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Role of Nutrient Imbalance on Yellow Leaf Disease in Smallholder Arecanut Systems on a Laterite Soil in India

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ABSTRACT
On-farm trials in India investigated the role of nutrient imbalance on yellow leaf disease (YLD) in arecanut on a laterite soil using compositional nutrient diagnosis (CND) approach. Soil fertility status was imbalanced with high organic carbon status and low phosphorus (P) and potassium (K). The CND norms indicated that the order of nutrient demand was changed with nutrient application. Interventions increased yield by 50% during 2007–2010. The correlations indicated positive effect of nitrogen (N) and K and negative effect of manganese (Mn) on yield. The CND indices for NPK were important discriminators between yellowed and apparently healthy populations both in 2007 and 2010. Linear regressions between leaf nutrient concentrations and CND indices were significant for P, K, iron (Fe), Mn, and copper (Cu) (R^2 = 0.44–0.53). Results suggest that the predisposing factor for YLD might be nutrient imbalance in the soil leading to deficit of major nutrients in plant.

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Arecanut; CND indices; nutrient imbalance; soil fertility; yellowing

Introduction

Arecanut (*Areca catechu* L.) is a commercial plantation crop in humid tropics of India and its cultivation has expanded rapidly to 0.397 million ha during the last two decades. The yields reported in national statistics of India range between 1.1 and 1.2 t ha^{-1} yr^{-1} (GOI 2011), which is considerably lower than attainable yields of 3.0–3.5 t ha^{-1} yr^{-1} with recommended package. About 16 million people are dependent on arecanut industry for their livelihood. Moreover, it is essentially a crop of small and marginal holders with insufficient income to sustain dependent families. The poor productivity of crops is mainly due to unavailability of essential nutrients. The palm has compact crown and grows to a height of about 10–15 m with production of 8–9 leaves per year. Huge yield gap, shallow root system, higher trunk biomass (70% of the total), large nutrient removal, and low nutrient use efficiency are serious concerns in arecanut cultivation. Arecanut is predominantly grown on acidic laterite soils (Ultisols) and the inherent constraints of these soils are widely reported (Bhat, Sujatha, and Jose 2012; West et al. 1997). Arecanut farmers perceive that organic farming approaches improve the yield and soil fertility. Nutrient demand of arecanut varies with biomass production and yield level (Bhat and Sujatha 2012), and application of organics alone cannot meet potassium (K) demand (Sujatha and Bhat 2012, 2013a; 2013b).

The arecanut belt in humid tropics receives about 3700 mm of rainfall annually and about 80% of the total rainfall is received during monsoon season (June–August). Arecanut plantations in laterite tract are affected by yellowing of leaves to varying intensity in sporadic patches, which is called as yellow leaf disease (YLD). Symptoms of YLD are pronounced immediately after the cessation of southwest monsoon, that is, August–September (Nayar 1976). Generally, the symptoms are masked after November except in case of severely yellowed palms. Characteristic yellowing starts at the tip of

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leaflets of two or three fronds of the outer most whorl (Rawther 2000) and gradually spreads to the inner whorl of leaves. As the disease progresses, the entire crown becomes yellow leaving only the spear leaf green. Disease incidence to the extent of 35% was reported earlier (Nair 1994). There is a long history of controversy about the causes for this malady. Earlier studies on soil and leaf nutrient status of affected plantations are not conclusive (Mohapatra, Bhat, and Devaraju 1975; Yadava, Mathai, and Vellaicham 1973). Reports indicated association of Phytoplasma (Manimekalai et al. 2010; Nair 1994) as well as nutrient toxicity/deficiency with the disease (UAS 1991).

The implications of nutrient imbalance are less understood. Nutrient imbalance due to blanket manurial additions and unscientific inter/mixed cropping with banana, coffee, and cocoa are also contributing to spread of YLD in arecanut growing regions (personal communication). Thus, efficient nutrient use is critical for correcting nutrient imbalance and imparting resistance to abiotic and biotic stresses in perennial systems. Previous studies in farmer's gardens indicated sustenance of palms with application of nutrients (Chandramohanan 2005). Nutrient stresses can be identified by comparing nutrient concentration in leaves with the critical values. However, there are nutrient interactions in plants that may interfere with the interpretation of the results. The techniques that take into account the multiple and complex interactions among nutrients are often preferable in the diagnosis of a crop's nutritional status.

Several approaches can be used to diagnose foliar nutrient status, that is, Diagnosis and Recommendation Integrated System (DRIS; Walworth and Sumner 1987) and compositional nutrient diagnosis system (CND; Parent, Cambouris, and Muhawenimana 1994; Parent and Dafir 1992). The CND approach is highly useful in determining the nutrient imbalances within the plant (De Vos et al. 2007; García-Hernández et al. 2005; Khiari, Parent, and Tremblay 2001; Raghupathi, Reddy, and Srinivas 2002). In the present study, soil and leaf nutrient status was assessed in seven arecanut plantations initially and three farmer's fields were selected for on-farm trials with interventions. CND norms and indices were calculated to diagnose the nutrient imbalance in YLD-affected arecanut plantations and significant nutrient interactions were identified through principal component analysis (PCA) taking in to account row-centered log ratios. An effort was also made to compare the soil and leaf nutrient status with optimum limits to further substantiate the nutrient imbalance.

Materials and methods

Details of study site

The study area covered seven different arecanut plantations in South Kanara and Coorg districts of Karnataka in India (12°29′ N latitude and 75°31′ E longitude and 12°31′ N latitude and 75°28′ E longitude, 133–136 m above sea level). Farms (n = 15) identified by key informants were visited. The locations for study were selected after exploratory survey. Average farm holding is small (0.20–0.45 ha). The age of arecanut plantations varied from 10 to 25 years and the yellowing intensity of palms in selected plantations varied from apparently healthy to severe. Soils are predominantly lateritic in nature. The climate of the experimental site is humid tropical with mean annual rainfall of >3600 mm. The rainfall is distributed in one season from June to October. Mean temperature ranges from 21°C (minimum) to 36°C (maximum). The average relative humidity varies between 61% and 94%. The soil of the study site is sandy clay loam (Ultisols). The cation exchange capacity (CEC) is 14 $cmol_c\ kg^{-1}$. During 2007–2011, on-farm research was conducted in three locations in laterite soil region to document the magnitude of yellowing and to develop management strategies.

Management aspects

Farmers adopted conventional agricultural practices since the establishment of plantations. Farmer's management strategies were oriented toward organic farming without giving due consideration to soil fertility status. Information on agronomic management practices was recorded, including the type and amount of inputs used, timing of crop and soil management activities, and average yields obtained. Irrigation is most important for arecanut. But, the crop was not irrigated during post-monsoon season as per recommendations. Although recommended spacing for arecanut is 2.7 m × 2.7 m, farmers adopted lesser spacing without uniform intra- and interrow spacing. Intercropping of cocoa, pepper, banana, and vanilla was done without adoption of proper spacing. Organic liquid mixture, that is, biodynamic preparation (10 kg cow dung + 10 L cow urine + 2 kg dry gram flour (chickpea flour) + 2 kg black jaggery (traditional uncentrifuged/unrefined sugar) + 200 g (one fist full) soil of same garden preferably near fence area in 200 L of water stirred two times for 3 days for soil application) was applied 2 L palm^{-1} at one location. Poultry manure (5 kg palm^{-1}), farm yard manure (FYM), and green leaf manures were applied at other locations.

Treatment details for management trial

The treatments were selected based on previous demonstration studies (Chandramohanan 2005) and farmer's perceptions. Two treatments viz. organic soil conditioner (trade name, Rich Gold, 2 kg + 200 g muriate of potash (MOP) + 12 kg FYM + 12 kg green manure per palm per year) and organic liquid mixtures were included as they reduced the intensity of yellowing based on farmer's perceptions. The experiment was laid out in November 2007 following randomized block design (RBD) with nine treatments and three replications in three farmer's gardens. Each treatment included eight palms as net plot. The treatments included: T1, RDF (recommended dose of fertilizers) + FYM; T2, RDF + FYM + 1 kg super phosphate in two splits; T3, application of NPK as per soil test + dolomite 1 kg per palm + vermicompost; T4, RDF + FYM + copper oxy chloride + carbofuran (applied twice in a year); T5, RDF + vermicompost + consortia of microorganisms; T6, RDF + vermicompost + *Pseudomonas fluorescens*; T7, organic soil conditioner (2 kg, Rich Gold) + 200 g MOP + 12 kg FYM + 12 kg green leaf manure per palm per year (farmer's treatment 1); T8, organic liquid mixture (2 L palm^{-1} once in 2 months) + 12 kg FYM + 12 kg green leaf manure (farmer's treatment 2); and T9, absolute control. Recommended dose of fertilizers (RDF) is 100:18:117 g of NPK per palm per year. Farm yard manure (FYM) and vermicompost were applied 12 and 2 kg palm^{-1}, respectively. Consortia of microorganisms (*P. fluorescens, Bacillus amyloliquefaciens*, and *Trichoderma harzianum*) and *P. fluorescens* were applied twice a year (200 g talc formulation/palm per application). Table 1 shows nutrient composition of organic sources and irrigation water.

Estimation of compositional nutrient diagnosis (CND) norms

Yields of arecanut were below average in YLD-affected plantations. Thus, for estimating the differences in nutrient status of yellowed and apparently healthy palms through CND approach, the populations were divided into palms with medium to severe yellowing and initial stage of yellowing to apparently healthy. This exercise also resulted in first category falling into low-yield group and second category into average to high-yield group among the selected populations.

Table 1. Nutrient composition of different organic sources and irrigation water.

	Major and secondary nutrients (%)					Micronutrients (mg kg^{-1})				
Organic source	N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B
Organic soil conditioner (Rich Gold)	1.58	0.98	2.58	4.37	1.80	4598	395	37	423	164
Organic liquid mixture	0.02	0.48	0.21	1.42	0.80	1222	366	7.7	440	513
FYM	0.55	0.10	0.40	0.80	0.20	3566	298	6.10	251	216
Vermicompost	2.12	0.40	0.9	1.91	0.66	4412	502	70	351	488
Irrigation water (mg kg^{-1})	25	0.22	1.2	8.5	4	0.19	ND	0.006	0.06	–

Palms were given scores 0–5 based yellowing intensity to divide the population into apparently healthy to severely yellowed. The scores are 0, apparently healthy; 1, yellowing of leaf tips of one leaf; 2, yellowing of 3–4 leaves; 3, yellowing of 4–5 leaves; 4, yellowing of 6–7 leaves; and 5, yellowing in all leaves. The score of 1 was considered as initial yellowing and scores of 2–5 were considered as medium to severely yellowed palms. Foliar nutrient concentrations (%) were used to compute CND norms and derive indices. The series of steps described by Parent and Dafir (1992) and Khiari, Parent, and Tremblay (2001) for CND approach in assessing the nutritional status of a crop was adopted in this study. The CND approach is based on row-centered log ratios where each nutrient is adjusted to the geometric mean of all nutrients and to a filling value (R).

Collection and analysis of soil/leaf samples

Soil samples were collected at 0–30 and 30–60 cm soil depths in arecanut root zone at 60 cm distance from the tree trunk in 2007 and 2010. 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-1 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 ultraviolet (UV) spectrophotometer (Gupta 1979).

Leaf samples were collected from the middle portion of fourth and sixth leaves separately for analysis. As the nutrient concentration in fourth and sixth leaves was similar, average 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 leaf samples were digested in a 3:1 nitric-perchloric acid mixture for estimation of total P, K, Ca, Mg, and micronutrients. Total P was determined by vanadomolybdate method (Piper 1966). Estimation of K, Ca, Mg, and micronutrients was done in AAS. Boron in leaf was estimated in UV spectrophotometer using azomethine-H (Gupta 1979).

Data analysis

Statistical analysis was done using standard analysis of variance (ANOVA) technique in MSTATC. The t-tests, linear correlations, nutrient norms (row-centered log ratios of concentration means and standard deviations), multiple regression, and PCA analyses were carried out using SPSS 13.0 for Windows standard version (SPSS, Inc., Chicago, IL, USA) and the Excel package (Microsoft 1997). PCA was performed on row-centered log ratio nutrient values to further explore nutrient interactions. PCs showing eigen values ≤1 were considered nonsignificant and were not considered further. The PC loadings having values greater than the selection criteria (SC) were given significance. The selection criterion was calculated as follows (Ovalles and Collins 1988):

$$SC = 0.5/(\text{PC eigen value})^{0.5}$$

Results

Leaf nutrient status

Leaf nutrient concentrations and CND norms (row-centered log ratios) for leaf nutrients are presented in Tables 2 and 3. The initial leaf nutrient status in May 2007 (Table 2) showed imbalance with lower values of major nutrients and higher values of secondary and micronutrients except Zn. Both in 2007 and 2010, the concentrations of leaf nutrients showed only marginal differences among different treatments except for Ca, Mg, and Fe in 2010. Thus, leaf nutrient status averaged over treatments and locations is considered. Pronounced differences in row-centered log nutrient ratios (CND norms) were noticed for Ca, Mg, and micronutrients during 2007–2010 (Table 3). Pre-experimental data showed that the order of nutrient demand was N > Ca > K > Mg > P in YLD-affected arecanut palms. The order of nutrient demand was changed to N > K > Ca > P > Mg in 2010 with nutrient application. Among major and secondary nutrients, large deviations in CND norms were particularly noticed for Ca and Mg.

Soil fertility status

Initial soil fertility status of YLD-affected arecanut plantations indicated very low availability of P and K (Table 4). Table 5 summarizes the variability in soil fertility status during experimental period (November 2007 to May 2010). Overall the soil fertility status was highly imbalanced in comparison

Table 2. Descriptive statistics for leaf nutrients in arecanut in different periods.

	Macronutrients (%)					Micronutrients (mg kg^{-1})				
Parameter	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
May 2007										
Mean (n = 80)	2.20	0.19	0.99	1.13	0.42	382	395	< 5	11.3	15
Standard error	0.045	0.006	0.04	0.03	0.01	19.4	15.8		1.2	1.5
Minimum	1.30	0.09	0.44	–	–	151	122		5.0	0
Maximum	2.96	0.33	1.99	–	–	912	777		61.5	68
2007 (Pre-treatment)										
Mean (n = 162)	–	0.18	0.97	1.13	0.41	808	327	30.3	36	38
Standard error	–	0.004	0.03	0.033	0.008	39.3	13.8	3.00	7.13	1.99
Minimum		0.06	0.38	0.37	0.17	108	117	0.0	5.3	0
Maximum		0.32	2.13	2.66	1.11	2907	1288	233	626	150
May 2010 (Post-treatment)										
Mean (n = 107)	2.27	0.20	1.04	0.55	0.15	105	83	168	6.0	30
Standard error	0.03	0.01	0.46	0.02	0.00	6.55	4.2	7.44	0.51	1.75
Minimum	1.60	0.10	1.70	0.27	0.07	31	28	69	2.5	11
Maximum	3.13	0.52		1.23	0.35	444	270	386	40.7	67

Table 3. Compositional nutrient diagnosis norms (mean and standard deviation (SD)of row-centered log ratios) for leaf nutrients in YLD-affected arecanut plantations (averaged over three locations).

	2007 (n = 162)		2010 (n = 107)	
Row-centered log ratio	Mean	SD	Mean	SD
V_N	1.243 ± 0.014	0.170	1.210 ± 0.009	0.094
V_P	0.147 ± 0.017	0.214	0.196 ± 0.011	0.117
V_K	0.887 ± 0.018	0.226	0.872 ± 0.015	0.158
V_{Ca}	0.936 ± 0.015	0.186	0.578 ± 0.011	0.117
V_{Mg}	0.516 ± 0.015	0.180	0.028 ± 0.011	0.115
V_{Zn}	−2.259 ± 0.104	1.293	−0.946 ± 0.014	0.142
V_{Cu}	−1.828 ± 0.032	0.398	−2.397 ± 0.019	0.192
V_{Fe}	−0.248 ± 0.019	0.232	−1.142 ± 0.019	0.198
V_{Mn}	−0.625 ± 0.016	0.195	−1.243 ± 0.014	0.144
V_B	−1.657 ± 0.036	0.445	–	
V_{Rd}	2.888 ± 0.013	0.157	2.844 ± 0.007	0.068

Table 4. Descriptive statistics for soil fertility parameters in May 2007 (average of seven plantations).

			Nutrient concentration (mg kg^{-1})								
	pH	SOC (%)	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
0–30 cm depth (*n* = 50)											
Mean	5.72	2.24	2.99	66.2	1298	128	29.4	22.3	1.76	7.5	0.41
Standard error (±)	0.052	0.106	0.88	10.25	101.8	11.9	1.73	2.09	0.22	0.82	0.05
Range	1.40	2.66	25.3	218	2151	264	36.6	43.4	4.40	22.3	1.67
Status*			Low	Low	High	Low					
30–60 cm depth (*n* = 50)											
Mean	5.80	1.48	1.17	68.7	987	96.3	21.2	20.9	1.12	2.49	0.28
Standard error (±)	0.038	0.104	0.146	14.8	92	7.8	2.03	2.24	0.19	0.23	0.031
Range	0.70	2.0	3.08	329	1927	197	40.8	45.1	5.02	5.65	0.93
Status*			Low	Low	High	Low					

*As per nutrient norms established for laterite soils (Bhat, Sujatha, and Jose 2012).

Table 5. Soil fertility status in YLD-affected plantations during experimental period of 2007–2010 (average of three locations).

			Nutrient concentrations (mg kg^{-1})										
Year	SOC (%)	pH	P	K	Ca	Mg	Cu	Zn	Fe	Mn	Pb	Cd	B
2007 (Pre-treatment) 0–30 cm depth													
Mean	2.87	5.88	5.2	97.4	1405	193	7.5	6.91	61.3	46.9	3.06	0.12	0.41
SE (±)	0.10	0.03	0.34	4.55	45.8	7.65	0.29	0.35	1.20	2.6	0.14	0.01	0.05
Range	3.56	1.05	27.0	320	2642	547	26.2	43.1	74.8	157	5.77	0.2	1.67
30–60 cm depth													
Mean	1.64	5.89	2.91	88.0	925	133	3.2	4.42	38.7	34.42	2.63	0.04	0.28
SE (±)	0.08	0.03	0.35	5.56	34.4	4.0	0.12	0.21	1.32	2.29	0.13	0.00	0.03
Range	3.08	1.49	34.4	314	2451	292	11.7	13.9	86	166	6.04	0.13	0.93
2010 (Post-treatment) 0–30 cm depth													
Mean	2.95		7.6	62.2	1858	174	13.7	3.39	56.3	34.2	–	–	0.39
SE (±)	0.09		0.69	3.07	71.3	8.8	0.74	0.13	1.88	2.42	–	–	0.08
Range	3.64		59.2	221	4993	609	61	7.2	177.8	146.6			0.77
30–60 cm depth													
Mean	1.69		3.3	57.8	1223	112	6.4	1.68	33.7	28.0	–	–	0.43
SE (±)	0.05		0.48	4.2	38.14	5.12	0.85	0.14	1.39	2.39	–	–	0.15
Range	2.94		54.8	360	4017	427	132	16.4	88.6	140			1.53

with nutrient limits for laterite soils (Bhat, Sujatha, and Jose 2012). Irrespective of treatments, Bray's P and soil test K were below optimum in all locations at 0–30 and 30–60 cm soil depths, respectively. DTPA extractable Fe was above optimum both in 2007 and 2010, while the availability of micronutrients like Zn, Cu, and Mn reduced during the same period.

Yield of arecanut

The dry kernel yields of arecanut did not vary significantly among different treatments during experimental period (Figure 1). The yield levels averaged over all three locations indicated that all treatments except control increased the yields during 2007–2010. On an average, there was 50% increase in yield in T1–T8 treatments. But, the yield increase was marginal in control (18%).

CND norms and interactions

From pre-experimental data in 2007, relations between leaf nutrient concentrations and CND indices were fitted for whole dataset (Figure 2). Linear regressions were highly significant for P, K, Fe, Mn, and Cu (R^2 = 0.44–0.53) with other nutrients showing the weakest relationships (R^2 = 0.15–0.36). A large proportion of palms were below sufficiency range in N, P, K, and Zn concentrations in leaf. All palms had excess concentrations of Mn, Cu, Fe, and B in leaf.

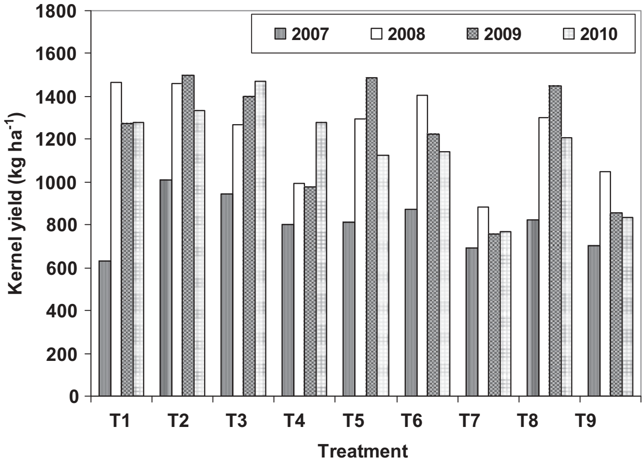

Figure 1. Influence of different treatments on kernel yield of arecanut averaged over three locations (CD: $p = 0.05$, NS in 2007–2009). T1, RDF + FYM; T2, RDF + FYM + 1 kg super phosphate in two splits; T3, application of NPK as per soil test + dolomite 1 kg per palm + vermicompost; T4, RDF + FYM + copper oxychloride + Furadan; T5, RDF + vermicompost + consortia of microorganisms; T6, RDF + vermicompost + *Pseudomonas fluorescens*; T7, organic soil conditioner (2 kg Rich Gold) + 200 g MOP + 12 kg each FYM and green leaf manure; T8, organic liquid mixture (2 L palm^{-1} once in 2 months) + 12 kg each FYM and green leaf manure—2; T9, absolute control.

The assessment of nutrient status was done based on CND indices between yellowed and apparently healthy palms during 2007–2010 as leaf nutrient concentrations did not vary significantly among treatments. Table 6 summarizes the variations in CND indices (I_X) in pre- and post-treatment situations at different situations. The CND indices except for I_{Zn} differed significantly between the two populations in 2007. Initial diagnosis based on CND indices revealed deficiencies in major and secondary nutrients and excess accumulation of micronutrients except Zn in yellowed palms compared with apparently healthy palms. The nutrient imbalance as evident from CND indices was reduced slightly due to treatments imposition during 2007–2010 irrespective of yellowing intensity. The impact of nutrient application for 4 years was discernible as the CND indices between two populations were significant only for N, K, and Mn in 2010. Overall order of nutrient limitation was different for yellowed and apparently healthy populations (Table 6).

Pearson correlations between CND indices (I_X) and yield are provided in Table 7. It is clear that kernel yield depended on N and K positively. However, Mn depressed the yield. In addition, this matrix also showed positive significant ($p < 0.05$) interactions for N–P, N–K, N–Mg, Ca–Mg, and Ca–Mn. The significant negative correlations were conspicuous among nutrients like N/P/K/Mg/R and micronutrients. Further, negative interactions noticed between all nutrients and the filling nutrient R highlight the important role of the filling nutrient R in arecanut.

Principal components (PC) were extracted from a correlation matrix constructed with the CND row-centered log ratios in 2010. Three PCs explained 67.9%, 66.6%, and 65.9% of total variance for populations of medium to high yellowing intensity, apparently healthy, and whole dataset (Table 8). In case of whole dataset, the first PC was dominated by significant positive loading of N–P–K–Mg–Rd and negative loading of Ca–Fe–Mn. In whole dataset, the first PC could be designated as the major nutrient component, suggesting significant positive interactions among N, P, and K. The second PC was correlated with V_{Ca} and V_{Mg}, and designated as the Ca–Mg component, possibly indicating a positive interaction between Ca and Mg. Similar nutrient interactions were noticed in apparently healthy palms. But the trend was slightly different in yellowed population with negative loading of all micronutrients in first PC.

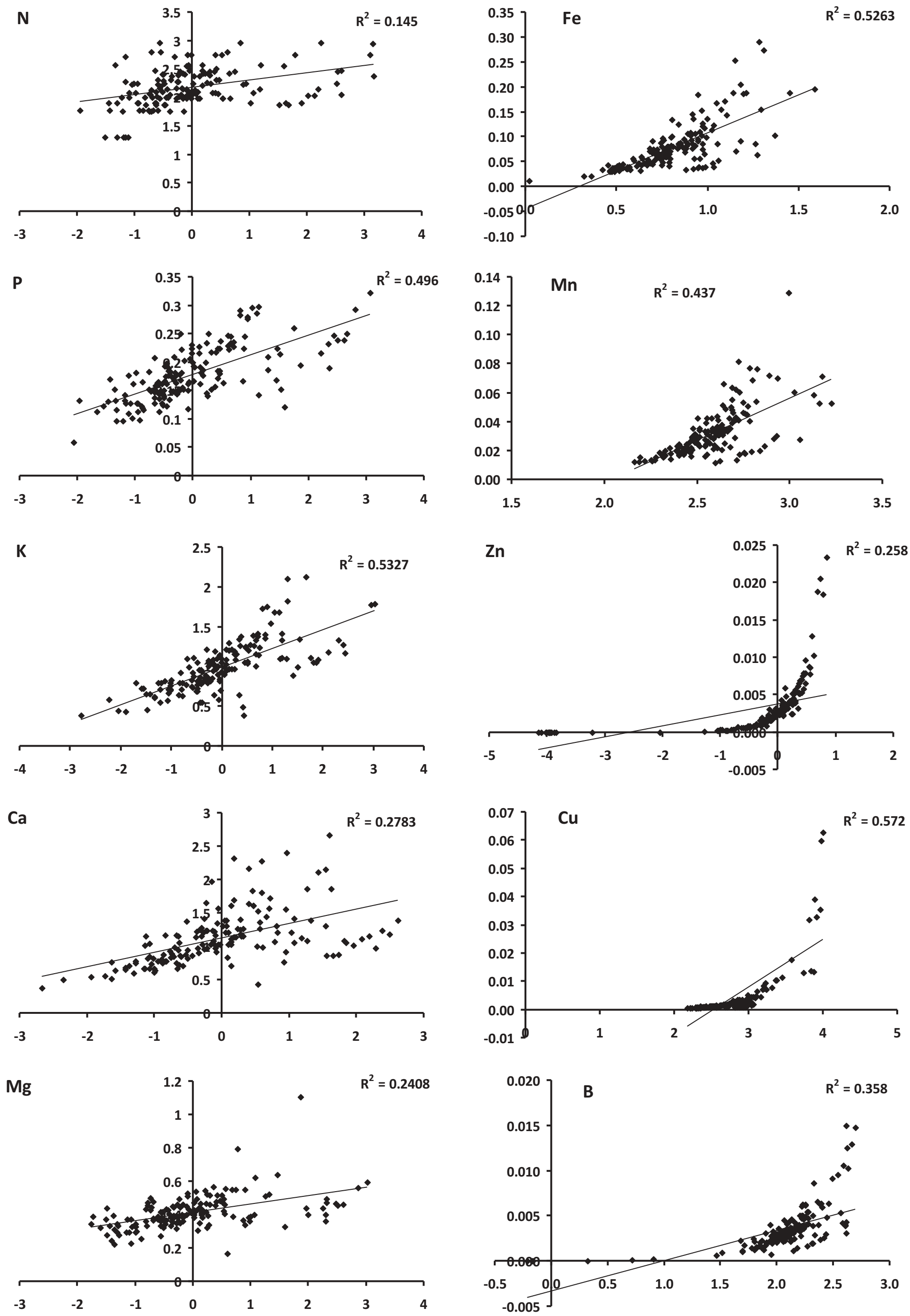

Figure 2. Relationships between percentage of leaf nutrient concentrations (*y*-axis) and their corresponding CND indices (I_X on *x*-axis) in YLD-affected arecanut plantations in 2007 (pre-experimental).

Table 6. Compositional nutrient diagnosis (CND) indices (I) for different yellowing conditions.

	2007			2010		
CND index	Medium to high intensity yellowing[a]	Initial yellowing to apparently healthy[b]	*t*-Test (*p*)	Medium to high intensity yellowing[a]	Initial yellowing to apparently healthy[b]	*t*-Test (*p*)
I_N	−0.194	0.456	0.001	−0.167	0.239	0.028
I_P	−0.393	0.923	0.000	−0.039	0.056	0.625
I_K	−0.363	0.851	0.000	−0.206	0.295	0.013
I_{Ca}	−0.164	0.386	0.005	0.087	−0.125	0.308
I_{Mg}	−0.274	0.643	0.000	−0.009	0.012	0.919
I_{Zn}	−0.431	−0.705	0.306	−0.070	0.10	0.407
I_{Cu}	2.818	2.638	0.001	0.123	−0.175	0.124
I_{Fe}	0.882	0.675	0.000	0.053	−0.076	0.498
I_{Mn}	2.631	2.479	0.000	0.207	−0.297	0.014
I_B	2.141	1.895	0.019	–	–	
I_R	−0.240	0.562	0.000	−0.151	0.218	0.058
Order of nutrient limitations	Zn > P > K> Mg > Rd > N > Ca > Fe > B > Mn > Cu	Zn > Ca > N >Rd > Mg > Fe > K > P > B > Mn > Cu		K > N > Rd > Zn > P > Mg > Fe > Ca > Cu > Mn	Mn > Cu > Ca > Fe > Mg > P > Zn > Rd > N > K	

[a]Low yielding (0.2 kg kernel per palm).
[b]High yielding palms (1.0 kg kernel per palm).

Table 7. Pearson correlation coefficients for yield and CND indices for the whole dataset (n = 107).

	Yield	I_N	I_P	I_K	I_{Ca}	I_{Mg}	I_{Zn}	I_{Cu}	I_{Fe}	I_{Mn}
I_N	**0.186**									
I_P	0.025	**0.245**								
I_K	**0.183**	**0.492**	0.031							
I_{Ca}	−0.082	**−0.213**	**−0.441**	**−0.314**						
I_{Mg}	0.023	**0.212**	−0.076	0.037	**0.361**					
I_{Zn}	0.110	**−0.229**	0.030	−0.161	**−0.314**	**−0.338**				
I_{Cu}	−0.141	**−0.300**	0.082	**−0.243**	**−0.266**	**−0.248**	−0.081			
I_{Fe}	−0.002	**−0.568**	**−0.356**	**−0.379**	0.085	**−0.454**	0.097	−0.035		
I_{Mn}	**−0.231**	**−0.331**	**−0.286**	**−0.512**	**0.379**	−0.027	−0.034	**−0.210**	0.145	
I_R	0.086	**0.732**	0.106	**0.629**	**−0.192**	**0.227**	**−0.318**	**−0.384**	**−0.423**	−0.347

Values in boldface are significant at $p < 0.05$.

Table 8. Loadings or correlations between the row-centered log ratios and the first three principal components (PCs) for the whole dataset (n = 107), yellowed (n = 63), and initial yellowing to apparently healthy palms (n = 63) in 2010.

	Medium to high yellowing intensity			Initial yellowing to apparently healthy			Whole dataset		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
V_N	**0.873**	0.116	0.107	**0.792**	0.146	0.095	**0.851**	0.086	−0.057
V_P	**0.386**	**−0.572**	0.139	**0.370**	**−0.534**	0.392	**0.357**	**−0.485**	0.397
V_K	**0.741**	−0.174	0.078	**0.720**	**0.378**	−0.339	**0.761**	−0.088	−0.332
V_{Ca}	−0.205	**0.815**	−0.074	**−0.646**	**0.581**	0.272	**−0.325**	**0.814**	0.081
V_{Mg}	**0.557**	**0.435**	−0.191	−0.170	**0.622**	**0.614**	**0.324**	**0.654**	0.382
V_{Fe}	**−0.794**	0.002	0.141	**−0.382**	−0.018	**−0.742**	**−0.676**	−0.098	−0.454
V_{Mn}	**−0.343**	**0.658**	0.150	**−0.754**	−0.024	−0.087	**−0.546**	**0.458**	−0.037
V_{Cu}	**−0.349**	**−0.453**	**−0.774**	0.167	**−0.630**	**0.423**	−0.253	**−0.500**	**0.645**
V_{Zn}	**−0.441**	−0.353	**0.666**	0.001	**−0.555**	−0.220	−0.271	**−0.494**	−0.380
V_R	**0.862**	0.100	0.085	**0.699**	**0.529**	−0.165	**0.854**	0.167	−0.240
Eigen value	3.619	1.996	1.170	2.961	2.159	1.542	3.264	2.082	1.249
SC	0.263	0.354	0.462	0.291	0.340	0.403	0.277	0.346	0.447
% of explained variance	36.2	20.0	11.7	29.6	21.6	15.4	32.6	20.8	12.5

Values in boldface indicate significant loading.

Discussion

Yellow leaf (disease) of arecanut on a laterite soil belt is continuing to be an unresolved problem for more than 60 years. Distressed arecanut farmers have cut the affected plantations at advanced stages of yellowing. It is well known that nutrition influences either directly or indirectly the incidence of diseases. Inadequate knowledge of the crop nutrient status can result in deficiencies or toxicities (Romheld 2012). Disorders like crown choking and bending are reported in arecanut due to nutrient imbalance (CPCRI 2011). Nutrient limits are established for arecanut (Bhat and Sujatha 2013) and laterite soils (Bhat, Sujatha, and Jose 2012). Comparison of earlier reports (Yadava, Mathai, and Vellaicham 1973; Mohapatra, Bhat, and Devaraju 1975; 1976) and results of the present study (Tables 2 and 4) with recently established nutrient limits indicated highly imbalanced soil and plant nutrient status. Significant points to be considered in earlier studies are higher SOC, low availability of P and K in soil, above optimum leaf P (0.3%), and critical leaf K levels in all YLD-affected areas.

In the present study, leaf nutrient status was similar irrespective of yellowing intensity (Table 2). The concentrations of major nutrients remained below optimum and that of secondary and micro-nutrients above optimum compared with the established nutrient limits (Bhat and Sujatha 2013). But, diagnosis based on CND indices revealed deficit of major nutrients and accumulation of micronutrients in yellowed palms compared with apparently healthy palms (Table 6). Further, CND indices for NPK were found to be important discriminators between yellowed and apparently healthy populations both in 2007 and 2010. The relation between raw nutrient concentrations and

CND indices of individual nutrients also indicated that large population had below sufficiency range of major nutrients, and entire population had above sufficiency range of micronutrients except Zn (Figure 2). Despite continuous nutrient application, the reasons for deficiency of major nutrients, especially univalent cation K^+, might be accumulation of divalent and trivalent cations like Ca, Mg Fe, Mn, and Cu. Pearson correlations among CND indices (Table 7) and the PCA of row-centered log ratios (Table 8) identified similar nutrient interactions. Furthermore, the results imply that apparently healthy palms might develop yellowing in due course if demand of major nutrients is not met as per soil and crop constraints.

The yield levels remained below 1500 kg ha^{-1} in this study despite interventions (Figure 1) compared with the average yield level of 2600 kg ha^{-1} under normal management (personal communication). The yield increase of 50% with interventions involving recommended nutrient application (Figure 1) might be due to slight improvement in leaf nutrient status during 2007–2010 as evident from the CND norms and indices (Tables 3 and 6). The positive influence of N and K on yield is obvious from the significant regression equation, though with low variability, between the yield and row-centered log nutrient ratios ($Y = -42.5 + 207.6V_{N} + 111.8V_{Zn} + 93.7V_{Fe} + 69.7V_{K} + 94.9V_{Mg}$, $R^2 = 0.15$). The critical nutrient imbalance index (CNR-r^2) was computed as 2.9 for high yielding population in well-managed plantation (personal communication), while the nutrient imbalance index was 9.5–10.5 in this study. The results imply that the problem of YLD might have developed due to nutrient imbalance for a long period and the remedial measures might take long time.

The possible reasons for nutrient imbalance in perennial arecanut ecosystem are discussed below. Regular nutrient application did not result in optimum levels of soil K (Tables 4 and 5) and leaf NPK as evident from the CND indices for NPK (Table 6). Further, the results imply that inadequate soil K leads to less N use efficiency despite high SOC status in affected plantations (Table 2 and 4). Higher availability of Ca and Mg in soil of the study site (Table 4) is known to suppress soil K availability and uptake of K (Brady and Weil 1999; Marschner 1995). The importance of adequate soil K for increased N use efficiency (Blevins 1985; Li et al. 2009), less available/exchangeable K in soils containing kaolinite minerals (Martin and Sparks 1985), the domination of sesquioxides and kaolinite in laterite soils (Hart, Wiriyakitnateekul, and Gilkes 2003; Kanket et al. 2005), and higher K immobilization in arecanut stem (Bhat and Sujatha 2012) explain the reasons for above findings. It is also clear from the study that higher SOC levels result in accumulation of Ca and Mg on the soil complex and depletion of soil test K (Tables 4 and 5). Evidence exists for the complexing of divalent and trivalent cations by humic and fulvic acid fractions of SOM, including the inability of K^+ and other monovalent cations to replace sorbed micronutrients in soil (Hue, Craddock, and Adams 1986; Stevenson 1982). Root growth is reduced in YLD-affected palms (Nair 1994). Although extensive root studies were not carried out in this study, observation of uprooted YLD-affected palms indicated reduced root growth that might be due to low Bray's P availability. Pellerin, Mollier, and Daniel (2000) stated that P is required for root growth, and root growth is critical for P uptake, especially when soil P availability is low.

Reduced root growth might have reduced the uptake of major nutrients due to competition from other nutrients in soil solution. The occurrence of yellowing in sporadic pockets in laterite soil belt of humid tropics can be attributed to faulty management, inherent soil constraints like absence of K-bearing minerals in soils, depletion of soil K, and adoption of organic farming approaches that might not meet the K demand of arecanut. The present study indicates that it is possible to manage yellow leaf (disease) and sustain the yield except in case of severely affected palms with precision application of organic and inorganic inputs to avoid antagonistic nutrient interactions in soil and plant. The role of Mn also needs to be investigated, as leaf Mn concentration was very high (395 mg kg^{-1}) in YLD-affected plantations. The YLD might be a multi-nutrient problem either due to deficit or excess of nutrients, or both. A typical symmetric pattern of nutritional disorders and nonsymmetric pattern of disease symptoms (Romheld 2012); nutrient demand of arecanut (Bhat and Sujatha 2012; Bhat, Sujatha, and Jose 2012); and the crucial role of potassium in plant growth, yield, quality, and stress tolerance (Cakmak 2005; Marschner 1995; Romheld and Kirkby 2010) substantiate the above conclusion. Thus, the predisposing factors for YLD might be nutrient imbalance in the soil leading to deficit of major nutrients in plant. Precision application of major nutrients in frequent splits is important to counteract constraints in smallholder arecanut systems on a laterite soil in humid tropics.

Conclusions

The results revealed that the soil fertility and plant nutrient imbalance might be the important predisposing factor for yellowing in arecanut. The diagnosis based on CND approach clearly identified deficit of major nutrients and accumulation of micronutrients. Although the present interventions improved the yield levels of arecanut in YLD-affected locations, precision application of nutrients is required for realizing profitable yields to counteract climatic, crop, and soil constraints. Split application of nitrogen, phosphorus, and potassium possibly in 4–5 splits in post-monsoon season is advisable as leaf N and K are very low. Spraying of N and K would be a better option for immediate recovery.

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