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Vochysia guatemalensis Donn. Smith, an alternative species for reforestation on acid tropical soils

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Abstract *Vochysia guatemalensis* Donn. Smith is a native species commonly used in small-scale reforestation programs in Costa Rica recognized for its fast growth under acidic and unfertile soil conditions. This study aimed to evaluate the nutrient concentration dynamics on individual trees of *V. guatemalensis* of increasing ages, in order to improve the understanding some aspects of its ecology as well as management of this tree species. Nutrient (N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, and B) and Al concentration in stems, branches and foliage were measured using false time series (also known as chronosequences) in 13 different tree stands (2–21 years) found in the Caribbean lowlands of Costa Rica. N, K and S concentrations in the stems showed a significant inverse relationship with DBH; while P, S, and Cu foliar contents increased with DBH. Average foliar concentrations of N, Ca, K, Mg, Fe, Zn, Mn, B, and Al showed little or no variation with tree growth. Foliar Al concentration (21, 297–28, 826 mg kg^{-1}) was higher than previously reported as toxic for non-Al accumulating species (<1000 mg kg^{-1}), confirming *V. guatemalensis* as an Al hyper accumulator. Our results reinforce the possibility of using *V. guatemalensis* for timber production, especially to improve the income of small farmers farming on very acidic soils. The nutrient concentrations that were obtained for different tree components provide baseline information for further studies where the objective is to evaluate the nutritional status of a site.

Keywords White Yemeri · Forest nutrition · Foliar nutrient concentration · Small-scale planted forests · Al tolerance, tropical lowland forest

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Introduction

Vochysia guatemalensis (Donn. Smith) is a native tree species from Northern Latin America, where it grows naturally on gentle slopes of tropical wet forests, and is associated with *Vochysia ferruginea* Mart. amongst other species. This tree species is used in small-scale forest plantations due its fast growth and prominent development on low fertility sites (Pérez et al. 1993; Arias 1994; Butterfield and Espinoza 1995; Montagnini et al. 2003; Alice et al. 2004; Piotto et al. 2010). In Costa Rica, about 1000 ha have been planted with *V. guatemalensis*, at a rate of 10 ha year^{-1} up until the 1990s and 50 ha year^{-1} since 2000 (Solís and Moya 2006). The productivity of this tree species is estimated to vary between 272 and 430 m^3 ha^{-1} for small-scale planted forests in rotations between 14 and 25 years (Alice et al. 2004; Petit and Montagnini 2004; Solís and Moya 2006; Piotto et al. 2010). Compared with *Gmelina arborea* or *Terminalia amazonia*, two other tree species grown in the same area, productivity indices obtained for *V. guatemalensis* are very similar and are considered as acceptable for reforestation in the region (Arias et al. 2011).

Vochysia guatemalensis, among other species, is adapted to low fertility soils with acidity problems (Herrera et al. 1999; Alvarado 2012). Those soils are considered as the most important group of soils in tropical areas (Lathwell and Grove 1986; Sánchez and Logan 1992). Therefore, knowledge about the tree nutritional status of *V. guatemalensis* is considered as critical in order to improve the knowledge of the trees basic ecology and to improve management recommendations in small-scale plantations where this tree species has been established.

Nutrient concentration in different aboveground biomass components varies depending on the species (provenances), site conditions, and stand management. Genetics also plays an important role in nutrient concentration dynamics as found for provenances of *V. guatemalensis* from Guatemala, Honduras and Costa Rica (Cornelius and Mesén 1997; González and Fisher 1997). In studies conducted in Costa Rica, nutrient concentration and accumulation in different aboveground biomass components of *V. guatemalensis* revealed seasonal variation, nutrient recycling and differences that were due to tree provenance (Montagnini et al. 1991; Pérez et al. 1993; Cornelius and Mesén 1997; González and Fisher 1997; Montagnini 2000; Arias et al. 2011). Nonetheless, very few of the published papers have focused on the dynamics of different nutrients over the plantation lifespan. Badilla (2012) carried out a study about nutrient concentration in aboveground biomass components of *V. guatemalensis* that ranged in age from 2 to 9 years, finding that macronutrients contents followed the tendency $N > K = Ca > Mg \gg S = P$, and minor elements followed the order $Al \gg Mn > Fe > B > Zn > Cu$. These results were similar to those found by Pérez et al. (1993) and González and Fisher (1997) in which the reported sequence was $Al \ggg Mn \gg Fe > Zn > B \gg Cu$. Regarding forest management, foliar analysis is a diagnostic tool widely used for the evaluation of nutritional status of a forest stand, the prediction of nutrient deficiencies and the design of fertilization plans (Drechsel and Zech 1991; Alvarado 2012).

Vochysia guatemalensis is considered an Al-hyper accumulator since the element concentration in the foliage is greater than 1000 mg kg^{-1} (Jansen et al. 2002), a result which has been documented in several different studies in Costa Rica (Pérez et al. 1993; González and Fisher 1997; Cornelius and Mesén 1997; Badilla 2012; Camacho 2014). The ability of *V. guatemalensis* to be an Al-hyper accumulator is of particular importance since the concentrations of other nutrients are not altered. This is also a property common to other species of the Vochyseaceae family (Chenery and Sporne 1976; Jansen et al. 2002) like *Qualea grandiflora*, *Qualea multiflora*, *Qualea parviflora*, *Vochysisa eliptica* and *Vochysia thysoidea* (Haridasan 1982; Geoghegan and Sprent 1996), where high foliar Al values ranging from 1012 to 16,390 mg kg^{-1} were observed. Although observed concentrations of Al are large and very much over toxicity values described for other tropical forest species (Cronan and Grigal 1995; Ericsson et al. 1995; Lenoble et al. 1996a, b; Yang et al. 2013), these concentrations did not affect growing of broad-leaved species at the Central Cerrado of Brazil (Haridasan 1982; Geoghegan and Sprent 1996).

For the research described in this paper, we defined core objective as: to assess the nutrient concentration dynamics in the components of the aboveground biomass of trees, i.e. branches, foliage and stem in stands ranging from 2 to 21 years old, aiming to understand specific ecological aspects of this tree species in order to develop improved management plans for plantations where the goal is sustainable wood production.

Materials and methods

Study area

Study sites were located in Las Mercedes de Guácimo, near the EARTH University campus, in the Caribbean lowlands of Costa Rica (Fig. 1) that are located at 50–100 m.a.s.l. The region is bioclimatically classified as tropical wet forest (basal and Premontane) according to Holdridge's life zones (Holdreige 1967); with a climate characterized by an average annual precipitation of 3000–4000 mm without a defined dry season. Soils of the study area have high organic matter content, good drainage, low fertility and high acidity. Soil data were adapted from Badilla (2012) and are summarized in Table 1. Soils in this area are classified as Andic Humudepts and Typic Humudepts developed on volcanic sediments deposited as eolian or alluvial materials (Sancho et al. 1989).

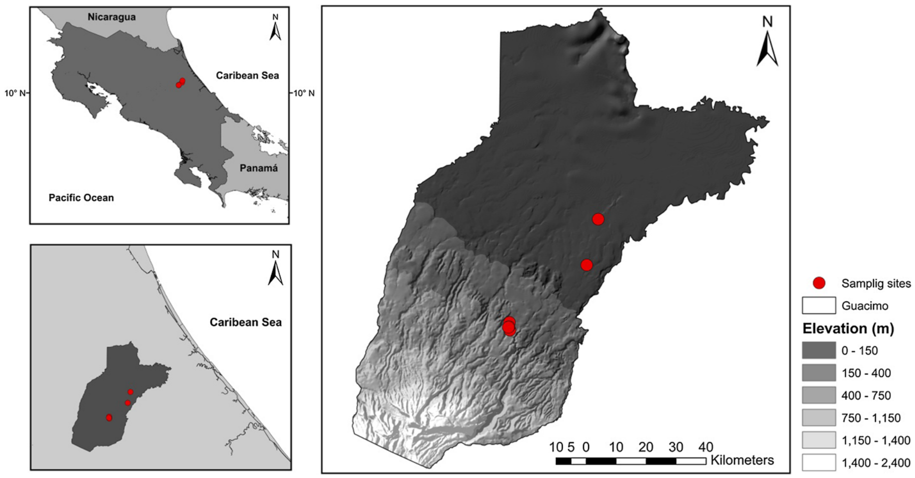

Fig. 1 Study area at Guácimo, Caribbean lowlands of Costa Rica. *Red points* represent the location of the 13 sampling points in *Vochysia guatemalensis* small scale forest plantations. (Color figure online)

Table 1 Soil fertility parameters in the *Vochysia guatemalensis* plantations at Guácimo, Caribbean lowlands of Costa Rica

Parameter	Units	Values
pH		4.8* (7)
Ca	[cmol (+) L^{-1}]	3.4* (90)
Mg	[cmol (+) L^{-1}]	1.5 (92)
K	[cmol (+) L^{-1}]	0.1* (94)
Acidity	[cmol (+) L^{-1}]	1.3* (81)
ECEC*	[cmol (+) L^{-1}]	6.3 (64)
P	[mg L^{-1}]	3* (52)
Zn	[mg L^{-1}]	3 (45)
Cu	[mg L^{-1}]	9 (34)
Fe	[mg L^{-1}]	120 (20)
Mn	[mg L^{-1}]	35 (57)
OM*	%	5.9 (44)
AS*	%	28* (88)

Coefficients of variation of means are in parentheses. Number of samples = 6. Soils of the region are classified as Typic and Andic Humudepts. Data adapted from and Badilla (2012)

ECEC effective cation exchange capacity, *AS* acidity saturation, *OM* organic matter

* Values outside the adequate reference soil levels (Bertsch 1998)

Field sampling, design and laboratory analysis

The false time series method (i.e., chronosequences) was used to analyze the nutrient concentration dynamics of White Yemeri with respect to tree age. Despite critiques of this method (Johnson and Miyanishi 2008), the false time series method is considered to be

Table 2 Site description of the different sampled stands of *Vochysia guatemalensis* studied at Guacimo, Caribbean lowlands of Costa Rica

Age (years)	DBH (cm)	Height (m)	Total aboveground biomass (kg $tree^{-1}$)
2	7	4.2	7
3	12	4.8	25
4	14	7.2	26
3	14	7.6	38
5	18	12.3	60
10	22	17.3	136
8	25	18.7	224
9	25	19.3	197
14	27	19.2	254
11	28	23.3	255
16	29	21.8	209
21	41	29.3	710
13	42	27.4	463

valid since all the studied stands are assumed to be under similar environmental conditions (e.g., soil and climate) and management practices. Thirteen tree stands were chosen within the study area, ranging from 2 to 21 years old and from 7.5 to 41.5 cm based on diameter at breast height (DBH) (Table 2). In each stand, dominant and co-dominant trees were selected, assuming optimal nutritional state and an excellent expression of genetic potential. These trees were representative of the plantations and no symptoms of disease or nutritional deficiency were detected. In plantations <10 years old two trees were sampled in each plot, but only one tree per stand was taken in the older plantations. Once trees were selected, DBH and height were measured. Selected trees were then felled and stem, branch and leaf components were separated and weighed. Subsamples of each component were transported to the University of Costa Rica for further analyses. Concentrations of P, Ca, Mg, K, S, Fe, Mn, Cu, Zn, B and Al were determined using an atomic absorption spectrometry model ICP OES Perkin Elmer optima® 8300, following the methodology described by Kalra (1998). Concentration of N was obtained by dry combustion in an autoanalyzer Elementar® rapid No 3. This work was conducted during the beginning of rainy season, between April and May 2013.

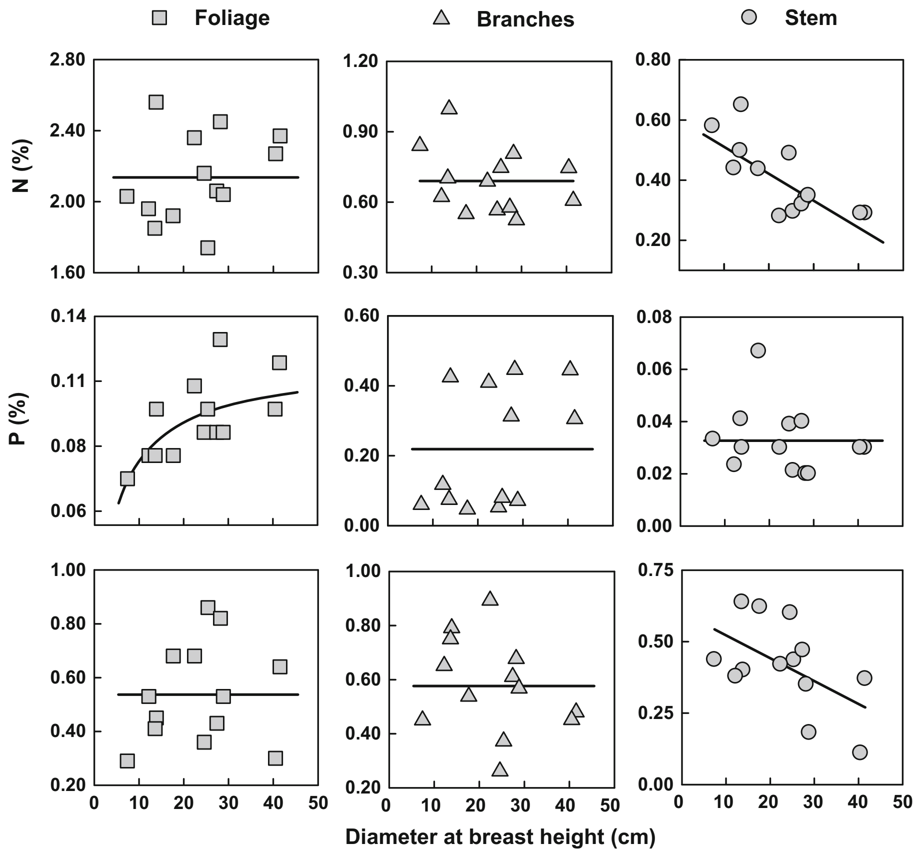

Fig. 2 Concentration dynamics of N–P–K related to DBH for aboveground biomass components of *Vochysia guatemalensis* trees in small scale forest plantations at Guácimo, Caribbean lowlands of Costa Rica. *Black lines* represent fitted models (Table 3)

Table 3 Regression models for macronutrient concentration (*y*) for different aboveground biomass components of *Vochysia guatemalensis* trees in relation to DBH (*x*) in small scale forest plantations in the Caribbean lowlands of Costa Rica

Component	Macronutrient (%)	Selected model	X	X (E.E)	b_0	$b_{0\ (E.E)}$	b_1	$b_{1(E.E)}$	R^2
Foliage	N	$y = x$ (average)	2.1	0.07					
	P	$y = (b_o + b_1x^{-1})^{-1}$			8.32	0.73	45.95	11.95	0.573
	Ca	$y = x$ (average)	1.2	0.08					
	Mg	$y = x$ (average)	0.4	0.02					
	K	$y = x$ (average)	0.5	0.05					
	S	$y = (b_o + b_1x^{-1})^{-1}$			3.49	0.46	26.75	7.48	0.537
Branches	N	$y = x$ (average)	0.7	0.04					
	P	$y = x$ (average)	0.2	0.05					
	Ca	$y = x$ (average)	0.6	0.05					
	Mg	$y = x$ (average)	0.3	0.04					
	K	$y = x$ (average)	0.6	0.05					
	S	$y = x$ (average)	0.2	0.05					
Stem	N	$y = b_o + b_1x$			0.6	0.1	−0.01	0.002	0.587
	P	$y = x$ (average)	0.03	0.003					
	Ca	$y = x$ (average)	0.21	0.017					
	Mg	$y = (b_o + b_1x^{-1})^{-1}$			6.6	1.339	64.9	21.823	0.446
	K	$y = b_o + b_1x$			0.60	0.096	−0.008	0.004	0.286
	S	$y = b_o + b_1x$			0.07	0.010	−0.001	0.0004	0.353

When the model was not statistically significant, the average (X) was calculated from the concentration

X concentration mean, *EE* mean standard error

Coefficients b_0 and/or b_1 were statistically significant ($p < 0.05$)

Statistical analysis

Linear mixed models were fitted for each aboveground biomass component (foliage, stem and branches), where DBH was considered the independent variable and the element concentration (N, P, Ca, Mg, K, S, Fe, Mn, Cu, Zn, B and Al) was considered the dependent variable. For each element, we tested the following models: (1) null hypothesis, using the form [$y = b_0$], i.e., no effects of DBH on nutrient concentration; (2) a linear model including intercept and slope [$y = b_0 + b_1x$] and (3) a model without intercept [$y = b_1x$]. Models were tested with original dates (no processed) and also in a transformed dataset using natural logarithm form (*ln*) and inversed form (x^{-1}), with the aim to improve their adjustment, as proposed by other authors (Chave et al. 2001, 2005; Montero and Montagnini 2006; Basuki et al. 2009; Fonseca et al. 2009). Hence, a total of 27 models were evaluated for each component and each nutrient. When none of these models presented statistical significance, the average of the data was calculated and the respective standard error was assessed. For models that were natural logarithm transformed (*ln*) a

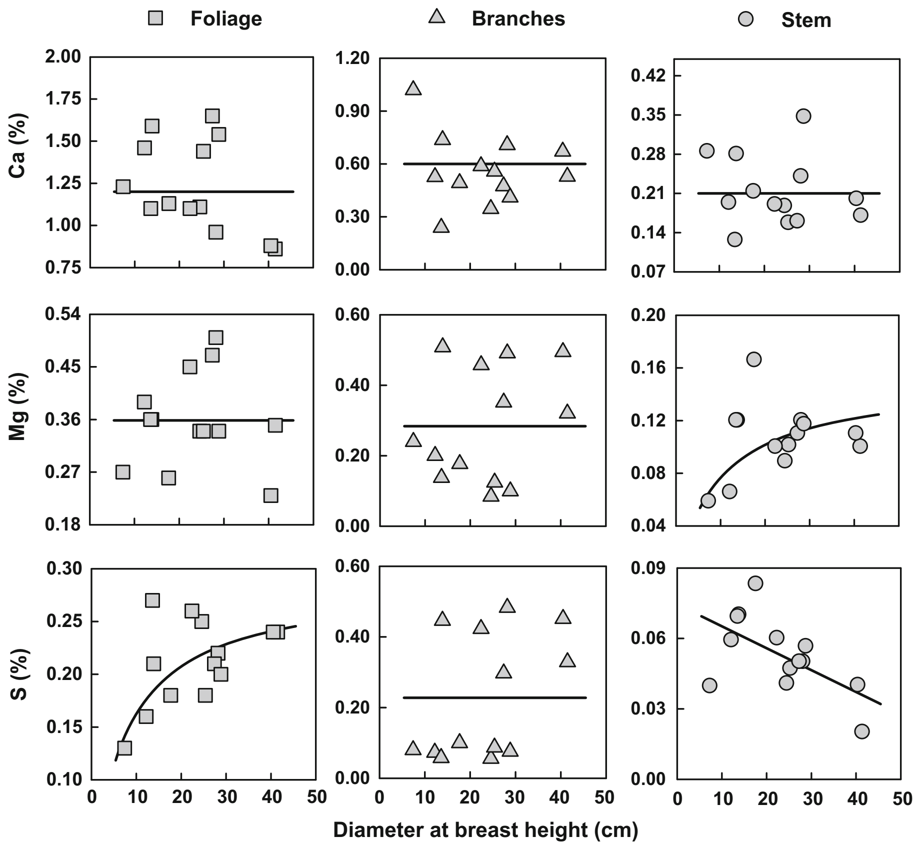

Fig. 3 Concentration dynamics of Ca–Mg–S related to DBH for aboveground biomass components of *Vochysia guatemalensis* trees in small scale forest plantations at Guácimo, Caribbean lowlands of Costa Rica. *Black lines* represent fitted models (Table 3)

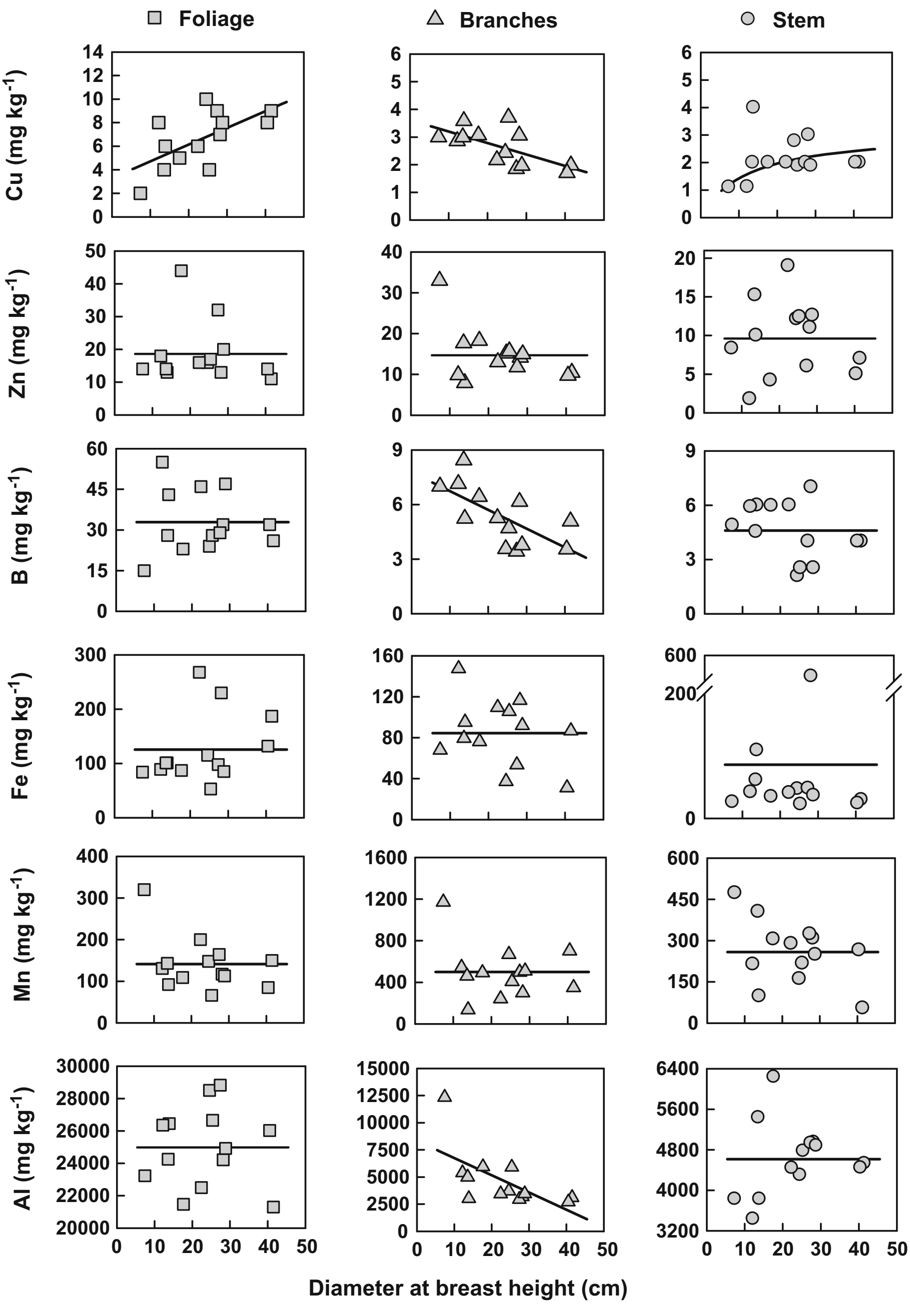

Fig. 4 Concentration dynamics of Cu–Zn–B–Fe–Mn–Al related to DBH for aboveground biomass components of *Vochysia guatemalensis* trees in small scale forest plantations at Guácimo, Caribbean lowlands of Costa Rica. *Black lines* represent fitted models (Table 4)

Table 4 Regression models for minor nutrient concentration (*y*) for different aboveground biomass components of *Vochysia guatemalensis* trees in relation to DBH (*x*) in small scale forest plantations in the Caribbean lowlands of Costa Rica

Component	Micronutrient (mg kg^{-1})	Selected model	X	X (E.E)	b_0	b_0 (E.E)	b_1	$b_{1(E.E)}$	R^2
Foliage	Fe	$y = x$ (average)	125.4	17.64					
	Cu	$y = b_0 + b_1x$			3.295	1.360	0.1	0.054	0.390
	Zn	$y = x$ (average)	18.6	2.57					
	Mn	$y = x$ (average)	141.4	17.87					
	B	$y = x$ (average)	32.9	3.17					
	Al	$y = x$ (average)	24,979	676.3					
Branches	Fe	$y = x$ (average)	84.5	9.00					
	Cu	$y = b_0 + b_1x$			3.611	0.377	−0.041	0.015	0.414
	Zn	$y = x$ (average)	14.7	1.76					
	Mn	$y = x$ (average)	498.9	71.30					
	B	$y = b_0 + b_1x$			7.769	0.871	−0.10	0.034	0.450
	Al	$y = b_0 + b_1x$			8336	1476	−158.6	58.11	0.404
Stem	Fe	$y = x$ (average)	86.1	42.95					
	Cu	$y = (b_0 + b_1x^{-1})^{-1}$			0.318	0.089	3.828	1.448	0.389
	Zn	$y = x$ (average)	9.6	1.33					
	Mn	$y = x$ (average)	258.6	31.85					
	B	$y = x$ (average)	4.6	0.43					
	Al	$y = x$ (average)	4616	202.9					

When the model was not statistically significant, the average (X) was calculated from the concentration

X concentration mean, *EE* mean standard error

Coefficients b_0 and/or b_1 were statistically significant ($p < 0.05$)

correction factor was calculated as suggested by Sprugel (1983). Models were fitted using Sigmaplot® version 11.0 and InfoStat® version 2011 software packages.

Results

The highest concentrations of nitrogen (N) were found in foliage (1.7–2.5 %), surpassing those found in the stem and branches (Fig. 2; Table 3). Nitrogen concentration in the foliage and branches did not vary with the DBH, suggesting that N is not limiting factor for growth of *V. guatemalensis* in the study region. Stem N concentration showed a decreasing tendency with DBH (p value <0.05). We assume that this result was a consequence of wood production with age where N and other elements concentration are the lowest (Fig. 2; Table 3).

The highest P concentrations were found in branches (0.40–0.45 %), followed by foliage (0.08–0.13 %) and stem (0.04–0.07 %). P concentration in branches and stem were not related to DBH (Fig. 2; Table 3), while in the foliage, P concentration increased positively with DBH (p value <0.05).

The highest K content was found in branches (0.79–0.89 %), followed by foliage (0.82–0.86 %). A decreasing tendency was observed between K stem concentration and DBH (p value <0.05), while no relation between K concentration and DBH was observed in the foliage or branches, respectively (Fig. 2; Table 3).

No relationship was found between Ca concentration and DBH for any of the three components studied (Fig. 3; Table 3). Similarly, no relationship between Mg concentration in branches or foliage and DBH was observed, while there was a positive relationship between Mg stem concentration and DBH. The concentration of S in the stem presented a similar behavior as K, while no tendency was observed in branches. Stem had the highest values of S (from 0.48 to 0.42 %). The S in the leaves increased in relation to DBH increase (Fig. 3; Table 3).

Fe, Mn and Zn concentrations did not show any relationship with DBH for any of the three components studied (Fig. 4; Table 4). For Cu, a positive relationship with DBH was found for foliage and stem, while for Cu, B and Al content in branches, a negative relationship with DBH was found. B and Al did not vary with DBH in stem and foliage. The concentration of Al in the foliage (21,297–28,826 mg kg^{-1}) was than the observed concentrations in stems and branches (2710–12,346 and 3434–6237 mg kg^{-1}, respectively).

Discussion

Nutrient status on aboveground components of *V. guatemalensis* trees

Despite the very low fertility parameters found for the soils in the area under study (Table 1), overall trees showed relative good growth (Table 2) according to the site index curve developed by Barraza and Días (1999) for tree species grown in the lowland humid tropics of Costa Rica. Nonetheless, under these soil conditions, newly established stands of some tree species like *Gmelina arborea* or *Tectona grandis* could present high mortality or significant reductions in growth rates for those trees that survive, due to high acidity or low availability of Ca, Mg or K (Zech and Drechsel 1991; Stuhrmann et al. 1994). Based on our results for *V. guatemalensis,* we propose that this tree species has a competitive advantage over teak and melina due to its better adaptability to low pH and high Al in soils.

Foliar N concentrations found in this study were higher than the references values found in the literature for other tropical species originating from the same region (Drechsel and Zech 1991; Fernández-Moya et al. 2013). Although N is sometimes considered the most limiting nutrient in many terrestrial ecosystems, several authors have reported that N is not a limiting factor for growth in old tropical forest-soil ecosystems (Vitousek 1984; Jordan 1985; Sánchez 1985; Hedin et al. 2009).

Nitrogen concentration in aboveground biomass components decreased with tree age as a result of: (a) the low amounts of N observed in the soil, which is not enough to maintain high growth or productivity rates, (b) the low uptake rates and high rates of translocation, and (c) the growth dilution effect, which can be explained in terms plant biomass and structural components that increase with age (Gower et al. 1996; Ryan et al. 1997; Binkley et al. 2002; Yuan et al. 2007; Hedin et al. 2009; Fernández-Moya et al. 2013).

Foliage P concentration increments with tree growth may indicate that this nutrient might be limiting the system's productivity. This fact has been reported as a common forest nutrition issue by several other authors (for a revision see Fox et al. 2011). Several authors found a reduction in K stem concentrations related with age in other tree species (Gower et al. 1996; Ryan et al. 1997; Montero 1999; Binkley et al. 2002; Fernández-Moya et al. 2013); this fact is being attributed to K translocation from the stem to the leaves to keep the adequate levels that hold the hypothetical greatest K requirements in larger mature trees, especially considering the role of this element in stomatal aperture and water regulation (Fernández-Moya et al. 2013).

The N, P and K concentrations obtained in the present study were considered as adequate when compared with results published by other authors (Montagnini et al. 1991; Pérez et al. 1993; Cornelius and Mesén 1997; González and Fisher 1997; Montagnini 2000). Nonetheless, the foliar P concentration indicated levels below those reported as adequate by Drechsel and Zech (1991). Several studies on nutrients supply in tropical forest systems reported P as the most limiting nutrient to primary productivity in highly developed tropical soils and very efficient P users (Herbert and Fownes 1995; Vitousek and Farrington 1997; Harrington et al. 2001; Davison et al. 2004). In addition Rao et al. (1999) reported that these tree species develop genetic and physiological adaptation mechanisms (i.e. root morphology changes) and partition P (retranslocation in the plant) in a way that helps the trees to grow efficiently in soils with low P availability.

The above mentioned for P is particularly true for Al hyper accumulator species (Foy et al. 1978; Cuenca et al. 1990; Jansen et al. 2002; Watanabe and Osaki 2002; Kochian et al. 2004). Geoghegan and Sprent (1996) studying 40 species from the Cerrado and neighboring regions of Bahía and Minas Gerais, found 20 species with Al foliar content above 10,000 mg kg^{-1}. Also, these same authors found examples where the content of P and K in the foliage was low (deficient according the literature) and explained that this is a common result in native species like *Chamaecrista repens* and *Chamaecrista viscose.* The low foliar content of P and K in hyper accumulators has been documented by Foy (1988). For *V. guatemalensis,* several prior studies confirmed our results previously described (González 1996; González and Fisher 1997; Young 2009).

The Ca, Mg and S concentrations found in the present study for the different aboveground biomass components agreed with those reported in the literature for the same species (Montagnini et al. 1991; Pérez et al. 1993; Cornelius and Mesén 1997; González and Fisher 1997; Montagnini 2000). The adequate micronutrient levels for stands growing on degraded lands have been previously documented for *V. guatemalensis* (Butterfield and

Fisher 1994; Fisher 1995; Haggar et al. 1997; Carpenter et al. 2004). The micronutrient balance mechanisms can be considered a way to perform of adapted species to this kind of ecosystems. The average concentrations of micronutrients found in the present study were higher than those considered as deficient, and slightly lower than those reported as intermediate for 40 tropical and subtropical broadleaved species in Africa (Drechsel and Zech 1991). Our results were in agreement with previous findings by other authors for *V. guatemalensis* (Montagnini et al. 1991; Pérez et al.1993; Cornelius and Mesén 1997; González and Fisher 1997; Montagnini 2000).

It should be noted that Al concentration in the three tree components was higher than what was reported as adequate by Drechsel and Zech (1991). Indeed, the Al concentration values were above the Al toxicity ranges proposed for most tropical species (Cronan and Grigal 1995; Ericsson et al. 1995; Lenoble et al. 1996a, b). High Al concentrations can lead to different types of damage including: (i) inhibition of root elongation and cell division, (ii) damage in the formation of DNA molecules, (iii) changes to both the fluidity and permeability of cell membranes, (iv) reduction of ATPase activity linked to membranes, (v) inhibition of the absorption of calcium, and (vi) phosphate precipitation (Cronan and Grigal 1995; Ericsson et al. 1995; Lenoble et al. 1996a; Yang et al. 2013). However, none of these damages were observed in the present study. We hypothesize that this is due to the Al hyperaccumulation capacity of *V. guatemalensis*, as previously reported by several authors (e.g. Chenery and Sporne 1976; Cuenca et al. 1990; Pérez et al. 1993; Cornelius and Mesén 1997; González and Fisher 1997).

Adaptability of *V. guatemalensis* to unfertile and acid soils

The ability of *V. guatemalensis* to survive with high levels of foliar Al has been attributed to the Al absorption by the rhizosphere as Al chelate and the subsequent translocation to leaves where it is deposited in the epidermis; as it is in this tissue that Al will not harm the plant (González and Fisher 1997). Other authors described different mechanisms that explain this interaction, including, the translocation of Al oxalate to vacuoles, Al phosphate complexes, or Al sequestration by substances such as citrate and other organic acids (Foy et al. 1978; van Praag and Weissen 1985, 1986; Cuenca et al. 1990; Masunaga et al. 1998; Shen et al. 2002; Watanabe and Osaki 2002; Kochian et al. 2004).

The capacity of *V. guatemalensis* to accumulate high quantities of Al probably represents an adaptation to very acidic soils (Table 1), as mentioned by several different authors (Jansen et al. 2002; Watanabe and Osaki 2002; Fournier 2002; Young 2009). This soil acidity problem represents a common issue in many sites throughout the tropics (e.g. Lathwell and Grove 1986; Sánchez and Logan 1992). Hyper accumulator species such as Vochysiae are prevalent in the early successional series of tree species (Jansen et al. 2002), most likely due to the ability to accumulate Al and survive on acidic and infertile soils. This observation is considered a primitive character of these tree species in tropical rain forest (Chenery and Sporne 1976). Given this ability to accumulate Al, *Vochysiae spp.* represent a very good alternative for reforestation in areas of highly acidic soils, either with an environmental, social or productive objective. Indeed, *V. guatemalensis* represents a very good choice to be established in small-scale private plantations in acid soils, where it will probably adapt and grow faster than other non-adapted forest species.

The results of the present study provide a reference for evaluating the nutritional status of White Yemery stands under similar site and management conditions. Foliar nutrient concentration is considered a useful management tool for evaluating the nutritional status of planted trees because it is a sensitive indicator of nutritional deficiencies and productivity in tropical tree species stands (Drechsel and Zech 1991; Barker and Pilbeam 2006; Lehto et al. 2004, 2010). Studies on foliar concentration values can be used as a guide to determine best management practices of tropical fast growing species like *V. guatemalensis.* This will help to more accurately define where nutrient deficiencies exist and to management those nutrients appropriately in order to achieve sustainable tree and timber production. Another way to utilize foliar concentration values is to quantify the extraction of toxic elements such as Al, for example, the removal of soil extractable Al by *V. guatemalensis* could work as a bioremediation process that improves soil properties for small landholder production of Al-adpated agricultural species like: cassava (*Manihot sculenta*), tall rain-feed rice (*Oriza sativa*), tea (*Camellia sinensis*), coffee (*Coffea arabiga*) or pineapple (*Annanas comosus*), as well as tolerant forestry species like: *V. ferruginea*, *Virola koschnyi*, *Hieronyma alchorneoides*, *Calophyllum brasiliense*, *Dipteryx panamensis*, and *Terminalia amazonia*, as mentioned by Montagnini (2000, 2007).

Conclusions

In general terms, the concentrations of nutrients in the different components of the tree (foliage, stem and branches) were not influenced by the variation in DBH. However, the stem concentration of N, K and S decreased as the DBH increased, while the Mg and Cu stem concentration increased with DBH. The Al concentration in the studied tree components was very high, especially in the foliage (21,297–28,826 mg kg^{-1}), confirming the ability of *V. guatemalensis* to growth under circumstances otherwise considered as Al toxicity. Conversely foliar P contents were considered low when compared to previously published values for the element. Values obtained in present study can be considered as a reference for further studies on *V. guatemalensis*. Our results reinforce the potential of using *V. guatemalensis* for wood production as well as to improve grower income when tree species are produced on very acidic soils.

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