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DRIS evaluation of teak (*Tectona grandis* L.f.) mineral nutrition and effects of nutrition and site quality on teak growth in West Africa

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Abstract

The objective of the investigation was to study the site variables controlling teak yield (*Tectona grandis* Linn.fil.) and to establish guidelines for the selection of high productivity sites in Benin, Côte d'Ivoire, Liberia, Nigeria and Togo. Depending on stand age, soil and region, between 70 and 90% of the variation in tree growth (site index, *SI*) could be explained by the supply of nitrogen, the root-available soil depth and precipitation. Diagnostic foliar analysis for a broad range of elements was carried out in all plantations with the exception of Nigeria. This showed that in 20% of the stands, various deficiency symptoms occur, and in an additional 40%, hidden demand of at least one nutrient is apparent. According to the Diagnosis and Recommendation Integrated System (DRIS), the most deficient nutrients besides N are Ca and P, while in 45% of all stands there is a relative Al excess. Recommendations for the evaluation and classification of site quality and the number of trees sampled for foliar analysis are given.

Keywords: Tectona grandis; DRIS; Soil analysis; Foliar nutrient analysis; Site index

1. Introduction

Teak (*Tectona grandis* Linn.fil.), one of the most well-known and heavily used timber species of high quality, is planted throughout the humid tropics. Afforestation in West Africa started in the first years of this century, but only small parts of these old plantations have survived until now. Decades of little or careless management, combined with exploitation of the best stems or early fellings, has given African teak a poor reputation. Today, the area afforested with teak in West Africa (Table 1) is estimated ac-

Table 1
Estimated area (ha) afforested with teak in West Africa in 1992

Benin	12000
Ghana	30000–45000
Guinea/Sierra Leone	1000
Côte d'Ivoire	18000
Liberia	1500
Mali/Burkina Faso	1000
Nigeria	38000–46000
Senegal	2000
Togo	10500
Total	~114000–137000

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cording to several sources as between 114 000 and 137 000 ha (Drechsel, 1992). However, plantation yield varies greatly owing to inadequate consideration of site suitability prior to planting (Chollet, 1967; Akinsanmi, 1976; Fagbenro and Agboola, 1982; Zech and Drechsel, 1991). The objective of this investigation was to study the site variables controlling yield and to establish guidelines for the selection of high productivity sites in this region. The three underlying questions to this research are as follows. (1) What is the nutritional status of teak in the research area? (2) What statistically significant impacts do site conditions and nutrition have on yield? (3) What practical conclusions can be deduced for the evaluation of afforestation sites and existing stands, and their management with respect to site and nutrition?

In order to answer these questions, we collected data from representative teak plantations of different growth and age carefully chosen from various geological, pedological and climatic regions in Togo, Benin, Côte d'Ivoire and Liberia. In addition, corresponding data of 3–9 year old teak from Nigeria were considered (Akinsanmi, 1976). Only limited information is available from other West African countries (e.g. Food and Agriculture Organization (FAO), 1957; Maheut and Dommergues, 1960; Streets, 1962).

2. Study area

The investigation covers 85 temporary study plots of about 0.06–0.09 ha in 27 representative forest districts in Togo, Benin, Côte d'Ivoire, Liberia and Nigeria. The exact locations are described in Drechsel (1992) and Akinsanmi (1976). The main field work was carried out in May 1990 in the period of highest annual nutrient requirement due to refoliation (Nwoboshi, 1984). Precipitation was 150–200 mm between January and April.

The plantations are situated between 40 and 500 m above sea level in (rainforest derived) savanna woodland. The study area is characterized by a relatively constant temperature over the year with means of 26–28 °C and an annual precipitation of 1100–1300 mm (Togo, Benin), 1200–2500 mm (Nigeria, Côte d'Ivoire) and 2000–3250 mm (Liberia). The main dry season usually lasts 3–4 months between November and February. According to latitude, an interruption of the rainy season can occur in August. Where this interruption forms a second dry season, such as in the most southern area near the Gulf of Guinea, teak will not grow successfully owing to two annual refoliations.

Most plantation soils belong to the units of ferruginous and ferrallitic soils. One-third of plantations had Acrisols, Lixisols or Alisols, and one-fifth had Cambisols, Fluvisols or Regosols, according to the classification of FAO–UNESCO (1988). Ferralsols and Plinthisols occur in 7% of all plantations and Vertisols in 16%. As the latter are restricted to the Lama depression in Benin and adjoining areas in Togo (near Tsévié), their importance is over-represented with respect to the whole region. Nevertheless, intensive reforestation programs with teak on these soils have been realized during the recent years (Zech et al., 1989).

The typical plantation topsoils (0–10 cm) are characterized by organic carbon contents of $1.41 \pm 0.58\%$ C_{org} (0.40–3.21%) and a mean pH(H_2O) of 6.6 ± 0.8. Acid soils with pH values around 4.0 mostly occur in Liberia. Alkaline pH values up to 8.15 and traces of lime have been found in some Vertisols in Benin. At 20–30 cm soil depth, the pH is in general 0.6 units lower than in the topsoil (0–10 cm): below topsoils of pH 4 about 0.9 units, below topsoils of pH 7 about 0.3 units. Further soil and site data are presented by Akinsanmi (1976) for Nigeria, Zech and Drechsel (1991) for Liberia as well as by Drechsel (1992).

3. Materials and methods

3.1. Field work

The between-tree variations in foliar nutrient concentrations allowed the calculation of the minimum number of trees to be sampled per stand for distinguishing significant differences of,

Table 2
Number of trees to be sampled to detect differences of 10% of the nutrient mean values between two stands. In contrast to this study, the data of *Pinus* sp. (Mead and Pritchett, 1974; Mead, 1984) and *Eucalyptus* sp. (Lamb, 1976) only relate to one site and in the case of *Eucalyptus*, to element-specific crown positions with low between tree variations

Element	Teak	*Eucalyptus deglupta*	*Pinus radiata*	*Pinus elliottii*
N	10	4	7	2
S	12			7
P	12	2–8	12	
Mg	12	11–12	30	18
K	14	23–28	16	26
Si	16			
Cu	16	25–31	11	
Ca	18	22–25	36	32
Zn	18	29–33	48	3
Fe	20	13–24		
Al	25			27
Mn	27	31–44	69	27
B		20–25	52	

for example, 10% ($P<0.05$) between the foliar data of different stands (see Lamb, 1976). The number of sampled co/dominant trees in this study (eight to ten per plot) is sufficient to detect differences of about 15% with regard to most nutrients (Table 2). From each tree, six to eight mature leaves were sampled from comparable positions of the upper crown according to the Tropical Forestry Handbook (Drechsel and Zech, 1993). Additionally, we measured different growth variables, kept notes of symptoms of mineral disorders and collected information about provenance, pre-use of the area and stand history, diseases, occurrence of fires, and understorey.

Samples for soil fertility analyses were taken at 0–10 and 20–30 cm soil depth on six points per plot. On selected plots soil samples were taken up to a depth of 100 cm for estimation of nutrient stores (kg m^{-2} or ha^{-1}) considering the stoniness of the soil (stones larger than 2 mm). At least one soil pit per plot was in front of a representative teak tree described in detail to obtain information on soil genesis and rooting behavior. In Nigeria, soil samples were generally taken in soil pits (Akinsanmi, 1976). Physical data concern soil texture and related variables like soil water and air capacity, physiological soil depth, absolute and main rooting depths, stoniness, soil density, intensity of mottling, monthly and annual temperature and rainfall during the life-span of each plantation, number of dry months, altitude and slope.

3.2. Laboratory analyses

Soil chemical analyses concern C_{org}, N_{total} (N_t), $CaCO_3$, pH (1:2.5 v/v), cation exchange capacity (CECeff, CECpH7), exchangeable Ca, Mg, K and acidity (H+Al) as well as base saturation. The 'available' fractions of K, Mg, Fe, Mn, Zn, Cu as well as PO_4, SO_4 and SiO_4 have been extracted following at least one method per element for data comparison with the corresponding foliar nutrient contents. Foliar analyses were carried out for every sampled tree and concern N, Si, P, S, Ca, Mg, K, Al, Fe, Mn, Zn, Cu and leaf dry mass, and for selected samples the concentrations of C, B, Cl and Mo. Elements were measured using atomic absorption spectrometry (AAS; partly with graphite-tube), photometry (soil PO_4), ion chromatography (soil SO_4), X-ray-fluorescence analysis (foliar P, S, Si, Cl) as well as N-titrator, C-Carmhomat and CN-analyzer. For detailed information and references see Drechsel (1992).

On the Nigerian plots, Akinsanmi (1976) analyzed soil texture, rooting depth as well as depth to a layer inhibiting root development (usable soil depth), C_{org} and pH. He considered precipitation data as well.

Statistical analysis was carried out using SPSS/PC+. The calculations concerning the Diagnosis and Recommendation Integrated System (DRIS) follow the description of Beaufils (1973). The data base for DRIS consisted of about 500 trees, divided into two subgroups (2–6 and 11–63 year old stands). This division was necessary because of age-dependent nutrient ratios. A further division of the younger group would have be useful but was not possible owing to the consequently reduced data base for the DRIS norm populations.

4. Results and discussion

4.1. Tree growth

On the basis of a broad range of stand ages (2–63 years) it was possible to establish site quality classes and corresponding growth curves as well as to calculate the site index (*SI*) of each plot according to Friday (1987). The guide curve derived from the temporary plots, using the log–log model, has the equation

$$SI = H(50/\text{age})^{0.522} \quad (1)$$

The *SI* refers to the average dominant height (*H*) at the age of 50 years. The growth quality class I represents the best 30% of the plantations with a minimum *SI* of 33.5 (Fig. 1). This class is found in Benin, Côte d'Ivoire, Nigeria and Togo but not in Liberia. It corresponds to a mean 'indice de productivité (Ip)' of about 8 according to the system introduced earlier in Côte d'Ivoire (CTFT, 1983). A higher *SI* is only possible in a very few regions like the Gambari Forest in Nigeria and the Forêt classée de Séguié (Côte d'Ivoire). This upper limit of class I is shown separately in Fig. 1 by data from the Gambari Forest (CTFT, 1983). The West African quality class II (Fig. 1) covers the second best 30% of the studied stands with *SI* between 26 and 33.5. The data show that the *SI* of a majority of stands exceed 24, which is suggested as a minimum (FAO, 1974). Nevertheless, neglecting the soil survey before planting results in numerous very slowly growing or declining stands or parts of stands. Owing to the very favorable site conditions in southwest Nigeria, the stands representing Nigerian teak in this study generally belong to class I (Akinsanmi, 1976; Akindele, 1991). Specific *SI* models for teak in southwest Nigeria and Benin were recently developed by Akindele (1991) and Houayé (1993).

4.2. Tree mineral nutrition

Soil and foliar analyses are well known methods used to evaluate the nutrient status of trees (Van den Driessche, 1974; Bowen and Nambiar, 1984; Brunck, 1987; Drechsel and Zech, 1993). With respect to tropical hardwoods, there exist until now no interpretation guidelines for soil data in contrast to foliar nutrient concentrations. However, these foliar reference values (Drechsel and Zech, 1991) are of limited value in the common cases of multiple mineral deficiencies and physiological nutrient interactions, dilution effects or if the reference values are related to other seasons or leaf sampling positions. To overcome most of these problems there has been increased interest by foresters in the use of the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils (1973) for the interpretation of foliar analysis (Schutz and De Villiers, 1987; Weetman and Wells, 1990).

The foundation of the DRIS system is the concept of nutrient balance, the interrelationships among all nutrients being considered simultaneously (Schutz and De Villiers, 1987). The result of the calculations are comparable indices for each element on the basis of its ratios with other nutrients. In view of a high-yielding 'reference (sub)population', negative element indices of the stands under study indicate a lower nutrient supply, positive indices a higher supply (Walworth and Sumner, 1987). In this study an index between +8 and −8 generally lies in the variation range of the reference population, while a DRIS index of −10 or less probably shows at least latent deficiency. Nutrient indices of −20 to −25

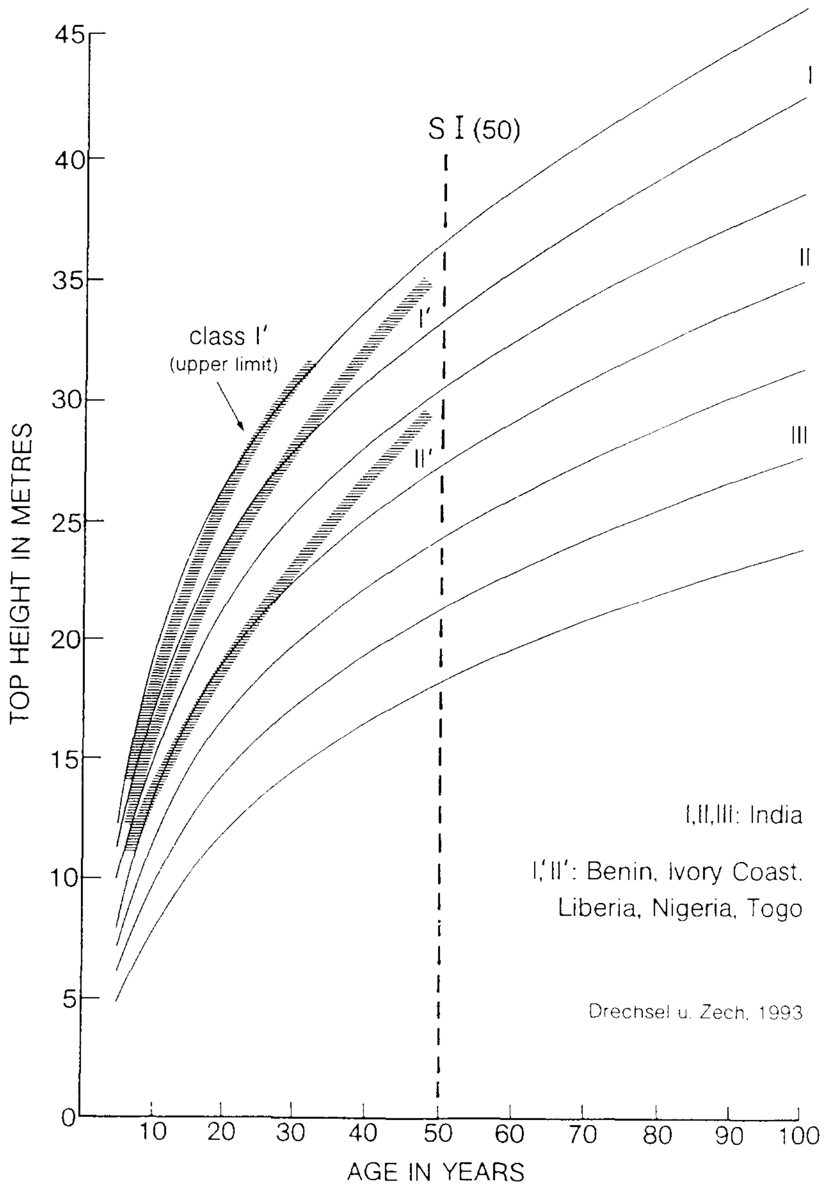

Fig. 1. Top height by site quality and age of *Tectona grandis* in India (Anonymous, 1957) and West Africa.

were generally connected with acute deficiency symptoms.

The main problem in use of DRIS for forest crops is the absence of adequate data on 'optimum' nutrient concentrations in high-yielding established populations to derive the DRIS norms (Weetman and Wells, 1990). Owing to the influence of tree age on nutrient concentrations and element ratios, norms derived from fertilizer experiments with seedlings could be in part not applicable to older trees. In the case of teak, the concentrations of N and P in particular, decrease during the first 4–6 years, while the concentrations of several other nutrients (e.g. K, Mg, Zn, Cu) remain approximately stable. Since no plantation in the study area was fertilized, the stands of growth quality class I (Fig. 1) were taken as the DRIS reference population although their nutritional status probably is not optimal (Table 3).

In 20% of all teak stands under study in Benin, Côte d'Ivoire, Liberia and Togo, various deficiency symptoms occur and in an additional 40% latent (hidden) deficiency of at least one nutrient was detected. In all these cases the most deficient nutrients are N (40%) and Ca (30%), followed by P as well as on particular sites by Mn, Mg, Zn or K. Owing to physiological and mathematical correlations between N and S, low concentrations of sulfur generally seem to be a secondary effect (see Kaul et al., 1972). The DRIS indices of N are, in 17 of 20 cases, lower than those of sulfur. With increasing age the significance of Ca deficiency (e.g. Fig. 2) seems to decrease and of N deficiency to increase, while P deficiency occurs regardless of age. Both N and P deficiency occur in most cases at the same time owing to location on marginal sites or physiological interactions. Phosphorus was the more deficient nutrient in only 25% of all stands with N and P deficiency, and in only 13% of sites with severe N and/or P deficiency. In Nigeria, where

Table 3
Preliminary DRIS diagnostic norms (mean ± SD of two age subclasses) for foliar analyses of *Tectona grandis* (yield class I; $n = 80$) in West Africa

Ratio[a]	2–5 year old trees	12–33 year old trees
N/S	16.1 ± 1.73	14.3 ± 2.36
N/P	12.8 ± 2.59	12.9 ± 2.87
1000N/K	1.70 ± 0.28	1.35 ± 0.34
1000N/Ca	3.33 ± 0.95	2.92 ± 0.79
1000N/Mg	9.48 ± 1.97	8.02 ± 1.65
1000N/Cu	1980 ± 400	1560 ± 34
1000N/B	ND	1402 ± 191
P/S	1.30 ± 0.23	1.13 ± 0.18
1000P/Ca	0.27 ± 0.08	0.23 ± 0.06
1000P/K	0.138 ± 0.03	0.108 ± 0.028
1000P/Mg	0.75 ± 0.14	0.64 ± 0.14
1000P/Al	33.1 ± 8.9	24.9 ± 9.4
1000P/Fe	25.3 ± 5.9	22.9 ± 6.3
1000P/Mn	63.0 ± 22.6	46.6 ± 17.7
1000P/Cu	160 ± 43	127 ± 30
1000P/Zn	121 ± 22	93.0 ± 22.4
Mg/K	0.186 ± 0.044	0.173 ± 0.046
Mg/Ca	0.36 ± 0.13	0.37 ± 0.08
Mg/1000S	1.75 ± 0.29	1.83 ± 0.36
Ca/Mn	244 ± 82	203 ± 60
Ca/Al	133 ± 47	111 ± 44
Ca/Fe	101 ± 30	103 ± 29
Ca/1000Si	1.02 ± 0.19	1.05 ± 0.26
K/1000S	9.7 ± 1.5	11.0 ± 2.6
K/Mn	465 ± 138	446 ± 169
K/Zn	899 ± 134	892 ± 204
K/Cu	1187 ± 282	1186 ± 251
Fe/Al	1.32 ± 0.30	1.09 ± 0.30
Cu/Zn	0.79 ± 0.17	0.76 ± 0.15
Mn/Al	0.58 ± 0.22	0.59 ± 0.27
1000Si/Al	134 ± 52	109 ± 41

[a] N, P, S, Si in mg g^{-1}, other elements in mg kg^{-1}.
ND, not determined.

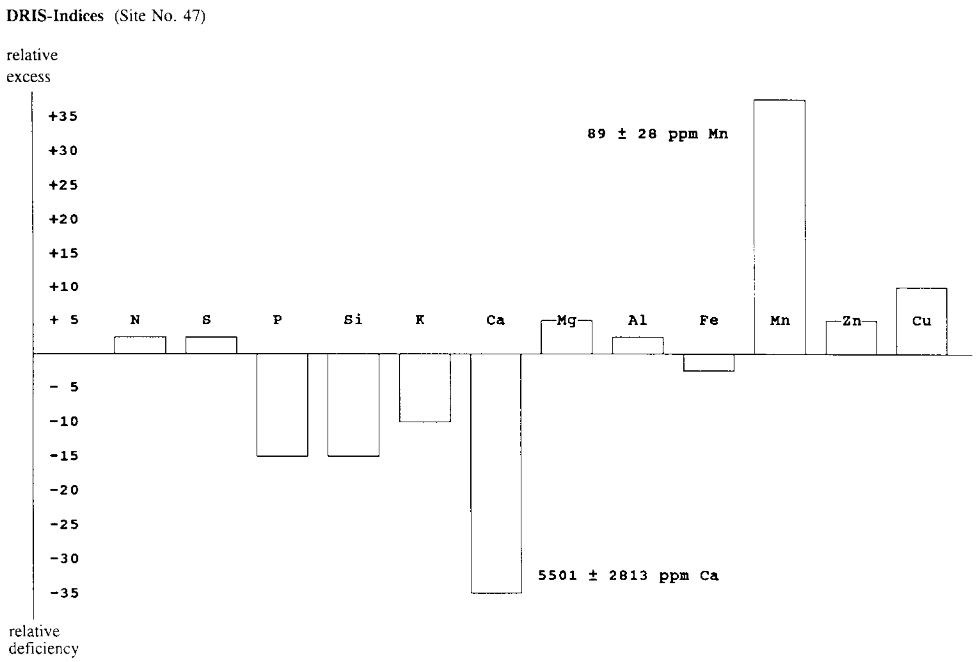

Fig. 2. Distribution of DRIS indices shown by the example of a 22-year-old teak stand (site 47) on an acid, stagnic Acrisol in the Forêt de Séguié (Côte d'Ivoire). This stand is mainly characterized by acute Ca deficiency, low P, Si and K levels and excess of Mn.

no foliar samples were taken, pot experiments with teak seedlings and soil samples from different teak plantations indicate P as more deficient than N (Adeola, 1983). Deficiencies in Mn and Zn are usually restricted to calcareous and/or alkaline Vertisols (Fig. 3). As in the case of Mg, serious deficiencies of Fe and Cu are rarely found.

In nearly half of all stands there is a relative Al excess (index higher than +10) compared with the DRIS reference population. The Al excess (rarely more than 350 ppm) is usually connected with P, Zn or N deficiency and interpreted in most cases as an element interaction. The soil was sufficiently acidic to release Al and to influence teak nutrition in only some of the studied plantation soils in Côte d'Ivoire and Liberia. However, foliar Al is a bad indicator of Al toxicity (Drechsel and Zech, 1993). Besides Al, an excess of Fe and Mn occurred in 18% of all stands, but not in sufficient concentrations to cause toxicity.

The sum of the absolute values of the DRIS indices per tree or stand is an expression of the imbalance of all nutrients (Beaufils, 1973). In leaves with deficiency symptoms the index-sum correlates well with increasing foliar discoloration (e.g. green leaves, 41; weak intercostal chlorosis, 69; pronounced intercostal chlorosis, 153). Because the keys for foliar symptom interpretation have been developed by inducing mono-element deficiency (e.g. Kaul et al., 1972; Nwoboshi, 1975), they are less suitable in the common (natural) case of multiple deficiencies. Nevertheless, DRIS allows the analysis of the order of limiting nutrients in these cases. For example, trees with pronounced intercostal chlorosis (ICC) suffer from nutrient deficiency in the order of N > P > Cu > Zn > S > Mn > K, while the supply of e.g. Fe and Al is in excess (Table 4). Pronounced Ca deficiency leads to characteristic, ribbon-like interveinal chloroses on a wrinkled leaf surface (WICC). The common green leaves show hidden N deficiency.

Although the evaluation of foliar data with DRIS showed more advantages than the interpretation with help of 'critical levels', only the

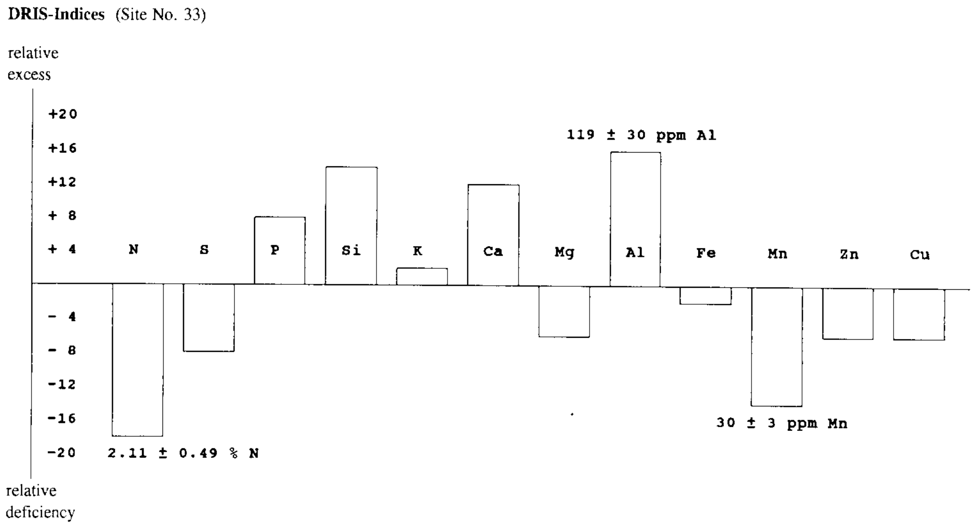

Fig. 3. Distribution of DRIS indices shown by the example of a 23-year-old teak stand on calcareous Vertisols in the south of the Lama depression in Benin (site 33). This stand is mainly characterized by (latent) N and Mn deficiency.

Table 4
DRIS indices of green leaves, leaves with pronounced intercostal chlorosis (ICC) and leaves with ribbon-like intercostal chloroses on a wrinkled leaf surface (WICC)

	N	P	S	Si	K	Ca	Mg	Al	Fe	Mn	Zn	Cu	Index-sum
GREEN	−9	−4	−3	−6	−1	−4	−1	8	2	1	−2	0	41
ICC	−36	−23	−8	4	−5	5	3	27	9	−6	−10	−17	153
WICC	4	−6	−8	−15	8	−56	−6	18	6	26	2	19	174

combination of both techniques allowed an efficient data interpretation. An example is the overestimation of Mn deficiency by DRIS in Mn-accumulating cashew trees, if the accumulation is highest in the well growing reference population (M. Krebs, unpublished data, 1991). Supplementary soil data will be necessary for the causal explanation of analyzed deficiencies as well as the correct interpretation of, for example, high Al indices (accumulation or toxicity).

4.3. Effect of nutrition and site on growth

Statistical analyses show that N nutrition, rooting depth and precipitation are the most important variables influencing teak growth in West Africa. On all soils except Vertisols, the extensive N deficiency (see above) is significantly ($r=0.8$–0.9, $P<0.01$) accompanied by a low site index, as indicated by foliar as well as soil nitrogen (Fig. 4). In addition, the DRIS index of nitrogen as well as the nutrient imbalance (sum of DRIS indices) correlate well with the *SI*, especially in stands up to 6 years of age ($r=0.684$* and $r=-0.795$*, respectively). Multiple regression analyses indicate that besides N, only P and Ca are of relative importance for the variations in growth.

The relationship between *SI* and soil N was most clearly seen in established, older stands and seems to be significantly influenced by the amount of rainfall, soil humus status, C/N ratio, annual plantation burning, and soil texture as well as by soil hydromorphy. With increasing rainfall at the beginning of the rainy season, we found higher amounts of N_t and a reduced C/N

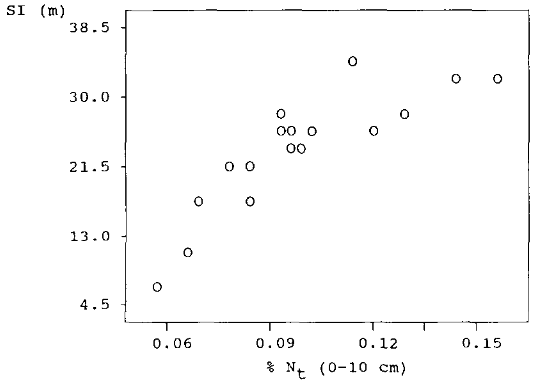

Fig. 4. Relationship between the *SI* and topsoil nitrogen (N_t) on 17 teak stands of different age north of approximately 8°N in Togo ($r=0.889^{***}$). Growth class I is usually not reached in this relatively dry region.

ratio in the plantation soils. Soil N correlates with the amount of clay ($r=0.729^{***}$) also, indicating water stress especially in the sandy soils of central and northern Togo. In southern Togo (south of about 7°30′N), disturbances in N nutrition and wide C/N ratios are common on loamy soils as is the occurrence of stagnic properties. The accumulation of soil organic matter on wet sites seems to prevent a strong correlation between *SI* and soil N_t or C_t.

Corresponding data from south Senegal are reported by Maheut and Dommergues (1960), who analyzed a restraining N mineralization and nitrogen availability as critical factors for teak growth. The studies of Sarlin (1957, 1963, 1969), mostly in Togo and Benin, focused on the analysis of Ca deficiency. However, these studies were based on soil analysis; diagnostic foliar analysis has until now been limited to pot experiments (Nwoboshi, 1973, 1975).

The published relationships between soil acidity and teak growth (Sarlin, 1963; Zech and Drechsel, 1991) are in principle valid for all the sites studied ($n=85$, pH (0–10 cm) $r=0.43^{***}$), especially in 3–6 year old stands ($n=27$, $r=0.736^{***}$), but are obviously less significant outside Liberia with its highly weathered ferrallitic soils. This also applies to teak in southwest Nigeria, where—under comparable actual precipitation as in Liberia—ferruginous soils of less intensive weathering dominate. Although the pH varies between 4 and 8, no significant relationship between teak growth and pH occurs in this region (Akinsanmi, 1976).

On Vertisols as well as on soils with stagnic properties the *SI* correlates with a broad range of elements analyzed in the foliage, but only with a low correlation coefficient, indicating a complex disturbed nutrient supply or uptake. Since Vertisol fertility is generally high, nutrient availability is reduced by waterlogging and alkalinity. Thus, in view of the chemical soil properties, only pH and available iron correlate negatively with the *SI* ($P<0.05$).

However, on Vertisols as well as on all plantation soils there are highly significant correlations ($n=85$, $r=0.57$, $P<0.001$) between *SI* and physiologically usable soil depth and/or rooting depth, as also reported by Lamouroux (1957), Jenkin (1962), Sarlin (1963), Chollet (1967) and Bruin (1972). While these studies focus on horizons through which roots cannot penetrate, such as laterite or gravel layers, we suggest the depth of intensive mottling as indicator of the physiologically usable soil depth and as *SI* predictor. This corresponds with the general requirement of well-drained soils for successful teak growth (FAO, 1957). However, we found no correlation between soil texture and *SI* with the exception of the depth of a dense clay pan inducing stagnic properties. In Côte d'Ivoire and Nigeria the minimum soil depth for teak is estimated to be 50–60 cm (FAO, 1957; Streets, 1962); for growth quality class II we estimated 65 cm.

Excluding Liberia, the annual amount of precipitation correlates positively with the *SI* owing to favorably growing teak in southwest Nigeria. The amount of monthly rainfall between October and May (especially in February) seems to be a good indicator of water stress. Water stress seems to be most relevant in the northern part of central Togo with at least 5 months of less than 100 mm of precipitation. Nevertheless, teak grows well on favourable soils in southern Senegal with 7 dry months and an annual amount of precipitation of about 1400–1600 mm (Maheut and Dommergues, 1960). Young teak stands have been established in Guinea with about 4500 mm precipitation on well-drained, loamy soils that are not greatly lateritized or too gravelly (FAO, 1957). However, a dry season of 4 months with less than 50 mm rainfall occurs in this region. A definite dry season is essential for teak to have an acceptable level of growth.

The influence of the geological substrate on the yield of teak has been discussed by Sarlin (1957) and Lamouroux (1957), who underline the positive effects of permeable and Ca-rich parent materials. Fertile alluvial soils along larger streams are reported to be particularly suited to the growth of teak in Ghana (FAO, 1957), as long as they are well drained and of low acidity (Sarlin, 1963). Dry hill tops and wet depressions are unproductive sites for teak (Jenkin, 1962; Akinsanmi, 1976; Zech and Drechsel, 1991), while burning can heighten soil erosion and degradation on slopes (Lamouroux, 1957). Besides local relationships, there have been no significant correlations between *SI* and slope or altitude above sea-level.

Depending on latitude, 75–91% of the variation of the *SI* of established stands (at least 10 years of age) could be explained by rooting depth and soil nitrogen. In Togo, north of about 8.0°N, N nutrition seems to be more important than rooting depth, while south of about 7°30′N it is the opposite. In young plantations, soil acidity (particularly the sites in Liberia), rainfall (particularly the sites in Nigeria (+) and Liberia (−)) and soil phosphorus accounted for 85% of the variation of the *SI*, while on Vertisols 88% could be explained by soil pit description alone, e.g. the topsoil depth showing no mottling.

In comparison with foliar analysis, site and soil data gave a higher degree of information about *SI* variations with respect to the older plantations (at least 10 years old) and the plantations on Vertisols. Nevertheless, in plantations up to 6 years of age, on non-hydromorphic sites, foliar analysis was superior to soil or site studies (Drechsel, 1992). With respect to all plantations from Liberia to Benin, regardless of age or site, the combination of soil and foliar analyses gave an obvious information increase to $R^2=0.73$ in comparison with soil ($R^2=0.55$) or foliar ($R^2=0.32$) analysis. The unexplained percentages are probably related to the different managing history of the stands and local site characteristics, which are not considered in the regression equation. Influences due to different provenances as well as diseases seem to be less important.

5. Conclusions

For practical application of the results the possibility of nutrient management as part of sustainable plantation management is discussed by Drechsel (1992). One crucial point is the protection of soil organic matter as well as litter by avoiding all kinds of fire in plantations of all ages. Besides N losses, litter burning will be harmful to soil water conservation, especially in the northern area of the region. The importance of N losses for tree nutrition by litter burning has been demonstrated on the N cycle in an established teak plantation (Drechsel and Zech, 1993). Under undisturbed conditions annual litter decomposition and atmospheric N input can supply more than 70% of the N requirements of the stand. Regular burning reduces this amount to less than 15%, increasing the contribution of the soil reserves to the N uptake. On less fertile sites with about 2000 kg N ha^{-1} this amount will not satisfy the N requirement of a stand of average growth (mineralization rate about 3%). Table 5 presents some guidelines for selecting and evaluating sites of teak growth quality class I and II. As mentioned above, a minimum soil depth of about 60 cm is recommended by several authors. According to Sarlin (1957) these soils should show in addition at least 10 meq exchangeable Ca+Mg+K per 100 g of fine earth in 0–15 cm or if the soil depth is about or greater than 120 cm at least 5 meq of exchangeable 'basic' cations to develop increments of 20 m^3 ha^{-1} year^{-1}.

The following preliminary soil reference values for sufficient foliar nutrient concentrations (in respect of class I stands) have been suggested by Drechsel (1992) for teak on average soils in the research area: over 150–160 ppm P_t (with-

Table 5
Site and soil conditions of teak plantations of growth class I and II in West Africa

I. Climatical requirements

To obtain an *SI* of at least 26 (quality class II) the main dry season should have not less than 3 or 4 months with less than 50 mm and 4 or 5 (but not more) months with less than 100 mm of precipitation. Annual precipitation can range between 1200 and about 2400 mm according to soil drainage, weathering status and monthly distribution of rainfall. Recommended are sites with 1500–2000 mm

II. Soil requirements	Non-Vertisols		Vertisols	
	For class II	For class I	For class II	For class I
(1) Physiologically usable soil depth	≥65 cm	≥110 cm		
(2) First weak mottling (5–10% of the horizon surface) in	≥60 cm	≥100 cm	≥50 cm	≥90 cm
(3) First strong mottling of about 50% of the horizon surface or layers with > 75 vol% laterite or stones in	≥100 cm	≥130 cm	≥70 cm	≥130 cm
(4) pH (H_2O)				
in 0–10 cm	6.4–7.4		6.3–7.3	
in 20–30 cm	5.9–7.1		6.3–7.3	
(5) Soil nitrogen (N_t)				
in 2–10 cm	≥0.10%		0.16–0.21%	
in 20–30 cm	≥0.06%			
C/N in 2–10 cm (May)	<13	≤12	<12–13	
(6) Soil phosphorus (see Glaser and Drechsel, 1991) in 2–10 cm	≥150–160 ppm		200–220 ppm	

$C(\%) = 14.15\,N(\%) - 0.077$ ($r = 0.96$***, non-Vertisols); $C(\%) = 15.95\,N(\%) - 0.714$ ($r = 0.94$***, Vertisols).

out $P_{occl.}$) in 0–10 cm (see Glaser and Drechsel, 1992), Ca/CECpH7 (20–30 cm) over 50%, Mg/CECeff (0–10 cm) over 15–20% as well as at least 15 ppm Mn(DTPA) in 0–10 cm and at least 2.0 ppm Zn(EDTA) in 0–10 cm.

With regard to the site possibilities in West Africa, the excellent teak growth on favorable sites and the enforced management of the older plantations in recent years, the future of teak in this region seems to be promising. However, there is a need for further investigations on early flowering and initial tree branching as well as an intensification of this study on permanent sample plots. The question of how long teak of different age can withstand different degrees of soil saturation, especially waterlogging on Vertisols, as well as the verification of our foliar reference values by fertilization programs are still required. Finally, research on teak mycorrhiza is recommended as well as the choice of other species for soils with stagnic properties.

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