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Assessing soil fertility of a laterite soil in relation to yield of arecanut (*Areca catechu* L.) in humid tropics of India

Ravi Bhat *, S. Sujatha, C.T. Jose

Central Plantation Crops Research Institute, Regional Station, Vittal, 574243, India

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ABSTRACT

The purpose of the study was to determine optimum nutrient norms for laterite soils (Ultisols) and to assess quantitative relationship of soil fertility, leaf nutrients and nutrient uptake with yield of arecanut. At 0–30 cm soil depth, optimum nutrient concentration for P, K, Ca, Mg, Fe, Mn, Cu, Zn and B was established as 15, 192, 925, 179, 37, 88, 26, 5.5 and 1.4 mg kg^{-1}, respectively. Optimum ranges for different nutrients were found out from second degree polynomial equations. Optimum nutrient values were higher for laterite soils in arecanut tract than generalized guidelines for interpretation of soil analysis data. Multivariate analysis of nutrient data indicated that nutrient uptake/removal would explain the variability in yield more than actual nutrient concentrations in soil and leaf with high degree of relation (R^2 = 0.92–0.98). Stepwise regression analysis identified the soil and leaf nutrient variables with a significant influence on the kernel yield of arecanut. The loadings of principal component analysis were in confirmation with the correlations among the nutrient variables and yield. The study clearly establishes the direct and significant relationship between soil nutrient status/nutrient uptake and yield. The findings of the study give scope for precision agriculture and judicious use of inputs.

1. Introduction

On a global scale, about 80% of the Ultisols are in tropical region and about 18% of the tropics are covered by Ultisols (Eswaran, 1993). Laterite soils (Ultisols) predominate in humid tropics of India (Velayutham et al., 1999). These soils are characterized by undulating topography and high rainfall (>3000 mm), which accentuate the process of leaching of nutrients. The CEC of the soils is quite low (3–14 $cmol_c\ kg^{-1}$) resulting in poor nutrient retention capacity (Shiva Prasad et al., 1998). These soils are poor in native soil fertility with abundant sesquioxides and low bases (Babu, 1981). Deficiency of nitrogen, potassium and zinc is reported (Badrinath et al., 1998). Availability of P is low as the soils are rich in hydrated as well as amorphous oxides of Fe and Al, which are potent phosphorus fixers (Perur, 1996; West et al., 1997). Kaolinite is the dominant clay mineral low in K fixation. These soils are deficient in zinc and possess a high zinc fixing capacity.

Thorough understanding of soil properties and response to management is required for enhancing and sustaining the productivity of Ultisols (West and Beinroth, 2000). Tisdale et al. (1985) stated that only 50% of nutrient removal from soil is recommended and it is good to allow build up of nutrients. Fertilization rates for crops are generally determined from concentrations of soil nutrients (Brady and Weil, 2002). Many researchers have proven the importance of soil fertility to higher crop yields (Cox and Barnes, 2002; Cox et al., 2003; Kravchenko and Bullock, 2000). Nutrient inputs must compensate nutrient outputs by losses and the target yield (Janssen and de Willigen, 2006a,b). Critical level of nutrients varies for different soils, crops and environments (Genc et al., 2002; Yin and Vyn, 2004). The reference values of soil and leaf analysis could be used provisionally as nutrient diagnostics (Srivastava and Singh, 2006) and for yield estimation (Rodríguez et al., 2007).

The laterite soil region is well known for large-scale cultivation of plantation and fruit crops (Velayutham et al., 1999). Arecanut (*Areca catechu* L.), which belongs to family *Palmae*, is a major plantation crop grown on this soil type. The economic part of the palm is called as 'betel nut' and is mainly used for masticatory purpose. India ranks first in area (0.397 million ha) and production (0.559 million tons) of arecanut in the world (GOI, 2008). The productivity (1184–1268 kg ha^{-1}) remained stagnant during the last decade mainly due to imbalanced nutrition. The palm grows to a height of about 10–15 m with production of 8 to 9 leaves per year. The leaf area is 25 m^2 per palm and net photosynthesis ranges between 2.4 and 8.2 μmol $CO_2\ m^{-2}\ s^{-1}$ (Balasimha, 2004). Huge yield gap of 191%, higher trunk biomass, shallow root system, large nutrient removal and low nutrient use efficiency are serious concerns in arecanut cultivation (Bhat and Sujatha, 2008, 2009; Bhat et al., 2007). Optimization of soil nutrient norms becomes imperative due to wide spread adoption of organic farming practices, depletion of soil K, increased cost of production and nutrient imbalance causing

* Corresponding author. Tel.: +91 8255 239238; fax: +91 8255 239666.
E-mail address: bhatravi@gmail.com (R. Bhat).

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disorders/diseases for sustaining yield and soil health in arecanut growing regions (CPCRI, 2010, 2011).

Several approaches like critical level, sufficiency level of available nutrient, or the basic cation saturation ratios and Diagnosis and Recommendation Integrated System (Hundal and Arora, 2001; Walworth and Sumner, 1987) are widely adopted for estimating the norms of soil nutrient data. Boundary-line approach is successfully used to overcome the limitations of above approaches for determining standards of nutrition (Vizcayno-Soto and Côté, 2004; Walworth et al., 1986). With this background, boundary line approach was selected to establish optimum nutrient norms for laterite soils in this study. An effort was made in this study to determine optimum nutrient norms for laterite soils based on the yield response of arecanut after managing the plantation with standard practices for 10 years. The quantitative relationship of soil nutrient availability, leaf nutrient status and nutrient uptake with kernel yield of arecanut was assessed through multivariate analysis.

2. Materials and methods

2.1. Description of study site

The study was conducted at Central Plantation Crops Research Institute, Regional Station, Vittal, Karnataka, India (12° 15′N latitude and 75° 25′E longitude, 91 m above MSL). The climate of the experimental site is humid tropical with mean annual rainfall of 3670 mm and 120 rainy days. The annual rainfall during 1998–2009 varied from 2869 mm in 2002 to 4325 mm in 1998. Mean temperature ranges from 21 °C (minimum) to 36 °C (maximum). The average relative humidity varies between 61 to 94%. The soil of the study site is sandy clay loam and classified as kaolinitic Kanhaplic Haplustults in Ultisols order. The textural composition of the soil is 50% sand, 14% silt and 36% clay at 0- to 60-cm soil depth. The bulk density and field capacity of soil are 1.61 g cm^{-3} and 18–22%, respectively. The cation exchange capacity (CEC) is 11.4 $cmol_c$ kg^{-1}. The soil fertility parameters of the study site are given in Table 1.

The arecanut plantation (*variety* Sreemangala) was established in September, 1997 in 0.456 ha area. Arecanut was planted at a spacing of 2.7 m × 2.7 m in 60 cm^3 pits. For this study, 100 palms were selected randomly from a block of 625 palms covering all rows. All recommended cultivation practices were followed for arecanut. Recommended fertilizer dose for arecanut (100:18:117 g N: P: K $palm^{-1}$ $year^{-1}$) was given in two splits i.e., 1/3 in May–June with the onset of monsoon and 2/3 in October at the cessation of monsoon. The sources of fertilizers used were urea, rock phosphate and muriate of potash. Farm Yard Manure (FYM) was applied @ 12 kg per palm every year. The nutrient content in FYM was estimated as 0.5% N, 0.12% P and 0.45% K. The crop was drip irrigated with 3 emitters of 8 L h^{-1} discharge at 100% pan evaporation (E_{pan}) during post monsoon season. The irrigation water contained 10–25 mg kg^{-1} NO_3–N, 0.2 mg kg^{-1} P, 3–9 mg kg^{-1} K, 30–40 mg kg^{-1} Ca, 4.0–7.5 mg kg^{-1} Mg, 1.7 mg kg^{-1} of Zn and 0.16 mg kg^{-1} of Fe with a pH of 6.9. Bordeaux mixture (1%) was sprayed on bunches twice at 45 days interval during monsoon season (June–September) to prevent fruit rot incidence caused by *Phytopthora palmivora*.

2.2. Estimation of above ground biomass

The trunk dry matter (Y) of arecanut was estimated by regression equation, Y = 0.01435 l (length of trunk) + 0.3442 g (girth of trunk) − 1.0017, and the data was cross checked with destructive sampling of few palms. Two leaves from 20 palms were collected and oven dried to estimate average leaf biomass. The average leaf biomass was multiplied with number of leaves to arrive at total leaf biomass per palm. The biomass of leaf, dry kernel and husk was added to trunk biomass to arrive at total biomass. Nutrient uptake was calculated by multiplying nutrient content and oven-dry biomass produced. The ripe nuts were harvested from October to March every year and dried to 8% moisture. Dried nuts were de-husked and kernel/husk weight was recorded for computing the yield. The average kernel yield of five years (2004 to 2009) was considered for drawing conclusions in this study.

Table 1
Descriptive statistics for soil fertility data at study site.

Nutrient (mg kg^{-1})	0–30 cm soil depth				30–60 cm soil depth			
	Mean	SE±	Minimum	Maximum	Mean	SE±	Minimum	Maximum
pH	6.03	0.05	5.35	6.33	5.75	0.07	4.81	6.22
OC (%)	2.45	0.07	1.72	3.34	1.84	0.04	1.40	2.38
P	12.4	0.76	3.3	28.6	5.4	0.47	1.04	34.7
K	252	13.9	75.8	781.6	183	9.3	48.8	629
Ca	894	19.1	490	2013	660	19.8	200	1453
Mg	173	3.3	81	282	152	4.5	43	285
Na	11.4	0.34	6.7	23	12.6	0.42	6.9	31.4
Fe	31	1.0	10.8	62.1	20	0.72	7.8	43.8
Mn	78	2.45	27.7	156.5	43	1.9	13.2	129.6
Zn	5.0	0.24	0.3	17.6	1.7	0.13	0.0	8.2
Cu	28	0.93	5.7	51.9	8.6	0.61	1.6	13.3
B	1.44	0.11	0.24	5.4	1.34	0.12	0.13	5.2
Al	1.82	0.24	0.0	14.4	7.99	1.28	0.04	85.7
Nutrient ratios								
P/Zn	2.67	0.17	0.62	10.9	3.92	0.36	0.51	26.5
K/P	25.2	1.83	3.62	115.2	48.7	3.70	3.27	228
K/Ca	0.29	0.02	0.09	1.08	0.30	0.02	0.06	1.23
K/Mg	1.50	0.09	0.44	5.67	1.34	0.09	0.25	7.29
Ca/Mg	5.23	0.10	3.42	12.24	4.44	0.09	2.48	8.44
Ca/B	952	57.8	115	2698	1124	102	110	6089
Fe/Zn	7.39	0.65	0.96	64.4	16.0	1.58	2.01	92.4
Fe/Mn	0.42	0.01	0.22	0.83	0.53	0.02	0.16	1.52
Fe/Cu	1.18	0.03	0.57	2.31	3.19	0.18	0.82	9.09
Mn/Zn	17.8	1.17	2.43	116.5	30.4	1.90	4.60	89.8
Mn/Cu	2.99	0.10	1.28	7.7	7.18	0.49	1.74	27.2
Zn/Cu	0.21	0.02	0.03	2.13	0.29	0.04	0.0	3.81

2.3. Collection and analysis of soil/leaf samples

Soil samples were collected at 0- to 30 and 30- to 60-cm soil depths in arecanut root zone at 60 cm distance from the tree trunk in 2009 for estimating optimum nutrient content. The air-dried soil samples were ground to pass through a 2.0-mm sieve and kept in labeled plastic bags for further analysis. Soil samples were analyzed for pH, organic carbon, available P and K using standard procedures (Jackson, 1973). Soil pH was measured in 1:2 soil water suspensions. Soil organic carbon (SOC) was measured by Walkley and Black method. Available P was estimated by ascorbic acid reductant method (Watanabe and Olsen, 1965) for color development after extraction with Bray's reagent. Available K, Ca and Mg were estimated in atomic absorption spectrometer (AAS) using ammonium acetate extract. The concentration of micronutrients was estimated in AAS using diethylene triamine pentaacetic acid (DTPA) extract (Lindsay and Norvell, 1978). Boron in soil was estimated by hot water method using azomethine-H in UV-Spectrophotometer (Gupta, 1979). Exchangeable aluminum was quantified by displacement with 1 M KCl (Bertsch and Bloom, 1996) and UV spectrophotometer using aluminon for color development.

Leaf samples were collected from the middle portion of 4th and 6th leaves separately for analysis. As the nutrient concentration in 4th and 6th leaves was found similar, mean of two leaves was considered. Leaf samples were cleaned with tap water followed by distilled water, air dried, packed in brown paper bags, oven dried at 60 °C to a constant weight and ground. The ground samples were kept in labeled butter paper bags for further analysis. The leaf samples were analyzed for total N using micro-Kjeldahl digestion method (Jackson, 1973). The powdered plant samples were digested in a 3:1 nitric–perchloric acid mixture for total P, K and micronutrient estimation. Total P was determined by vanadomolybdate method (Piper, 1966). Estimation of K, Ca, Mg and micronutrients like Cu, Zn, Fe and Mn was done in AAS. Boron in plant samples was estimated in UV spectrophotometer using azomethine-H (Gupta, 1979). Estimation of aluminum was done in UV spectrophotometer using aluminon.

2.4. Data analysis

Three approaches were used to describe and quantify the relation between soil nutrients and kernel yield of arecanut.

(i) Boundary line approach was followed for determining optimum nutrient value and range (Vizcayno-Soto and Côté, 2004; Walworth et al., 1986). The steps involved in construction of boundary lines and to find out the optimum nutrient value and range are given below.

  (1) Scattergrams were plotted between yield vs. nutrient concentration and nutrient ratios for one nutrient at a time (bivariate relations) with yield on Y-axis and nutrient concentration/ratios on X-axis with correction for outliers.
  (2) The X-axis was split into 8–14 equal parts to cover all the points. Then the highest point from each interval is selected. Once the points were selected, the new data subsets of yield and nutrient concentrations were fit to second degree polynomials with yields as dependent and nutrient concentration/ratio as independent variable.
  (3) Optimum nutrient concentrations were determined by calculating the concentration corresponding to a slope of 0 for the second-degree polynomials.
  (4) The optimum range was assessed by solving the quadratic polynomial for the nutrient concentration corresponding to 90% of the maximum yield (yield at a slope of 0).

(ii) Linear correlation and stepwise multiple regression were worked out to establish the quantitative relationship between soil nutrients, leaf nutrients and nutrient uptake with yield.

(iii) The principal component analysis (PCA) using PRINCOMP procedure of SAS was employed to explain the relation of different soil nutrient variables. The soil nutrient values were standardized with mean equal to 0 and variance equal to 1. The number of PCs was determined by using a rule of thumb that the PCs selected are those that explain at least 100/P percent of the total variance, where P is the number of variables. Eigenvectors having a value larger than the selection criterion were considered in drawing conclusions in each PC. Selection criterion (SC) was calculated using the following equation:

$$SC = 0.5/(Eigen\ Value)^{0.5}$$

3. Results and discussion

3.1. Biomass and nutrient distribution in arecanut palm

The biomass and nutrient partitioning pattern in arecanut and nutrient removal/uptake by different parts of the palm are presented in Table 2. The trunk biomass accounted for 70% of the total biomass (41 kg palm^{-1}). Nutrient removal of N and K were higher than other nutrients. Average yield of five years from 2004–2005 to 2008–2009 was used for developing quantitative relationship between yield and nutrients in soil and leaf. This nullifies the influence of weather and other external factors on yield (Walworth et al., 1986). The kernel yield (kg palm^{-1} year^{-1}) varied from 1.87 ± 0.19 to 4.51 ± 0.23 with a mean of 3.56 ± 0.17. Biomass and nutrient partitioning studies help in deciding suitable fertilization program (Alva et al., 2003; Hanafi et al., 2009).

3.2. Optimum concentration and range of nutrients

Optimum concentration and range for each nutrient is presented in Table 3. Optimum concentration for P, K, Ca and Mg was 15.3, 192, 925 and 179 mg kg^{-1}, respectively for first depth interval. Optimum micronutrient concentrations (mg kg^{-1}) were estimated at 37 for Fe, 88 for Mn, 26 for Cu, 5.5 for Zn and 1.4 for B. Optimum concentrations for P, K, Ca and Mg at 30–60 cm depth were 6, 173, 620 and 114 mg kg^{-1} respectively, whereas optimum concentration of micronutrients (mg kg^{-1}) was 19 for Fe, 60 for Mn, 7 for Cu, 1.9 for Zn and 1.6 for B. The results of the present study clearly suggest that boundary line approach is useful for establishing soil nutrient norms as this method derived highly significant second degree polynomial equations (R^2 = 0.633–0.848). The advantage of second degree polynomial quadratic response curve derived from boundary line method is that it can be used for single factor in a multifactored system (Walworth et al., 1986).

Optimum range for Bray's P was 7–24 and 1–11 mg kg^{-1} at 0–30 and 30–60 cm depths respectively. The optimum available K ranged from 122–262 and 69–278 mg kg^{-1} at 0–30 and 30–60 cm soil depths, respectively. Optimum range for Ca and Mg concentration (mg kg^{-1}) was estimated at 697–1152 and 138–220, respectively at 0–30 cm depth while it was 483–757 and 32–197 at 30–60 cm depth. Among micronutrients, the optimum range (mg kg^{-1}) was 24–49 for Fe, 59–106 for Mn, 3.5–7.4 for Zn, 0.7–2.0 for B and 17–35 for Cu at 0–30 cm depth. At 30–60 cm depth, the optimum range was 6–34, 23–96, 0.96–2.86, 0.3–2.9 and 1.5–12.6 mg kg^{-1} for Fe, Mn, Zn, B and Cu, respectively. It was observed from scattergrams that slight deviation in concentration of micronutrients from optimum range reduced the yields considerably compared to major and secondary nutrients. These findings give scope for judicious use of inorganic fertilizers.

The optima and optimum range for soil test K and micronutrients in the present study are higher for laterite soils (Table 3) than generalized guidelines for interpretation of soil analysis data (FAO, 1980;

Table 2
Nutrient content in different parts of arecanut palm (± standard error).

Nutrient	Trunk	Leaf	Kernel	Husk	Total nutrient removal	Total nutrient uptake
Dry matter (kg palm^{-1})	28.5 ± 0.54	6.63 ± 0.08	3.57 ± 0.17	2.29 ± 0.12		
Major and secondary nutrients						
%					g palm^{-1}	
N	0.39 ± 0.11	2.75 ± 0.026	1.05 ± 0.06	0.92 ± 0.008	241 ± 4.6	352 ± 6.3
P	0.05 ± 0.009	0.23 ± 0.0031	0.10 ± 0.01	0.09 ± 0.006	21.6 ± 0.44	35.8 ± 0.6
K	0.67 ± 0.12	1.05 ± 0.018	0.43 ± 0.01	1.18 ± 0.05	112 ± 2.9	303 ± 5.9
Ca	0.27 ± 0.03	0.56 ± 0.012	0.09 ± 0.02	0.21 ± 0.02	45.7 ± 1.1	122 ± 12.2
Mg	0.05 ± 0.01	0.19 ± 0.004	0.04 ± 0.003	0.08 ± 0.005	16.1 ± 0.4	30.3 ± 0.6
Micronutrients						
mg kg^{-1}					mg palm^{-1}	
Cu	21.3 ± 8.2	15.1 ± 2.6	10.3 ± 0.27	63.6 ± 0.88	275 ± 15.5	882 ± 19.2
Zn	4.32 ± 3.45	50.8 ± 2.0	ND	9.34 ± 5.38	522 ± 16.2	645 ± 17.2
Fe	371 ± 69.7	167 ± 9.9	406 ± 9.9	869 ± 7.07	4548 ± 179	15,109 ± 340
Mn	28.9 ± 12.3	94 ± 3.09	17.1 ± 0.65	34.7 ± 1.83	762 ± 21.7	1585 ± 28.6
B	11.2 ± 3.56	34.1 ± 2.28	24.4 ± 3.03	33.9 ± 0.78	378 ± 15	697 ± 17.2

Note: Total biomass (kg palm −^{1}) was 41.0 ± 0.8.

Johnson and Fixen, 1990; Ludwick, 1995; Martens and Lindsay, 1990; Soil and Plant Analysis Council, 1992). Optimum soil test K for laterite soils is high (192 mg kg^{-1}) due to inherent soil constraints like absence of K fixation sites and low CEC (11.4 cmol$_c$ kg^{-1}). The study suggests the need for split application of K fertilizers. Substantial yield increase is reported due to frequent fertigation of K (Bhat et al., 2007). Optimum soil test values of micronutrients are also higher in this study. This can be attributed to higher SOC and slightly acidic soil pH (Adiloglu and Adiloglu, 2005; Li et al., 2007; Shetty et al., 2008; Srivastava and Singh, 2006). Further, micronutrient availability pattern indicates much higher significance of Zn nutrition over that of the other micronutrients.

3.3. Optimum nutrient ratios in laterite soils

Optimum nutrient ratios were developed with significant R^2 values of 0.618–0.821 at 0–30 and 0.758–0.974 at 30–60 cm depths (Table 4). The optimum ratios of P:Zn, K:P, K:Ca, K:Mg, Ca:Mg and Ca:B ratios were 2.53, 22.4, 0.22, 0.95, 4.95 and 344, respectively at 0–30 cm soil depth. At same depth, the optimum ratios between micronutrients were found to be 8.67, 0.35, 1.37, 19.9, 0.51 and 0.21 for Fe:Zn, Fe:Mn, Fe:Cu, Mn:Zn, Mn:Cu and Zn:Cu, respectively. At 30–60 cm soil depth, optimum ratios of P:Zn, K:P, K:Ca, K:Mg, Ca:Mg and Ca:B ratios were estimated at 4.57, 39.5, 0.19, 0.14, 4.59 and 593, respectively. The optimum ratios computed for Fe:Zn, Fe:Mn, Fe:Cu, Mn:Zn, Mn:Cu and Zn:Cu were13.9,0.42, 3.99, 40.1, 5.61 and 0.29, respectively at 30–60 cm depth (Table 4). The nutrient ratios of trace elements need to be maintained at optimum levels as wide variation from optimum resulted in huge yield reduction. There is very little research evidence to show that these ratios have either a positive or negative effect on crop production. However in the present study, the highly significant relation between nutrient ratios and yield clearly indicates the importance of nutrient ratio in soil. It is stated that the ratios of soil test values do not change with target yield and are most important for advice on the relative amounts of nutrients to be added (Janssen and de Willigen, 2006b).

Table 3
Polynomial equation, optimum concentration and range of nutrients (mg kg^{-1}) in laterite soil and comparison with generalized guidelines for interpretation of soil analysis data.

Nutrient	Polynomial equation	R^2	Optimum concentration	Yield at optimum content (kg palm^{-1})	Optimum range	Generalized guidelines
0–30 cm depth						
P	$y = -0.010x^2 + 0.307x + 4.487$	0.747	15	6.84	7–24	8–15
K	$y = -0.00014x^2 + 0.05385x + 1.67625$	0.804	192	6.85	122–262	100–150
Ca	$y = -0.000014x^2 + 0.025896x - 4.762452$	0.736	925	7.21	697–1152	801–1600
Mg	$y = -0.00041x^2 + 0.14660x - 6.17578$	0.837	179	6.93	138–220	101–200
Fe	$y = -0.0047x^2 + 0.3449x + 0.8049$	0.696	37	7.13	24–49	2.1–4.0
Mn	$y = -0.00084x^2 + 0.1476x + 0.369$	0.758	88	6.86	59–116	1.0–2.0
Cu	$y = -0.009x^2 + 0.462x + 1.527$	0.777	26	7.46	17–35	0.2–0.5
Zn	$y = -0.177x^2 + 1.944x + 1.364$	0.633	5.5	6.70	3.5–7.4	0.5–1.0
B	$y = -2.081x^2 + 5.692x + 3.22$	0.680	1.37	7.11	0.70–2.00	0.5–1.0
Al	$y = -0.1750x^2 + 0.4834x + 6.2952$	0.870	1.38	6.63	1.22–1.55	–
30–60 cm depth						
P	$y = -0.024x^2 + 0.286x + 6.004$	0.743	6	6.86	1–11	
K	$y = -0.000063x^2 + 0.022063x + 4.8642$	0.689	173	6.76	69–278	
Ca	$y = -0.00003x^2 + 0.03722x - 5.9009$	0.795	620	5.64	483–757	
Mg	$y = -0.0001x^2 + 0.0229x + 5.4979$	0.819	114	6.81	32–197	
Fe	$y = -0.004x^2 + 0.161x + 5.369$	0.808	18.8	6.89	6–34	
Mn	$y = -0.00138x^2 + 0.1642x + 1.8762$	0.633	60	6.76	23–96	
Cu	$y = -0.029x^2 + 0.403x + 5.709$	0.720	7	7.11	1.5–12.6	
Zn	$y = -0.790x^2 + 3.023x + 4.462$	0.848	1.9	7.35	1–3	
B	$y = -0.382x^2 + 1.190x + 5.413$	0.747	1.6	6.34	0.3–2.9	
Al	$y = -0.138x^2 + 1.237x + 3.976$	0.662	4.48	6.75	2.27–6.69	

Table 4
Polynomial equation, optimum nutrient ratios and yield of arecanut at optimum ratio.

Nutrient ratio	Polynomial equation	R^2	Optimum ratio	Yield at optimum ratio (kg palm^{-1})
0–30 cm soil depth				
P:Zn	$y = -0.473x^2 + 2.395x + 3.164$	0.744	2.53	6.20
K:P	$y = -0.004x^2 - 0.1791x + 4.736$	0.749	22.4	6.74
K:Ca	$y = -26.63x^2 + 11.77x + 5.582$	0.727	0.22	6.88
K:Mg	$y = -1.7315x^2 + 3.2898x + 5.345$	0.816	0.95	6.91
Ca:Mg	$y = -1.156x^2 + 11.45x - 21.24$	0.770	4.95	7.12
Ca:B	$y = -0.00000084x^2 + 0.00057831x + 6.357$	0.691	344	6.46
Fe:Zn	$y = -0.058x^2 + 1.017x + 1.636$	0.661	8.67	6.04
Fe:Mn	$y = -21.02x^2 + 14.609x + 4.225$	0.821	0.35	6.76
Fe:Cu	$y = -4.938x^2 + 13.51x - 2.279$	0.738	1.37	6.96
Mn:Zn	$y = -0.0158x^2 + 0.6314x + 0.4776$	0.800	19.9	6.79
Mn:Cu	$y = -0.0882x^2 + 0.0891x + 7.818$	0.773	0.51	7.84
Zn:Cu	$y = -26.08x^2 + 11.13x + 5.045$	0.618	0.21	6.23
30–60 cm soil depth				
P:Zn	$y = -0.0638x^2 + 0.5769x + 5.178$	0.820	4.57	6.49
K:P	$y = -0.001x^2 + 0.079x + 5.265$	0.824	39.5	6.83
K:Ca	$y = -24.17x^2 + 9.286x + 5.562$	0.758	0.19	6.45
K:Mg	$y = -0.455x^2 + 0.124x + 6.722$	0.794	0.14	6.73
Ca:Mg	$y = -0.6123x^2 + 5.6172x - 5.7787$	0.881	4.59	7.11
Ca:B	$y = -0.000003x^2 + 0.003557x + 6.055252$	0.974	593	7.11
Fe:Zn	$y = -0.004x^2 + 0.111x + 6.128$	0.890	13.9	6.90
Fe:Mn	$y = -10.59x^2 + 8.7981x + 4.7251$	0.712	0.42	6.55
Fe:Cu	$y = -0.2034x^2 + 1.6181x + 3.932$	0.812	3.99	7.16
Mn:Zn	$y = -0.0016x^2 + 0.1284x + 4.3675$	0.758	40.13	6.94
Mn:Cu	$y = -0.00920x^2 + 0.1016x + 6.4012$	0.874	5.61	6.68
Zn:Cu	$y = -29.414x^2 + 17.206x + 3.9503$	0.870	0.29	6.46

3.4. Relation between kernel yield and soil/leaf nutrients/removal/uptake of nutrients

3.4.1. Multiple regression analysis

Application of stepwise regression technique to identify the nutrient variables with a significant influence on the kernel yield (Y) resulted in the following equations, where the variables are written in the increasing order of p-level.

The fitted model for soil and leaf nutrients is

$$Y = 5.8626 – 0.02225 \text{ leaf Cu} + 0.3759 \text{ soil B} + 3.819 \text{ leaf Ca} – 9.0968 \text{ leaf Mg} – 1.1869 \text{ leaf N} + 0.03189 \text{ soil Cu} – 0.1029 \text{ soil Zn} \left(R^2 = 0.345\right) \quad (1)$$

The fitted model for soil and leaf nutrient ratios is

$$Y = 3.4803 + 0.480 \text{ leaf K/Mg ratio} – 1.2268 \text{ leaf K/Ca} – 0.00083 \text{ soil Ca/B} + 0.0295 \text{ soil Mn/Zn} \left(R^2 = 0.252\right) \quad (2)$$

The fitted model for nutrient removal (r) and yield (Y) is

$$Y = -1.999 + 0.00054\, Fe_r + 0.0185\, K_r + 0.0482\, P_r \left(R^2 = 0.916\right) \quad (3)$$

The fitted model for total biomass (B) and total uptake (tu) is

$$B = 0.1838 + 0.0009\, Fe_{tu} + 0.05917\, K_{tu} + 0.05821\, Ca_{tu} + 0.10571\, P_{tu} + 0.00089 Mn_{tu} – 0.00133 Zn_{tu} \left(R^2 = 0.986\right) \quad (4)$$

Leaf Ca, soil Cu and soil B had positive impact on yield, while leaf nutrients like N, Mg and Cu and soil Zn showed negative impact. The low R^2 values for Eqs. (1) and (2) indicate only some of the variability in yield could be explained by the estimated soil and leaf nutrient variables. Despite low R^2 values, the importance of soil and leaf nutrients on yield cannot be understated. However, stepwise multiple regression analysis of removal/uptake of nutrients with yield showed different trend with high degree of relation (Eqs. (3) and (4)). Nutrient

Table 5
Principal component analysis loadings performed on soil nutrient data at different depths. (values in boldface indicate significant loadings)

Variables	0–30 cm			30–60 cm		
	PC1	PC2	PC3	PC1	PC2	PC3
pH	0.235	**−0.505**	0.102	**0.392**	−0.312	0.036
OC	0.271	0.217	0.218	0.026	0.144	−0.137
P	0.269	0.201	**−0.551**	0.150	**0.355**	−0.413
K	0.210	−0.074	**−0.435**	0.210	0.311	0.378
Ca	**0.371**	**−0.355**	0.079	**0.434**	−0.198	−0.076
Mg	0.285	**−0.424**	0.203	**0.392**	−0.308	−0.066
Zn	0.242	0.044	−0.140	0.183	0.268	0.167
Fe	**0.414**	0.218	−0.173	**0.279**	**0.353**	−0.355
Cu	**0.425**	0.189	0.102	**0.395**	0.317	−0.067
Mn	**0.350**	0.309	0.362	0.170	**0.344**	**0.488**
B	0.010	0.241	**0.459**	0.040	−0.041	**0.506**
Al	−0.056	0.327	−0.001	**−0.374**	**0.330**	−0.061
Eigen values	3.008	2.261	1.346	3.411	2.364	1.457
Explained variance (%)	25.07	18.84	11.22	28.42	19.70	12.14
Cumulative variance (%)	25.07	43.91	55.13	28.42	48.13	60.27
Selection criteria	0.288	0.332	0.431	0.271	0.324	0.414

Table 6
Pearson correlation coefficients for yield and soil fertility variables at two soil depths.

	Yield	P	K	Ca	Mg	Zn	Fe	Cu	Mn	B	Al	pH
0–30 cm												
P	0.069											
K	−0.043	0.275**										
Ca	−0.041	0.049	0.140									
Mg	0.002	0.000	0.118	0.567**								
Zn	−0.082	0.289**	0.202*	0.137	0.118							
Fe	0.135	0.541**	0.129	0.300**	0.084	0.156						
Cu	0.244*	0.289**	0.160	0.363**	0.106	0.130	0.629**					
Mn	0.198*	0.093	0.083	0.142	0.087	0.192	0.456**	0.534**				
B	0.204*	−0.059	−0.135	−0.225*	−0.061	0.096	−0.005	0.168	0.281**			
Al	−0.044	−0.010	−0.003	−0.204*	−0.269**	0.064	0.040	−0.066	0.216*	0.034		
pH	−0.080	−0.119	0.230*	0.585**	0.635**	0.189	0.016	0.050	−0.017	−0.124	−0.264**	
OC	0.066	0.160	0.039	0.120	0.128	0.199*	0.215*	0.297**	0.495**	0.020	0.090	−0.086
30–60 cm												
P	−0.036											
K	0.097	0.056										
Ca	0.224*	0.040	0.138									
Mg	0.218*	−0.002	0.017	0.749**								
Zn	0.014	0.249*	0.273**	0.074	0.033							
Fe	−0.024	0.581**	0.249*	0.221*	0.118	0.074						
Cu	0.065	0.398**	0.436**	0.418**	0.260**	0.330**	0.681**					
Mn	0.208*	0.050	0.489**	0.103	−0.072	0.313**	0.158	0.368**				
B	0.137	−0.045	0.076	−0.057	0.110	−0.031	−0.161	−0.002	0.248*			
Al	−0.026	0.088	−0.042	−0.605**	−0.594**	−0.099	−0.065	−0.247*	−0.013	−0.076		
pH	0.102	−0.024	0.078	0.584**	0.651**	0.091	0.133	0.274**	−0.018	0.115	−0.730**	
OC	0.222*	0.141	0.013	0.070	0.077	0.077	0.040	0.062	0.103	−0.070	0.099	−0.145

* Significant at the 0.05 level.
** Significant at the 0.01 level.

removal of Fe, K and P influenced the yield with high degree of variability. These results highlight that nutrient uptake/removal would explain the variability in yield more than actual nutrient concentrations in soil and leaf. Similar opinion was expressed by Janssen and de Willigen (2006a,b). As nutrient uptake of K, Ca and P showed significant impact on yield of arecanut, replenishment of these nutrients is essential to avoid depletion. Nutrient uptake studies are most important for perennial crops as higher fraction of nutrients are immobilized in standing biomass (Hartemink, 2005; Millard and Nielsen, 1989).

3.4.2. Principal component analysis of soil nutrient data

Principal component analysis revealed that the first component was dominated by positive loading of Ca and micronutrients like Fe, Mn and Cu explaining 25% of the total variance at 0–30 cm soil depth (Table 5). PC1 can be termed as micronutrient component as significant correlations were observed between kernel yield and Cu/Mn/B. Soil pH, Ca and Mg were included in PC2, which can be termed as pH component, with explained variance of 19%. The strong positive correlations among pH, Ca and Mg (Table 6) substantiates the presence of these three variables together. The graphical representation of PC1 and PC2 also indicated grouping of pH, Ca, and Mg and grouping of SOC along with P and micronutrients at both the soil depths (Fig. 1.) At 30–60 cm soil depth, the first PC reflected the influence of positive loading of pH, Ca, Mg, Fe and Cu and negative loading of Al. The significant positive correlation of Ca and Mg with yield indicates that higher level of Ca and Mg would increase the soil pH and in turn kernel yield of arecanut. At 0–30 cm soil depth, nutrients like Cu, Mn and B had a significant correlation with yield although none was large (Table 6). Largest correlations were obtained for pH and Mg (r = 0.635) and soil Fe and Cu (r = 0.629). Correlations were negative between pH/Ca/Mg and Al and positive between SOC and micronutrients. Similar findings were reported by several workers (Li et al., 2007; Rodríguez et al., 2007; Shetty et al., 2008; Srivastava and Singh, 2006). The relatively low percentage of explained

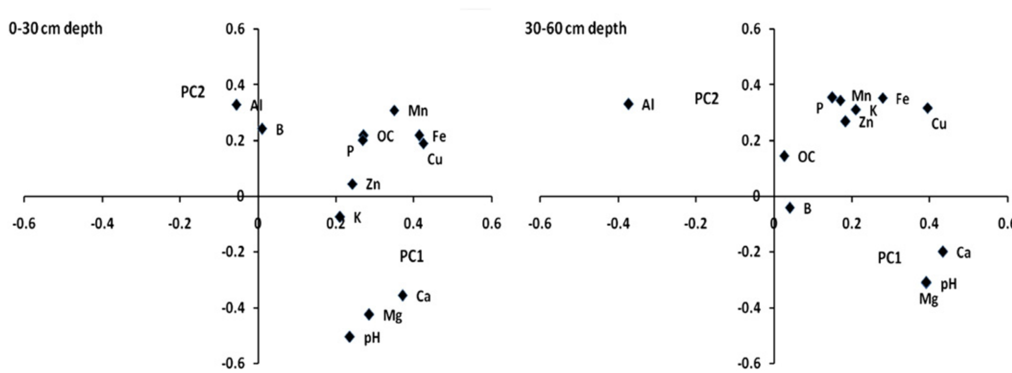

Fig. 1. Values of eigenvector loadings for soil fertility variables in components 1 and 2.

variation by the first and second components and the differential loading of soil properties on the first three components suggest complexity of the studied soil nutrient status.

4. Conclusions

It can be concluded from the present study that boundary line approach is useful for establishing nutrient norms for laterite soils. Optimum soil nutrient limits are vital for diagnosing nutrient constraints, judicious use of fertilizers and reducing environmental pollution. This study clearly establishes the direct and significant relationship between soil nutrient status/nutrient uptake and yield. A clear understanding of soil fertility, biomass production and nutrient uptake helps in development of nutrient management strategies. The findings of the study give scope for precision agriculture.

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