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Allometric equations for biomass and contents of macronutrients in a young *Tectona grandis* stand

Márcio Luiz dos Santos[(1)], **Helio Garcia Leite**[(2)], **Valéria Santos Cavalcante**[(3)*], **Loane Vaz Fernandes**[(3)] **and Júlio César Lima Neves**[(3)]

(1) Universidade Federal de Viçosa, Departamento de Agronomia, Programa de Pós-graduação em Fitotecnia, Viçosa, Minas Gerais, Brasil.
(2) Universidade Federal de Viçosa, Departamento de Engenharia Florestal, Viçosa, Minas Gerais, Brasil.
(3) Universidade Federal de Viçosa, Departamento de Solos, Programa de Pós-Graduação em Solos e Nutrição de Plantas, Viçosa, Minas Gerais, Brasil.

ABSTRACT: Evaluations of biomass and nutrient contents in teak stands are necessary alternatives for avoiding early cutting to provide supplemental data for the plant module of fertilization recommendation systems. This study aimed to adjust allometric equations to estimate the accumulation of biomass and nutrient contents in teak plantations in the central region of Brazil. Plots in seminal and clonal stands contained 81 trees aged 75 months, that had not received previous fertilization or thinning. Additional clonal stands aged 15, 51 and 63 months and a seminal stand aged 63 months had been previously fertilized during implantation. Allometric equations for biomass and macronutrient contents were obtained for components of the aerial parts of trees as a function of diameter at 1.3 m height (DBH), and the possibility of using an equation or the need for specific equations was evaluated for genetic material (seminal or clonal) and the fertilization scheme (not fertilized or fertilized). The equations adjusted to the four sets of stands, all with elevated predictive capacity, did not differ among each other based on an identity test. Thus, the use of a robust equation adjusted with data from all stands is recommended to obtain estimates with a high degree of accuracy. The biomass and accumulation of macronutrients in components of the aerial parts of teak trees should be considered to obtain the nutrient contents in both the exportable components in thinned trees and the components maintained in the area and available for biogeochemical cycling.

Keywords: seminal teak, clonal teak, carbon partitioning, nutrient partitioning.

*** Corresponding author:**
E-mail: valeria.cavalcante.agro@gmail.com

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INTRODUCTION

Even-aged forest stands occupy approximately 7 % of the world's total forest area, corresponding to 131 Mha (FAO, 2020), and they are undergoing important expansion (Nepal et al., 2019). Forest stands can contribute to reducing harvesting pressures in uneven-aged forests that are essential for sustainable local subsistence, mitigating climate change and preserving biodiversity (Bull et al., 2006). One forest species cultivated in even-aged stands is *Tectona grandis* (teak).

Teak stands cover approximately 7 Mha, with approximately 6 % of this area located in the tropical Americas (Kollert and Kleine, 2017). Species of the genus *Tectona*, especially *T. grandis*, stand out for their production of high-quality wood of pronounced beauty, which adds greater market value (Kollert and Cherubini, 2012). Teak trees are characterized by rapid growth in comparison to other species that occur in uneven-aged stands, which consequently leads to greater rates of accumulation of nutrients and carbon (Kumar et al., 2009; Meunpong et al., 2010).

Teak plantations have high nutritional demands and can be found at sites with a wide variety of soils, including Oxisols (*Latossolos*) with low natural fertility (Fernández-Moya et al., 2015). The adequate fertilization of these soils and the adoption of well-defined silvicultural practices, such as thinning, contribute to relatively high productivity, especially under Brazil's favorable site conditions.

Fertilizers and nutritional management prescriptions in silvicultural stands can be obtained based on nutrient balance in the soil-tree system. This requires estimating the accumulation of biomass and nutrients, as well as their partitioning among the components of the trees, in addition to the soil nutrient supply (Barros and Novais, 1996). Nutrient accumulation can be estimated using allometric equations (Chave et al., 2014; Djomo and Chimi, 2017).

For teak trees, allometric equations are used to estimate the biomass of aerial parts and roots (Chaturvedi and Raghubanshi, 2015; Ounban et al., 2016; Djomo and Chimi, 2017; Aguilar et al., 2019; Kenzo et al., 2020). However, no allometric equations have been elaborated to estimate the macronutrient contents in teak stands.

Due to the elevated market value of teak in the wood industry, alternatives that can be used to evaluate its biomass and nutrient contents without its logging are highly desirable, such as the use of allometric equations. Thus, the hypothesis that allometric equations estimate the accumulation of biomass and nutrients in teak stands with a high degree of accuracy emerges. This study aimed to provide allometric equations to estimate the accumulation of biomass and nutrients in *T. grandis* plantations to provide supplemental data for fertilizer recommendation systems.

MATERIALS AND METHODS

Study area

The study was conducted at the Apasa Farm of the *Guavirá Industrial e Agroflorestal Ltda*, located in the municipality of Nova Maringá, Mid-North region of the state of Mato Grosso, Brazil (12° 29' 64.3" S and 57° 09' 44.0" W), with an average altitude of 350 m. Clonal and seminal teak stands aged 15, 51, 63 and 75 months growing under the same site conditions were examined in this study. The region's climate is hot, subhumid tropical, the average rainfall is 1,741 mm, and the mean annual temperature is 24 °C, with five months of drought, from May to September. It is a flat region, and the predominant soil class is Oxisol (US Soil Taxonomy)/ *Latossolo* (Brazilian Classification System) of sandy texture (IUSS Working Group, 2006; Santos et al., 2018), which was characterized chemically according to the methods described by Defelipo and

Ribeiro (1981) and Claessen (1997) (Table 1). The natural vegetation in this region is a transitional forest between the Amazon Forest and the Cerrado.

Regarding the clonal plantations, two teak clones were used (A1 and A3) in a mixture, propagated by micropropagation (*in vitro* cultivation). Stands aged 75 months (one clonal and the other seminal) had not been previously fertilized or thinned.

Clonal stands aged 15, 51 and 63 months and a seminal stand aged 63 months had received liming (6 t ha^{-1}) and fertilization (270 kg ha^{-1} NPK 00-25-00, 30 kg ha^{-1} FTE BR12, 200 kg ha^{-1} NPK 05-30-15, 30 kg ha^{-1} of FTE CO, 40 kg ha^{-1} of ammonium sulfate, 5 kg ha^{-1} Borogran 10 % B and 3 kg ha^{-1} of boric acid) during implantation. Limestone was applied by broadcasting, and NPK 00-25-00 was applied in two ridges at approximately 0.30 m on the side of the plant, while the other fertilizers were divided into two side pits at 0.15 m of the plant 30 days after planting. One year later, the following fertilizers were applied in two pits at 0.30 m from the plant: 200 kg ha^{-1} of NPK 05-30-15, 60 kg ha^{-1} of KCl, 3 kg ha^{-1} of Borogran 10 % B, and 3 kg ha^{-1} of boric acid. Two years after planting, 100 kg ha^{-1} of KCl was applied by broadcasting.

Data collection and analysis

In square plots containing 81 trees with a planting spacing of 4 × 4 m, trees were measured for diameter at 1.3 m height (DBH). Three trees were felled in each plot based on the distribution of diameters: one tree belonging to the central class of DBH, one in the class where the central value minus the standard deviation was found, and the third tree belonging to the class where the central value plus the standard deviation was observed. Therefore, 18 trees were felled, 12 clonal and 6 seminal.

Table 1. Chemical properties of the soil in areas with clonal and seminal teak stands, in the municipality of Nova Maringá, Mid-North region of the state of Mato Grosso, Brazil, located at 12° 29’ 64.3” S and 57° 09’ 44.0” W

Age	Layer	$pH(H_2O)$[(1)]	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al	SB	CTC(t)	CTC(T)	V	m	OM	P-Rem
months	m		— mg dm^{-3} —		——— $cmol_c\ dm^{-3}$ ———							—— % ——		dag kg^{-1}	mg L^{-1}
15 Clonal	0.00-0.20	5.35	4.80	18.33	1.14	0.50	0.00	2.40	1.69	1.69	4.09	41.63	0.00	1.45	34.83
	0.20-0.40	5.42	1.27	15.67	0.54	0.22	0.10	2.93	0.80	0.90	3.73	21.23	9.70	0.94	30.03
	0.40-0.60	5.36	0.67	18.33	0.43	0.12	0.27	2.67	0.60	0.86	3.26	18.27	30.67	0.73	28.27
51 Clonal	0.00-0.20	5.51	1.63	4.33	1.96	0.42	0.13	2.77	2.38	2.52	5.15	43.20	8.77	1.20	31.30
	0.20-0.40	5.36	1.27	5.67	1.35	0.32	0.27	2.77	1.69	1.95	4.45	33.73	26.27	1.07	31.50
	0.40-0.60	5.00	0.47	3.67	0.38	0.12	0.30	2.87	0.51	0.81	3.38	15.10	35.30	0.60	30.20
63 Clonal and seminal	0.00-0.20	5.29	2.33	7.00	2.16	0.58	0.00	2.10	2.76	2.76	4.86	55.87	0.00	1.32	35.63
	0.20-0.40	5.32	0.57	5.33	0.77	0.31	0.13	2.23	1.09	1.23	3.33	33.73	13.20	0.73	33.23
	0.40-0.60	5.28	0.50	3.33	0.38	0.18	0.33	2.47	0.57	0.90	3.03	18.63	36.20	0.60	33.07
75 Clonal	0.00-0.20	5.25	2.57	13.00	2.09	0.46	0.00	2.30	2.58	2.58	4.88	49.70	0.00	1.45	30.30
	0.20-0.40	5.27	0.63	7.00	0.75	0.20	0.20	2.60	0.96	1.16	3.56	27.00	17.70	0.94	27.13
	0.40-0.60	5.40	0.63	6.33	0.54	0.17	0.23	2.90	0.73	0.96	3.63	20.37	25.53	0.81	26.83
75 Seminal	0.00-0.20	5.35	3.97	10.33	2.00	0.65	0.00	1.87	2.68	2.68	4.55	59.43	0.00	1.49	32.23
	0.20-0.40	5.71	1.00	11.00	0.96	0.24	0.00	2.40	1.23	1.23	3.63	33.97	0.00	0.94	30.23
	0.40-0.60	5.32	0.73	10.67	0.73	0.20	0.03	2.33	0.96	0.99	3.29	30.10	3.80	0.86	28.30

[(1)] $pH(H_2O)$ at a soil:water ratio of 1:2.5; P and K: extracted by Mehlich-1; Ca^{2+}, Mg^{2+} and Al^{3+}: extracted by KCl 1 mol L^{-1}; H+Al: calcium Acetate extractant 0.5 mol L^{-1} (pH 7.0); SB: sum of bases ($Ca^{2+}+Mg^{2+}+K^+$); t: effective cation exchange capacity; T: cation exchange capacity at pH 7.0; V: base saturation; m: aluminum saturation; OM (Organic Matter): oxidizing C with dichromate ($Cr_2O_7^{2-}$) in an acidic medium (Yeomans and Bremner, 1988); Prem – remaining phosphorus, equilibrium solution P method.

Total height of each felled tree was measured with a measuring tape. Subsequently, the separation, weighing and sampling of leaves, branches, bark, and wood were performed to determine the nutrient contents in these components. For bark and wood sampling, 2.5 cm thick disks with bark were collected at 0, 25, 50, 75 and 100 % of the commercial height. Therefore, the stem of each sampled tree was divided into four sections. The volume of each tree was obtained using the Smalian equation – equation 1 (Campos and Leite, 2017):

$$V = \sum_{i=1}^{4} h_i\,(g_{Ii} + g_{2i})/2 \qquad \text{Eq. 1}$$

in which: h_i is the length of section i with sectional areas at its extremities; $g_{Ii} = 40\,000^{-1}\,\pi d_{Ii}^2$ and $g_{2i} = 40\,000^{-1}\,\pi d_{2i}^2$, with d_{1i} and d_{2i} being the diameters of extremities 1 and 2 of section i (i = 1, 2, 3, 4), respectively.

Samples collected from trees and litter were dried in an oven with forced air circulation at 70 °C for 96 h and then weighed to calculate the moisture contents of samples from all tree components. Samples of wood were obtained from the surfaces of disks, with the aid of a stainless-steel drill, for all five disks from each tree, while the sawdust was homogenized for further chemical characterization.

In samples of plant material, N was determined by the Kjeldahl method in extracts of sulfuric mineralization (Bremner and Mulvaney, 1982), while P was evaluated in extracts of nitric-perchloric mineralization using phosphomolybdate-reduction colorimetry with 20 g L^{-1} ascorbic acid (Braga and Defelipo, 1974). The concentration of K was measured by flame emission photometry (Tedesco et al., 1995), Ca and Mg by atomic absorption spectrophotometry and S by sulfate turbidimetry.

From the masses of fresh matter obtained in the field and the moisture values determined in the laboratory, the dry biomass of the components of aerial parts was calculated. The nutrient contents of the tree components were calculated by multiplying the dry biomass values by the evaluated concentrations.

Allometric equations were adjusted considering the following sets of trees:

1) trees from all stands sampled (18 trees, 12 clonal and 6 seminal);

2) trees from fertilized stands and unfertilized clonal stands (15 trees, 12 clonal and 3 seminal);

3) trees from fertilized stands (12 trees, 9 clonal and 3 seminal), and;

4) trees from fertilized clonal stands (9 trees).

The allometric model used was ln Y = $\beta_0 + \beta_1$ ln $DBH + \varepsilon$ ($m1$), $\varepsilon \sim NID(0, \sigma^2)$, in which Y is one of the dependent variables: dry biomass (DB) or macronutrient accumulation (C) in the aerial part (AP), stem (S), canopy (C) or wood (W). The choice of the model was made according to the potential relationships expected beforehand between dependent variables and DBH, i.e., $Y = aX^b$. Considering that for most variables, the variance of Y increases proportionally to DBH, each model was linearized, and the approximate shape was adjusted, defined by the application of the Neperian logarithm ($m1$).

The model $m1$ was adjusted for each dependent variable (Y), considering each one of the four sets of trees. Subsequently, the equations estimated for each of the datasets 2, 3 and 4 were compared with those estimated with dataset 1. Thus, for each dependent variable, the following hypotheses were evaluated:

$H_0(1)$: the equation adjusted with data from fertilized and unfertilized clonal stands (15 trees, 12 clonal and 3 seminal) does not differ from the equation adjusted with data from all stands (18 trees, 12 clonal and 6 seminal) *vs.* $H_a(1)$: not $H_0(1)$;

$H_0(2)$: the equation adjusted with data from fertilized stands (12 trees, 9 clonal and 3 seminal) does not differ from the equation adjusted with data from all stands (18 trees, 12 clonal and 6 seminal) *vs.* $H_a(2)$: not $H_0(2)$;

$H_0(3)$: the equation adjusted with data from fertilized clonal stands (9 trees) does not differ from the equation adjusted with data from all stands (18 trees, 12 clonal and 6 seminal) *vs.* $H_a(3)$: not $H_0(3)$.

Both hypotheses were evaluated using model identity tests (Regazzi, 1996; Santos et al., 2017). For each hypothesis evaluated, the *p*-value of the F test was estimated.

RESULTS

Hypotheses $H_0(1)$, $H_0(2)$ and $H_0(3)$ were not rejected (p>0.05) for any of the dependent variables (Table 2). A spatial view of the amplitude of p-values for each variable and hypothesis evaluated was observed (Figure 1).

Table 2. Estimation of parameters and *p*-values of the F-statistics of identity test of allometric models ($LnY = \beta_0 + \beta_1 \, \text{Ln}dbh + \varepsilon$), for biomass (kg/tree) and nutrient content (g/tree) in tree components of young teak stands in Brazil

Variables	All stands			Fertilized and clonal not fertilized				Fertilizers				Clonal Fertilizer			
	β_0	β_1	R^2	β_0	β_1	R^2	(2) vs (1) p-valor	β_0	β_1	R^2	(3) vs (1) p-valor	β_0	β_1	R^2	(4) vs (1) p-valor
DBAP	-2.8665	2.4624	0.9966	-2.8787	2.4567	0.9978	0.7386	-2.8622	2.4397	0.9986	0.3250	-2.8543	2.4352	0.9990	0.3628
DBS	-3.5188	2.6036	0.9967	-3.5300	2.6025	0.9971	0.9358	-3.5103	2.5827	0.9979	0.5142	-3.4934	2.5633	0.9995	0.1529
DBW	-3.7946	2.6492	0.9958	-3.8083	2.6471	0.9964	0.9097	-3.7883	2.6274	0.9970	0.5604	-3.7677	2.6057	0.9993	0.1890
DBC	-3.4181	2.1059	0.9551	-3.4427	2.0853	0.9691	0.7796	-3.4346	2.0746	0.9669	0.7368	-3.4690	2.1305	0.9793	0.9860
CNAP	-0.0311	1.8866	0.9894	-0.0145	1.8803	0.9913	0.9955	-0.0247	1.8854	0.9923	0.9979	-0.0361	1.9142	0.9966	0.4943
CNS	-1.7051	2.1395	0.9907	-1.6925	2.1453	0.9924	0.8711	-1.6622	2.1168	0.9944	0.9207	-1.6559	2.1251	0.9965	0.9503
CNC	-0.1590	1.7523	0.9675	-0.1433	1.7393	0.9732	0.9702	-0.1849	1.7695	0.9796	0.9691	-0.2080	1.8105	0.9886	0.5304
CNW	-1.9757	2.0475	0.9890	-1.9749	2.0483	0.9892	0.9986	-1.9417	2.0174	0.9915	0.7339	-1.9251	2.0171	0.9964	0.8506
CPAP	-2.2471	1.7909	0.9710	-2.2845	1.7795	0.9846	0.6503	-2.2822	1.7766	0.9831	0.6801	-2.2545	1.7586	0.9944	0.5627
CPS	-3.5902	2.0439	0.9415	-3.6568	2.0311	0.9644	0.7132	-3.6224	2.0030	0.9623	0.5983	-3.5647	1.9378	0.9924	0.1964
CPC	-2.4856	1.5853	0.9572	-2.4918	1.5730	0.9636	0.9033	-2.5264	1.5975	0.9672	0.9886	-2.5460	1.6445	0.9822	0.6163
CPW	-3.6331	1.8552	0.8397	-3.7359	1.8285	0.9066	0.6608	-3.6966	1.7991	0.9021	0.6149	-3.6089	1.6833	0.9860	0.1515
CKAP	-0.2635	2.0493	0.9893	-0.2531	2.0474	0.9895	0.9947	-0.2244	2.0164	0.9942	0.6674	-0.2090	2.0023	0.9968	0.4936
CKS	-1.0239	2.1867	0.9796	-0.9989	2.1963	0.9847	0.8188	-0.9579	2.1546	0.9907	0.9375	-0.9347	2.1304	0.9951	0.7408
CKC	-0.7305	1.7771	0.9649	-0.7517	1.7559	0.9859	0.5996	-0.7608	1.7563	0.9879	0.6021	-0.7668	1.7669	0.9884	0.8111
CKW	-1.2569	2.1437	0.9809	-1.2317	2.1507	0.9848	0.8486	-1.1858	2.1082	0.9901	0.9138	-1.1555	2.0813	0.9977	0.6557
CCaAP	-0.6265	2.1509	0.9744	-0.6389	2.1336	0.9841	0.7862	-0.6350	2.1224	0.9855	0.6647	-0.6340	2.0991	0.9906	0.3793
CCaS	-1.7625	2.3480	0.9815	-1.7779	2.3365	0.9855	0.8527	-1.7728	2.3212	0.9887	0.6476	-1.7618	2.2766	0.9975	0.1189
CCaC	-0.9238	1.9516	0.9338	-0.9367	1.9265	0.9559	0.8204	-0.9310	1.9172	0.9543	0.7877	-0.9427	1.9181	0.9600	0.8035
CCaW	-2.4634	2.1988	0.9867	-2.4503	2.1968	0.9870	0.9926	-2.4104	2.1618	0.9910	0.7806	-2.3834	2.1325	0.9963	0.3901
CMgAP	-1.9101	2.2868	0.9911	-1.9094	2.2831	0.9927	0.9862	-1.9279	2.2930	0.9935	0.9959	-1.9314	2.2992	0.9931	0.9809
CMgS	-2.7653	2.4139	0.9946	-2.7675	2.4122	0.9952	0.9896	-2.7763	2.4134	0.9965	0.9670	-2.7661	2.3949	0.9982	0.6176
CMgC	-2.4890	2.1458	0.9505	-2.4895	2.1379	0.9541	0.9859	-2.5204	2.1585	0.9535	0.9976	-2.5480	2.2057	0.9617	0.8183
CMgW	-3.0915	2.2769	0.9819	-3.1096	2.2690	0.9844	0.8874	-3.1214	2.2774	0.9865	0.9441	-3.0897	2.2268	0.9988	0.2951
CSAP	-2.3929	2.1575	0.9961	-2.3844	2.1495	0.9978	0.9157	-2.3743	2.1385	0.9982	0.6462	-2.3763	2.1468	0.9984	0.9464
CSS	-3.5553	2.3752	0.9959	-3.5472	2.3728	0.9961	0.9977	-3.5205	2.3481	0.9977	0.6223	-3.5063	2.3327	0.9990	0.3137
CSC	-2.6363	1.9246	0.9695	-2.6321	1.9086	0.9774	0.9019	-2.6478	1.9183	0.9776	0.9571	-2.6763	1.9617	0.9870	0.8392
CSW	-3.7530	2.3537	0.9931	-3.7475	2.3491	0.9938	0.9902	-3.7162	2.3216	0.9957	0.6385	-3.6959	2.2998	0.9985	0.2846

DB – dry biomass; AP – aerial part; S – stem; W – wood; C – content of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). (1) All stands. (2) Fertilized and Clonal not Fertilized. (3) Fertilizers. (4) Clonal Fertilizer.

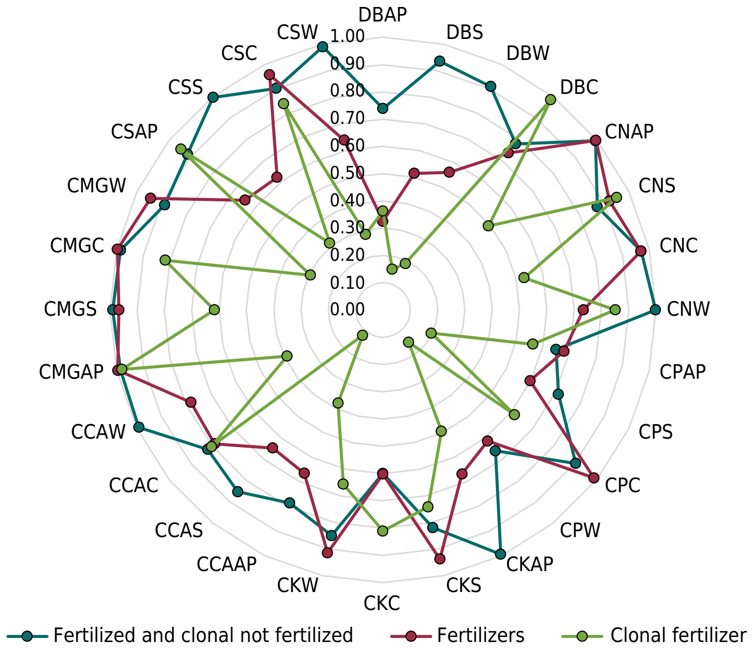

Figure 1. *p*-value of the F test to evaluate the identity of allometric equation adjusted for biomass (DB, kg/tree) and macronutrient content (C, g/tree) in the aerial part (AP), stem (S), wood (W) and canopy (C) of trees from sets of teak stands *versus* the equations adjusted for all data from all stands.

The hypothesis $H_0(3)$ (stands with clonal teak fertilized) presented the lowest p-values for the variables studied (Figure 1), while the other hypotheses $H_0(1)$ and $H_0(2)$ showed similar p-values for the partitioning of nutrients N, P, K, Ca and Mg. The estimated equations were graphically represented in potential form, with all the data (Figures 2, 3, 4, 5 and 6). The equations obtained for model m1, that is, in linearized form, adjusted to the four datasets, were all significant ($p<0.05$) and displayed high values of R^2 (Table 2).

DISCUSSION

Allometric models are equations that relate tree-associated variables such as biomass (Djomo and Chimi et al., 2017; Stahringer, 2017) and nutrient contents in trees such as *Pinus* and *Eucalyptus* (Stahringer, 2017) to variables taken as independent, such as stem diameter. The main advantage of using allometric models is the easy, rapid, and low-cost acquisition of estimates that would otherwise require the use of a destructive assessment through cutting trees and determining their biomass and nutrient contents, which, although it is the referential method, involves high financial resources (Chave et al., 2014) and a relevant expenditure of time.

Considering the same genetic material, the use of allometric models from a variable such as DBH - which reflects site conditions, i.e., climate, physiography of soil and management conditions - on the growth of trees generates equations that can hopefully be used in a safe and reliable manner, aiming to produce estimates for other site and management conditions, in relation to a tree's age, i.e., with time as an explanatory variable. In contrast, predictive equations in which the independent variable is the age of trees are specific for the site and management conditions in which those data were obtained. In this sense, Stahringer (2017) reported that the use of DBH for *Pinus* and *Eucalyptus* leads to a greater degree of universality in comparison to chronological age.

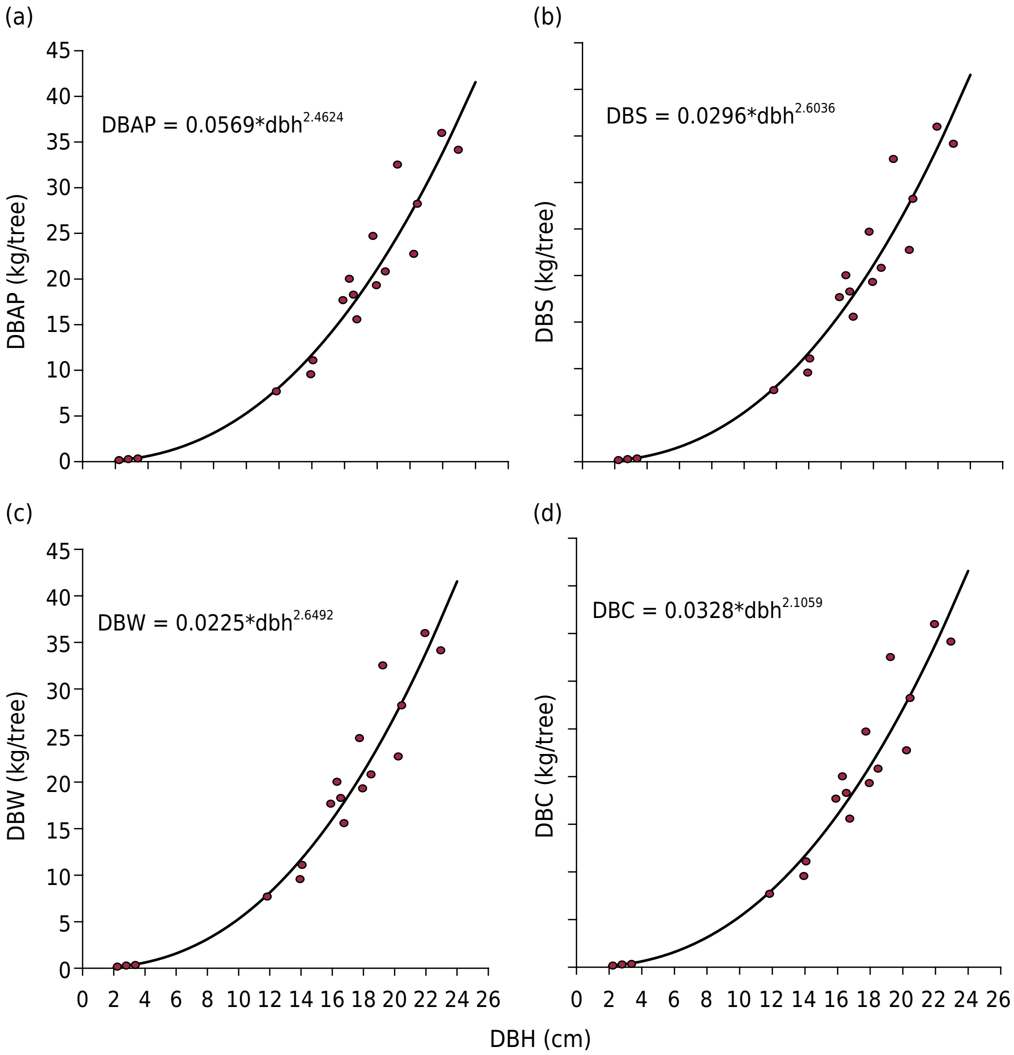

Figure 2. Estimates of the dry biomass of aerial part – DBAP (a), stem – DBS (b), wood – DBW (c) and canopy – DBC (d), in the function of diameter at 1.3 m height (DBH) of trees from teak stands.

In teak plantations in Thailand, it was verified that allometric equations that were generated using only DBH could precisely estimate the biomass above and below ground, but these should not be used in different countries or regions (Kenzo et al., 2020). In this sense, other studies aiming to estimate the biomass of aerial parts and roots of teak trees have been carried out in various countries (Chaturvedi and Raghubanshi, 2015; Ounban et al., 2016).

In this study, the failure to reject the null hypothesis (Table 2, Figure 1) provided evidence that the effects of fertilization and genetic material (clonal or seminal) did not require specific allometric models to estimate the biomass of aerial part components. Fertilization and genetic material effects on growth are reflected in the DBH, a variable that is considered explanatory in the obtained allometric models, justifying the use of adjusted allometric models with data from all studied teak stands due to its robustness. Using high-accuracy estimates of the biomass of teak tree components, applying the allometric model obtained in this study, and the C contents in these components (Kraenzel et al., 2003), enabled us to estimate the C accumulation in teak stands as a function of the growth of trees.

Regarding the use of nutrient balance models for fertilization prescriptions, although the acquisition of accurate estimates of biomass is important, as seen for teak models (Oliveira, 2003; Behling, 2009; Pontes, 2011), there is a need to estimate the nutrient contents of tree components. This can be based on allometric models as a function of diameter (DBH), especially for teak stands, in which thinning is commonly based on removing a percent of the basal area. In this sense, it is possible to obtain estimates of the nutrient contents exported from the area by the boles of the pruned trees removed from the site, as well as the nutrient contents of the parts that were maintained in the area (usually the canopy), and in case debarking is carried out, the bark (Figures 3, 4, 5 and 6).

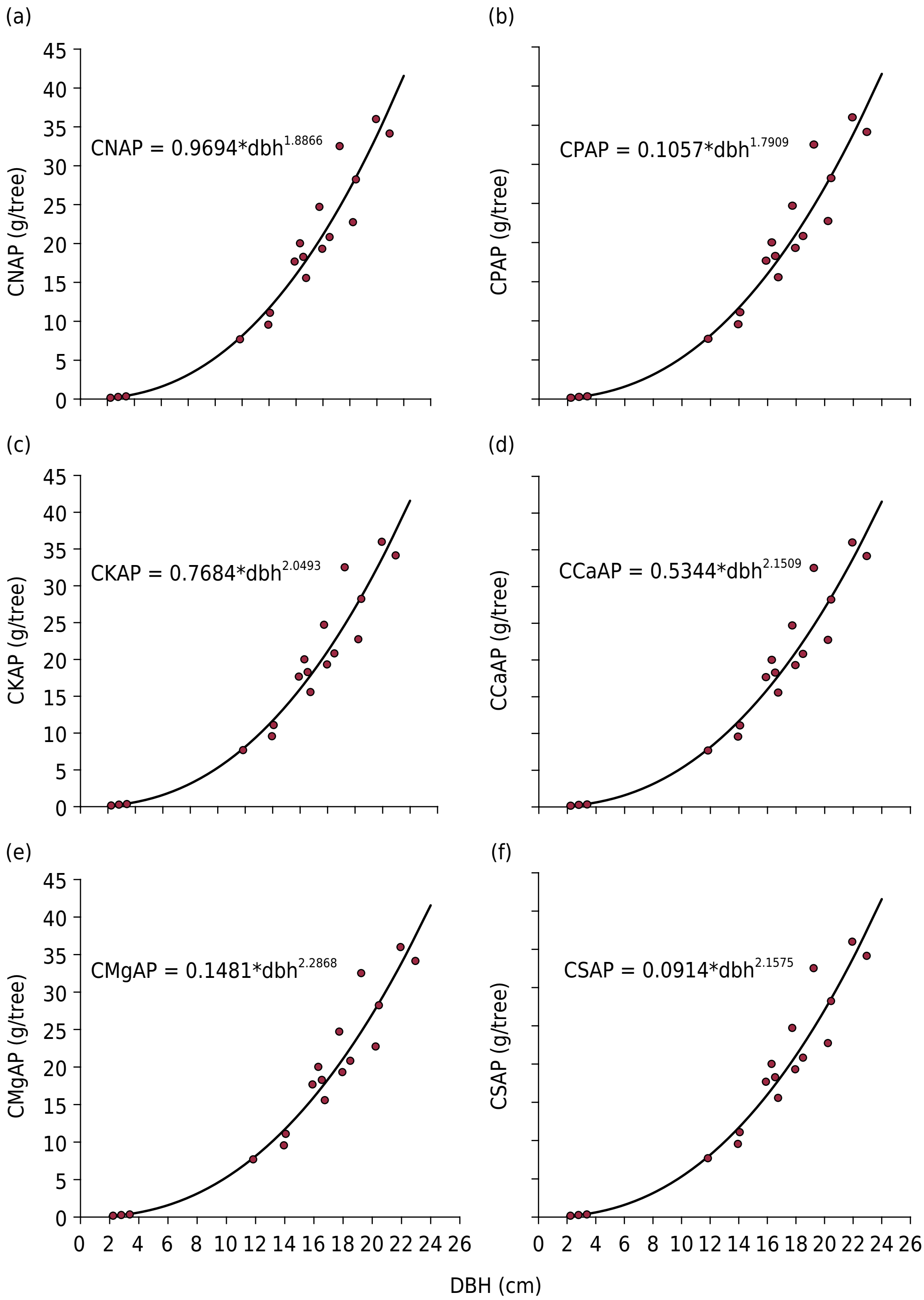

Figure 3. Estimates of aerial parts' contents of nitrogen – CNAP (a), phosphorus – CPAP (b), potassium – CKAP (c), calcium – CCaAP (d), magnesium – CMgAP (e), and sulphur – CSAP (f), in the function of diameter at 1.3 m height (DBH) of trees from teak stands.

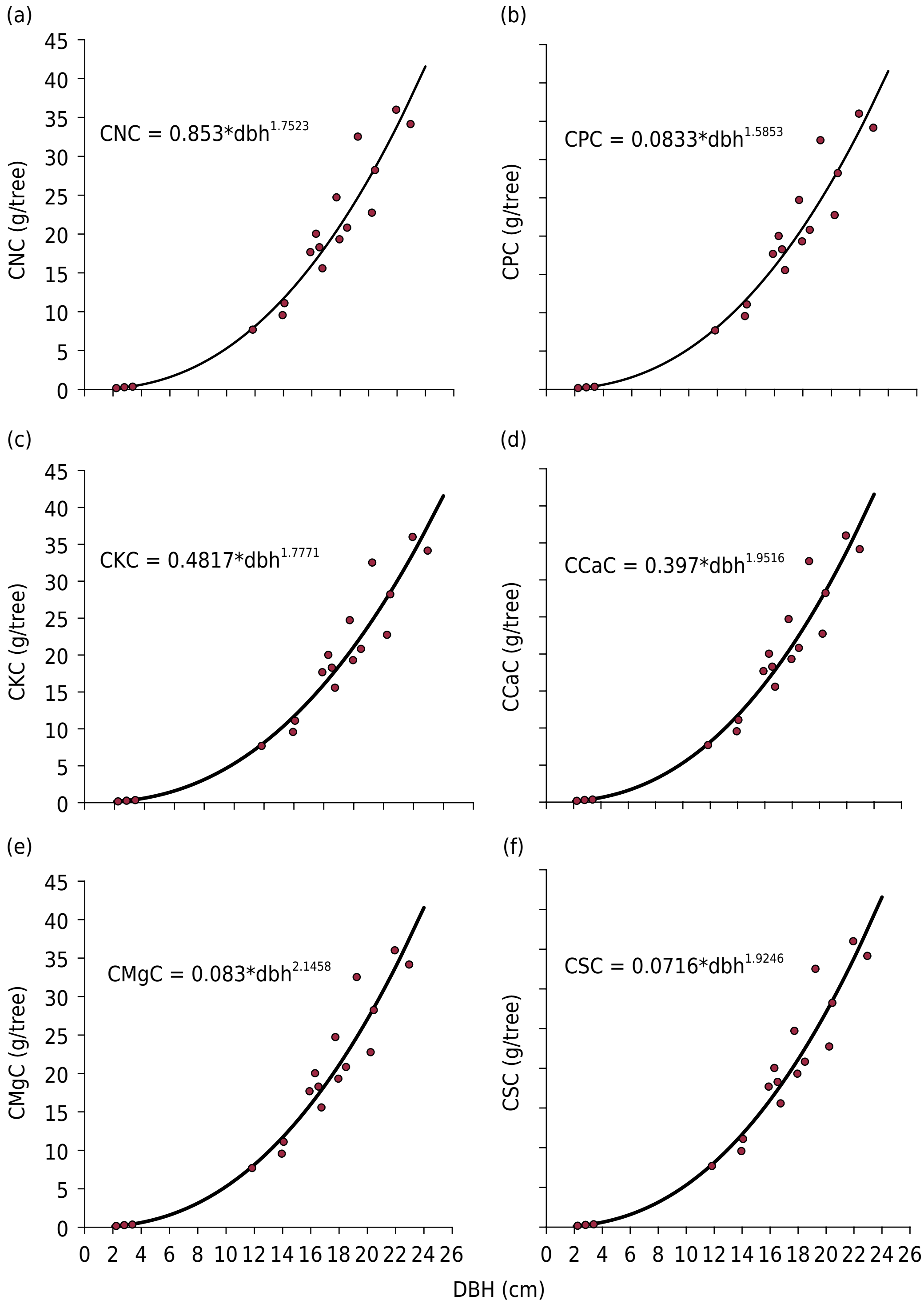

Figure 4. Estimates of canopy contents of nitrogen – CNC (a), phosphorus – CPC (b), potassium – CKC (c), calcium – CCaC (d), magnesium – CMgC (e), and sulphur – CSC (f) in the function of diameter at 1.3 m height (DBH) of trees from teak stands.

As observed in this study, failure to reject the null hypothesis (Table 2, Figure 1) justifies the use of an adjusted allometric model with data from all teak stands to estimate the accumulation of macronutrients, which has great utility for properly feeding the plant modules in nutrient balance-based systems. In addition, allometric models used to estimate biomass and nutrients as a function of DBH can be used in an integrated approach with process-based models of growth and production, such as the model 3-PG (Landsberg and Waring, 1997), coupled with models of diametric distribution as performed by Pontes (2011) for teak and by Stahringer (2017) for *Pinus* and *Eucalyptus*.

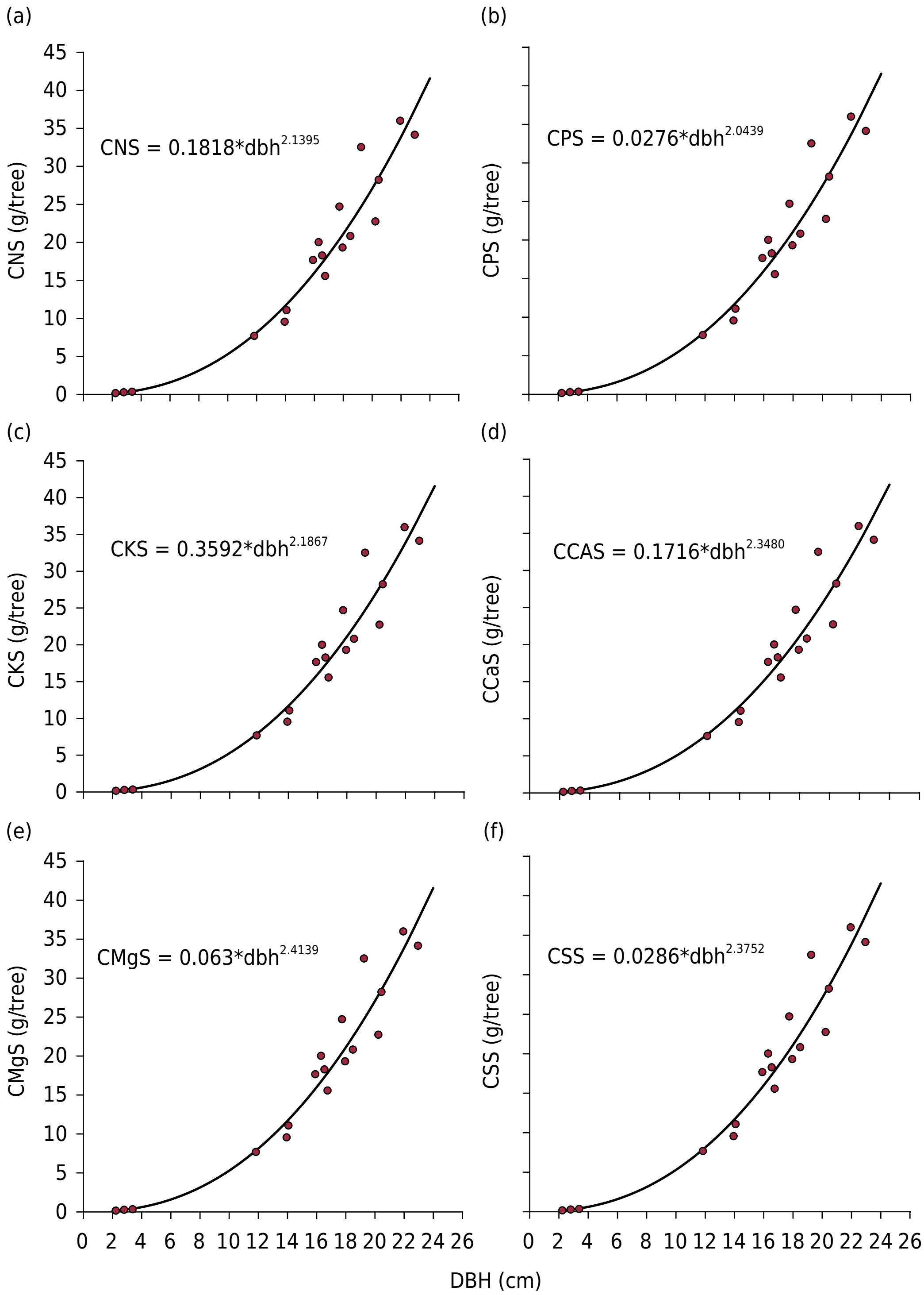

Figure 5. Estimates of the stem contents of nitrogen – CNS (a), phosphorus – CPS (b), potassium – CKS (c), calcium – CCaS (d), magnesium – CMgS (e) and sulphur – CSS (f), in the function of diameter at 1.3 m height (DBH) of trees from teak stands.

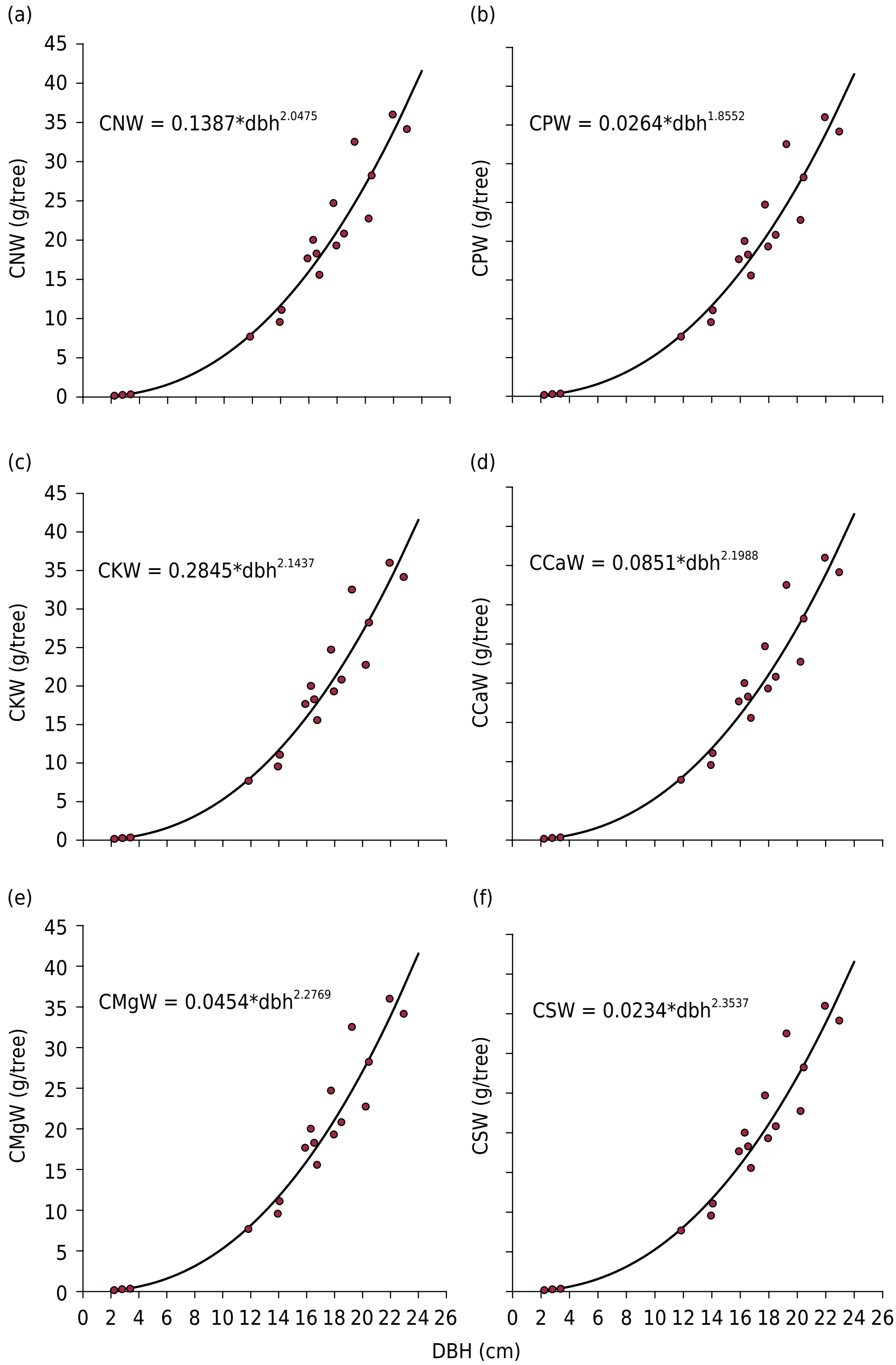

Figure 6. Estimates of the wood contents of nitrogen – CNW (a), phosphorus – CPW (b), potassium – CKW (c), calcium – CCaW (d), magnesium – CMgW (e), and sulphur – CSW (f), in the function of diameter at 1.3 m height (DBH) of trees from teak stands.

CONCLUSIONS

Allometric equations were obtained to estimate the biomass and macronutrient contents in components of the aerial parts of teak trees as a function of the diameter at 1.3 m height (DBH), considering four sets of stands, covering clonal and seminal stands, fertilized or not. The equations adjusted to the four sets of stands, all with high predictive ability, were not different from each other. Thus, the use of the allometric equation adjusted with data from all stands is recommended, as it is more robust and has a greater degree of accuracy for the acquisition of biomass estimation and accumulation of macronutrients in components of the aerial parts of young teak trees.

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AUTHOR CONTRIBUTIONS

Conceptualization: Júlio César Lima Neves and Márcio Luiz dos Santos (equal).

Data curation: Helio Garcia Leite (equal), Júlio César Lima Neves and Márcio Luiz dos Santos (equal).

Formal analysis: Helio Garcia Leite (equal), Júlio César Lima Neves and Márcio Luiz dos Santos (equal).

Funding acquisition: Júlio César Lima Neves and Márcio Luiz dos Santos (equal).

Investigation: Márcio Luiz dos Santos (equal).

Methodology: Márcio Luiz dos Santos (equal).

Project administration: Márcio Luiz dos Santos (equal).

Resources: Loane Vaz Fernandes (equal), Márcio Luiz dos Santos (equal) and Valéria Santos Cavalcante (equal).

Supervision: Júlio César Lima Neves (lead).

Validation: Helio Garcia Leite (equal), Júlio César Lima Neves and Valéria Santos Cavalcante (equal).

Visualization: Helio Garcia Leite (equal), Júlio César Lima Neves, Loane Vaz Fernandes (equal) and Valéria Santos Cavalcante (equal).

Writing - original draft: Helio Garcia Leite (equal), Júlio César Lima Neves and Valéria Santos Cavalcante (equal).

Writing – review & editing: Júlio César Lima Neves, Loane Vaz Fernandes (equal) and Valéria Santos Cavalcante (equal).

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