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ACCUMULATION AND EXPORT OF NUTRIENTS IN HARVESTED WOOD OF *VOCHYSIA GUATEMALENSIS* IN SMALL-SCALE FOREST PLANTATIONS

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To enhance knowledge required for better management of tropical forest plantations, aboveground nutrient accumulation in different tree tissues (stem, branches, foliage and total) at different growth stages of *Vochysia guatemalensis* (white yemeri) was studied. False time series were used from 16 small farmer sites in humid tropical lowlands of Costa Rica. A 17-year-old stand with density of 483 trees ha^{-1} and 35 cm diameter at breast height (dbh) accumulated 818 kg ha^{-1} N, 686 kg ha^{-1} K, 552 kg ha^{-1} Ca, 284 kg ha^{-1} Mg, 114 kg ha^{-1} P, 152 kg ha^{-1} S, 11 kg ha^{-1} Fe, 101 kg ha^{-1} Mn, 0.5 kg ha^{-1} Cu, 2 kg ha^{-1} Zn, 1 kg ha^{-1} B and 1063 kg ha^{-1} Al. The expected nutrient export by timber harvest (stem) was 499 kg ha^{-1} N, 485 kg ha^{-1} K, 314 kg ha^{-1} Ca, 188 kg ha^{-1} Mg, 46 kg ha^{-1} P, 69 kg ha^{-1} S, 8 kg ha^{-1} Fe, 29 kg ha^{-1} Mn, 0.5 kg ha^{-1} Cu, 1.4 Zn, 0.6 kg ha^{-1} B and 783 kg ha^{-1} Al. Aluminium accumulation was higher than other nutrients, confirming that *V. guatemalensis* is an Al-hyperaccumulator species. Aluminium exported as wood represented between 74–93% of the total accumulated, so large amounts of this element was taken out of the planting site during harvest. Nitrogen and K also had high percentages of accumulation. Thus, the management of this system should pay special attention to the dynamics of these three nutrients.

Keywords: White yemeri, forest nutrition, nutrient accumulation, small-scale planted forests, Al tolerance, tropical lowland forest

INTRODUCTION

Forest plantations with native species are increasing throughout the wet tropics due to increased demand for timber products, high yields of these species and their ability to adapt to and even restore degraded lands (González & Fisher 1994, Arias et al. 2011). Plantations of white mahogany or white yemeri (*Vochysia guatemalensis*) in particular is popular due the desirable characteristics of the species, namely, its fast growth and prominent development even in low-fertility lands (Alice et al. 2004, Piotto et al. 2010). In Costa Rica, approximately 1000 ha have been planted with this species at a rate of 10 ha year^{-1} in 1990's to about 50 ha year^{-1} since 2000 (Solís & Moya 2006). The productivity of this species is estimated to vary from 272 to 430 m^3 ha^{-1} for small-scale planted forests in rotations from 14 to 25 years (Alice et al. 2004, Petit & Montagnini 2004, Solís & Moya 2006, Piotto et al. 2010).

Due its high growth rate and adaptation to low-fertility soils, *V. guatemalensis* is considered suitable for ecological restoration of degraded land and as alternative species in forestry production for small land owners with limited production possibilities or in mixed plantations (Alice et al. 2004, Montagnini 2007). Mineral nutrition management in these short-harvest period plantations is a key issue to get high and sustainable wood production, avoiding soil degradation and depletion (Herrera et al. 1999, Arias et al. 2011).

Nutrient accumulation in aboveground biomass components varies depending on species, soil 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 & Mesén 1997, González & Fisher 1997). Foliage has the highest concentrations of nutrients in aboveground biomass (Miller 1984, Turner & Lambert 2008). However, the large amount of dry matter accumulated in the stem makes this species an important sink of nutrients. These nutrients are removed from the system when the tree is harvested, and thus have direct impact on soil fertility of the plantation site. This soil depletion can cause a decrease in forest productivity during the second harvest (Fölster & Khanna 1997, Arias et al. 2011, Osman 2013).

The determination of nutrient accumulation in *V. guatemalensis* had always been carried out for short and specific periods and never at the later stages of its rotation period. Therefore, it becomes necessary to estimate the amounts of nutrients removed during the felling of a forest plantation in order to understand the relationship between soil fertility and tree nutrition. Findings about nutrient accumulation and dynamics in forestry species can be used to estimate (1) the amount of nutrients exported when stem is harvested (Arias et al. 2011), (2) maximum uptake rate during a rotation, nutrient recycling by non-exportable tissues such as branches and foliage (Laclau et al. 2003) and (3) minimum amount of fertiliser necessary for one cycle of production (Bertsch 1998, Alvarado 2012). Hence, the objective of this study was to evaluate the amount of nutrients accumulated in the aboveground biomass of 2–21-year-old *V. guatemalensis* using chronosequence approach in the Caribbean lowlands of Costa Rica.

MATERIALS AND METHODS

Study site

The study site is located in Las Mercedes de Guácimo, near the EARTH University campus in the Caribbean lowlands of Costa Rica (10° 8' N, 83° 39' W) at 50–100 m above sea level. The region is bioclimatically classified as tropical wet forest (basal and premontane) (Holdridge 1967), with a climate characterised by 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 fertility parameters are summarised in Table 1 (Badilla 2012). These soils are classified as Andic Humudepts and Typic Humudepts developed on volcanic sediments deposited as eolian or alluvial materials (Sancho et al. 1989).

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

Parameter	Unit	Value	CV
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
Organic matter	%	5.9	44
Acidity saturation	%	*28	88

ECEC = effective cation exchange capacity; CV = coefficients of variation, number of samples = 6; *values outside the adequate reference soil levels according Bertsch (1998)

Field sampling, design and laboratory analysis

The false time series method (i.e. chronosequences) was used to analyse nutrient accumulation of *V. guatemalensis* with age. This method was considered valid since all the studied stands had similar environmental conditions (soil and climate) and management practice. A total of 13 stands were chosen along the study area ranging between 2 and 21 years old and 7.5 and 41.5 cm of diameters at breast height (dbhs). In each of these stands, dominant and codominant trees were selected, assuming optimal nutritional state and excellent expression of genetic potential. These trees were representative of the plantations and no symptoms of disease or nutritional deficiency were detected. In plantations less than 10 years old, two trees were sampled at each plot, but only one tree per stand were taken in the older ones. Once the trees were selected, their dbh and height were measured. These selected trees were felled and their components (stem, branches and leaves) were separated and weighed. Subsamples of each component were taken and analysed at the University of Costa Rica. Concentrations of P, Ca, Mg, K, S, Fe, Mn, Cu, Zn, B and Al were determined using atomic absorption spectrometry following the methodology described by Kalra (1998) and N using combustion in an autoanalyser. This work was conducted during the beginning of the rainy season between April and May 2013.

Data analysis

Accumulation of nutrients in biomass of tissues was the target variables of this work and was calculated by multiplying nutrient concentration by biomass for each component (stem, branches and leaves). Total nutrient accumulation represents a weighted sum from all sampled tissues. No detailed information about thinning regime of the studied stands or the dynamics of tree density with age was available.

In order to upscale individual tree measurements to estimate the exported nutrient values for the stand, tree stocking at different stand ages were considered, namely, 1111, 483, 483 and 200 trees ha^{-1} at 15, 25, 35 and 45 cm dhbs respectively. These values are considered as average values normally used in plantations in Central America. Site stability index was estimated based on information of soil plantations sites (Fassbender & Bornemisza 1982, Arias et al. 2011).

Statistical analysis

Linear mixed models for each aboveground biomass component (foliage, stem, branches and total) were fitted using dbh as independent variable and accumulation of elements (N, P, Ca, Mg, K, S, Fe, Mn, Cu, Zn, B and Al) as dependent variables. For each element, model types were tested: (1) null hypothesis, using the form ($y = b_0$), i.e. no effects of dbh on nutrient accumulation, (2) linear model including intercept and slope ($y = b_0 + b_1x$) and (3) model without intercept ($y = b_1x$). Original data was transformed using natural logarithm (ln) and inversed (α^{-1}) forms (Chave et al. 2001, Montero & Montagnini 2006, Basuki et al. 2009). Models were compared based on r^2, overall model significance, regression parameters b_0 and b_1 and evaluations of models assumptions including normality and constant variance. For models that were natural logarithm transformed, a correction factor was calculated as suggested by Sprugel (1983). The models were developed using Sigmaplot® and InfoStat® software packages.

RESULTS

Nutrient accumulation and distribution in aboveground biomass of *V. guatemalensis*

The proposed models used to estimate nutrient accumulation in *V. guatemalensis* trees based on their dbhs are given in Table 2. Based on these models a graph representation for the accumulation of nutrients in different components of aboveground biomass of trees was generated (Figure 1). In general there was an increase in the accumulation of nutrients because biomass increase was positively correlated with increase in dbh.

Hence, the highest N accumulation was found in the stem (1.8 kg tree^{-1}) while accumulation in leaves and branches was lower (0.83 and 0.59 kg tree^{-1} respectively). Greatest amount of P were found in branches (0.35 kg tree^{-1}) followed by stem (0.24 kg tree^{-1}) and leaves (0.03 kg tree^{-1}). Highest potassium accumulation was in the stem (1.59 kg tree^{-1}) followed by branches (0.35 kg tree^{-1}) and foliage (0.19 kg tree^{-1}).

Table 2 Models for estimating nutrient accumulation (y) of aboveground biomass components for *Vochysia guatemalensis* trees inferred from diameter (x) in small-scale forest plantations in the Caribbean lowlands of Costa Rica

Component	Nutrient	Model	b_0	SE_{b0}	b_1	SE_{b1}	r^2	FC
	Macronutrient (kg tree^{-1})							
Foliage	N	$y = (b_1 x^{-1})^{-1}$			128	12	0.90	
	P	$y = (b_1 x^{-1})^{-1}$			3274	319	0.90	
	Ca	$y = (b_1 x^{-1})^{-1}$			219	33	0.78	
	Mg	$y = (b_1 x^{-1})^{-1}$			848	107	0.84	
	K	$y = (b_1 x^{-1})^{-1}$			695	97	0.81	
	S	$y = (b_1 x^{-1})^{-1}$			1598	1s87	0.86	
Branch	N	$y = \exp(b_0 + b_1 \ln x)$	-9.93	1.51	2.51	0.49	0.71	1.43
	P	$y = \exp(b_0 + b_1 \ln x)$	-14.32	1.96	3.46	0.64	0.73	1.83
	Ca	$y = \exp(b_0 + b_1 \ln x)$	-10.21	1.53	2.53	0.50	0.70	1.44
	Mg	$y = \exp(b_0 + b_1 \ln x)$	-11.95	1.61	2.83	0.52	0.73	1.50
	K	$y = \exp(b_0 + b_1 \ln x)$	-10.11	1.55	2.50	0.50	0.69	1.27
	S	$y = \exp(b_0 + b_1 \ln x)$	-14.29	1.78	3.47	0.58	0.77	1.64
Stem	N	$y = \exp(b_0 + b_1 \ln x)$	-8.90	0.34	2.51	0.11	0.98	1.02
	P	$y = \exp(b_0 + b_1 \ln x)$	-12.39	0.68	2.83	0.22	0.94	1.07
	Ca	$y = \exp(b_0 + b_1 \ln x)$	-10.64	0.65	2.87	0.21	0.94	1.07
	Mg	$y = \exp(b_0 + b_1 \ln x)$	-12.37	0.46	3.21	0.15	0.98	1.03
	K	$y = \exp(b_0 + b_1 \ln x)$	-8.89	0.85	2.50	0.27	0.88	1.12
	S	$y = \exp(b_0 + b_1 \ln x)$	-11.35	0.72	2.65	0.23	0.92	1.09
Total	N	$y = \exp(b_0 + b_1 \ln x)$	-6.24	0.55	1.90	0.18	0.91	1.05
	P	$y = \exp(b_0 + b_1 \ln x)$	-10.31	0.87	2.49	0.28	0.88	1.12
	Ca	$y = \exp(b_0 + b_1 \ln x)$	-7.09	0.58	2.03	0.19	0.92	1.05
	Mg	$y = \exp(b_0 + b_1 \ln x)$	-9.16	0.50	2.43	0.16	0.95	1.04
	K	$y = \exp(b_0 + b_1 \ln x)$	-7.67	0.69	2.26	0.22	0.90	1.08
	S	$y = \exp(b_0 + b_1 \ln x)$	-9.43	0.71	2.33	0.23	0.90	1.08
	Micronutreint (g tree^{-1})							
Foliage	Fe	$y = (b_1 x^{-1})^{-1}$			27.65	2.69	0.90	
	Cu	$y = (b_1 x^{-1})^{-1}$			798.52	144.74	0.72	
	Zn	$y = (b_1 x^{-1})^{-1}$			183.64	29.25	0.77	
	Mn	$y = (b_1 x^{-1})^{-1}$			17.47	3.80	0.64	
	B	$y = (b_1 x^{-1})^{-1}$			115.90	18.75	0.76	
	Al	$y = (b_1 x^{-1})^{-1}$			0.11	0.01	0.84	
Branch	Fe	$y = \exp(b_0 + b_1 \ln x)$	-7.11	1.71	2.39	0.56	0.63	1.58
	Cu	$y = \exp(b_0 + b_1 \ln x)$	-10.34	1.66	2.33	0.54	0.63	1.54
	Zn	$y = \exp(b_0 + b_1 \ln x)$	-8.58	1.39	2.30	0.45	0.71	1.35
	Mn	$y = \exp(b_0 + b_1 \ln x)$	-5.61	1.81	2.46	0.59	0.62	1.66
	B	$y = \exp(b_0 + b_1 \ln x)$	-9.37	1.41	2.24	0.46	0.69	1.36
	Al	$y = \exp(b_1 \ln x)$			1.38	0.08	0.96	
Stem	Fe	$y = \exp(b_0 + b_1 \ln x)$	-7.81	1.70	2.98	0.55	0.73	1.57
	Cu	$y = \exp(b_0 + b_1 \ln x)$	-11.76	0.53	3.24	0.17	0.97	1.04
	Zn	$y = \exp(b_0 + b_1 \ln x)$	-10.04	1.20	3.13	0.39	0.85	1.25
	Mn	$y = \exp(b_0 + b_1 \ln x)$	-4.81	1.36	2.51	0.44	0.75	1.33
	B	$y = \exp(b_0 + b_1 \ln x)$	-9.33	0.88	2.69	0.29	0.89	1.13
	Al	$y = \exp(b_0 + b_1 \ln x)$	-3.56	0.50	3.08	0.16	0.97	1.03
Total	Fe	$y = \exp(b_0 + b_1 \ln x)$	-5.38	1.45	2.40	0.47	0.70	1.40
	Cu	$y = \exp(b_0 + b_1 \ln x)$	-9.33	0.70	2.64	0.23	0.93	1.08
	Zn	$y = \exp(b_0 + b_1 \ln x)$	-7.29	0.71	2.45	0.23	0.91	1.08
	Mn	$y = \exp(b_0 + b_1 \ln x)$	-3.69	1.20	2.31	0.39	0.77	1.25
	B	$y = \exp(b_0 + b_1 \ln x)$	-6.31	0.64	1.99	0.21	0.89	1.07
	Al	$y = \exp(b_1 \ln x)$			2.16	0.03	0.98	

SE = standard error, FC = correction factor according Sprugel (1983), coefficients b_0 and b_1 are present in the model when they are statistically significant at $p < 0.05$

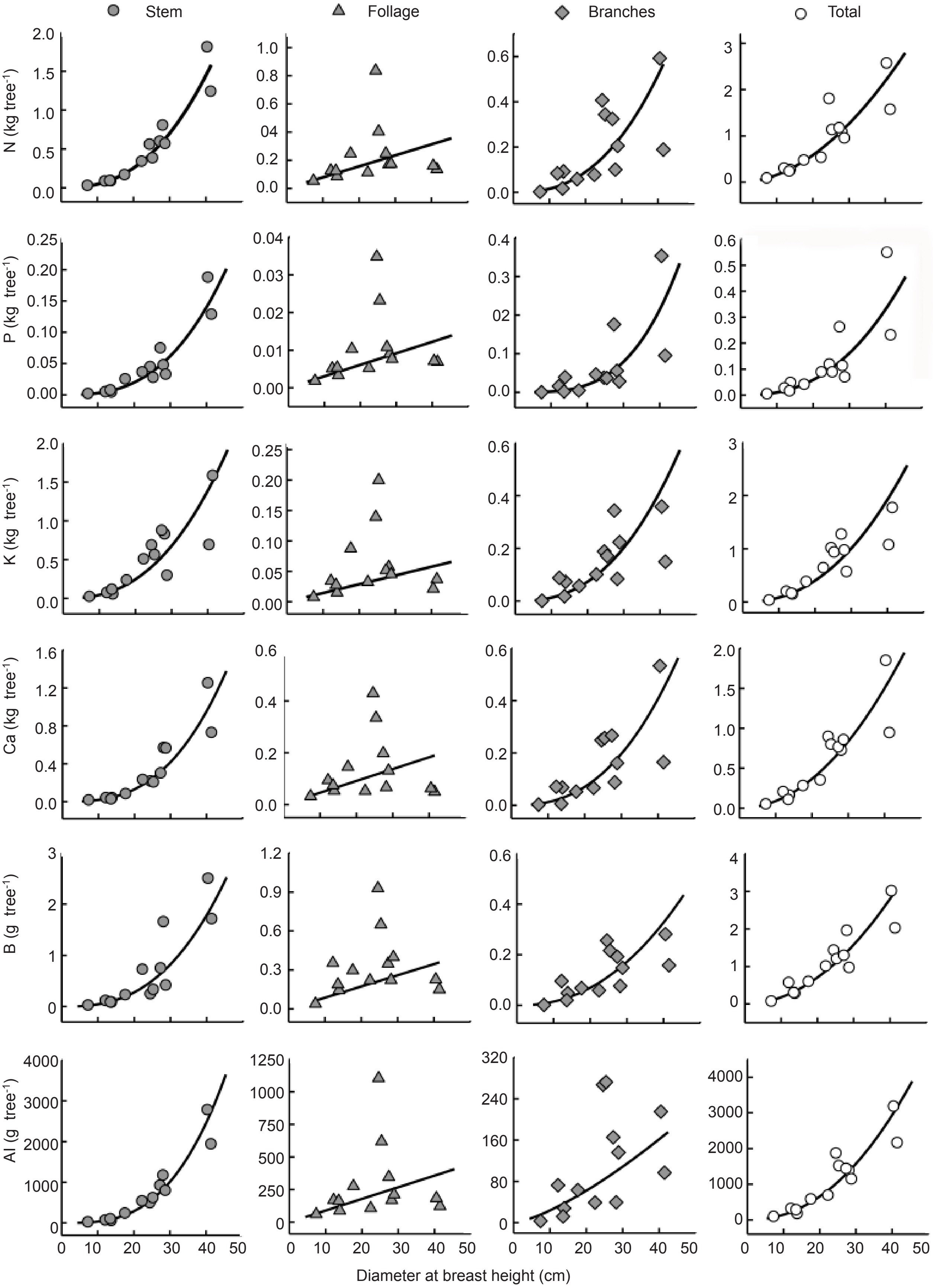

Figure 1 Accumulation of N, P, K and Ca as well as B and Al as functions of dbh for foliage, branch, stem and total aboveground biomass of *Vochysia guatemalensis* trees in small-scale forest plantations at Guácimo, Caribbean lowlands of Costa Rica; black lines represent the best fit model reported in Table 2

Similar to N, Ca accumulated mainly in the foliage until the tree reached dbh values between 13 and 14 cm (Figure 1). Therefore stem accumulation increased at higher rates than foliage. Magnesium accumulation in foliage was also higher than in the stem until the tree attained 12–13 cm dbh, while Mg stem accumulation was higher afterwards. Sulphur showed similar trend to Mg except that, at dbh 17–18 cm, Mg contents increased exponentially in the stem and slowly in the foliage. Sulphur was largely accumulated in the stem until dbh 33 cm when higher values were obtained in the branches. Stem had the highest percentage of S, followed by branches and foliage. Micronutrients showed similar trends to the macronutrients. Stem had the highest accumulation of Cu (1.25 g tree^{-1}), followed by foliage (0.38 g tree^{-1}) and branches (0.18 g tree^{-1}).

The highest values of accumulated Zn, Fe and Mn were in the stem (3.12, 140 and 165 g tree^{-1} respectively) followed by branches (1.08, 4.5 and 4.9 g tree^{-1} respectively) and foliage (0.62, 4.5 and 5.8 g tree^{-1} respectively). Similar to these nutrients, the highest accumulated values of B and Al were in the stem (2.5 and 2773 g tree^{-1} respectively) followed by foliage (0.93 and 1103 g tree^{-1} respectively) and branches (0.28 and 273 g tree^{-1} respectively) (Figure 1). Aluminium was the most accumulated micronutrient.

Export of nutrients in stem biomass for *V. guatemalensis*

When *V. guatemalensis* is harvested, great amounts of nutrients accumulated are exported as wood products. The amount of nutrient exported varied according to the dbh of harvested trees (Table 3). Plantation harvest at the end of the rotation corresponded to the highest output and loss of nutrients from the forest system. With a selected diameter of 35 cm and its corresponding tree density, export of nutrients reached up to 499 kg N ha^{-1}, 46 kg P ha^{-1}, 314 kg Ca ha^{-1}, 188 kg Mg ha^{-1}, 485 kg K ha^{-1}and 69 kg S ha^{-1} (Table 3).

Aluminium removed by *V. guatemalensis* (i.e. accumulated in aboveground biomass) can be considered as a bioremediation process. For trees with dbh of 45 cm, Al exported as wood can reach 93% of the total Al accumulation in the tree. Site stability index showed that K and P values were over 100% for all dbh values (Table 4). This meant that high amounts of K and P were removed from the soil in the exported wood, reducing possibility for a second harvest turn at the same site.

Table 3 Nutrient export by timber extraction at three possible diameters at breast height (dbhs) for *Vochysia guatemalensis* plantations in Caribbean Costa Rica

Nutrient (kg)	Dbh 25 cm			Dbh 35 cm			Dbh 45 cm		
	Total	Stem	Exported as wood (%)	Total	Stem	Exported as wood (%)	Total	Stem	Exported as wood (%)
	Nutrient ha $^{-1}$			Nutrient ha^{-1}			Nutrient ha^{-1}		
N	431.00	214.00	50	818.00	499.00	61	547.00	388.00	71
P	49.00	18.00	36	114.00	46.00	40	89.00	39.00	44
Ca	279.00	119.00	43	552.00	314.00	57	381.00	267.00	70
Mg	125.00	64.00	51	284.00	188.00	66	216.00	175.00	81
K	321.00	209.00	65	686.00	485.00	71	501.00	377.00	75
S	70.00	28.00	41	152.00	69.00	45	113.00	55.00	49
Fe	5.10	2.91	57	11.44	7.94	69	8.66	6.96	80
Cu	0.21	0.126	60	0.51	0.38	73	0.41	0.35	85
Zn	0.88	0.50	57	2.00	1.45	72	1.53	1.32	86
Mn	43.20	12.50	29	101.76	29.10	29	79.85	22.58	28
B	0.53	0.24	46	1.03	0.60	58	0.71	0.49	69
Al	513.23	277.72	54	1063.45	783.12	74	758.74	703.38	93

Export data were calculated using statistical models summarised in Table 2 at two densities, namely, 483 trees ha^{-1} for dbhs 25 and 35 cm and 200 trees ha^{-1} for dbh 45 cm

Table 4 Nutrient stability index estimated for *Vochysia guatemalensis* stands in the Caribbean of Costa Rica

Dbh (cm)	Nutrient stability index (%)							
	P	Ca	Mg	K	Fe	Cu	Zn	Mn
25	298	9	18	268	1	1	8	18
35	772	23	52	622	3	2	24	42
45	650	20	49	483	3	2	22	32

Dbh = diameter at breast height; nutrient stability index < 0.6% is considered very stable, index >100% is extremely unstable (Arias et al. 2010)

DISCUSSION

Nutrient accumulation and distribution in aboveground biomass of *V. guatemalensis*

The high values of P and N accumulation in *V. guatemalensis* suggested high consumption or low-use efficiency of these nutrients by this species. Therefore, in forest management, special attention must be given to contents of these nutrients in the soil because they can be the limiting factor for forest development (Chapin et al. 1986, Vitousek & Farrington 1997).

The lowest values of macronutrient accumulation in all components were for P. This low accumulation was probably related to internal mechanisms involved in P accumulation, reducing storage and partitioning or retranslocation of this nutrient in the plant to achieve more efficient use of the nutrient in Al-hyperaccumulator species such as *V. guatemalensis* (Rao et al. 1999, Watanabe & Osaki 2002, Kochian et al. 2004). These mechanisms help species to grow efficiently in soils with low P availability (Rao et al. 1999), which is very common in tropical forest systems. High Ca contents found in stem are consistent with those reported for other species (Ponette et al. 2001, Segura et al. 2005, Fernández-Moya et al. 2014). These high values are explained by the functions of this nutrient in structural tissues (Miller 1984). Cell walls stabilise and expand as nutrients accumulate in the stem (Marschner 1995). Magnesium and S were accumulated in lower amounts than the macronutrients above except for P, which had the lowest values. This is in agreement with results reported for other species of importance in Costa Rica such as *Tectona grandis* (Fernández-Moya et al. 2014) and *Alnus acuminata* (Segura et al. 2005).

High values of Al were accumulated in total aboveground biomass of *V. guatemalensis. Acacia mangium* had low amount of Al (6.3 kg ha^{-1} at 3.8 years old) accumulated in its aboveground biomass and understorey (Nykvist et al. 1996). Loblolly pine (*Pinus taeda*) had 15.2 kg Al ha^{-1} (mean 2.28 kg ha^{-1} year^{-1}) in aboveground biomass (Markewitz & Richter 1998). Values from these species are considerably lower than that found for *V. guatemalensis*, confirming the Al-hyperaccumulator behaviour of the latter (González & Fisher 1997, Young 2009).

Results from this study can be used as reference for further research in mineral nutrition management of tropical species. Generally tropical soils are characterised as highly weathered, with high amounts of Al, Fe and Mn but commonly deficient in Zn, B, Cu and Mo (Sánchez 1981). Hence, special care should be taken to evaluate the B and Zn status because they could be limiting factors for growth of planted forests in the tropics (Boardman & McGuire 1990, Lehto et al. 2010).

Nutrients export in stem biomass of *V. guatemalensis*

The export of nutrients at the end of rotation represented between 28 and 93% of nutrients accumulated in total aboveground biomass (Table 3). The rest of the accumulated nutrients in branches and foliage usually remain on site, and could eventually be recycled during the next rotation if proper management is performed (Jordan 1985, Fölster & Khana 1997). Successive rotations can affect soil fertility and, therefore, the site productivity aimed at future productions. Thus, sustainability indicators have been developed such as the plantation stability index of the plantation which could be used as tool to perform proper nutrient management for future production (Fölster & Khana 1997, Arias et al. 2011). Therefore, the removal of P and K by this species should be considered as a very important concern for future rotations based on the low levels of these nutrients in the soil (Table 4).

Aluminium exported as wood represented 93% of the total Al accumulation in the tree, indicating that large amounts of this element left the planting site during harvest. This huge loss could greatly reduce the amount of soil exchangeable Al and phytotoxic effects on other species. Values mentioned above represent a considerable Al output from plantation site compared with other species such as loblolly pine (Markewitz & Richter 1998). Therefore, future research on this species could be focused on Al export as wood and impact on soil Al cycle, especially in tropical soils where this element is considered abundant (Sánchez 1981).

CONCLUSIONS

Total accumulation sequence for macronutrients was N > Ca = K > Mg > S > P until tree reached 14 cm dbh. Thereafter accumulation sequence changed to N > K > Ca > Mg > S > P. Total accumulation of micronutrients showed the following trend: Al >> Fe >> Mn > Zn > B > Cu. Accumulation of Al was very high in the stem, i.e. between 74 and 93% of the total accumulated Al in tree. The amounts of N and K and Ca should be given special emphasis in the management of nutrients for *V. guatemalensis*. To ensure sustainable production, stability indices and models to estimate nutrient accumulation are essential tools to improve nutrient management in plantations.

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