Report on Trip to Costa Rica
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SM-CRSP Project *Decision Aids for Integrated Nutrient Management*

Traveler:
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Objectives:

The objective of this trip was to discuss P diagnostics and fertilization experiments for peach palm (*Bactris gasipaes*) with Costa Rica collaborators and to visit peach palm plantations in order to refine the research protocols for these experiments. The overall goals of this portion of the project are:

1. To determine advantages and disadvantages among methods to diagnose nutrient P sufficiency in mature peach palm plantations.
2. Evaluate and implement the best diagnostic method in the improved Integrated Nutrient Decision-Support System

Itinerary:

Monday, August 3	Arrival in San Jose; meetings with A. Alvarado and R. Salas from CIA (Centro de Investigaciones Agronómicas)-University of Costa Rica to discuss approaches to the P experiments on peach palm; tour of CIA labs and library.
Tuesday, August 4	Meeting with E. Molina to examine existing data on soil and foliar nutrients in peach palm from the DEMASA farm and discuss approaches to P diagnosis; F. Cox from University of North Carolina arrived in San Jose.
Wednesday, August 5	Discussion on approaches to determine soil P buffer capacity led by F. Cox and attended by A. Alvarado, R. Salas, L. Uribe and A. Ares; seminars organized by CIA and the Costa Rican Soil Science Association given by F. Cox and A. Ares. F. Cox's seminar dealt with soil P buffer coefficients while A. Ares talked about P diagnostics methods in perennial crops. The seminars were attended by about 25 people and were both followed by lively discussions. The audience provided quite valuable criticisms on the conceptual approaches to the covered topics, research applicability to Costa Rica sites and design and duration of future experiments. Discussion with L. Uribe about possible approaches to determine mycorrhizae in peach palm.

Thursday, August 6	Travel to DEMASA farms (Agropalmito and Indaco) accompanied by F. Cox, R. Salas and G. Soto. Visit to peach palm seed production area, nursery and ongoing field research (litter decomposition study by G. Soto and others). In-situ discussion of potential tissues for P diagnosis based on management practices for peach palm. Photographs were taken for further discussions.
Friday, August 7	Discussion (led by F. Cox. and attended by R. Salas and A. Ares) on designing a soil incubation experiment to determine P buffer capacity on a variety of soils and a P fertilization experiment with peach palm in the greenhouse. Meeting with E. Molina to further discuss existing data on P nutrition of peach palm as well as design and measurements in the planned experiments. Final meeting with A. Alvarado and R. Salas.
Saturday, August 8	Departure for the U.S.

Approaches to Determine P Diagnostics Methods for Peach Palm

Data from a fertilization experiment within the DEMASA farm showed that soil P levels were somehow correlated to foliar P concentrations ($r^2 = 0.18$, P = 0.05 for a linear model; $r^2 = 0.29$ for a logarithmic model) (Centro de Investigaciones Agronómicas, 1997). Neither soil P nor foliar P correlated to several yield and productivity indices. The different plots, however, had received different fertilization regimes resulting in a confounding (and then discontinued) experiment and yield measurements were taken only during about three months (E. Molina, personal communication). The range of soil P levels measured by the modified Olsen method was quite broad (4.3 to 25.8 mg L^{-1}). In 10 out of 21 sites, soil P levels were above the tentatively proposed critical level of 10 mg L^{-1} for peach palm. In all the sites, foliar P levels were above the proposed sufficiency level of 0.16% for old leaves in peach palm but only one value was higher than the sufficiency level of 0.23% proposed for young leaves (Molina, 1997). For the above-mentioned experiment, the sampled tissue was likely the third leaf on the main stem (a relatively young tissue). The data showed no relationship between applied P and yield, hearts of palms per plant or harvested boxes per ha. There was instead a positive correlation between these variables and applied N ($r^2 = 0.28$). The combined effect of several nutrients on peach palm yield could not be tested as applied amounts of the different nutrients were highly correlated in most cases. Applied P was related to soil P ($r^2 = 0.29$, P = 0.01) but it was not related to foliar P.

It may be possible that current sampling strategies and methods for determining foliar and soil P in peach palm plantations are not adequate. For other perennial crops, increase P demand and positive response to P additions at certain stages of stand development did not correlate to changes in foliar P or to soil chemical analysis (Dighton and Harrison, 1990).

There was agreement among Costa Rica collaborators that peach palm tissues of different age and soil P values by different methods (e.g. modified Olsen, Mehlich-3) and at different depths should be compared to select the best method of P diagnosis. Currently, the third leaf on the main stem is used for sampling purposes but there is no information comparing tissues of different age for peach palm in Costa Rica (Molina, 1997). Modified Olsen is currently the standard method at

CIA but it is considered that Mehlich 3 might be preferable for a variety of soils as well as for methodological reasons (lower cost, easier laboratory procedures, multi-nutrient extraction) (Cabalceta and Cordero, 1994). For soil P and K analysis of Vertisols and Ultisols of Costa Rica, results from Mehlich-III correlated well with those from modified Olsen (Molina and Cabalceta, 1990). Critical soil P levels (using *Sorghum bicolor* as the test plant) for Costa Rica soils have been found to vary widely depending on soil order and the extracting solution (Cabalceta and Cordero, 1994).

Moreover, soil organic P may play an important role in regulating P availability in peach palm plantations and could be determined in parallel to the extraction of inorganic P (P_i) by other methods (E. Molina, personal communication). Previous research work in Costa Rica showed that the organic fraction represented 22 to 60% of the total P extracted with 0.5 *M* $NaHCO_3$, 1.0 *M* H_2SO_4 and 0.5 *M* NaOH (Henriquez et al., 1992). Among four soil orders (Andisols, Ultisols, Vertisols and Inceptisols), the higher values of organic P were found in Andisols while Ultisols and Vertisols showed the lowest values. In mature plantations, it is possible that peach palm takes an important proportion of their nutrients from easily mineralized organic P pools.

Vesicular-arbuscular mycorrhizae (VAM) are likely an important component of peach palm nutrition. Previous research conducted at La Selva in Costa Rica showed that most non-mycorrhizal plants of peach palm died within one year while inoculated plants reached about 30 cm in height during the same period (Janos, 1977). The dependence on mycorrhizae of peach palm may be genotype-specific. Accordingly, two peach palm land races were found to be either marginally or highly mycorrhizal dependent (Clement and Habte, 1995). In oil palm (*Elaeis guineensis*), VAM inoculation increased phosphate fertilizer efficiency 2.7- to 5.6-fold depending on the soil and fertilizer (Blal et al., 1990). VAM inoculation is not practiced in the peach palm nurseries in Costa Rica but it is likely that roots are colonized by native VAM populations. Research would provide valuable information on early growth enhancement (and possible shortened time to harvest) of peach palm in response to VAM.

Alternative methods for P diagnosis (root analysis, enzyme activity) were also discussed with the Costa Rica collaborators. There was interest from the CIA collaborators to test some of these methods in peach palm. Preliminary experiences should be carried out in a small scale (e.g. during the greenhouse experiment) before a major study effort with these methods.

Researchers from CIA and some of the attendants to the seminar session expressed concern about the possibility of carrying out the experiments within small farms as initially planned because of potential problems to (i) adequately estimate peach palm yields, (ii) get information about important variables related to heart of palm quality and processing efficiency, and (iii) assure the necessary continuity of the experiments. A potential problem with the DEMASA farm is that most of the sites are likely enriched with applied P and, therefore, it would be difficult to find a sufficiently broad range of soil and foliar P levels to test for sufficiency and deficiency. This problem, however, will be addressed by a careful selection of the study sites and pre-sampling. Also, the experiments should continue long enough to provide reliable results.

Review of P Experiments on Peach Palm

Fertilization trials on peach palm are scanty and experimental conditions are often not well documented (see review paper in Appendix). In general, results showed no (or weak) response to P additions and, therefore, the suitability of P diagnosis methods remained untested. One of the best responses was obtained in a greenhouse experiment in which peach palm was grown on an Oxisol (Rhodic Eustrostox, Wahiawa series) with three P solution levels (0.008, 0.02 and 0.2 mg L^{-1}) (Clement and Habte, 1994). Although foliar P levels were higher for the high-P treatment compared to the other two treatments, a re-analysis of the data showed that differences between treatments were higher if P contents were expressed on a leaf area basis.

Follow-up

Based on the information from the trip to Costa Rica and a later phone conversation of E. Molina with R. Yost and A. Ares, the following steps are proposed:

1. Soil sampling at two depths (0-5 and 5-20 cm) within an area of about 15 ha within the DEMASA farm (Indaco) and soil P analysis following the modified Olsen and Mehlich-3 methods. Samples will be stored for organic P determinations. This data set would eventually be complemented with additional soil P data for the whole farm. The data will allow to select sub-areas with low P levels.
2. A superimposed P fertilization experiment to test foliar and P diagnostic methods in peach palm. The experiment will be designed based on the preliminary data and available resources.

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APPENDIX

Fertilization Responses and Nutrient Diagnostic Methods for Peach Palm (*Bactris gasipaes*)

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Introduction

One of the primary concerns of agricultural research in the tropics has been to increase crop production through the efficient use of fertilizers. Perennial crops are particularly valuable in tropical regions for their potential to improve food security and achieve sustainable land use. Assessing these crops' nutritional status is fundamental to developing a rational and efficient fertilization program. Over the years, soil and plant scientists have developed diagnostic techniques such as foliar and soil analysis that are used to determine the mineral status of plants and the soils that feed them. More importantly, scientists use these diagnostic techniques to evaluate soil fertility and determine whether applied fertilizers are sufficient to ensure satisfactory crop growth. Through extensive experimentation and refinement of these methodologies, fertilizer recommendations for specific crops have been developed.

Research on mineral nutrition of agronomically important crops has been compiled and published in the literature. As a result, growers can locate nutrient requirements and fertilization recommendations for a wide variety of crops (Martin-Prevel et al., 1984; Mills & Benton Jones, 1996). However, because of the shear number of food crops available throughout the world, information pertaining to some crops may be lacking in the literature. This is the case with peach palm (*Bactris gasipaes Kunth*), a perennial tree crop native to tropical America. In recent years, the demand for heart-of-palm, which is extracted from the shoots of young peach palm trees, has increased dramatically in Europe and the United States (Clement et al., 1996). Increasing demand for heart-of-palm on the world market has lead to dramatic rises in peach palm production in Costa Rica (Alvarado & Smith, 1998). In Brazil, there is interest in peach palm in monocultures and intercropping systems as a replacement for the severely depleted native palms of the genus *Euterpe* (Yuyama 1997).

Despite its rise as an important economic crop, relatively little is known about the nutritional requirements of peach palm. Over the last twenty years, scientists and commercial growers in Brazil, Costa Rica and Peru have conducted fertilization experiments, but there still do not exist reliable guidelines on the nutrient requirements for this crop. At present, scientists in Brazil and Costa Rica have begun research programs on nutrient management strategies in peach palm production. This paper reviews some of the available literature on peach palm focusing on its nutrient requirements, and then discusses the use of foliar analysis as a diagnostic technique in perennial crops. Peach palm is used as an example through which concepts of nutrient management for perennial species can be developed. Among all the essential nutrients for plant nutrition, greater emphasis was put on P as the major target in our current research efforts on decision support systems for integrated nutrient management.

Peach Palm

History

Peach palm, alternately known as pejibaye (Costa Rica), pupunha (Brazil), chontaduro (Colombia, Ecuador), pijiguao (Venezuela), pijuayo (Peru), tembe (Bolivia), parepon (French Guayana) has been an important native food tree of the Amerindian people of tropical America for thousands of years. In traditional societies of Panama, Costa Rica, the Pacific coast of Colombia, and western Amazonia, all parts of this palm were used: roots in medicine, stems in weaponry and construction, leaves for thatch, palmito (heart-of-palm) as a vegetable, and fruit for food. Today, peach palm continues to be an important food crop in tropical America. Recently, peach palm has been recommended as a promising addition to agroforestry systems in the humid tropics (Clement, 1989; Benites, 1990; Szott el al., 1991).

As a modern agronomic crop, the meristem of peach palm is produced on a large scale for heart-of-palm in Costa Rica and Brazil (Clement, 1989). In Costa Rica, heart-of-palm is a growing export - between 1994 and 1996 exports increased by 71% bringing in $21.7 million (Alvarado & Smith, 1998). The same authors report that typically peach palm is cultivated on small plots of 5 ha or less with a small minority of large-scale operations. Additionally, peach palm, as a specialty crop targeting the gourmet restaurant business, has caught the attention of researchers in Hawaii (Clement et al., 1996).

Ecology

Peach palm is known to grow well on a wide range of soils in the humid tropics (Molina, 1997). Highest yields, however, occur on nutrient rich, young alluvial soils, with a deep, well-drained profile, and high organic matter content. It is best suited to areas with abundant rainfall throughout the year (2000-3000 mm), moderately high temperatures (24-28 ºC), and elevations ranging from 5-700 m a.s.l (Clement, 1989). Peach palm is also well adapted to the nutrient poor, acid soils common to the humid tropics. It is cultivated intensively on highly weathered Oxisols, Andisols, and Ultisols in Brazil and Costa Rica with pH as low as 4.5, high Al saturation, and low organic content (Molina, 1997; Clement, 1989; Perez et al., 1987).

Peach palm, like many palms, has a shallow root system. In a four-year old plantation on an Andisol in Costa Rica, 65% percent of the roots were found in the top 20 cm of the soil profile (Jongschaap, 1993). Fine roots were evenly distributed up to 1.5 m from the stem while large and medium-sized roots were found within 50 cm of the stem. In a medium-textured, yellow Oxisol in Brazil, 58% of the root biomass of 13 year-old peach palms were concentrated in the upper 20 cm of the soil profile while 53% of the root biomass was found within the crown projection area (Ferreira et al., 1980). In a follow-up study with 17 year-old peach palms growing in a pasture field, approximately 80% of the root biomass was found in the top 20 cm of a clay textured Oxisol that included the Ap and part of the A horizon (Ferreira et al. 1995). Ninety percent of the root biomass was located within the crown projection area.

Peach palm is known to form a symbiotic relationship with vesicular-arbuscular mycorrhizae (VAM) for enhanced water and nutrient uptake (Janos, 1977). Mycorrhizal infection in peach palm roots may partially explain its relatively high yields in nutrient poor soils (Clement & Habte, 1995). While peach palm survival and growth are enhanced by mycorrhizal infection (Janos, 1977), the degree of mycorrhizal dependency varies between different peach palm progenies (Clement & Habte, 1994; Clement & Habte, 1995). Additionally, mycorrhizal effectiveness was correlated to background soil P concentrations. In soils where P was below 0.02 mg L^{-1} in 0.01 M $CaCl_2$ extracts, the mycorrhizal effect was absent suggesting that a minimum soil P is necessary for mycorrhiza to be effective. At the other extreme, in soils containing high levels of P (> 0.04 mg L^{-1}) no further response to added P was observed in either the mycorrhizal or the non-mycorrhizal treatments (Clement & Habte, 1994). Also, inoculation with mycorrhizae and diazotrophic bacteria increased dry matter production and N and P-use efficiencies in thornless peach palm seedlings (Carvalho et al., 1997).

While there is a paucity of data on the environmental requirements of peach palm, the available research (Molina, 1997; Jongschaap, 1993; Clement, 1989) indicates that peach palm growth is limited in: 1) poorly drained soils known to flood; 2) soils with low nutrient and organic matter content; and 3) areas prone to drought (more than three months with less than 50 mm of rainfall). In the Amazon region, some peach palms lost more than one third of their foliage during the dry season (Wolf, 1997).

Agronomic Management of Peach Palm for Heart-of-Palm Production

Peach palm has been an important perennial crop in Costa Rica for the last 25 years where it is managed intensively for heart-of-palm production (Alvarado & Smith, 1998). Typically, seeds from mature trees are harvested and planted for seedling production in a nursery bed. Seedlings are transplanted to the field after two months. Presently, the recommended planting density is approximately 5000 plants ha^{-1} with 1 m spacing within rows and 2 m between rows (Clement et al., 1996). In the older plantations it is still common to find planting densities as low as 3200 plants ha^{-1} (Herrera, 1989). Harvesting for the heart-of-palm begins as early as one year following transplanting. Harvests occur on a regular basis throughout the year, and any given plantation remains under production for up to 15 years (Clement, 1989). One stem from each plant unit (a plant unit contains about four stems and six-eight suckers) is harvested approximately every two weeks. In Costa Rica production rates for hearts-of-palm show considerable variation primarily because peach palm is grown by both small farmers and large companies (Alvarado & Smith, 1998). Yields of approximately 9600 heart-of-palm ha^{-1} yr^{-1} on an intensively managed large plantation have been reported (Herrera, 1989).

Soil Fertility and Fertilization

Although the literature suggests that peach palm is well adapted to acid infertile soils of the tropics (Clement, 1989; Molina, 1997), fertilization is commonly practiced in commercial peach palm production. Small farmers in Costa Rica seem to apply up to 300 kg N, 82 kg P, and 250 kg K ha^{-1} yr^{-1} (Alvarado & Smith, 1998) although it has been argued that most farmers may apply less than these amounts (Jongschaap, 1993). Larger commercial plantations are known to apply N rates of up to 500 kg ha^{-1} yr^{-1} (Herrera, 1989). Developing optimum fertilization rates should be based on results collected from controlled fertilizer experiments.

Existing fertilization trials on peach palm report significant responses to applied N while the response to other nutrients such as P has been less frequent (Table 1). In a four year fertilizer trial conducted in Costa Rica, Guzmán (1985) measured a significant effect of applied N on heart-of-palm production. Number and weight of hearts per hectare per year were maximized when N was applied at a rate of 367 kg ha^{-1}. At the highest level of N, yield decreased significantly. No significant effects were found for applied P and K. Foliar levels of N, P, and K did not change with the different fertilization levels, despite a growth response to N. Similar results were obtained in a six-year study on peach palm grown in Peru (Perez et al., 1987). A quadratic response in palm growth to applied N occurred with optimal rates of about 180 kg N ha^{-1} yr^{-1} while fruit yield responded linearly to N. The study did not find any response to P. Foliar nutrient levels showed no relationship to growth or fruit yield. A study in Costa Rica showed significant N effect on leaf area index, height of plant, number of shoots, diameter at base, total dry weight, and stem dry weight of peach palm young plants (Jongschaap, 1993). The only significant effect of P was on the girth of the stem while no significant effects for K were measured. It was suggested that the P effect may have been masked by 1) the high P fixation capacity of the soil, 2) the presence of mycorrhizae, or 3) the insufficient accumulation of P in the soil due to the young age of the palms. Foliar N and P levels did not change significantly with increasing fertilization rates.

In Brazil, responses of peach palm to NPK additions have been reported (Arkcoll, 1982). An annual doses of 50 g of NPK per plant was recommended for young stands of peach palm growing on an Oxisol (Gomes et al., 1987). Among 27 different combinations of N, P and K, a dose of 2 kg ammonium sulfate, 1 kg of superphosphate and 0.5 kg of potassium chloride per cubic meter of substratum induced the higher growth rates in peach palm seedlings growing in nursery beds (Kato et al., 1997). There was also a linear response of early growth of peach palm to P additions while the response to N and K showed a parabolic trend (Lopes Reis, 1997).

About three and a half years after transplanting, peach palm reacted positively to increased doses of a complete fertilizer in Manaus, Brazil (Wolf, 1997). In this study, peach palm showed greater biomass accumulation and nutrient-use efficiency compared to other woody tropical species. For most nutrients, the difference in concentration between leaves and wood was higher in peach palm suggesting an efficient allocation of nutrients to tissues that more closely drive biomass production.

Since field experiments designed to measure growth responses to nutrient additions are difficult to locate, current fertilization rates are based upon field experience gained over the last 25 years. Research on soil characteristics of peach palm fields conducted and compiled at the University of Costa Rica (Center for Agronomic Investigation (UCR-CIA) provides a summary of the available data on soil requirements for peach palm production (Table 2). The data indicate the great range and versatility of this crop regarding soil fertility. It is not clear, however, whether the data is based upon the standard top 20 cm of the soil profile. Depth of sampling may be an important consideration especially since the standard sampling depth may include both the organic layer, richer in available nutrients and in root abundance, and the mineral soil.

There is evidence suggesting that fertilizer practices have had detrimental effects on soil quality in some Costa Rican peach palm plantations (Guzmán, 1985; Herrera, 1989). High N fertilization rates (400 kg N ha^{-1} yr^{-1}) over six years decreased soil pH from 5.4 in the control to 4.5 (Herrera, 1989). Similarly, exchangeable acidity increased from 0.5 to 2 mmol 100g $soil^{-1}$ while exchangeable Ca, Mg, and K dropped significantly. These findings suggest that the high N rates currently in use in Costa Rica pose a significant threat to soil quality, and that fertilization rates should be lower.

Nutrient Cycling

In any perennial plant system, nutrient cycling plays an essential role in the nutrition of the plants. In natural systems, nutrients released from decomposing litterfall represent the primary nutrient pool (Binkley, 1986). Litterfall accumulation in forests from eight different sites ranged from 3.4 to 6.2 t ha^{-1} yr^{-1} (Miller, 1984). In tropical ecosystems where litterfall turnover rates are high, nutrient cycling contributes significantly to plant nutrition (Kimmins, 1997; Drechsel & Zech, 1993). Therefore, in perennial systems, quantifying the nutrient contribution from litterfall is a necessary component that will reduce the fertilizer recommendation. Researchers can estimate this contribution by measuring decomposition and mineralization rates of the residue, the relative distribution of nutrients within the organic and inorganic soil fractions, and root profiles.

In the case of peach palm for heart of palm production where cut leaves and stems are left in the field following harvests, annual residue production is considerable while biomass and nutrient exports from the system are relatively small. On one mature peach palm plantation in Costa Rica, for example, only 1.76 t ha^{-1} yr^{-1} of biomass was removed from the field in the form of heart-of-palm (Herrera, 1989). This translated in a nutrient removal of 28, 4.8 and 31 kg ha^{-1} yr^{-1} of N, P, and K in the heart-of-palm.

In Costa Rica, peach palm was found to extracted nutrients from the soil in the following order of magnitude: K > N > Ca > P > Ca > Mg > S > Mn > Zn > Fe > B > Cu (Herrera, 1989). The order was K > N > P > Ca > Mg > Fe > Zn > Mn > B > Cu in a peach palm stand on an Oxisol in Manaus, Brazil (Cravo et al., 1996).

A recent study (Haron et al., 1998) conducted in an oil palm (*Elaeis guineensis* Jacq.) plantation in West Malaysia measured soil organic matter dynamics in relation to residue quantities and placement. Soil microbial biomass and organic C were measured in the 0 - 15 cm layer from three positions (weeded and cleared area near the base, in the palm avenues, and under pruned piles of palm fronds) in three stands of increasing age (5, 10, and 20 yrs). The pruned palm fronds represented approximately 10 t ha^{-1} yr^{-1} of dry matter. Organic carbon in the soil increased significantly over time, and was consistently highest under the piles of palm fronds (Table 3). The relatively small differences detected in soil organic C between the weeded circles and the areas under the piles of palm fronds suggest that roots contribute significantly to soil organic matter build up. Despite large quantities of frond residues, soil organic matter content increases were not large. The small changes in soil organic matter content suggest that the palm fronds may not have contributed significant quantities of nutrients to the palm trees. Biomass C, which usually relates to soil nutrients, increased over time, but the relative contribution of the palm fronds is again small. In contrast, peach palm residue in plantations in Costa Rica has contributed significantly to organic C build up in the soil (R. S. Yost, per. comm.).

Diagnostic Methods

Background

Optimum productivity in any cropping system depends primarily on the adequate supply of essential plant nutrients. Plant and soil scientists are particularly concerned with developing diagnostic methods that reliably determine whether a plant is adequately supplied with nutrients or not. The observation of visual symptoms is perhaps the simplest of diagnostic methods. Nutrient disorders such as deficiencies or toxicities can be detected by observing identifiable symptoms. While this is a simple tool, the appearance of visual symptoms often indicates severe nutritional disorders usually accompanied by drastic reductions in yield. Relying exclusively on this method precludes the possibility of anticipating nutrient problems.

Plant analysis which involves the chemical analysis of selected plant tissues is a more complex diagnostic tool that provides valuable information on the nutritional status of plants. It has been used routinely to verify deficiency symptoms and monitor plant nutrient levels during the growing season. On a more complex level, scientists want a diagnostic tool that will not only detect a nutritional problem, but also detect a response to a particular treatment. However, the relationship between foliar nutrient levels and crop response to fertilization treatments has often not been well established.

Visual Symptoms

As discussed earlier, the observation of visual deficiency symptoms is a quick and simple method of detecting nutritional problems. In controlled laboratory experiments, several deficiency symptoms were observed in young peach palm plants grown in nutrient solution (La Torraca et al., 1984; Falçâo et al., 1994) (Table 4). In oil palm, fronds of P deficient plants turn a dark green while in Zaire palms not receiving P showed increased desiccation of older leaves, a symptom usually associated with K deficiency (Williams & Hsu, 1970). In mature palm plants (e.g. of oil palm and probably of peach palm as well), however, symptoms of P deficiency may be not well delineated and are seldom unequivocal indicators of deficiency (Hartley, 1977). Deficiencies of nitrogen (widespread yellowing of leaves), magnesium (yellow stripes on leaflets) and boron (leaflets of young leaves fused at their tips) have been reported in peach palm plantations for fruit production (Mora-Urpí et al., 1997).

Foliar Analysis

Foliar analysis is a diagnostic method commonly used in agriculture to assess the nutritional status of crops, and to help predict growth response to fertilization. Currently, plant analysis is routinely conducted on the leaf principally because it is the focus of most plant metabolic activities, and the leaf provides a snapshot of the plant’s nutrient status (Mills & Benton Jones, 1996; Martin-Prevel, 1984; van den Driessche, 1974). While foliar analysis is generally viewed as a reliable method in assessing a plant’s nutritional status, this technique has not always performed well in predicting crop response to fertilization (Martin-Prevel et al., 1984; Mead, 1984). In tree crops, predicting response is complicated by such factors as nutrient cycling (Miller, 1984), retranslocation of nutrients within the plant (Van den Driessche, 1984), stand age, foliage age and position within the canopy, and seasonal variations (Mead, 1984). Each of these factors can cause significant variation in foliar nutrient concentration, and, therefore, careful consideration of leaf sampling method is essential.

Two fundamental criteria must be considered when leaf sampling methods are developed: sensitivity and stability (Foster, 1976). These criteria have fueled an ongoing debate in the literature (van den Driessche, 1974). On the one hand, sensitivity requires that leaf samples should reflect nutrient uptake in plants, especially in response to fertilization. In other words, the nutrient analysis corresponds to particular physiological processes in the plant. On the other hand, meaningful comparisons can only occur when the samples provide stable nutrient concentrations. In this case, the primary consideration is minimizing variability, and low variability often occurs when the leaf is least active physiologically. Traditionally, minimizing variability has been the driving force in the development of guidelines for foliar analysis in trees and perennial crops (for detailed review of the literature on this issue see Mills & Benton Jones, 1996; Drechsel & Zech, 1993; Foster, 1976; van den Driessche, 1974). Work in forestry (Evans, 1979; Mead, 1984) and especially oil palm (Foster, 1976) has examined leaf sampling methods and their relationship to phenology.

Data on foliar nutrient concentrations in peach palm are scarce, and no standard values are available in the literature. Measured nutrient concentrations generally fall within the general range for higher plants as reported in Mills & Benton Jones (1996). Moreover, foliar nutrient levels were approximately similar to available data on oil palm in Malaysia (Table 5). The upper range for N, P, and K appears high in comparison with oil palm, and may be due to high fertilization rates commonly used in peach palm plantations (Molina, 1997).

Leaf Position and Position Within the Leaf

Leaf position is an important factor to consider in sampling perennial crops. Considerable work has evaluated the effect of leaf position on nutrient concentration in oil palm in sub-Saharan Africa and Malaysia. Early research in oil palm in Malaysia (Chapman and Gray, 1949) set the standard for which leaf to sample. Based upon a fertilizer trial, leaf 17 (approximately 8.5 months old) showed the best correlation between N, P, and K and yield as compared to younger leaves. Subsequent work found that leaf 17 also provided the most stable measurements for N, P, K, and Ca (Coulter, 1958; Tan, 1976). For peach palm in Costa Rica, currently, the third leaf from the top of the stem to be harvested is taken for analysis (Molina, 1997).

Other research has indicated that plant age must also be considered in leaf selection. In two-year old palms, leaf number nine is sampled while both leaf nine and 17 are analyzed in three-year old trees. In older palms sampling is confined to leaf 17 (Rognon, 1984).

In perennial tree crops leaf position within the canopy significantly affects nutrient levels. Generally, leaves in the outer apical portion of the crown have higher levels of mobile nutrients N, P, and K while Ca and Mg levels tend to increase in the lower inside portions of the canopy (Husni et al., 1996; Bergman et al., 1994; Drechsel and Zech, 1991; Lamb, 1976). Standard methods for sampling trees in the tropics suggest using fully exposed leaves from the upper crown (Drechsel & Zech, 1991, 1993). Regarding leaf sampling for deciduous trees, van den Driessche (1974) cautioned conflicting data exists in the literature.

Researchers have found that when the leaf to be sampled is large as in oil palm and banana (*Musa spp.*), the position within the leaf has significant effects on nutrient levels. In oil palm, for example, P concentrations increase in the central portions of the leaflets, vis a vis the edges. In frond number nine, leaf P increased towards the tip of the leaflet while in frond 17 foliar P decreased towards the tip (Chapman & Gray, 1949). Typically, leaf samples are taken from the middle 10 cm of two pairs of pinnae (Coulter, 1958). In banana, variations in nutrient levels vary not only between leaf halves, but also show considerable variability within each half (Martin-Prevel, 1984). In broad-leaved tree species, the entire leaf is routinely used for analysis (Weetman & Wells, 1990). In peach palm, N, Ca and Mg concentrations tended to increase in apical leaflets compared to basal ones (Falçâo et al., 1994). Leaflets located in the middle sector of the leaf have contents of nutrients close to the average values from the three sampled positions (basal, middle and apical). This fact suggests that current standard sampling techniques (i.e. as followed in Costa Rica) using the middle third of the leaf are adequate to address nutrient variations as a function of leaflet position in peach palm.

Leaf Age

Leaf age has a significant effect on nutrient concentrations. Generally, younger leaves contain higher concentrations of the mobile nutrients (N, P, K, S) while in older leaves Ca, Mg, Al, Fe, Mn, and B concentrations tend to increase. In an experiment conducted on young peach palm plants, preliminary results for young and old (age not specified) leaves in peach palm show similar trends (Table 6), with the exception of K. Accordingly, N, P and K concentrations of four and a half year-old peach palm plants decreased with leaf age while Ca and Mg increased (Grau Alvarado, 1986). The coefficients of variation (although the actual values were higher than those reported) for a sample of 40 plants tended to increase especially in leaves older than the leaf 10 and, therefore, the author suggested leaf eight as a standard for sampling. In eight year-old peach palms in Brazil, contents of N, P, K and Cu were higher in young leaves while Ca and Fe increased with leaf age (Falçâo et al., 1994) (Table 6).

In palms, leaf position and leaf age are synonymous and as stated earlier younger leaves (lower number) generally have higher concentrations of the mobile nutrients. In Costa Rica, mature peach palm leaves that have ceased growing, but are not yet senescent, are currently taken for routine laboratory analysis (Molina, 1997).

In work on macadamia (*Macadamia integrifolia*) in Hawaii, leaf P concentrations were consistently higher in three month-old leaves compared with six month-old leaves (Cooil et al., 1966). A recent comparison of leaf P levels in young and mature leaves from three different locations in Hawaii, found that there was as much as a 40% decrease in foliar P content between a young leaf and a mature leaf (Yost et al., 1998). In this study, it was clear that an incorrect diagnosis of P deficiency resulted if leaves were sampled too young. Similarly, N, P, and K concentrations were generally higher in the younger leaves of *Eucalyptus deglupta* trees grown in Papua New Guinea (Lamb, 1976). Trees commonly retranslocate mobile nutrients from older senescent leaves to areas of new growth (Kimmins, 1997). Since leaf nutrient concentrations vary considerably with age, it is essential that comparisons are made between leaves of the same age. For example, if critical nutrient levels are developed on mature leaves, comparison with young leaves will not provide an accurate assessment of the tree's nutrient status.

In addition, tree age affects mineral composition of the leaves. In general, N and K concentrations decrease with age (Rognon, 1984), while the concentrations of Ca, Mg, B, Mn, and Fe increase as the tree ages (Ng et al., 1969). Contents of N, K, P and Mg in trunk, roots and whole plants of oil palm decreased gradually over time but the crown tended to maintain rather constant nutrient levels throughout (Ng et al., 1968). Consequently, leaves did not detect a drain in nutrient reserves, at least in the short term. This fact may have explained a lag period of about 18-24 months before response from fertilizer application was obtained. Also, foliar N levels in peach palm in Peru remained relatively unchanged despite strong response to N additions (Perez et al., 1993).

Environmental Factors

Nutrient fluxes in foliar tissues are also related to changes in the environment. Two important factors to consider are the effects of diurnal and seasonal cycles on foliar nutrient content. Plant behavior often follows a 24 hour cycle, and the cyclical changes in light, temperature, and moisture cause distinct fluctuations in foliar nutrient concentrations (Mills & Jones, 1996). In oil palm, leaf N content was observed to fall as the day progressed (Coulter, 1958), but increases in leaf K have been observed (Foster, 1976). Currently, it is recommended that leaves be sampled between 7 and 11 AM to minimize variability caused by diurnal cycles (Martin-Prevel, 1984).

There is general agreement that seasonal cycles cause significant variations in leaf nutrient levels (van den Driessche, 1974; Lamb, 1976; Mead, 1984; Drechsel & Zech, 1993). However, opinions differ regarding when leaf samples should be collected. Two general schools of thought are apparent in the literature (van den Driessche, 1974). One approach favors sampling when the tree is least active physiologically and nutrient levels in the leaves are relatively stable; in temperate climates this coincides with late autumn and winter while in the tropics it generally occurs during the dry season. The second approach favors sampling during the growing season in order to analyze nutrient availability during periods of high demand.

Considerable research in oil palm in Africa and Malaysia has sought to clarify the effect of the dry and wet seasons on foliar nutrient levels. A literature review reported strong seasonal differences common in Africa had pronounced effects on nutrient concentrations in palm leaves (Foster, 1976). Generally, leaf N and P decreased during the dry season and increased with the rains. These increases have been related to increased availability of inorganic N and P resulting from higher mineralization rates of soil organic matter following the beginning of the rainy season. In West Malaysia, where climatic differences are less pronounced between the two seasons, similar findings regarding foliar N levels were found. Reduced uptake of P by oil palm roots was observed during the dry season by using radioactive P (Forde 1976). In another study, foliar P achieved a maximum at the end of the wet season (Ochs & Olivin, 1976). Some other studies report low coefficients of variation (3-4%) for seasonal fluctuations in foliar P (Teoh et al. 1981; Foster & Chang, 1976).

Other Organs and Methods

While foliar analysis is considered the standard method in plant nutrition diagnosis, its limitations have lead researchers to explore alternative techniques that use other plant organs (van den Driessche, 1974; Mead, 1984). Research using plant roots, the site of nutrient uptake from the soil, have shown promise in predicting the nutrient status of tree crops (Dighton & Jones, 1991). Using a root bioassay technique, P deficiency in a Sitka spruce stand was detected and alleviated by P additions (Dighton & Harrison, 1990). The root bioassay was able to distinguish P deficiency in stands where foliar analysis failed to show differences. This technique requires equipment and technology for ^{32}P tracers which may limit its widespread adoption.

In oil palm, root analysis has been shown to differentiate P uptake better than foliar analysis. A large difference in P concentration in roots of fertilized and unfertilized oil palm (0.114 vs. 0.051%) was detected whereas the leaf levels were only marginally, though significantly altered (0.177 vs. 0.170%) (Hartley, 1977). Additionally, enzyme activity in the rhizosphere has also been related to plant nutrition. Acid phosphatase activity (APA) has been correlated with P deficiency in annual crops (Ascencio, 1994; Ascencio, 1997). Using a relatively simple methodology, Ascencio (1997) found that APA was a reliable biochemical marker for P stress in plants. In peach palm, foliar APA was inversely related to N additions, but there was no relationship with P (Bovi et al., 1998). In this study, peach palm did not respond to fertilization with P and probably increased APA was not a needed mechanism to enhance P availability.

Conclusions

The present review provides a general view of the mineral requirements of peach palm. Available research indicates that peach palm is highly responsive to N fertilization, but does not seem to respond to P (even at low soil P levels, 3.5 μg g^{1}) inputs especially in mature stands. This suggests that peach palm has a low P requirement or utilizes soil P reserves with a high degree of efficiency. However, before making either of these conclusions, further research on the P requirements of peach palm is required.

Unlike most agronomically important crops, standard nutrient requirements for peach palm are not available in the literature. The standardization process requires the implementation of rigorous field trials and the careful selection and employment of diagnostic methods. As research on peach palm proceeds the following points should be addressed:

- To determine what tissues are more sensitive to reflect plant nutritional status and response to nutrient additions.
- To evaluate the extent of seasonal climatic and year to year variations on plant nutrient concentrations.
- To explore the possibilities of novel diagnostic methods such as root bioassays and foliar/root enzyme analysis.
- To fulfill knowledge gaps on nutrient cycling on contrasting soil conditions to determine the contribution to peach palm nutrition of different soil organic and inorganic nutrient pools as well as mechanisms such as plant nutrient retranslocation and mycorrhizal nutrient uptake.

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Table 1. Summary of experiments on peach palm response to P and other nutrients.

Source	Plant Age	Soil Type/ Substratum	Soil P	Foliar P	P Application Rates	Growth/Yield Measures	Response to P	Response to Other Nutrients
			µg g^{-1}	%	ha^{-1} yr^{-1}			
Bovi et al., 1998	4 years	Aluvial alico	9 (resin)	0.19-0.28	0, 200 kg P_2O_5	Stem diameter, height, biomass, etc.	No	To N
Molina, 1998 (unpublished data)	Adult	Ultisol	4.8-25.8 (Mod. Olsen)	0.18-0.26 (3rd leaf)	9.2 to 282 g of P/ plant/year	Yield, hearts of palm/cepa, boxes of heart of palm/ha	No	To N and Mg
Guzmán, 1985	Transplanting to year 4	Typic Dystrandepts	About 6	Not reported	0, 200 kg P_2O_5 at planting	Number, size and weight of hearts of palm, yield	No	To N and K
Perez et al., 1987	Transplanting to year 6	Typic Paleudult	3.5 (Mod. Olsen)	0.19-0.21 Intermediate age leaf (likely the 3rd)	0, 12, 22, 44 kg P at planting and years 2 and 3	Stem diameter, height, fruit production at year 6	No	Quadratic to N at 0-3 years, then linear. Also, to K and Zn
Jongschaap, 1993	7 months (experiment lasted 132 days)	Thaptic Hapludand	Not reported	0.17-0.31 (leaf) Plants divided in leaf, stem and root for nutrient analysis	0, 300 kg P_2O_5 at day 27	Stem diameter, leaf area, number of leaves, shoot dry weight	Only in dbh	To N
Zamora & Flores, 1984	Transplanting to year 5.5	Not reported	7	Not reported	0, 36, 72, 108 and 144 g per plant	Weight, length, diameter and number of hearts of palm	No	Apparently to N and K
Lopes Reis, 1997	Transplanting	Not reported	1-2	Not reported	0,100 and 200 kg P_2O_5	Height, stem diameter, number of harvestable plants and heart of palm yields	Linear response for all the variables	To N and K
La Torraca et al., 1984	60 days (exp. lasted 80 days)	Silica	Not reported	Suff.: 0.23 (young), 0.16 (old);Def: 0.06 (young) and 0.03(old)	Not reported	Nutrient levels in complete and deficient solutions	Not reported	N/A

Source	Plant Age	Soil Type/ Substratum	Soil P	Foliar P	P Application Rates	Growth/Yield Measures	Response to P	Response to Other Nutrients
			µg g^{-1}	%	ha^{-1} yr^{-1}			
Clement and Habte, 1994	Up to 121 and 148 days (two trials)	Rhodic Eutrostox, Wahiawa Series	0.008 mg/L in solution	0.13-0.37 Disk near the tip of newly expanded leaf	0.008, 0.02, 0.2 mg/L P (as KH_2 $P0_4$) in solution	Leaf area, biomass accumulation and partitioning	Yes	N/A

Table 2. Tentative ranges and optimum soil characteristics and nutrient levels for peach palm production in Costa Rica (From Hue et al., 1998[1] and Molina, 1997[2]).

	Range[1]	***Optimal value[2]***
pH (H_2O)	4.1 - 6.0	5.5 - 6.0
Organic Matter (%)	-	> 5
P (mg/L)	4 - 34§	> 10
Ca (cmol (+)/L)	1.1 - 8.5†	> 4.0
Mg (cmol(+)/L)	0.2 - 2.3†	> 1.0
K (cmol(+)/L)	0.1 - 0.6†	> 0.3
Al (cmol(+)/L)	0.2 - 4.4§	< 1.0
% Al Saturation	2 - 71	< 30
S (mg/L)	-	> 10
Fe (mg/L)	74 - 2098§	10 - 50
Mn (mg/L)	2 - 94§	5 - 50
Cu (mg/L)	-	1 - 10
Zn (mg/L)	0.7 - 10.1§	3 - 15
B (mg/L)	-	0.5 - 2

† 1.0 M KCl extraction, § Hunter's Modified Olsen solution

Table 3. Organic C and biomass C measured in oil palm plantations in W. Malaysia (From Haron et al., 1998)

Plantation Age	**Treatment**	**Organic C**	**Biomass C**
yrs		%	µg C g^{-1}
5	weeded circle	0.80	109.4
	avenue	0.84	143.9
	frond piles	0.82	196.5
10	weeded circle	1.98	263.3
	avenue	1.53	273.8
	frond piles	2.47	390.7
20	weeded circle	2.42	288.9
	avenue	2.00	254.5
	frond piles	3.09	376.3

Table 4. Symptoms of deficiency of peach palm seedlings growing in hydroponic solution.

Nutrient	**La Torraca et al., 1984**	**Falçâo et al., 1994**
N	Small plants with little development, yellowing of older leaves especially at leaf extremities.	Little development, chlorosis in old leaves followed by necrosis of leaf margins and subsequent generalized chlorosis.
P	Stunted growth with no visual symptoms.	Reduced size of young and old leaves. Yellowing of old leaves followed by necrosis of leaf extremities. Young leaves turn opaque green.
K	Chlorosis along edges of older leaves that is eventually replaced by necrosis of the tissue. The effect is most intense at the points of the leaves. Symptoms can extend to leaves of intermediary age, and in the older age effect extends from the point of the leaves in direction to the rachis.	Chlorosis followed by necrosis of margins and tips of old leaves.
Ca	Light green new leaves with a wavy appearance. New leaves appear folded and there is an absence of thorns on the leaf surface.	Not reported.
Mg	Intervenal chlorosis or yellowing in the older leaves, beginning from the tip of the leaf to the base. At an advanced stage of deficiency, symptoms are present in leaves of intermediate age, older leaves show a complete loss of chlorophyl, and presence of necrotic tissue.	Not reported.
S	Loss of green color in the tips of the older leaves and change to a lighter green color in young leaves.	Not reported.
B	Intense green color appears in the older leaves accompanied by a wavy surface. In the new leaves leaflets fold abruptly in two where they join the rachis, the same folding can occur towards the middle of the leaflet.	Impaired and abnormal development of young leaves.
Fe	Not reported.	Chlorosis of young leaves followed by bleaching. Abnormal development (narrowed and acute) of the second and third leaves.

Table 5. Range of foliar nutrient concentrations in peach palm in Costa Rica and critical levels in oil palm in Malaysia (From [1]Molina,1997 and [2]Rognon, 1986).

Nutrient	[1]Peach palm	[2]Oil palm
N	2.50 - 4.0 %	2.50 %
P	0.15 - 0.3 %	0.150 %
Ca	0.20 - 0.5 %	0.60 %
Mg	0.20 - 0.3 %	0.24 %
K	0.80 - 1.5 %	1.00 %
Fe	100 - 200 mg/kg	50 - 250 mg/kg
Mn	50 - 200 mg/kg	50 mg/kg
Cu	8 - 15 mg/kg	-
Zn	15 - 25 mg/kg	18 mg/kg
B	10 - 25 mg/kg	12 - 14 mg/kg

Table 6. Nutrient concentration in young and old peach palm leaves [From (1) La Torraca et al., 1984; (2) Falçâo et al., 1994)]

Nutrient	Young Leaves		Old Leaves	
(%)	(1)	(2)	(1)	(2)
N	2.76	3.25	2.20	2.07
P	0.23	0.21	0.16	0.13
K	3.02	1.27	3.06	1.09
Mg	0.46	0.15	0.69	0.16
Ca	0.68	0.30	1.43	0.60
S	0.23	0.26	0.20	0.22