Fe	Zn	Mn	Cu	Ca	Mg	Fe	Zn	Mn	Cu
(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	(%)			(mg ha^{-1})			(%)			(mg ha^{-1})		
0	0	0	0.43±0.03	0.17±0.05	93±3	43±1	45±5	7±1	0.48±0.02	0.11±0.04	105±5	48±3	55±1	6±0
0	19.7	75.0	0.75±0.13	0.07±0.01	91±15	52±15	38±1	8±0	0.54±0.06	0.02±0	86±6	32±4	44±3	7±1
0	39.3	75.0	0.30±0.04	0.05±0.02	64±6	41±15	34±0	7±3	0.39±0.01	0.02±0	93±27	35±3	42±1	4±1
0	59.0	75.0	0.38±0.02	0.07±0.01	70±0	34±0	38±1	5±1	0.46±0.04	0.02±0.01	85±2	31±2	52±1	5±1
0	19.7	150.0	0.40±0.03	0.12±0.01	67±2	35±2	49±3	8±0	0.60±0.08	0.08±0.03	73±3	44±4	52±6	7±1
0	39.3	150.0	0.41±0.01	0.07±0.01	69±2	31±5	42±6	6±0	0.74±0.06	0.03±0.01	76±10	24±0	56±0	6±0
0	59.0	150.0	0.56±0.01	0.08±0.03	68±6	29±3	42±7	6±0	0.79±0.01	0.03±0.01	94±3	28±3	48±3	4±0
0	19.7	225.0	0.39±0.04	0.09±0.01	100±20	31±1	44±1	7±1	0.58±0.02	0.06±0.02	75±6	27±6	36±3	7±1
0	39.3	225.0	0.36±0.01	0.07±0.01	77±3	26±3	31±3	7±1	0.41±0.05	0.02±0	107±12	30±1	36±3	5±1
0	59.0	225.0	0.46±0.11	0.07±0	66±6	23±2	37±5	6±1	0.43±0.10	0.02±0.01	82±4	29±2	44±4	5±1
Sufficiency levels*			0.40	0.25	60	15	60	5						

*From Molina (1999).

foliar Mg variation between old and new leaves in palms (Broschat 1997). In coconut, Mg concentration increased with leaf age, as in our study of the second-to-fifth-leaf range. In Canary Island date palm, foliar Mg decreased with leaf age and symptoms of Mg deficiency were evident on leaves with less than

Table 6. Annual fertilization rates and nutrient retranslocation in peach palm in the fertilization trials in Central Amazonia. Values are mean ± one standard error.

Annual NPK rate			Retranslocation rate			
N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	N	P	K	Mg
			Yuricam for heart-of-palm			
0	0	0	0.20±0.1	0.11±0.1	0.33±0.0	0.27±0.1
225	10.9	150	0.25±0.0	0.39±0.0	0.52±0.0	0.47±0.1
225	39.3	150	0.45±0.1	0.52±0.1	0.44±0.2	0.48±0.1
			Rieda for heart-of-palm			
0	0	0	0.43±0.1	0.33±0.1	0.54±0.0	0.45±0.1
41.5	8.6	60	0.46±0.0	0.43±0.1	0.24±0.1	0.31±0.0
41.5	17.3	60	0.49±0.0	0.53±0.0	0.65±0.0	0.34±0.1
83.0	8.6	60	0.53±0.0	0.57±0.1	0.53±0.1	0.47±0.0
83.0	17.3	60	0.44±0.0	0.40±0.1	0.24±0.1	0.38±0.0
124.5	8.6	60	0.32	0.45	0.42	0.40
124.5	17.3	60	0.51±0.1	0.47±0.1	0.56±0.1	0.37±0.1
41.5	8.6	120	0.61±0.1	0.49±0.1	0.54±0.0	0.51±0.1
41.5	17.3	120	0.50±0.0	0.44±0.0	0.27±0.3	0.20±0.2
83.0	8.6	120	0.10	0.12	0.00	0.04
83.0	17.3	120	0.53	0.43	0.44	0.35
124.5	8.6	120	0.37±0.0	0.39±0.0	0.43±0.1	0.33±0.2
124.5	17.3	120	0.40±0.1	0.32±0.1	0.15±0.1	0.19±0.0
			Yuricam for fruit			
0	0	0	0.25±0.2	0.17±0.1	0.43±0.1	0.42±0.1
0	19.7	75.0	0.18±0.1	0.09±0.0	0.00±0.0	0.71±0.1
0	39.3	75.0	0.32±0.1	0.35±0.1	0.30±0.3	0.57±0.2
0	59.0	75.0	0.05±0.2	0.09±0.0	0.21±0.1	0.72±0.1
0	19.7	150.0	0.27±0.3	0.38±0.1	0.25±0.2	0.45±0.4
0	39.3	150.0	0.56±0.1	0.56±0.1	0.44±0.1	0.74±0.1
0	59.0	150.0	0.43±0.1	0.24±0.0	0.18±0.1	0.69±0.1
0	19.7	225.0	0.34±0.2	0.45±0.1	0.32±0.3	0.63±0.1
0	39.3	225.0	0.50±0.1	0.36±0.1	0.24±0.2	0.75±0.1
0	59.0	225.0	0.41±0.2	0.34±0.2	0.22±0.2	0.71±0.1

0.12% Mg. A symptom severity index correlated well with leaf position and leaf Mg concentration. Coconut leaves had higher Mg concentrations (about 0.25 to 0.29%) than Canary Island date palm leaves (0.05 to 0.16%), and did not display symptoms of Mg deficiency. A remobilization rate index was more than 100 times higher in Canary Island date palm than in coconut.

In the present study, Mg retranslocation rates in peach palm were higher in the stand that had striking symptoms of Mg deficiency than in the other experiments. The relationship between leaf Mg concentration and leaf age has been found to vary widely with plant species and plant age in palms (Amalu et al. 1988). Retranslocation of Mg may be highly responsive to nutrient status, because ratios between Mg concentrations in young and old leaves can vary widely, in contrast to more constant patterns for other macronutrients. For example, we measured higher foliar Mg concentration in the fifth leaf (0.27% on average) than in the third leaf (0.22%) of well fertilized peach palm plants in Hawaii (A. Ares, personal observation). A similar trend was observed in a fertilization experiment in Costa Rica, in which Mg concentration in the third leaf varied between 0.25 and 0.28%, and between 0.28 and 0.31% in the fifth leaf (Ares et al. 2002). The above mentioned trends are opposite to the one found in these experiments in Amazonia. This suggests that Mg is highly mobile within the peach palm plants in response to Mg deficiencies, and that the ratio between Mg concentration in young and old leaves may be useful in detecting incipient Mg deficiency.

At the beginning of this study, there were no standard fertilization recommendations for peach palm in the Amazon region. Results of this study indicated that annual N-P-K doses of 125–225:20–40:60–150 kg ha^{-1} were needed to sustain peach palm growth. Relatively high yields of heart-of-palm were obtained at Rieda farm with N:P:K rates similar to the low values in the above ranges (125:17:60 kg ha^{-1} yr^{-1}), probably because this site, with a recent history of secondary forest, had higher fertility than the other 'terra firme' soils in our study, as suggested by the soil nutrient contents before fertilization. For other cropping areas, researchers have proposed the following annual N:P:K fertilization rates for heart-of-palm production: 200–250:22–44:41–166 kg ha^{-1} (Molina 1999), and 200–250:9:130–170 kg ha^{-1} (Herrera 1989) in Costa Rica; and 160–300:17.5–35:83–216 kg ha^{-1} (Bovi and Cantarella 1997) in southern Brazil. In Costa Rica, researchers have also recommended annual applications of 25–60 kg Mg ha^{-1} and 40–80 kg S ha^{-1} to peach palm (Herrera 1989; Molina 1999). In southern Brazil, it was advised to complement NPK fertilization in peach palm with 20–50 kg S ha^{-1} and 1–2 kg B ha^{-1} per year (Bovi and Cantarella 1997). In one of the few fertilization experiments in peach palm for fruit, a rate of 180 kg N ha yr^{-1} was recommended in Peru (Pérez et al. 1993).

Soil P determined after common extractions proved to be extremely variable in some cases, and did not have good diagnostic value. The order in the amount of P extracted by each method (Mehlich-1, Mehlich-3 > Modified Olsen) at 0–5 and 5–20 cm depths was as previously found in tropical soils (Molina and Cabalceta 1990). The results of this study did not question the accuracy of the methods, but do question their usefulness for diagnosis of soil P for palms. Even if more detailed field experiments become available, critical soil P levels in peach palm may be too low for the tested methods (e.g., 5–6 mg kg^{-1} for Mehlich-1, and 1–2 mg kg^{-1} for Mehlich-3 and Modified Olsen) to be reliable as diagnostic tools.

Other methods used for tropical soils such as the Olsen-Dabin and the ion-exchange resin (Raij 1978) procedures could be tested in peach palm agroecosystems. The Olsen-Dabin method extracts much more P than the standard Olsen test and has been used mainly with African soils (R. Yost, personal observation). The ion-exchange resin method is not used in the Amazon region, but it has been simplified and routinely used in the state of São Paulo. A review study indicated that P extractions with ion-exchange resin had a higher correlation to P plant uptake than 11 other methods including Mehlich-1 and the original Olsen method (Da Silva and Raij 1999), although in soils with less than 20% clay, Mehlich-1 and resin methods provided similar results (Da Silva and Raij 1996). The Mehlich-3 method provided better detection of P sufficiency/deficiency than an ion-exchange method in corn growing on a clayed Typic Kandihumult in Hawaii (Cai et al. 1997). Also, the Mehlich-3 method was suitable to evaluate P availability in Oxisols and Spodosols with different textures from the Amazon region (Brasil and Muraoka 1997).

Australian researchers have advocated the use of solution P extracted with $CaCl_2$ 0.01 M as diagnostic method for woody species in the nursery and field (Smethurst 2000). In an experiment with peach palm in the Amazon region, however, solution P collected with ceramic suction cups was very low and too variable to be a good index of P availability (Schroth et al. 2000).

Complementary studies suggest that alternative analysis (e.g., P concentration of petioles or roots, soil organic P measurements) may be more useful as P diagnostic criteria in peach palm. In four stands of peach palm growing in Costa Rica on soils with modified-Olsen P ranging from 7 to 38 mg kg^{-1}, the range of P concentration in petioles and coarse roots was 0.15–0.42% and 0.20–0.50%, respectively, while foliage P only varied between 0.25 and 0.36% (A. Ares, personal observation). The petiole is the standard organ for diagnosing P deficiency/sufficiency in papaya (Awada 1976). For tropical timber species in northeastern Australia, researchers have also found that P concentration in petiole was a better indicator of response to P fertilization than P concentration in the leaf lamina (Webb et al. 2000).

Conclusions

Growth of peach palm was severely reduced without fertilization in Central Amazonia. Standard foliar and soil analysis showed limitations for diagnosing P deficiency. Foliar N concentration was partially useful in detecting N deficiencies, but foliar P failed to follow growth responses to P additions. Available soil P measured by three methods was often too variable and too low in relation to sample error to be useful as a diagnostic tool. Magnesium deficiency may have interfered with peach palm response to other nutrients. Plants in the fruit orchard experiment showed striking symptoms of Mg deficiency and a steep gradient of increasing Mg from the fifth to the second leaf, a trend opposite to that found in fertilized peach palm elsewhere. Additional research is needed to diagnose P deficiency, for which visual symptoms are often inconspicuous and equivocal in perennial crops such as peach palm.

Acknowledgements

We wish to thank the Decision Aids for Soil Nutrient Management Project-Soil Management Collaborative Research Support Program, USAID for financial support, and the Instituto Nacional de Pesquisas da Amazônia for support to obtain measurements in field experiments and for using laboratory facilities. Thanks are due to E. Chaves, S. Morais, and M. Sarrazin for technical support. This paper is College of Tropical Agriculture and Human Resources University of Hawaii Journal Series No. 4608.

References

Amalu U.C., Ataga D.O. and Omoti U. 1988. The distribution of nutrient elements in the leaves of Nigerian Tall coconuts. Niger J. Palms Oil Seeds 9: 2–15.

Ares A., Cox F., Molina E., Falcao N., Yost R.S., Yuyama K. et al. 2002. Requerimientos de fósforo y respuesta a la fertilización fosforada del palmito en vivero y en plantación. Proceedings International Meeting on Design of Decision Support Tools for Integrated Nutrient Management. Guápiles, Costa Rica, January 7–9, pp. 30–44 .

Awada M. 1976. Relation of phosphorus fertilization to petiole phosphorus concentrations and vegetative growth of young papaya plants. Trop. Agricult. 53: 173–181.

Bovi M.L.A. 1998. Palmito pupunha: Informações basicas para cultivo, Boletim Técnico 173. Instituto Agronômico, Campinas, Brazil.

Bovi M.L.A. and Cantarella H. 1997. Pupunha para extracao de palmito. In: Raij B.V., Cantarella H., Quaggio J.A. and Cangiani Furlani A.M. (eds), Recomendações de adubação e calagem para o estado de São Paulo. Boletim Técnico no. 100. Instituto Agronômico, Campinas, Brazil, pp. 240–242.

Bovi M.L.A., Tucci M.L.S., Spiering S.H., Godoy G. and Lambais M.R. 2000. Biomass accumulation and arbuscular mycorrhizal colonization in pejibaye (*Bactris gasipaes* Kunth) as a function of NPK fertilization. Acta Hort. 513: 153–167.

Brasil E.C. and Muraoka T. 1997. Extratores de fósforo em solos da Amazônia tratados com fertilizantes fosfatados. Rev. Bras. Cien. Solo 21: 599–606.

Broschat T.K. 1997. Nutrient distribution, dynamics, and sampling in coconut and Canary Island date palms. J. Am. Soc. Hort. Sci. 122: 884–890.

Cai T.T., Olsen T.W., Yost R.S. and Silva J.A. 1997. Performance indices for tests of soil nutrient status: extractable phosphorus. Commun. Soil Sci. Plant Anal. 28: 329–339.

Chapman H.D. and Pratt P.F. 1973. Métodos de análisis para suelos, plantas y aguas. Editorial Trillas, Mexico, 195 pp.

Clement C.R. 1989. The potential use of the pejibaye palm in agroforestry systems. Agrofor. Syst. 7: 201–212.

Cravo M.S. and Smyth J.T. 1997. Manejo sustentado da fertilidade de um Latossolo da Amazonia Central sob cultivos sucesivos. Rev. Bras. Cien. Solo 2: 607–616.

Da Silva F.B. and Raij B.V. 1996. Avaliação da disponibilidade de fósforo, por diversos extratores, em amostras de solos cultivados com cana-de-açúcar. Rev. Bras. Cien. Solo 20: 83–90.

Da Silva F.B. and Raij B.V. 1999. Disponibilidade de fósforo em solos avaliada por diferentes extractores. Pesq. Agrop. Bras. 34: 267–288.

Deenik J., Ares A. and Yost R.S. 2000. Fertilization response and nutrient diagnosis in peach palm (*Bactris gasipaes*): a review. Nutr. Cycl. Agroecosyst. 56: 195–207.

Diaz Romeu R. and Hunter A. 1978. Metodología de muestreo de suelos, análisis químico de suelos y tejido vegetal e investigación en invernadero. CATIE, Turrialba, Costa Rica.

Gama Pacheco R., Cardoso A.A., Barros N.F., Martinez H.P. and Bovi M.L.A. 1997. Crescimento de mudas de pupunha (*Bactris gasipaes* H.B.K.) em resposta a calagem e as relacoes Ca/Mg do solo. Proceedings Brazilian Soil Congress. Rio de Janeiro, Brazil, p. 26.

Guzmán P. 1985. Nutrición y fertilización de pejibaye. Respuesta del pejibaye para palmito a la aplicación de N-P-K. Sétimo informe de labores de diversificación agrícola. ASBANA, Costa Rica, pp. 41–46.

Herrera W. 1989. Fertilización del pejibaye para palmito. Serie Técnica Pejibaye. Universidad de Costa Rica, San José Boletín Informativo 1: 1–8.

Jongschaap R. 1993. Palmito (*Bactris gasipaes* H.B.K.) growth and management in the humid lowlands of the Atlantic zone of Costa Rica. Report No. 60. Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Agricultural University Wageningen, Ministerio de Agricultura y Ganadería de Costa Rica.

Lopes Reis E. 1997. Respostas da pupunheira ao NPK na produção de palmito no sul da Bahia. Expanded Abstract 26th Brazilian Soil Science Congress. Rio de Janeiro, Brazil.

McGrath D.A., Comerford N.B. and Duryea M.L. 2000. Litter dynamics and monthly fluctuations in soil phosphorus availability in an Amazonian agroforest. For. Ecol. Manage. 131: 167–179.

Mehlich A. 1953. Determination of P, K, Na, Ca, Mg and NH_4. Soil Test Div Mimeo, Department of Agriculture, Raleigh, North Carolina.

Mehlich A. 1984. Mehlich no. 3 extractant: A modification of Mehlich no. 2 extractant. Commun. Soil Sci. Plant Anal. 15: 1409–1416.

Meynard J.M., Aubry C., Justes E. and Le Bail M. 1997. Nitrogen diagnosis and decision support. In: Lemaire G. (ed.), Diagnosis of Nitrogen Status in Crops. Springer-Verlag, Berlin, pp. 147–161.

Molina E. 1999. Suelos, nutrición mineral y fertilización. In: Mora Urpí J. and Gainza Echeverría J., Palmito de pejibaye *(Bactris gasipaes* Kunth): Su cultivo e industrialización. Editorial de la Universidad de Costa Rica, San José, Costa Rica.

Molina E. and Cabalceta G. 1990. Correlación de diferentes soluciones extractoras en Vertisoles y Ultisoles de Costa Rica. Agronomía Costarricense 14: 37–44.

Mora Urpí J., Weber J.C. and Clement C.R. 1997. Peach palm, *Bactris gasipaes* Kunth. Promoting the conservation and use of underutilized and neglected crops 20. International Plant Genetic Resources Institute, Rome, Italy.

Moreira Gomes J.B., Menezes J.M. and Viana P. 1987. Efeito de níveis de adubação e espacamento na produção de palmito de pupunheira em solo de baixa fertilidade na região de Ouro Preto D'Oeste. Proceedings of National Meeting of Researchers on Palmito, March 26–28. Curitiba, Brazil.

Murphy J. and Riley J.R. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27: 31–36.

Nelson D.W. and Sommers L.E. 1972. Determination of total nitrogen in plant material. Agron. J. 65: 109–112.

Novais R.F. 2000. Diagnosis of soil nutrient constraints and recommendations for lime, nitrogen and phosphorus in Brazil. In: Osmond D.L., Metra-Corton T., Smyth T.J., Yost R.S. and Reid W.S. (eds), Decision processes for determining diagnostic and predictive criteria for soil nutrient management. Workshop Proceedings. SMCRSP Technical Bulletin 2000-03, Maligaya, Philippines, pp. 66–71.

Pérez J., Szott L.T., McCollum R.E. and Arévalo L. 1993. Effect of fertilization on early growth of pijuayo (*Bactris gasipaes* HBK) on an Amazon Ultisol. In: Mora Urpí J., Szott L.T., Murillo M. and Patiño M. (eds), Proc IV Congreso Internacional sobre Biología, Agronomía e Industrialización del Pijuayo. Editorial de la Universidad de Costa Rica, San José, Costa Rica, pp. 209–223.

Raij B.V. 1978. Seleção de métodos de laboratório para avaliar da disponibilidade de fósforo em solos. Rev. Bras. Cien. Solo 2: 1–9.

SAS Institute Inc. 1989. SAS/STAT User's Guide, version 6, 4th edn, Vol. 2. SAS Institute Inc., Cary, North Carolina.

Schroth G.R., Seixas L.F., Silva Lda T. and Zech W.G. 2000. Nutrient concentration and acidity in ferralitic soil under perennial cropping, fallow and primary forest in central Amazonia. Eur. J. Soil Sci. 51: 219–231.

Smethurst P.J. 2000. Soil solution and other soil analyses as indicators of nutrient supply: a review. For. Ecol. Manage. 138: 397–411.

Soil Survey Staff 1999. Soil Taxonomy. Basic System of Soil Classification for Making and Interpreting Soil Surveys. USDA/NRCS Agriculture Handbook No. 436. USDA, Washington, DC.

Webb M.J., Reddell P., Hambleton A. and Robson K. 2000. Growth response of four tropical plantation timber species to increasing phosphorus supply and assessment of phosphorus requirements using foliar analysis. New Forests 20: 193–211.

Yost R., Ares A., Bajita J. and Wang X. 1999. Diagnosing nutrient deficiencies. In: Osmond D.L., Metra-Corton T., Smyth T.J., Yost R.S. and Reid W.S. (eds), Decision processes for determining diagnostic and predictive criteria for soil nutrient management: Workshop Proceedings. SMCRSP Technical Bulletin 2000–03, Maligaya, Philippines., pp. 107–119.

Yuyama K. 1997. Sistemas de cultivo para produção de palmito da pupunheira. Horticult. Bras. 15: 191–198.