

Site factors, foliar nutrient levels and growth of *Cordia alliodora* plantations in the humid lowlands of Northern Costa Rica

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Received 4 March 1994. Accepted in revised form 29 July 1994

Key words: *Cordia alliodora*, Costa Rica, foliar nutrients, growth rates, K-deficiency, reafforestations

Abstract

Within the perhumid, Atlantic lowlands of northern Costa Rica, *Cordia alliodora* plantations were studied in order to explain the observed pattern of growth irregularities. The soils, that were partly used as pastures over long periods, could be classified roughly into two units: (i) red, deeply weathered, slightly acidic soils from Mg-enriched parent material and (ii) brown, strongly acidic soils with high saturation of exchangeable Al (up to 80%).

Leaf analysis revealed that *Cordia* is a highly demanding species in respect to macronutrients. Poorly growing trees in slope position suffered from an insufficient supply of N and P. K/Mg ratios of chlorotic leaves are very low. Soil analysis showed that nutrient deficiencies were related to (i) insufficient soil nutrient reserves of the poor, tropical soils or (ii) to an inhibition of nutrient uptake by soil physical or chemical factors.

All sites are characterized by very low K reserves and losses of nutrients that are organically bound (N, P) caused by erosion. In the Mg-rich red soils, low amounts of K lead to K/Mg imbalances. Soil compaction caused by cattle grazing occurs on both soil units. It negatively influences the root development of *Cordia*, and hence nutrient uptake. In the brown soils, high amounts of exchangeable Al hinder a sufficient supply of nutrients (e.g. P) to the assimilation organs.

Introduction

The Costa Rican tropical lowlands are continuously deforested at an alarming rate of 60,000 ha per annum (Hartshorn, 1982) because of the high national demand for timber and arable land. Consequently, increasing efforts are made to reafforest degraded soils. In this context, much importance is currently attached to *Cordia alliodora* as a preferred species in recently established plantations.

Cordia is native to Central America and northern parts of South America. Its abundance in secondary vegetation was considered to prove its tolerance for a variety of conditions with regard to soils, water and nutrient supply and climatic regime (CONIF, 1988; Johnson and Morales, 1972; Lamprecht, 1986). Although many studies, were and still are, carried out in respect of provenance and multicropping sys-

tems (Benites, 1990; CONIF, 1988; Weaver, 1979), detailed data on *Cordia*'s nutrient demand and its growth behaviour under monocultural plantations are still not available.

In the reforestation efforts, patterns of growth irregularities were observed to be closely related to the landscape topography with stands of poor growth on inclined sites. The objectives of this work are to (i) characterize the nutritional status of *Cordia* stands of different vitality, and (ii) relate growth of this species to site parameters of the plantations in order to determine the main factors influencing the productivity of a site. A similar study was carried out on *Gmelina arborea* plantations (Stuhmann et al., 1994). Based on these results, we can compare the behaviour of the two tree species on similar sites and make some suggestions for further reforestation activities.

Materials and methods

Study area

All plantations included in this study are located in the perhumid Atlantic lowlands of northern Costa Rica (10° 15'N - 11° 00'N and 84° 00'E - 85° 00'E) at elevations below 300 m a.s.l., generally at about 100 m a.s.l. A description of landscape, geology, climatic conditions and soils is given by Stuhmann et al. (1994).

Site selection and sampling

Within the study area, 10 *Cordia* plantations, all about 30 months old, that show the typical growth pattern were chosen. These growth patterns include: poor tree growth and chlorotic leaves (sites with totally died trees also occur) at the slopes, fast tree growth and dark green foliage at the plateaux and in slope base positions. The plantations were of varying sizes (2–120 ha) depending on the property situations. Within these 10 plantations a total of 22 “microsites” were selected (12 with vigorously growing trees, 9 with poorly growing ones). A microsite was defined as a part of a plantation with homogeneous site and growth conditions and a size of at least 15×15 m (about 25 trees). At each microsite a soil pit (1.5×1.5 m, 1.5 m deep) was dug.

For leaf sampling and growth measurements (total height, diameter at 30 cm height and diameter at breast height (DBH)) five trees were chosen in the direct vicinity of the pit. Leaf samples were taken per tree at the end of the dry season (March to May) in 1991. Only the first mature leaves from the upper part of the crown were sampled. The grade of chlorosis was documented by classifying the leaves roughly according to their green colour intensity (dark green - green - slightly yellow (chlorotic) - yellow (chlorotic) - necrotic).

From soil pits, samples for chemical analyses were taken per horizon, and undisturbed soil cores (5 replicates) for physical measurements were collected from three depths (0–5 cm, 50–55 cm, 100–105 cm). The soil profile was described as suggested by AG Bodenkunde (1982).

Laboratory methods

Leaf and soil samples were analyzed for nutritional elements. Leaves were dried (65°C) and ground, N was determined in unextracted material with a CN-Analyzer (Carlo Erba), and P, K, S, Ca, Mg, Al, Fe,

Mn, and Cu after digestion with concentrated HNO₃ in the 1:10 solution by plasma atomic emission spectrometry (ICP). Soil samples were air-dried and extracted with 0.5 N NH₄Cl. K, Ca, Mg, Al, Fe, Mn, Cu were measured by atomic absorption spectrometry. P was measured photometrically (molybdene-blue) in an HCl-extract as ‘available P’ (Bray-1-method) and as ‘total P’ (without the occluded fraction) by the method of Saunders and Williams (Olsen and Sommers, 1982). The soil’s pH (aqua bidest. and 1 N KCl, 1:2.5, w/v) and effective cation exchange capacity (sum of cations in 0.5 N NH₄Cl-extract) were determined.

Undisturbed 100 mL-cores were used to determine bulk density (dB), water retention curves (pF-WG-curves) and saturated hydraulic conductivity.

Laboratory methods are described in detail in Stuhmann et al. (1994). For statistical tests, the SAS statistical package was used.

Results and discussion

Nutritional status of *Cordia*

Table 1 shows the ranges and average values of foliar nutrient concentrations of *Cordia*. These values are within the range of so far published data (Drechsel and Zech, 1992; Zech and Drechsel, 1992; Zech et al., unpublished), revealing relatively low concentrations of foliar K and P and quite high levels of foliar Ca and Mg for the studied trees. Clear differences can be observed between stands of different vitality, i.e. trees with chlorotic leaves and those with green foliage. According to Table 1, healthy green leaves contain significantly more N ($p < 0.001$), P and S ($p < 0.1$) but less Mg ($p < 0.01$) and higher K/Mg-ratios ($p < 0.01$) than yellow leaves. Due to these results it is assumed that chlorosis of *Cordia* growing in slope position is mainly the result of N deficiency besides low supplies with P and S.

Correlation analysis shows that, apart from tree health (grade of leaf chlorosis), also the growth rate of trees depends on their mineral nutrition since foliar N, Mg as well as foliar K/Mg ratios are significantly related to height increments per month (Figs. 1a-c). From these figures, “critical levels” can be determined graphically, roughly separating the healthy, well growing trees from the chlorotic, poorly growing ones. This critical level represents the foliar concentration of an element that seems to be necessary to avoid visible deficiency symptoms (chlorosis), which obviously

Table 1. Ranges of foliar nutrient concentrations of *Cordia alliodora* on 21 sites with varying grade of tree vitality and growth (averages of five trees per site) are presented. At one site, all trees had died. Means are given for all sites and for sites with healthy (12 sites) and chlorotic trees (9 sites) separately. Critical levels (crit. lev.) between healthy and stunted tree development are proposed

Foliar nutrients	[g 100g dry matter ⁻¹]						[mg kg dry matter ⁻¹]				
	N	P	S	K	Ca	Mg	Mn	Fe	Al	Cu	K/Mg
Min-max	2.1-4.1	0.1-0.24	0.2-0.5	0.9-2.3	1.6-4.6	0.6-1.5	17-143	65-293	56-248	7-27	0.7-3.2
means	3.0	0.17	0.29	1.7	2.7	0.92	63	119	118	17	2.0
Chlorotic ^a	2.4a	0.15e	0.26e	1.6	3.0	1.5c	56	127	143	12	1.5c
Healthy	3.4b	0.18f	0.31f	1.8	2.6	0.8d	68	119	106	20	2.3d
Crit. lev.	2.65	0.15	0.25	1.8		0.9	105		125	16	1.75

^a different letters indicate significant differences; a,b: $p < 0.001$; c,d: $p < 0.01$; e,f: $p < 0.1$.

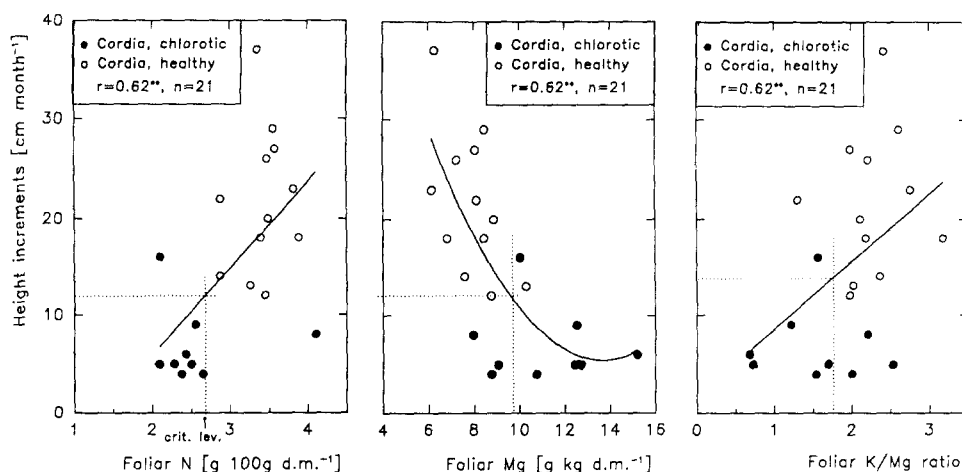


Fig. 1. Relations between height increments [cm month⁻¹] and foliar N (a), Mg (b) and K/Mg (c) levels.

coincides with growth height increments of about 12 cm/month. Critical levels are summarized in Table 1. The same approach was used for *Gmelina arborea* plantations (Stuhrmann et al., 1994). A comparison of both species reveals that *Cordia* is highly demanding in respect to macronutrient supply.

Summarizing the results of **foliar analyses**, it becomes obvious that the decline phenomena of *Cordia* growing in slope position are caused by a multiple **nutrient disorder**, mainly N deficiency and K/Mg imbalances.

Possible reasons might be: - (i) The tropical soils offer **insufficient nutrient reserves** and hence, cannot provide *Cordia* sufficiently with K. - (ii) An **antagonism** exists between K and Mg in the soil, which is assumed by the close relationship between chlorosis or poor tree growth (Table 1, Fig. 1c) and the foliar K/Mg ratios. - (iii) On steep slopes accelerated **soil**

erosion reduces the thickness of the humic A horizon, thus reducing organically bound soil nutrient reserves (N, P).

In order to further identify the processes that are responsible for the decline phenomena of trees growing on inclined sites, **soil physical and chemical analyses** were carried out.

Soil nutrient reserves

General characterization of the studied soils

During our studies in the northern Costa Rican lowlands, we analyzed soils of 22 sites with *Cordia alliodora* and of 24 sites with *Gmelina arborea* (cf Stuhrmann et al., 1994).

All soils could be distinguished in the field by colour and were preliminarily classified into two main units: (1) deeply weathered red soils on dissect-

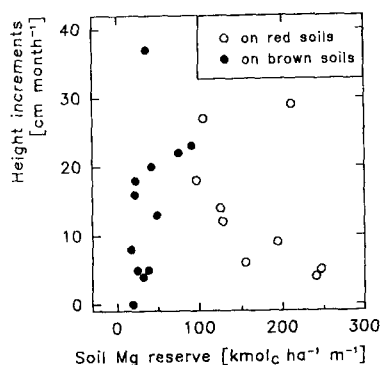


Fig. 2. Relation between height increments [cm month⁻¹] and soil Mg reserves over one metre soil depth [kmol_c ha⁻¹ m⁻¹]_{c=charge}. The red and brown soils can be separated in respect of their Mg reserves. On both soils, similar growth irregularities can be observed.

ed terraces formed from Mg-enriched fluvio-basaltic deposits, and (2) profound brown soils developed in more acidic parent materials from pleistocene lava flows or tertiary volcanic remnants.

Only data from soils of *Cordia* sites will be discussed in detail in this paper.

Table 2 summarizes the mean total reserves of C, N, P and some exchangeable cations as well as average values for CEC effective (=CEC_{eff}), pH and bulk density (0-5 cm) (=d_{B0}). Results are given separately for the red and the brown soil units (11 sites each).

In general, the soils are characterized by high contents of total C and N and very low contents of K and P. Similar data have been documented for soils on the Atlantic side of Costa Rica by Martini and Macias (1974). High total amounts of C and N seem to be due to the high annual precipitation of 3000–4000 mm in the Atlantic lowlands, and very low K and P contents are characteristic for these soils. The generally low bulk densities also seem to be typical for the soil parent materials of the study area (cf. e.g. Wielemaker and Lansu, 1991). Nevertheless, the comparison of both soil units indicates significant differences. The brown soils are more acidic with lower contents of Ca and Mg and higher amounts of Al, and even lower bulk densities. Figure 2 illustrates the separation of both soil units with respect to soil Mg reserves. *Cordia* planted on red soils showed poorer growth if soil Mg reserves were high, whereas growth on brown soils was positively correlated with the soil Mg stock within one metre of soil depth. This difference is mainly due to the more acid character of the parent material of the brown soils. Additionally, the application of dolomitic limestone to the red soils, which have been under cul-

tivation for longer time (about 20 yrs) than the brown soils, may contribute to the results described in Table 2.

Plant available nutrient reserves

The availability of nutrients for plants was determined by correlation analyses of foliar element contents to soil nutrient reserves. Significant relations could be found (Figs. 3a,b).

The highest positive correlation coefficient was calculated for "foliar P" with "P-Bray soil reserves" (A horizons) for the brown soils (Fig. 3a). Apart from this soil P fraction which is the "more available P", also a "total P fraction" was determined because "P-Bray" could only be detected in very small quantities in the organic surface horizons (=Ah). But "less-available" P can also become available for trees, e.g. made accessible by root exudates or by mycorrhizae. As no clear relation between "foliar P" and "soil total P" could be found, it is assumed that the young *Cordia* trees are still dependent on the organically bound, readily available P reserves.

For the red soils, the K supply to the trees is correlated with the K reserves of the uppermost 30 cm of the profile ($r = 0.65^*$). A negative relation between tree K supply and soil Mg reserves (0-30 cm) could be found for both soil units (Fig. 3b). This emphasizes that high amounts of Mg limit the supply of K to the trees.

Summarizing the results of the correlation analysis on "nutrient availability", it can be stated that in many cases low foliar nutrient levels, especially of P and K, depend on low available soil nutrient reserves. It seems surprising that despite high total amounts of N, a deficiency of N was indicated by foliar analysis and no significant correlation could be found. This fact may be due to the presence of heterocyclic compounds, in which the nitrogen is bound tightly and unavailable to the plants.

Low nutrient reserves caused by erosion

In tropical soils, most of the nutrients are stored in the organic substance, which may quickly be lost by erosional activity.

This explains that the soil nutrient reserves of the studied *Cordia* plantations depend strongly upon the thickness of the humic A layer (Table 3).

Therefore, it is supposed that the tree mineral nutrition, as reflected by foliar nutrient levels, depends upon the existence of sufficient organic material. Figures 4a-c and Table 4 illustrate the close relation between foliar

Table 2. Mean total reserves of C, N, P, and some exchangeable cations, as well as average values for effective CEC, bulk density (0-5 cm) and pH of the red and brown soils (11 sites each) in the *Cordia* plantations under study. "P-bray" could only be detected in humic A-layers (=Ah). Exchangeable cations and CEC are expressed in [kmol_c ha⁻¹ m⁻¹], c=charge

	C	N	P-bray	K	Ca	Mg	Al	CECeff	dB ₀	pH _{H₂O}	K/Mg	K/Mg
	[t ha ⁻¹ m ⁻¹]		[kg ha ⁻¹ Ah ⁻¹]	[kmol _c ha ⁻¹ m ⁻¹]					[g cm ⁻³]		30cm	100cm
Red soils ^a	143	14	0.33	16	313e	144	33c	525	0.91a	5.6a	0.2g	0.1e
Brown soils	138	12	0.59	13	160f	83	398d	681	0.71b	4.9b	0.3h	0.3f

^a different letters indicate significant differences; a,b: $p < 0.001$; c,d: $p < 0.05$; g,h: $p < 0.1$.

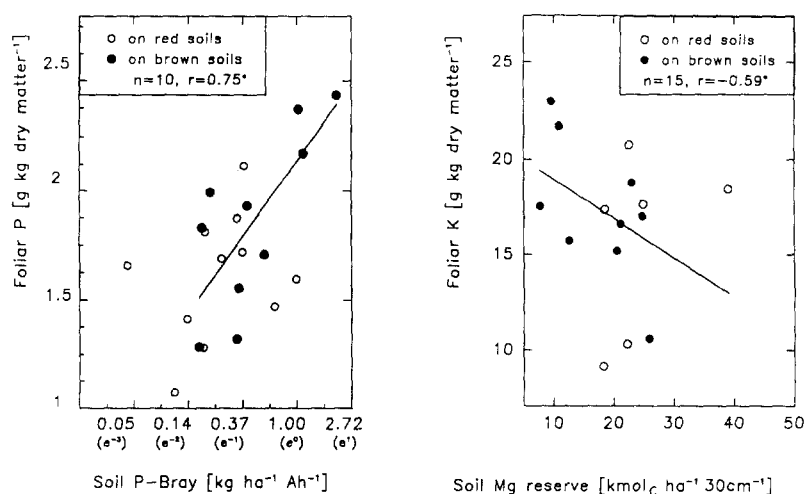


Fig. 3. Relations between foliar P level and soil P-bray reserves (a) and between foliar K level and soil Mg reserves (b). P-Bray was determined in the humic A layer (=Ah). Regression curves are given for the brown soil sites in a) and for all sites in b). Reserves in [kmol_c ha⁻¹ m⁻¹], c=charge.

Table 3. Correlation coefficients indicating the dependence of the soil nutrient reserves, effective CEC and bulk density (dB₀) upon the thickness of the humic A layer. (Abbreviations see Table 2)

	C	N	P-bray	K	Ca	Mg	Al	CEFeff	dB ₀
	[t ha ⁻¹ m ⁻¹]		[kg ha ⁻¹ Ah ⁻¹]	[kmol _c ha ⁻¹ m ⁻¹]					[g cm ⁻³]
Ah - red soils	0.61*	0.65*	ns	0.69*	ns	ns	ns	ns	-0.72*
Ah - brown soils	ns	ns	0.65*	0.78**	0.65*	0.71*	0.61*	0.62*	-0.54*

Table 4. Correlation coefficients indicating the dependence of the foliar nutrient concentrations (g 100 g dry matter⁻¹) and the growth of *Cordia* (cm/month) upon the thickness of the humic A layer (cm)

	N	P	K	S	Mg	K/Mg	Growth
Ah - red soils	0.85***	(0.4)	ns	0.74**	-0.85***	0.69*	0.72*
Ah - brown soils	(0.48)	ns	ns	ns	-0.79**	ns	0.85***

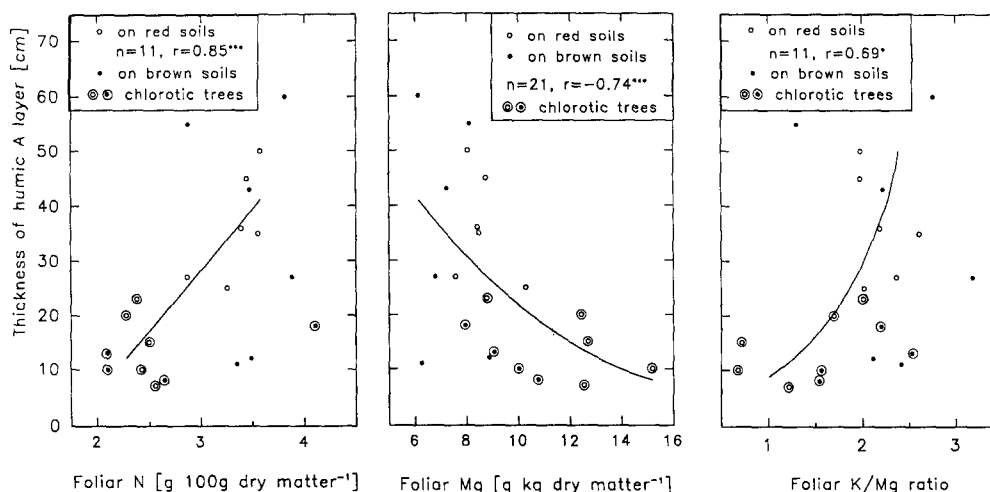


Fig. 4. Relations between the thickness of the humic A layer and foliar N (a), Mg (b) and K/Mg (c) levels.

levels of nutrients that are predominantly bound in the organic matter and the thickness of the A horizon. Thus, tree growth can also be related to the thickness of the humic A layer.

These relationships between foliar nutrient levels and thickness of the Ah horizon are especially clear for the red soils. The high negative correlation coefficient of foliar Mg with Ah thickness is notable (Table 4 and Fig. 4b). In the figure, the grade of chlorosis is added as a third dimension, marked with dotted circles for chlorotic trees. Poorly growing, chlorotic trees on sites with thin humic A layers seem to accumulate Mg. The positive correlation coefficients of tree growth on red soils and their foliar or soil K/Mg ratio lead to the assumption that the accumulation of Mg may be an indicator of a K/Mg imbalance in the soil. This observation again emphasises the theory of an inhibition of K uptake by relatively high amounts of Mg. Soil K/Mg ratios occasionally below 0.03 prove this assumption, which was also found in *Gmelina* plantations (Stuhrmann et al., 1994). The main cause may lie in the Mg-rich parent material and, additionally, in the liming practice mentioned above (Von Uexkull, 1986). Similar phenomena have been described for crop plants in Costa Rica by Carvajal (1978), who gives a critical K/Mg level in soils at 0.26 indicating an excess of Mg.

In order to verify whether erosion really is a serious problem in slope positions, the thickness of A horizons was correlated with the inclination of the sites. For most of the sites, this relation was found to be significant ($r = -0.74^{***}$, $n=15$), indicating less organic material on slopes, where tree growth is stunted.

Some sites obviously do not fit this theory. They were called "exceptional sites", providing relatively high amounts of organic matter in slope positions or showing very thin humic A layers on plateaux. In these cases, good growing, healthy trees can be observed on slopes, stunted, chlorotic, and occasionally died trees on plain sites. "Exceptional sites" occur more frequently among sites of the brown soil type.

It was assumed that other, unfavourable soil properties than those discussed so far play a distinctive role in brown soils. Also, the more evident results of the soil nutrient reserve analyses for the red soils lead to the hypothesis that nutrient availability in the brown soils is inhibited indirectly, e.g. by soil physical conditions, not by nutrient deficiency itself.

Apart from nutrient deficiency, the chemical toxicity of Al or Mn as another problem that possibly causes decline phenomena within the studied *Cordia* plantations has to be taken into account. In this context, the organic matter gains further importance as it may not only be responsible for much of the cation retention capacity of these soils but also can bind Al in organic chelate complexes. Accelerated erosion will therefore reinforce toxicity problems on soils with high amounts of exchangeable Al.

Inhibition of nutrient uptake

Chemical toxicities

A high Al saturation in the soils can exert a negative influence on the nutrient uptake. High amounts of exchangeable Al, up to 80% saturation of the cation

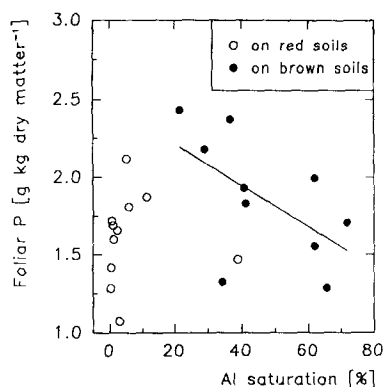


Fig. 5. Relation between the foliar P level and the Al saturation within the uppermost 30 cm of the soil. For the brown soils a correlation curve is given ($r=-0.59$, $p=0.07$, $n=10$).

exchange complex, particularly occur in the brown soils. For those soils, an inhibition effect could be demonstrated especially for the P uptake (Fig. 5). High concentrations of exchangeable Al restrict root development and P uptake by forming Al-phosphates (Von Uexkull, 1986). Similar phenomena were described for *Gmelina arborea* reforestations (Stuhrmann et al., 1994).

Soil physical properties

According to our field observations, we supposed that unfavourable soil physical properties as soil compaction influence tree growth, especially on sites that had been used for many years as pastures prior to the establishment of the plantations. Some reforestations could be included in the study that comprise both, sites used as pastures for several years and sites that had been covered with rainforest just before. Therefore, samples of undisturbed soil cores were taken from each site for the measurement and calculation of soil physical parameters. Unfortunately, from the information given by farmers it was not possible to deduce a quantitative index of cattle grazing intensity.

The negative effect of cattle grazing can be demonstrated clearly (Fig. 6): the water retention curves compare two sites on brown soils of the same plantation which lie within a distance of a few hundred metres. Both curves cross typically at about $pF 2 = 10$ kPa and at higher and lower pF values enclose areas which are proportional to the gain of primary and the loss of secondary pore volume, respectively, with increasing soil compaction. Particularly, the secondary pores, originating from particle aggregation, are susceptible

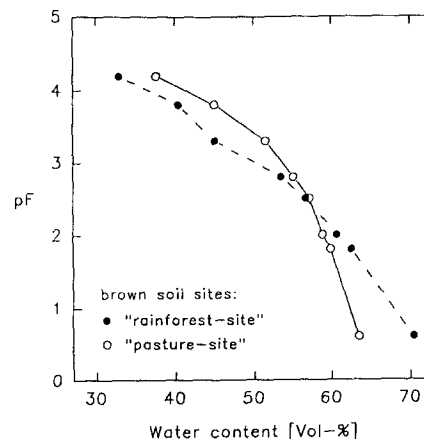


Fig. 6. Comparison of two sites on brown soils which lie within a distance of a few hundred metres. The negative effect of cattle grazing is demonstrated.

to soil compaction which is most pronounced in clayey substrates.

Summarizing the information from Figure 6, it can be stated that the "pasture soil" has lost secondary pores which coincides with an increase in fine and medium pores. Similar results are reported by Spaans et al. (1989) and Wielemaker and Lansu (1991).

Table 5 shows that the determined soil physical parameters correlate closely with soil bulk density of the surface soil (0-5 cm), as does the length of the grazing period (number of years). This could be shown for almost all sites of the *Cordia* and *Gmelina* plantations studied by the authors ($r = 0.76^{***}$, $n=43$). Tree growth also depends on bulk density. Although bulk density seems to be slightly different for different soils (cf. Table 2), it can be concluded from the results discussed above, that dB is a suitable parameter to quantify the intensity of soil compaction by cattle trampling. This conclusion is plausible because (i) it was possible to examine soils of different "treatment" within short distance, so that the same parent material can be presupposed, and (ii) the effect of loss of secondary pores is stronger than the natural range of the bulk density within one material which is the sum of the material's "raw density" plus the pore volume that can be enclosed by the particles of given sizes and forms.

Further aspects

The close relationships of many years of pastoral use and thin organic A horizons as well as relatively higher bulk densities may explain the at first sight unexpected, stunted tree growth on some plateaux and the obser-

Table 5. Correlation coefficients indicating the dependence of the soil physical properties, as well as foliar N and P levels and growth rate increments upon soil bulk density (pore volume (=pv), fine pores(=fp), medium pores(=mp), plant available water (=paw)). The relations between dB and the length of the grazing period is significant

	pv	fp [in % of pv]	mp	paw	growth	foliar N	foliar P	grazing period [years]
dB ₀ - both soil units	-0.71***	0.47*	-0.91***	-0.87***	-0.52*	-0.48*	ns	-0.50*
dB ₀ red soils	-0.72*	ns	-0.89***	-0.89***	ns	-0.71*	0.5*	ns
dB ₀ brown soils	-0.65*	0.61*	-0.81**	-0.80**	-0.67*	ns	ns	-0.73*

vation of well growing, healthy trees in “exceptional” slope positions.

Further, the supply of the trees with macronutrients is restricted on soils with relatively high soil bulk densities: the supply with N is related to the soil bulk density with $r = -0.71^*$ (for red soils), the P-supply with $r = -0.5^*$ (for red soils). The fact that *Cordia* exhibits a clear dependence of growth or nutrient supply on bulk density of the surface soil may be explained by the typical root development pattern of this species during its first years. The root system is developed laterally and in the uppermost 5 to 10 cm of the soil (Conif, 1988). Thereby, nutrient uptake can be impaired severely by compaction of the thin humic layer.

Main factors that restrict tree growth

In order to quantify the impact of different soil and site factors on the growth of *Cordia*, the dependent variable, growth (height increments per month), was regressed on all physical and chemical soil properties presented above. A number of suitable regression models could be found:

Even though soils and sites differ obviously and “exceptional sites” have been included in this study, a regression model can be presented for all sites:

$$\begin{aligned} \text{growth} = & 25 + 0.3 \text{ A layer thickness} \\ & -28(\text{K reserve}_{30\text{cm}})^{-1} - 14 \text{ dB}_0 \\ & + 3 \ln (\text{P} - \text{Bray reserve}); \\ r^2 = & 0.71^{***}, n = 22 \end{aligned}$$

This model emphasizes the strong impact of erosion (Ah thickness) and compaction (dB₀) on the growth increments of *Cordia* on all studied soils. Another important role plays the K supply (negative mathematical influence because of transformation of data; positive influence on growth). The substitution of this variable by the K/Mg ratio is possible but would not

lead to a significant equation. The importance of sufficient available P reserves is also demonstrated.

The following model gives a remarkable result:

$$\begin{aligned} \text{growth} = & 12 + 0.5 \text{ Ah} - 11 \text{ dB}_0; \\ r^2 = & 0.61^{***}, n = 22. \end{aligned}$$

Only two easily obtainable site factors need to be measured in the field (i.e. A layer thickness, soil density), in order to describe growth irregularities significantly. This can help selecting the most suited reforestation sites in Costa Rica prior to the establishment of plantations in the future.

For the red soils, apart from erosion and low K reserves, a favourable pH value (in water; 0-30 cm) is concluded to be more important for sustaining satisfying tree growth than bulk density, which is not included in the model. A too high pH value indicates that relatively high amounts of exchangeable bases (Ca, Mg) limit the supply of K to the tree:

$$\begin{aligned} \text{growth} = & 71 + 0.2 \text{ A layer thickness} \\ & - 10 \text{pH}_{\text{H}_2\text{O}} - 34 (\text{K reserve}_{30\text{cm}})^{-1}; \\ r^2 = & 0.70^*, n = 11 \end{aligned}$$

Trees growing on the brown soils are more negatively influenced by soil compaction and related soil physical properties than by thin A layers. This is shown by the following regression model:

$$\begin{aligned} \text{growth} = & 92 - 61 (\text{K reserve}_{30\text{cm}})^{-1} \\ & - 76 \text{dB}_0 - 0.2 \text{ Al saturation}_{30\text{cm}}; \\ r^2 = & 0.85^{**}, n = 11 \end{aligned}$$

On these acidic soils the saturation with Al (0-30 cm) plays an important role for tree growth by restricting root development (e.g. cf. Von Uexkull, 1986) and nutrient uptake (cf. Fig. 5). The close dependence

of growth upon soil K reserves also indicates that the cation exchange complex is dominated by Al and available macronutrient reserves are low. Neither the variable "A layer thickness" nor "P reserves" can improve this model significantly.

Nitrogen is not included in any of these models despite the fact that N deficiency has been diagnosed by foliar analysis. This was explained by the high amounts of soil total N reserves that are supposed to be bound heterocyclically and thus unavailable to the plants in the organic substance.

Conclusion

On both soil units that occur in the studied plantations, *Cordia* showed similar growth irregularities. Leaf analysis reveals that insufficient macronutrient supply seems to be responsible for reduced height increments and tree health, i.e. grade of chlorosis.

On the generally poor soils, problems may arise after short time, because (i) *Cordia* is quite demanding in respect to macronutrients, especially if compared to other species as e.g. *Gmelina arborea*, which was studied simultaneously (Stuhrmann et al., 1994), and (ii) nutrient ratios are easily imbalanced as soil reserves are very low. Therefore, more fertile soils (e.g. alluvia) should be used for the reforestation with *Cordia*. Less fertile soils and particularly inclined sites should more and more be reforested with native species which currently are subject of detailed investigations (cf e.g. Condit et al., 1993; Montagnini and Sancho, 1990). Sandner and Nuhn (1971) already mentioned species like *Vochysia ferruginea*, *Tabebuia chrysantha* and *Cecropia* sp. to inhabit slopes or e.g. *Pentaclethra macroloba* to cope better with periodical water stagnation than *Cordia*. Mixed stands with N-fixing species should be considered as another possibility to improve reforestation practices.

Soil analysis also indicates that loss of the organic-rich topsoil by erosion influences tree growth negatively on all sites, as does the deterioration of soil physical properties by long grazing periods or the use of heavy forest clearing machinery. This strong negative effect of compaction on tree growth may be explained by *Cordia*'s behaviour of developing only a lateral, superficial root system within its first years. Multiple regression analysis also emphasizes the deficient macronutrient supply, which is caused mainly by K/Mg imbalances in the red soils and high Al saturation in the brown soils.

The highly significant relationship between tree growth of *Cordia* and quickly measurable site factors as Ah-thickness and soil density may allow, in future, quite an easy selection of the most suited reforestation sites in Costa Rica for *Cordia*, prior to the establishment of plantations.

Acknowledgements

The manuscript is based on the Master Thesis of C Bergmann, carried out at the Institute of Soil Science and Soil Geography at the University of Bayreuth, where all chemical analysis could be conducted. The research work was part of the German - Costa Rican project "Cooperación en los Sectores Forestal y Maderero" (COSEFORMA), financed by the GTZ (Gesellschaft für Technische Zusammenarbeit, Eschborn; Federal Republic of Germany). We are indebted to A Kastl and A Barkow (COSEFORMA, GTZ). Oscar Sanchez of the "Dirección General Forestal" (DGF, San José) helpfully and friendly supported our fieldwork, Prof M Villalobos and Mario Quirós generously enabled us to work at the soil physics laboratory of the "Instituto Tecnológico de Costa Rica" (ITCR), Cartago, and Dr M Kaupenjohann helped with critical comments and discussions.

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Section editor: R F Huettl