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Site productivity estimation using height-diameter relationships in Costa Rican secondary forests

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Abstract

Site quality was assessed in four secondary forests dominated by the commercially important tree species *Vochysia ferruginea* in Northern Costa Rica. A variation of the site quality concept known as site form (i.e. the expected mean height at 25 cm dbh) was used. Twenty-nine sample plots (20 × 20 m) were installed covering soil and topographic variation within and between sites. Site form was estimated for each plot using a linear model. The site form estimations show a high variation between plots (from 16.2 m to 32.2 m), which could indicate large variation in site productivity. Site form of *V. ferruginea* was significantly correlated with total stand basal area of all species, which supports the potential value of site form as an indicator of site productivity. Twenty-six physical and chemical soil variables showed significant correlation with site form. Adjusted multiple regression models of site form on soil variables were fitted by stepwise regression analysis (forward selection method). The best fit was obtained using only the percentage of sand at 12-30 cm as the independent variable (r^2 = 59.3%, s.e.= 3.0 m). The results of this study suggest that site form appears to be a potentially useful indicator of site quality in broadleaved neotropical secondary rainforests when age is unknown.

Key words: forest management, forest soils, secondary rainforest, site form, site quality.

Resumen

Estimación de la capacidad productiva de la estación en bosques secundarios costarricences

En el presente artículo se presentan los resultados de la evaluación de la calidad de la estación en cuatro bosques secundarios dominados por *Vochysia ferruginea* en Costa Rica. Como índice de la capacidad productiva de la estación se utilizó el índice de forma (i.e. la altura media esperada a un diámetro a la altura del pecho de 25 cm). Con tal fin se instalaron en campo 29 parcelas (20 × 20 m) de forma tal que cubrieran el rango de variabilidad edáfica y topográfica presente en el área de estudio. El índice de forma presentó una alta variabilidad entre parcelas (entre 16,2 m y 32,2 m), lo cual indica una importante variación en términos de productividad de la estación. El índice de forma de *V. ferruginea* resultó correlacionado significativamente con el área basimétrica de todas las especies, así como con 26 variables del suelo, quedando entonces respaldado el valor del índice de forma como indicador del rodal de la productividad. Se han ajustado modelos de regresión múltiple entre el índice de forma y las variables edáficas, utilizado el método de inclusión de variable paso a paso. El mejor ajuste se obtuvo al incluir únicamente como variable explicativa el porcentaje de arena en el suelo a una profundidad entre 12-30 cm (r^2 = 59,3%, e.e. = 3,0 m). Los resultados del trabajo muestran la potencialidad del índice de forma como indicador de la calidad de estación en los bosques secundarios húmedos neotropicales cuando la edad no es conocida.

Palabras clave: bosques secundarios, calidad de estación, índice de forma, gestión forestal, suelos forestales.

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Introduction

Forest management requires a reliable measure of site productivity. Growth and yield forecasting requires precise evaluations of site productivity, as this may influence growth, mortality and recruitment predictions. In spite of the relevance of site productivity estimations for forest management, there are few studies on site quality assessment techniques in tropical broadleaved forests (Vanclay, 1994; Herrera, 1996; Herrera and Alvarado, 1998).

Variation in site productivity may be described within the conceptual framework of site quality, defined as the capacity of a land to produce vegetation of given characteristics, as determined by particular environmental conditions (Carmean, 1975; Hägglund, 1981). Most studies of site quality have been carried out in even-aged stands (planted or naturally regenerated) (Herrera and Alvarado, 1998). Several methods for estimating site quality, including those based on forest measurements (Clutter *et al*., 1983; Vanclay, 1994), abiotic factors (Schönau and Aldworth, 1991; Clutter *et al.,* 1983; Vanclay, 1994), as well as indicator species and composition of ground vegetation (Daubenmire, 1976; Shafer, 1989) have been developed and applied. However, the method most frequently used in even-aged stands, even in tropical regions, is the estimation of site index (Carmean, 1975; Ortega and Montero, 1988; Herrera and Alvarado, 1998). One problem in natural, broadleaved tropical rainforests is that the age of trees cannot be readily determined, as most species do not form annual rings. In the case of secondary tropical forest, stand age (i.e., the time since the site was abandoned from any activity) is also frequently unknown or difficult to estimate. That means that a reliable estimation of classical site indices is not possible (Alder, 1980).

Site quality in neotropical natural forests has been estimated at an experimental level. For example, Gutiérrez and Mize (1993) applied the site quality concept to predict the characteristics of a forest from information on precipitation, topography and soils. Herrera *et al*. (1999), in the same 28 yr old secondary tropical forest as the present investigation (Florencia site, see section Study sites), applied the dominant height concept (defined as the mean height of the 100 tallest trees per hectare) to estimate the site quality of a forest dominated by *Vochysia ferruginea*. Although dominant height was considered a potentially useful site productivity indicator in broadleaved neotropical secondary rainforests, it is applicable only to forests of similar age. Thus, it is necessary to find an age-independent indicator of site quality applicable to tropical forests.

Several authors have applied height-diameter relationship to estimate site quality for pure and mixed even-aged stands (e.g., Stout and Shumway 1982). Vanclay (1992, 1994) presents a comprehensive compilation of site quality studies using height-diameter relationships in even-aged stands, pointing out the advantages and disadvantages of each one. In uneven-aged stands, Vanclay and Henry (1988) applied the height-diameter relationship to forests dominated by *Callitris glaucophylla*, in Queensland, Australia. The height at a defined index diameter was used as a measure of site productivity and was called site form, to avoid confusion with site index derived from height-age relationships. In their study, they concluded that site form has the following desirable characteristics that can also be considered good measures of site productivity:

i) Reproducible and consistent over long periods.

ii) Indicative of site and not influenced by stand condition or management history.

iii) Correlated with the site's productive potential.

iv) Determined easily from normal inventory measurements, meaning that site form estimations do not require data from permanent plots.

In this paper, the concept and methodology suggested by Vanclay and Henry (1988) are applied to describe the site productivity of four secondary forests dominated by *Vochysia ferruginea* Mart. (Vochysiaceae) in Northern Costa Rica. During the present research, it was possible to estimate the year of abandonment of the stands and therefore the year of origin of the secondary forest, but in practice this is frequently unknown.

Materials and Methods

Study sites

Study sites are located at Florencia, San Carlos, Alajuela Province and at Cureña, La Virgen of Sarapiquí, Heredia Province, Costa Rica. The Florencia site is fully described by Herrera and Finegan (1997). It is located in Holdridge's Tropical Wet Forest life zone (Tosi, 1969) at ca. 320 meters above sea level (m.a.s.l.). Mean annual precipitation is ca. 3,300 mm and mean annual temperature 28^{o}C. The hilly, 32.5 ha stand was 28 years old at the time of the study. At the Cureña site three stands of approximately 4-15 ha were selected. They are located in the Holdridge's Tropical Wet Forest life zone (Tosi, 1969) at ca 40 m.a.s.l. Mean annual precipitation is ca. 3,600 mm and mean annual temperature 21ºC (Instituto Meteorológico Nacional 1998). The stands were between 16 and 18 years old at the time of the study. At the Florencia site, the predominant soils are Inceptisols, but it is possible to find a small area dominated by Ultisols. The slopes vary between 15 and 60% (Vásquez, 1994). At the Cureña sites soils are mainly Ultisols, with slopes between 4 and 60% (Vásquez, 1991; Herold, 1994).

All stands are dominated by the species *V. ferruginea* (Table 1), a large, commercially important and long lived pioneer species (Finegan, 1992 and 1996). The species is common in secondary forest of Northern Costa Rica (Finegan, 1992), particularly associated with less fertile soils of slopes and hilltops (Montagnini and Sancho, 1994; Herrera and Finegan, 1997; Herrera *et al*., 1999; Herrera and Alvarado, 2001). This species represents approximately 42% of the total basal area in both sites. Other important species in the study sites are *Simarouba amara* (3.06 m^2 ha^{-1}) and *Miconia sp.* (1.06 m^2 ha^{-1}). Details related to other stand attributes are presented in Table 1, while the data corresponding to each plot is depicted in Table 2.

Sampling

Twenty-nine sample plots of 20m × 20m were established for this study. In Florencia site, 12 plots were established, while 3, 4, and 10 plots were established in each stand located in Cureña site. Plot size took into account low levels of within-plot variability (i.e., homogeneous growth conditions, see Herrera *et al*., 1999), which is desirable in studies of site quality (Carmean, 1975).

Plots were established according to the following criteria pointed out by Herrera *et al*. (1999): sampling of the complete gradient of soil and topographical conditions present within the site; uniform soil and topography within each 20 m × 20 m plot and no evidence of disturbance in the plot. As was mentioned by Herrera *et al*. (1999), approximately half of the total forest area at Florencia was subjected to an experimental thinning in 1994; therefore, plots were not located within this area. Sampling includes the entire range of dbh (diameter at breast height, 1.3 m) and total height variability presented at the sites. Only forest areas destined for timber production under current Costa Rican forestry regulations were sampled. Thus areas of slope > 50º or within 20 m of permanent or seasonal watercourses were excluded from the study.

In each plot, dbh was measured for all trees ≥ 10 cm dbh which were identified by vernacular name. The total height was measured in each plot for 423 individuals ≥ 10 cm dbh of *V. ferruginea* (Table 2). Slope percentage, plot topographical position and plot exposition were also measured. Soil samples were taken at two depths, 0-12 cm and 12-30 cm in each sample plot. Soil analysis was carried out in the laboratory of the Center for Agricultural Research (CIA) at the University of Costa Rica in San José, Costa Rica using standard laboratory

Table 1. Attributes of *V. ferruginea* and the remaining species at the study sites*

	Florencia site (n = 12) 28 years since site abandonment		**Cureña site (n = 17) 16-18 years since site abandonment**	
	V. ferruginea	**Remaining species**	***V. ferruginea***	**Remaining species**
Number of trees (ha)	501	294	158	166
Mean diameter at breast height (cm)	26.7 (4.8)	18.2 (3.7)	21.4 (4.7)	18.1 (3.5)
Mean basal area (m^2/ha)	9.6 (3.5)	13.2 (5.2)	18.5 (6.5)	24.5 (8.2)
Total basal area (%)	42	58	43	57
Mean height (m)	20.3 (2.9)	—	22.0 (2.6)	—
Dominant height (m)	22.3 (3.5)	—	25.2 (3.0)	—
Total basal area (m^2/ha)	22.8	43.0		
Total number of tree species	23		29	

* Number in parenthesis shows standard deviation.

Table 2. Diameter at breast height, total height and other attributes of *V. ferruginea* in each of the 29-plots established in two study sites in Northern Costa Rica

Plot number	Site	Number of trees in the plot	Diameter at breast height (cm)	Total height	Basal area of *V. ferruginea* (m^2/ha)	Total basal area (m^2/ha)
1	CU	22	19.69	19.5	18.50	23.50
2	CU	14	24.00	19.5	17.10	22.71
3	CU	24	19.93	22.3	20.20	25.76
4	CU	20	21.57	21.5	20.00	26.91
5	CU	20	28.58	28.2	33.80	35.98
6	CU	10	27.77	23.6	15.70	22.80
7	CU	34	15.90	21.0	19.20	27.76
8	CU	30	20.09	23.0	26.90	29.02
9	CU	33	16.58	20.2	19.00	22.84
10	CU	20	18.55	22.5	15.10	20.98
11	CU	19	18.62	22.5	14.30	26.40
12	CU	17	21.39	21.9	17.00	21.20
13	CU	15	21.73	17.0	16.10	17.64
14	CU	16	19.77	22.8	12.80	19.35
15	CU	13	33.62	26.7	29.60	29.88
16	CU	13	17.42	21.1	8.40	22.51
17	CU	16	17.79	20.0	10.80	22.20
18	FL	5	27.60	22.2	8.20	15.01
19	FL	5	33.30	25.2	12.40	18.11
20	FL	6	19.88	18.2	4.80	11.62
21	FL	5	27.90	21.8	9.00	13.79
22	FL	9	30.77	24.9	19.00	22.70
23	FL	4	24.65	17.1	6.10	10.01
24	FL	8	18.18	17.4	5.60	6.67
25	FL	9	24.12	19.7	10.80	11.51
26	FL	6	27.82	19.7	10.20	11.93
27	FL	4	33.40	21.2	9.10	10.41
28	FL	7	29.59	20.7	12.50	13.48
29	FL	6	23.33	15.8	8.00	13.19

methods (Henríquez *et al.*, 1995). pH was determined in water with a potentiometer. P, K, Fe, Cu, Zn, and Mn were extracted with a modified Olsen solution, Ca and Mg by 1*M* KCl. P were determined colorimetrically and the remaining elements by atomic absorption spectrophotometry. Exchangeable acidity was measured using 1 *M* KCl as a neutral solution and titrating with 0.01 *M* NaOH, organic matter using the Walkley and Black method and soil texture using the Bouyoucos method.

Data analysis

Among several linear and non-linear models tested, the simple linear model, equation [1], was found to be suitable for describing the height-diameter relationship (Fig. 1). The index diameter chosen was 25 cm dbh (Vanclay and Henry 1988), as trees of this diameter commonly occur in the study stands.

$$H = a + bd \qquad [1]$$

Where:

H = mean total height (m).

a = 1.3 m, to constrain the model to predict a height of 1.3 meters at zero dbh.

b = (SF – 1.3)/25, to constrain the model to pass through the index height at 25 cm dbh.

SF = site form, the expected height of a 25 cm dbh tree.

d = mean dbh (cm).

The site form of *V. ferruginea* was estimated for each plot using model [1], mean dbh and mean total height of trees with dbh ≥ 10 cm.

Pearson's coefficients of correlation were estimated for soil variables and site form of *V. ferruginea*. A correlation matrix was estimated including site form and all soil variables. In order to determine the degree

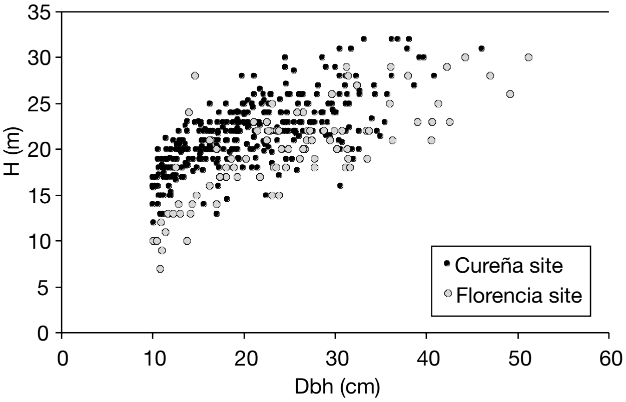

Figure 1. Scatter plot of total height (H) *vs.* diameter at breast height (dbh) of *V. ferruginea* in tropical secondary forests (423 trees on 29 plots).

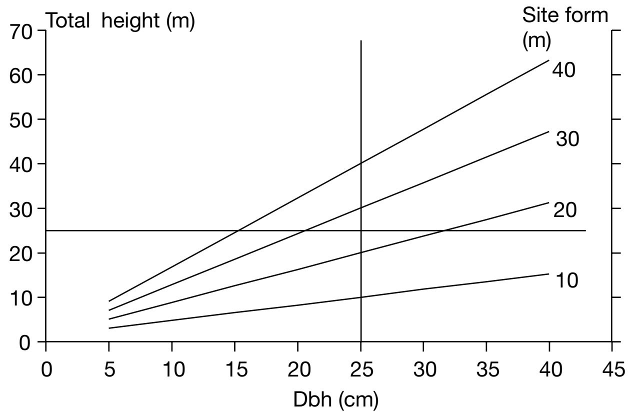

Figure 2. Site form curves estimated by linear regression for *V. ferruginea* in tropical secondary forests of Northern Costa Rica.

of collinearity between the variables included in the matrix, variance inflation factors (VIFs) were calculated from the inverse of the correlation matrix. One of any pair of variables showing VIFs > 10 indicate collinearity problems, meaning these should be eliminated for purposes of multiple regression analysis (Kleinbaum *et al.,* 1998). It was not necessary to eliminate variables for the analysis in the present study. Only soil variables showing a $p < 0.05$ correlation with site form were used for regression analysis purposes. Stepwise regression analysis (forward method) was used to fit a regression model relating site form to the soil variables selected by the procedure described.

Results

Site form of *V. ferruginea* as an indicator of site productivity

The site form can be estimated with model [1] or graphically (Fig. 2) by plotting the heights and diameters of individual trees and manually fitting the best curve. The linear pattern of the diameter-height relationship shown by data (Fig. 2) may be due to the lack of large trees (i.e., 50 dbh or higher and 32 m in height or higher), which has altered the expected typical form of a dbh-height curve.

The site form (i.e., the expected mean height at 25 cm dbh) varied widely between plots, from 16.2 m to 32.2 m. Furthermore, site form of *V. ferruginea* was strongly correlated with total plot basal area of all species ($r = 0.59$, $p = 0.0008$).

Substrate variation and site productivity

Correlation between site form and substrate variation

In terms of soil variation, the 29 sample plots were located on slopes from 4-42%, with most plots in intermediate topographical positions and concave form. Soils were loamy, loamy-sandy, loamy -clay and clay (Table 3). An interpretation of soil fertility, according to the criteria defined by Bertsch (1987) for agronomic use, showed the following: pH was < 5.5 in all sample plots; the values of exchangeable acidity (Al in Table 3) were high at both soil depths, and the aluminum saturation (Al sat. in Table 3) was found to be in very high percentages (> 50%); the cations Ca, K and Mg were found in low concentrations, Mn was present at intermediate to high levels; P was found at intermediate to low concentrations (Table 3), probably attributed to the low pH and the presence of high concentration of Al and Fe (Sánchez, 1982); organic matter (o.m in Table 3) percentages were relatively high; Fe was found at very high levels, while Cu and Zn were considered intermediate.

Strong correlations ($p < 0.005$) between site form and 26 soil variables were found for both soil depths (Table 4). Slope percentage, plot topographical position and plot exposition, however, did not show correlation ($p < 0.05$) with site form. Variables related to soil texture, except the percentage of silt, presented correlation coefficients higher than 0.56, with the percentage of sand at 12-3 0cm of soil depth ($r = 0.77$, Table 4) showing the highest correlation.

The pH values at both soil depths, showed negative correlations with site form. Interchangeable Al and

Table 3. Mean, minimum and maximum for soil variables assessed for *V. ferruginea* plots (n = 29)

	pH	Ca	Mg	K	Al	ECEC	P	Cu	Fe	Mn	Zn	Al sat.	o.m.	Sand	Silt	Clay
		cmol (+)/L					mg/L					%				
Minimum	4.1[1]	0.2	0.2	0.04	0.23	2.6	2.5	4.5	160	4.7	1.8	2	2.0	20	8	21
	4.3[2]	0.1	0.1	0.03	0.37	2.9	2.6	6.4	94	3.9	1.5	5	2.3	15	7	33
Mean	4.7[1]	2.4	1.1	0.11	1.97	5.5	11.0	16.1	2,058	32.0	6.7	47	8.1	41	15	44
	4.7[2]	1.6	0.7	0.08	2.22	4.6	11.0	18.5	2,316	35.0	6.3	59	5.2	33	14	33
Maximum	5.4[1]	7.8	3.7	0.25	3.80	12.3	21.0	33.4	6,907	123	23.0	89	12.4	59	45	62
	5.5[2]	6.9	2.7	0.17	3.60	9.3	19.8	40.7	7,596	120	23.0	94	7.4	47	29	47

[1] 0-12. [2] 12-30. ECEC:effective cation exchange capacity. Al sat.: aluminum saturation. o.m.: organic matter. At the Florencia site, predominant soils are Inceptisols (Typic Dystropepts, Vásquez, 1994) originated from volcanic mudflows, while at the Cureña sites, soils are Ultisols (Humic Hapludults, Herold, 1994) originated from alluvial deposits. The Inceptisols presented a relatively higher acidic conditions, lower bases saturation, lower aluminium concentration, as well as lower percentages of sand and higher percentages of clay than the Ultisols (Herrera and Alvarado, 2001). These differences yield the high variability observed in the individual soil variables.

percentage of Al saturation showed positive correlations: between 0.53 and 0.67. Ca and Mg concentrations at both soil depth, and K at 0-12 cm, displayed negative correlations: between –0.57 and –0.63 (Table 4). P soil content (0-12 cm) presented a poor positive correlation ($r = 0.43$, $p = 0.0216$) with site form (Table 4).

The Cu soil content at both soil depths showed the second highest correlation ($r_{0\text{-}12} = -0.66$ and $r_{12\text{-}30} = -0.67$) with site form. Meanwhile, Mn at both depths and Zn content between 0-12 cm, showed negative correlations with the same variable. Fe soil content showed positive correlations between 0.41 and 0.48 (Table 4).

Regression model

Equation [2] was found to best predict site form (SF) using soil variables.

$$SF = 9.560 + 0.413\ \%sand_{(12\text{-}30\ cm)} \qquad [2]$$

$r^2 = 0.593$, adjusted $r^2 = 0.578$, standard error = 3.0 m

The variance explained by model [2] (59.3%) and its low standard error indicates its good predictive value, particularly considering the numerous factors that could affect forest productivity. The use of one independent variable in model [2], which is relatively easy to measure in the field and requires low laboratory costs, also offers great practical usefulness.

Discussion

Height-diameter relationships have a good potential to provide reliable indicators of site quality in natural tropical forests. In particular, site form appears to be a useful indicator of site productivity (e.g., basal area) for broadleaved neotropical secondary rainforest stands; this is supported by its high between-plot variability, significant correlation with other site productivity indicators and significant correlations with soil factors. Vanclay (1994) also reported significant correlations of site form with the basal area and periodic annual volume increment of a *Callitris* forest in Australia. Regarding soil factors, many studies have showed the relevance of individual chemical and physical soil factors in the productivity of even-aged forest (e.g., Marques, 1991; Herrera and Alvarado, 1998; Herrera *et al.*, 1999). Moreover, some of the observed variation in site form may be attributed to other sources such as genetic factors and inter-tree competition (Campos, 1989). The results suggest that site quality effects the production of timber, and therefore it is necessary to take into account site productivity in the development of models of stand dynamics, growth and yield in secondary forest.

Due to the above-mentioned characteristics, site form could be considered a more practical measure of site productivity for broadleaved tropical forests than those that require the age of the stand for the site quality estimation (e.g., dominant height). Nevertheless, the database used for the purposes of this research has deficits since the expected typical sigmoid shape of height-a diameter curve was not observed. It is highly recommended that future studies include older stands with larger trees in order to improve the expected shape of height-diameter curve, and thus improve site form

Table 4. Correlation coefficients (probability associated) between site form of *V. ferruginea* and soil variables

Soil variable	Unit	Pearson's coefficient of correlation (r)
pH[1]	—	–0.51 (0.0050)
pH[2]		–0.49 (0.0072)
Ca[1]		–0.62 (0.0004)
Ca[2]		–0.64 (0.0002)
Mg[1]		–0.57 (0.0013)
Mg[2]	cmol (+)/L	–0.60 (0.0006)
K[1]		–0.57 (0.0012)
Acidity[1]		0.58 (0.0010)
Acidity[2]		0.53 (0.0029)
ECEC[1]		–0.57 (0.0013)
ECEC[2]		–0.62 (0.0003)
P[1]		0.42 (0.0216)
Cu[1]		–0.66 (0.0001)
Cu[2]		–0.67 (0.0001)
Fe[1]	mg/L	0.48 (0.0087)
Fe[2]		0.41 (0.0273)
Mn[1]		–0.56 (0.0017)
Mn[2]		–0.59 (0.0008)
Zn[2]		–0.38 (0.0425)
Al. sat.[1]		0.64 (0.0002)
Al sat.[2]		0.67 (0.0001)
Sand[1]		0.65 (0.0001)
Sand[2]	%	0.77 (0.0001)
Silt[2]		–0.41 (0.0273)
Clay[1]		–0.64 (0.0002)
Clay[2]		–0.56 (0.0015)

[1] 0-12 cm. [2] 12-30 cm. ECEC: effective cation exchange capacity. Al sat.: aluminum saturation. o.m.: organic matter. Only significant correlations ($p < 0.05$) are shown.

estimations. However, it should be taken into account that stands with those characteristics are not common in Northern Costa Rica because of the recent progress of agricultural development in this region. Furthermore, it is required to test the association of site form with the increment in stand volume and the effect of thinning in this attribute (Vanclay 1988, 1994), in order to establish a direct relation to site productivity (Clutter *et al.,* 1983).

In terms of the associations between soil variables and site form, the positive correlation found in this research between percentages of sand is similar to those obtained in a previous research by Herrera *et al*. (1999), who reported a negative correlation between site productivity of *V. ferruginea* in a secondary forest that was indirectly estimated by the dominant height and soil clay content. The correlation could be associated with better root development and internal drainage at higher values of this soil variable (Donahue *et al*., 1977). The associations found between soil base content, soil acidity, and site form confirms the well-known adaptation of *V. ferruginea* to grow in acidic and low nutrient soils (Pérez *et al*., 1993; Herrera and Finegan, 1997; Herrera *et al*., 1999; Herrera and Alvarado, 2001). In this research, P showed a positive association with site productivity. This result contrasts with those reported by Herrera *et al*. (1999), who found a negative correlation ($r = –0.59$, $p = 0.001$) between P and the dominant height (as indicator of site productivity) of *V. ferruginea* in a secondary forest. This difference can be explained in terms of the possible capacity of this species to growth under different nutrient conditions (Haridasan and Monteiro de Araujo, 1988; Pérez *et al.,* 1993). However, it should be taken into account that in most cases P concentration was below 14 mg/L, level that, for most species growth, is considered low (Bertsch, 1995).

The results here presented confirm that *V. ferruginea* is well adapted to acidic and infertile soils. In this sense, it appears necessary to design specific research that provides more information on the relationships found between Al concentration, soil interchangeable bases, P content and productivity of *V. ferruginea.* Special interest, due to scarce research (Haridasan and Monteiro de Araujo 1988), is to investigate the response of this species to higher soil fertility conditions in terms of reduced aluminium uptake and increased uptake of other nutrients.

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