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INFLUENCE OF DENDOMETRIC AND MORPHOLOGICAL CHARACTERISTICS ON STEMFLOW IN A FOREST-SAVANNA TRANSITION AREA IN THE BRAZILIAN AMAZON

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Species-specific morphological characteristics play a decisive role in determining stemflow. However, in tropical forests, as a result of high biodiversity, the results can be conflicting. The objective of this study was to analyse the influence of tree morphology on water running down tree trunks in a forest-savanna transition area in the Brazillian Amazon. A total of 46 trees were installed samplers for stemflow monitoring. Rainfall events with a volume of > 10 mm were recorded. Dendometric variables and morphological characteristics of the trees were related to the stemflow volume. Circumference at breast height, basal area and canopy projection area were determinants for the formation of distinct tree groups, whereas these variables were not significantly correlated with stemflow volume. When the trees were grouped according to their morphological characteristics, significant correlations were identified for basal area and circumference at breast height for stemflow from trees with an upright trunk and rough bark. Mean stemflow volume from trees with a smooth bark was higher than the other trees. However, when the variable trunk inclination was inserted, the mean stemflow from upright trunks was lowest and that from inclined trunks was highest, showing the relevance of this variable for stemflow production.

Keywords: Tree morphology, trunk inclination, trunk roughness, forest hydrology, tropical forest

INTRODUCTION

Forests represent an important interface between the atmosphere and land surface, and can interact with/alter/influence/modify rainwater interception by the canopy (Munishi & Shear 2005, Frost & Levia 2014). In hydrological studies of forest ecosystems, it is essential to determine the precipitation volume partitioned by the canopy, by separating the intercepted fraction, the fraction that passes freely through the canopy (throughfall) and the fraction that flows off down the trunk (stemflow) (Giglio & Kobiyama 2013, Metzger et al. 2019). Interception represents the water evaporated from the canopy, whereas throughfall and stemflow represent fractions of the water entries into the system. Throughfall passes directly through canopy openings or is released as drops or splashes from the canopy surfaces, while stemflow is the part of the intercepted water that runs slowly down tree trunks into the forest soil (Zhang et al. 2013, Carlyle-Moses et al. 2018).

Despite representing a minor fraction of the total precipitation, stemflow is essential for hydrological functioning of ecosystems (Staelens et al. 2008, Levia & Germer 2015). It is a concentrated point source of water and nutrients that transports solutes (i.e. ions leached from tree structures) from the canopy to the forest soil (Burbano Garcés et al. 2014, Cayuela et al. 2018).

The process of stemflow production involves complex interactions between multiple biotic and abiotic factors (Van Stan & Levia 2009, Van Stan & Friesen 2020). It is therefore difficult to quantify these separate factors but morphological characteristics of tree species play an important role in determining the amount of water flowing down the trunk (Van Stan & Levia 2009). Stemflow volume differs between species due to differences in bark texture and tree size (Levia et al. 2010). Variability in stemflow production has also been contributed to contrasting biophysical characteristics among tree species, such as canopy size, leaf shape and orientation, branch angle and bark roughness (Van Stan & Levia 2009, Van Stan et al. 2016).

Although these relationships are well-documented for temperate forests, conflicting results have been observed in the tropics (Marin et al. 2000). Information about interspecific variations in stemflow production of tree species is important for plant/tree survival during dry periods (Yang et al. 2018).

Water balance of the Amazon forest, which sustains the highly diverse biome, is indispensable for the local, regional and global climate regulation (Nobre 2014), although little is known about the hydrological cycle (Nobre et al. 2004). The study of water–forest interaction for soil conservation and management is more important now especially for recovering degraded areas and combating deforestation. Therefore, the objective of the study was to analyse the influence of tree morphology on stemflow of forest species in the forest-savanna transition area of the Brazilian Amazon.

MATERIALS AND METHODS

Study location

The study was carried out in a fragment of the Terra Firme (upland rainforest) in the Amazon region, in a forest-savanna transition area, of the Federal University of Amapá, Campus Marco Zero, known as Mata do Sussurro (Figure 1). The State of Amapá has a super humid equatorial climate, with temperatures of around 27 °C. Mean annual rainfall at the coastal region of the capital Macapá is 3250 mm and practically 90% of the annual rain volume falls between December and July (Drummond 2004).

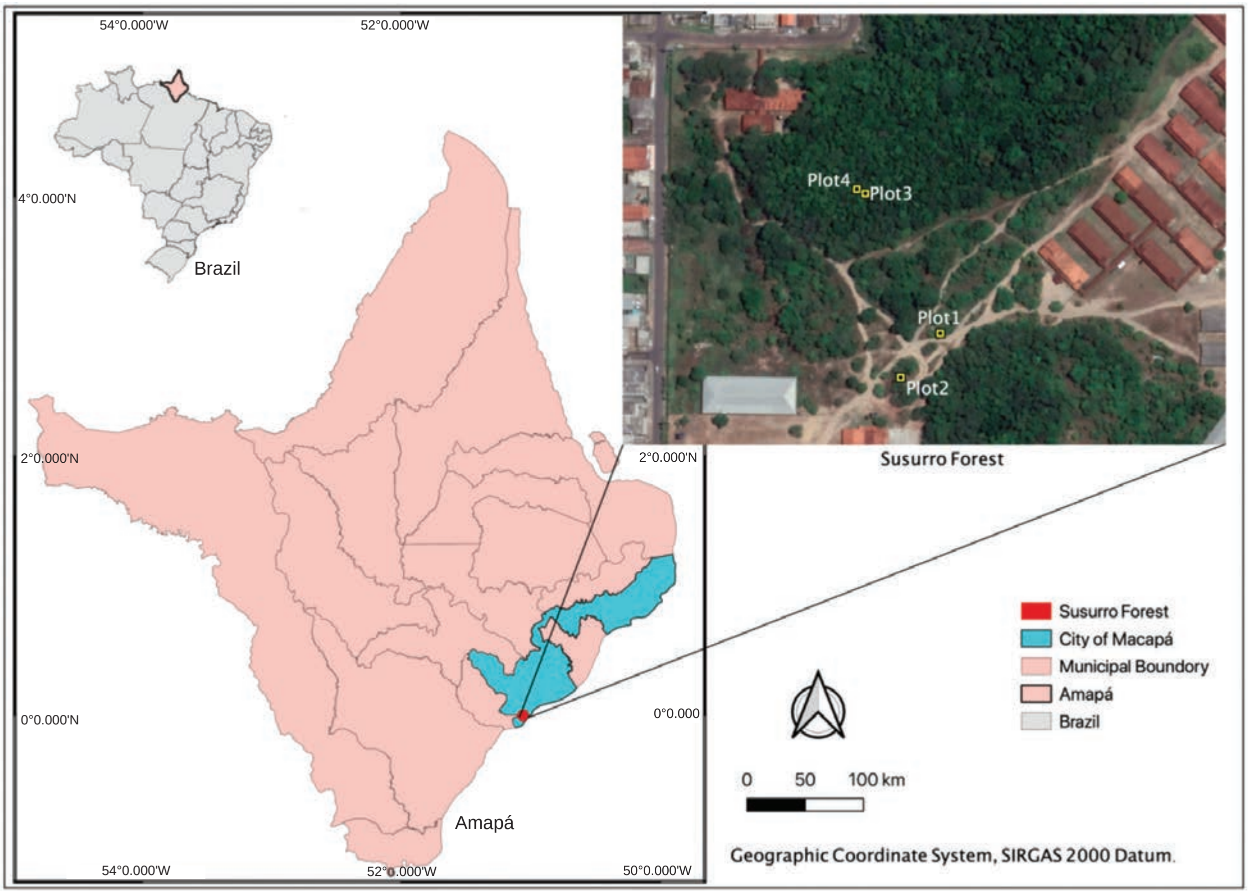

Figure 1 Location of the study area in a forest-savanna transition area at the Terra Firme, Amazon region

Experimental design

Plot description

Four plots were installed, where plots 1 and 2 (Figures 2a and b) were located at the edge of the forest fragment and plots 3 and 4 (Figures 2c and d), within the fragment. The characteristics of each plot are shown in Table 1.

Dendometric characterisation

Trees with a circumference at breast height (CBH) of > 15 cm were measured for tree height, basal area and canopy projection area.

The basal area (BA) was calculated by the equation:

$$BA = \frac{\pi \times DBHi^2}{4}$$

where, DBHi = individual diameter at breast height (DBH) of a tree (cm²), calculated as follows:

$$DBHi = \frac{CBH}{\pi}$$

The canopy area was measured by the edge length from the vertical plane through the trunk centre to the tip of the branches, at 45° angles to each other, thus forming eight triangles or subareas. The canopy area (A) was calculated by the equation:

$$A = \frac{\Sigma (a \times b \times \sin 45°)}{2}$$

Figure 2 Experimental plots along the forest edge (plots a and b) and in the forest interior (plots c and d)

Table 1 Characteristics of study plots

Plot	Area (m²)	No. of trees	Mean height (m)	Relative density (trees m⁻²)
1	69.28	7	3.43	0.10
2	60.41	7	6.74	0.11
3	82.96	16	6.26	0.19
4	58.43	16	5.31	0.27

where, A (m^2) is the sum of the area of each section, and a and b are the lengths (m) of two sections angled at 45°.

Morphological characterisation

The morphological characterisation of the trunk characteristics of each species were analysed by considering the traits of the bark and trunk:

(1) bark texture: rough or smooth bark surface (Figure 3), according to the characterisation proposed by Nultsch (2000),
(2) trunk inclination: inclined or upright (Melo et al. 2005).

Monitoring stemflow

Stemflow collectors were assembled with containers and plastic hoses cut crosswise and wound around the trunk to conduct the flow to storage containers (Figure 4). These runoff collectors were installed on trees with a circumference at breast height of ≥ 15 cm.

The stemflow was captured from August 2018 to July 2019, after each rainfall of > 10 mm, in a 500 mL graduated cylinder. Open rainfall was measured with a rain gauge near plot 1, in an area without vegetation influence.

Data analysis

The dendometric variables and total stemflow volumes were subjected to cluster analysis (Euclidean distance and average linkage method), to check the formation of dendometric similarity groups by the construction of dendrograms using IBM SPSS (2020). The variables that significantly influenced cluster formation were identified by analysis of variance, which were later correlated (Pearson) with stemflow volume, within sets with distinct morphological characteristics.

RESULTS AND DISCUSSION

The circumference at breast height values of the trees in the study area varied from 18 to 82 cm, tree height from 2.5 to 8.5 m, basal area from 0.00 to 0.05 m^2, canopy projection area from 1.07 to 67.57 m^2 and total stemflow volume from 2.54 to 82.82 L (Table 2). High variability in stemflow volume has been highlighted in several studies (Garcia-Estringana et al. 2010, Honda et al. 2014). Of the total of 46 trees, 28 had rough bark while 18 had smooth bark. A total of 35 trees had inclined trunks and 11, upright trunks.

Considering only the dendometric characteristics and total stemflow volumes, multivariate analysis was carried out to form groups of similar trees in relation to the analysed variables. This resulted in the formation of six clusters (Figure 5). ANOVA was applied ($p \leq 0.05$) to identify the variables responsible for cluster formation. All variables except tree height influenced the formation of similarity groups (Table 3).

The number of trees in each cluster showed two major groups (clusters 1 and 3) which comprised 46.6 and 32.6% of the trees respectively. An analysis of only the major

(a) (b)

Figure 3 Bark texture (a) rough and (b) smooth

Figure 4 Stemflow collection system

groups showed that 76% of the trees in group 1 had inclined trunks and 66% had rough bark texture. Of the trees in group 3, the percentages were 87 and 66% respectively. This indicated that the bark microrelief and trunk inclination, together with significant variables, were decisive for the definition of the runoff pattern down tree trunks in the transition forest of the Amazonian savanna. All trees in groups 4 and 5, had smooth and inclined trunks and all trees in group 6 had rough and upright trunks.

The Pearson's correlation analysis showed that there was low correlation between dendometric variables (circumference at breast height, basal area and canopy projection area) with total stemflow volume (Table 4). For tree species of the Brazilian Cerrado, Honda et al. (2014) found low correlations between circumference at breast height and basal area and stemflow volume. Circumference at breast height and stemflow volume of tropical forest species were also weakly correlated (Dietz et al. 2006). A significant correlation between stemflow volume and canopy projection area and circumference at breast height was identified by Návar (2011) who studied conifer, oak and shrubs. Crockford and Richardson (2000) reported significant correlation between stemflow and basal area. In invasive species, increased stemflow production was detected by Whitworth-Hulse et al. (2020) as a result of higher basal area and canopy area.

The Person´s correlation was performed by grouping trees in relation to morphological characteristics (Table 5). For the tree groups with upright trunks, stemflow volume was strongly correlated with the dendometric characteristics.

Considering only trees with upright trunks, the dendometric characteristics circumference at breast height and basal area had moderate negative correlation with total stemflow volume (-0.54 and -0.51 respectively). This indicated that the parameters related to circumference at breast height were not determinants for stemflow. Actual stemflow yield can be computed from a large number of biotic and abiotic variables related to each other in an integrated analysis (Cayuela et al. 2018, Rakestraw et al. 2019). The stemflow component is frequently neglected in water budgeting for trees and shrubs due to its presumed small volume and limited research. Studies of stemflow in shrub species are especially rare. This study focused on stemflow in shrubs and specifically examined its relationship to plant morphology and meteorological factors. Studies that proved the influence of tree size on stemflow production took into account the characteristics of rainfall, among other meteorological factors (Levia et al. 2010). This was not taken into account in our study and the results indicated that size (represented by circumference at breast height) did not influence volumes.

Trees with upright trunks and rough bark, had even higher correlations for circumference at breast height (-0.83) and basal area (-0.81) than individuals with upright trunks, without considering the texture. For trees with upright trunk and smooth bark, only canopy projection area was strongly correlated with stemflow (0.88), indicating that the larger the canopy projection area, the higher the stemflow volume.

The stemflow volume cannot be explained by only one variable but instead by a set of variables. In this study, when the trunk inclination was included in the analysis, the correlation was significant for upright trunk and increased after the inclusion of bark texture. A significant correlation between stemflow and bark roughness as well as for trunk inclination was reported by Honda et al. (2014).

The analysis of mean stemflow volumes of the monitoring period showed that stemflow production from smooth-bark trees was greater (29.4 L) than trees with rough bark (Table 6). Rough-bark species have greater water retention capacity, generally resulting in a lower stemflow production than smooth-bark species (Brooks

Table 2 Individual dendometric and morphological characteristics and total stemflow of 46 surveyed trees

Tree	Dendometric characteristic				Morphological characteristic		Total stemflow (L)
	CBH (cm)	Height (m)	Basal area (m^2)	Canopy projection area (m^2)	Bark	Trunk	
1	27	4.20	0.01	17.17	Rough	Inclined	25.55
2	23	3.20	0.00	10.57	Smooth	Inclined	15.77
3	24	3.90	0.00	67.45	Smooth	Inclined	28.46
4	18	2.50	0.00	3.27	Rough	Inclined	3.93
5	30	2.80	0.01	7.36	Smooth	Inclined	16.96
6	32	3.10	0.01	10.95	Smooth	Upright	5.80
7	61	4.30	0.03	15.69	Smooth	Upright	18.79
8	20	4.50	0.00	1.07	Rough	Upright	44.43
9	41	8.00	0.01	3.97	Rough	Upright	16.17
10	43	8.40	0.01	14.83	Smooth	Upright	14.30
11	30	6.80	0.01	2.66	Rough	Upright	34.12
12	40	7.50	0.01	10.90	Rough	Inclined	12.40
13	29	7.10	0.01	12.10	Smooth	Inclined	23.74
14	82	4.90	0.05	25.67	Rough	Upright	2.54
15	78	8.00	0.05	43.50	Rough	Upright	18.61
16	32	7.00	0.01	5.00	Rough	Inclined	53.92
17	30	6.50	0.01	16.11	Rough	Inclined	38.34
18	30	6.50	0.01	6.28	Smooth	Inclined	24.26
19	26	6.50	0.01	9.22	Smooth	Inclined	22.90
20	40	8.50	0.01	23.75	Rough	Upright	40.89
21	22	5.00	0.00	8.85	Rough	Inclined	51.39
22	19	5.00	0.00	11.18	Smooth	Inclined	22.26
23	21	4.50	0.00	12.03	Smooth	Inclined	55.11
24	58	7.50	0.03	5.53	Rough	Inclined	20.68
25	53	7.50	0.02	3.40	Rough	Inclined	19.85
26	33	7.50	0.01	3.40	Rough	Inclined	9.00
27	20	4.50	0.00	3.40	Smooth	Inclined	21.24
28	33	7.00	0.01	4.89	Rough	Inclined	5.50
29	30	7.00	0.01	16.57	Rough	Inclined	13.86
30	40	7.00	0.01	11.38	Rough	Inclined	50.13
31	34	6.00	0.01	6.62	Smooth	Inclined	36.67
32	34	6.50	0.01	9.02	Smooth	Inclined	35.30
33	46	6.00	0.02	10.13	Smooth	Inclined	76.45
34	39	7.50	0.01	7.51	Rough	Inclined	25.33
35	28	6.00	0.01	14.44	Smooth	Upright	20.58
36	28	3.50	0.01	4.90	Rough	Inclined	22.54
37	28	6.00	0.01	8.38	Smooth	Inclined	82.82
38	23	7.00	0.00	9.28	Rough	Inclined	28.62
39	22	5.50	0.00	13.86	Rough	Inclined	9.89
40	19	3.00	0.00	12.00	Rough	Inclined	10.73
41	44	4.00	0.02	7.11	Rough	Inclined	23.35
42	21	5.00	0.00	15.12	Rough	Inclined	4.01
43	25	4.00	0.00	3.62	Rough	Inclined	15.18
44	51	6.00	0.02	28.20	Smooth	Inclined	7.36
45	49	4.00	0.02	9.37	Rough	Inclined	27.12
46	70	5.00	0.04	40.65	Rough	Upright	5.90

CBH = circumference at breast height; the null values of basal area occurred due to the use of only two decimal places, so that some extremely low values appear as zero in the analysis

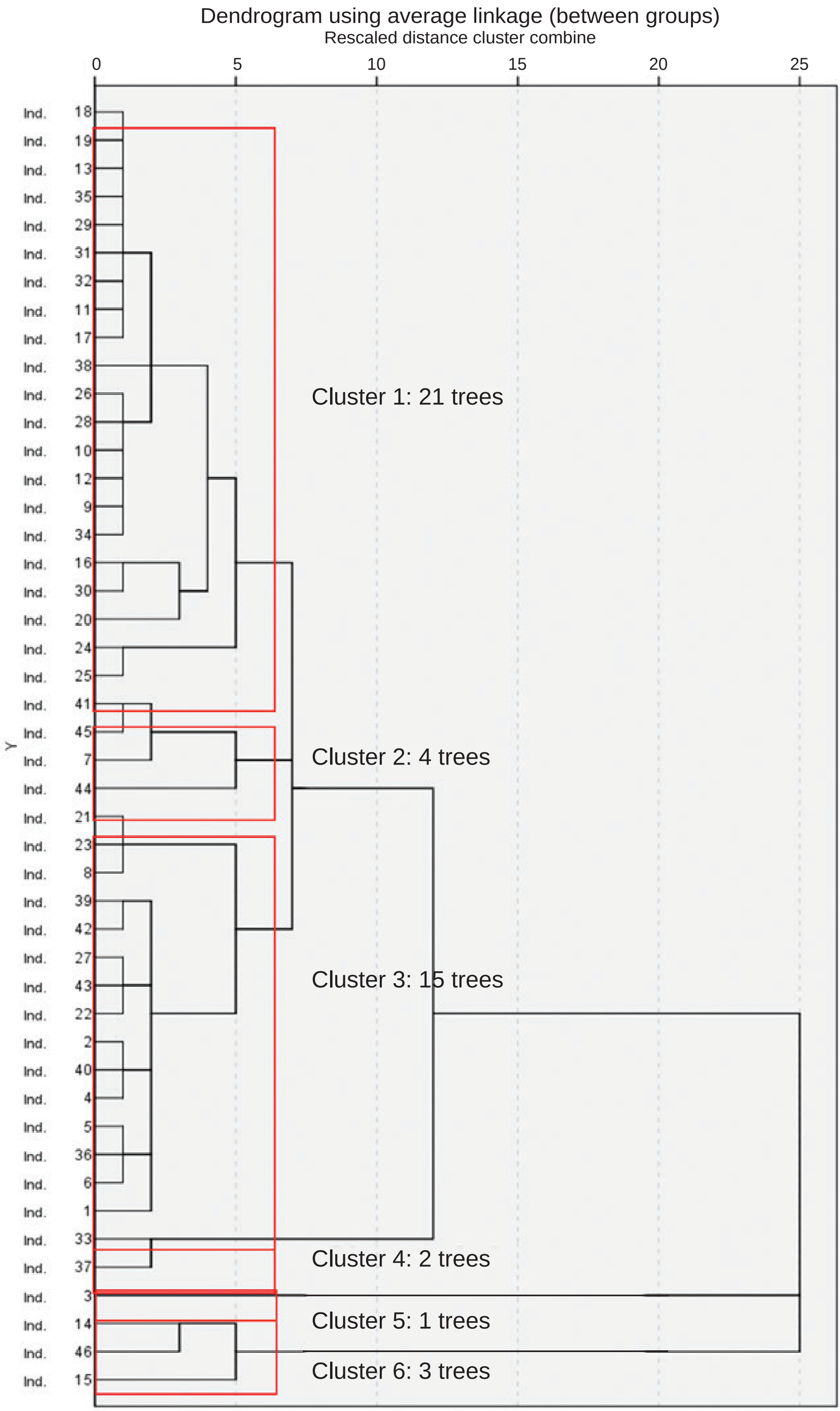

Figure 5 Similarity dendrogram for dendometric characteristics of the 46 trees studied

Table 3 ANOVA results ($p \leq 0.05$) of the variables responsible for cluster formation

Variable	Cluster		Error		F ratio	Significance
	Mean square	df	Mean square	df		
Circumference at breast height (cm)	1781.9	5	42.8	40	41.6	0.000
Tree height (m)	4.2	5	2.6	40	1.6	0.173
Basal area (m^2)	.001	5	.000	40	30.2	0.000
Canopy projection area (m^2)	1015.6	5	37.4	40	27.2	0.000
Total stemflow (L)	2472.5	5	56.6	40	43.7	0.000

Table 4 Pearson's correlation coefficients between dendometric variables and stemflow

	CBH	BA	CPA
Total stemflow	- 0.17	-0.21	-0.14

CBH = circumference at breast height, BA = basal area, CPA = canopy projection area

Table 5 Pearson's correlation coefficients between dendometric variables and stemflow for different morphological characteristics

		Rough bark	Smooth bark	Upright trunk	Inclined trunk
Rough bark	TStF × Cap	-0.21	-	-0.83	-0.01
	TStF × BA	-0.26	-	-0.81	-0.08
	TStF × CPA	-0.20	-	-0.41	-0.15
Smooth bark	TStF × Cap	-	-0.06	0.29	0.12
	TStF × BA	-	-0.08	0.33	0.07
	TStF × CPA	-	-0.12	0.88	-0.14
Upright trunk	TStF × Cap	-	-	-0.54	-
	TStF × BA	-	-	-0.51	-
	TStF × CPA	-	-	-0.29	-
Inclined trunk	TStF × Cap	-	-	-	-0.03
	TStF × BA	-	-	-	-0.08
	TStF × CPA	-	-	-	-0.09

CBH = circumference at breast height, BA = basal area, CPA = canopy projection area, TStF = total stemflow

et al. 2012). In a measurement of the bark microrelief of two tree species, Van Stan and Levia (2009) identified bark roughness as the factor that determined stemflow volume. The authors found that species with smooth bark produced higher stemflow volumes even after smaller rainfall events. The stemflow production in more rugged classes is lower, due to the greater water storage capacity in the bark (Levia et al. 2010, Carlyle-Moses & Price 2006, Liang et al. 2009). Trees with smooth bark and also upright trunk, had the lowest mean stemflow volume (14.9 L). Canopy projection area was strongly correlated with stemflow (0.88), indicating that the larger the canopy area, the higher the stemflow.

Honda et al. (2014) found that the most efficient trees in stemflow production were trees with smooth bark and upright trunks. This contrasts with the pattern observed in this study whereby mean stemflow volume was highest (33.5 L) from trees which had smooth bark and inclined trunks. In a highly heterogeneous

Table 6 Mean stemflow volume (L) for trees with different morphological characteristics

	Rough bark	Smooth bark	Upright stem	Inclined stem
Rough bark	22.6	-	26.12	21.7
Smooth bark	-	29.4	14.9	33.5
Upright stem	-	-	21.6	-
Inclined stem	-	-	-	26.3

environment, as that of a tropical forest, stemflow volume of inclined trees will increase when additional stemflow from neighbouring trees drips directly onto the inclined trunk.

CONCLUSIONS

Circumference at breast height, basal area, canopy projection area and stemflow are important determinants for the formation of similar tree groups. No correlation was observed between dendometric characteristics and stemflow. However, when trees were grouped according to their morphological characteristics, significant correlations were identified between basal area and circumference at breast height and stemflow from trees with an upright trunk and rough bark and between canopy projection area and stemflow from smooth-bark trees. Mean stemflow volumes were higher from smooth trees. However, when the variable trunk inclination was taken into consideration, the mean values were lowest for upright and highest for inclined trunks, demonstrating the importance of this variable for stemflow production.

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