# THROUGHFALL PATTERNS AND CANOPY COVER INDICES IN A HIGHLY HETEROGENEOUS FOREST

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**Abstract**

While rainfall interception controls how much water will be ultimately available for many ecological functions, it is not well understood how canopy structure controls the spatial and temporal distribution of throughfall inside forests. Specially in subtropical and highly heterogenous forests, such as the Atlantic Forest in Brazil, rainfall interception has been only timidly studied. In this paper we investigated how the spatial and temporal variations of throughfall are controlled by the canopy structure. Throughfall spatial variability was measured for a period of over a year using 28 throughfall gauges uniformly distributed in a 28 m² Atlantic Forest plot in Southern Brazil. We proposed the use of the number of overlapping crowns (NOC) as a measure of canopy structure and compared it to the commonly adopted Canopy Cover Fraction (CCF) and the Leaf Area Index (LAI). Locations with a higher CCF, LAI and NOC have a large throughfall variability among rainfall events, even though throughfall amounts could not be directly related to those canopy cover indices. This result implies that the throughfall variability is due to preferential pathways created by the overlapping canopy layers. Additionally, throughfall spatial distribution for periods with lower amounts of gross rainfall is similar to NOC, suggesting that for smaller events the canopy storage capacity is the major control of the amount of rainfall reaching the soil.

Key-words: Throughfall; canopy cover indices; number of overlapping crowns; Atlantic Forest.

## 1. INTRODUCTION

Rainfall interception by forests controls how much water reaches the soil and the amount that will be ultimately available for many ecological and hydrological functions. Throughfall (*Tf*) is the major component of incident rainfall for forest floor, may influence soil moisture patterns (Coenders-Gerrits *et al.*, 2013) and varies in space and time mainly due to meteorological conditions and the heterogeneity of the vegetation (Allen *et al.*, 2020; Van Stan *et al.*, 2020). The canopy controls the storage and release of water (Levia et al., 2011; Allen et al., 2014). Therefore the interception process might be influenced by several vegetation characteristics, such as forest type (Pypker *et al.*, 2005; Staelens *et al.*, 2008), orientation (Carlyle-Moses and Schooling, 2015; Levia *et al.*, 2015), height and density of the vegetation (Rahmani *et al.*, 2011; Levia and Germer, 2015), degree of plant development (Shachnovich *et al.*, 2008), forest age (Brantley et al., 2019), presence of lichens and fungi (Rosier *et al.*, 2015; Savenije, 2018), and crown branching patterns and inclination angle of the branches (Huber and Iroumé, 2001; Carlyle-Moses and Schooling, 2015; Levia *et al.*, 2015).

Due to the complexity of the canopy structure, Leaf Area Index (LAI) and the Canopy Cover Fraction (CCF) are the parameters commonly used to represent the vegetation influence on *Tf*. Even though the spatial distribution of *Tf* can be related to canopy cover indices (e.g. Germer et al., 2005; Zhao et al., 2019), relating canopy characteristics to *Tf* or interception evaporation is not straightforward (e.g. Krämer and Hölscher, 2009). While some studies reported a positive correlation between LAI and interception evaporation (Fleischbein et al., 2005; Siles et al., 2010; Fan et al., 2015), evaporation of intercepted rainfall can vary broadly due to different leaf properties for canopies with the same LAI (Benyon and Doody, 2015). Canopy cover is thought to control *Tf* patterns, however most studies found only a weak relationship between *Tf* and CCF (Johnson, 1990; Marin et al., 2000; Loescher et al., 2002; Deguchi et al., 2006; Konishi et al., 2006; He et al., 2014).

Any model that deals with vegetation has serious problems imposed by the environmental changes, climatic zone, phenology and leaf morphology (Muzylo *et al.*, 2009; Fatichi *et al.*, 2016). The temporal stability of the *Tf* patterns may vary seasonaly (Zimmermann *et al.*, 2008) and its persistence for different rainfall events will depend on forest type (Keim et al., 2005). Uncertainty in interception parameters and *Tf* patterns may also depend on storm size (Zimmermann et al., 2010; Zimmermann and Zimmermann, 2014). In order to improve evaporation estimation in forests, it is important that we understand how forest structure controls the spatial redistribution of rainfall (Fatichi *et al.*, 2016). The relationship between *Tf* and the canopy cover is still poorly understood for most forest types in the world (Allen et al., 2020), specially in subtropical and highly heterogenous forest.

Even though Brazilian native forests are hotspots for biodiversity conservation (Myers *et al.*, 2000) and play an important role in climate regulation and the water cycle (Avissar and Werth, 2005; Davidson *et al.*, 2012), rainfall interception has been only timidly studied in these forests (Giglio and Kobiyama, 2013). The spatial variability of *Tf* has been mostly studied in the Amazon (Lloyd and Marques, 1988; Germer et al., 2005; Cuartas et al., 2007). While there are some studies on the interception process of Atlantic Forest, they mostly analyzed the seasonality of the interception process for different types of vegetation (Castro et al., 1983; Coelho Netto et al., 1986; Arcova et al., 2003; Alves et al., 2007; Shinzato et al., 2011; Moura et al., 2012; Lorenzon et al., 2013; Gasparoto et al., 2014). To our knowledge hitherto, only a few studies analyzed canopy parameters (i.e., Ávila et al., 2014; Tonello et al., 2014) and just one investigated the *Tf* spatial variability in this biome (Sari e*t al.*, 2015).

In this study, we investigated how the spatial and temporal variations of *Tf* are controlled by the canopy structure. We proposed the use of the number of overlapping crowns (NOC) as a measure of canopy structure, and compared it to the widely used indices: CCF and LAI. Throughfall spatial variability and canopy were measured in a plot of Atlantic Forest in Southern Brazil for a wide range of storm conditions.

## 2. MATERIALS AND METHODS

### 2.1. Study site

This study was carried out in the Araponga stream experimental catchment located in Southern Brazil (26°29'27"S, 49°29'44"W) (Figure 1). This is a second-order catchment (5.3 ha). The catchment is completely covered by secondary Mixed Ombrophilous Forest. The most common flora inside the study plot are small trees and shrubs; the major-sized trees are sparse; the bromeliads, lianas, and bamboo clumps are broadly present. Its altitude varies from 880 to 1006 m above the sea level. The catchment belongs to the headwaters of the Iguaçu river basin. The regional climate is the Köppen Cfb type, i.e., temperate climate without dry season and with warm summer (the mean temperature of the hottest month is always under 22°C) (SANTA CATARINA, 1997). Based on the data obtained during the period between 1975 and 2010, the mean annual gross rainfall was 1544 mm and the mean monthly temperature was 18°C. May to September are the colder months and November to February are the warmer ones.

### 2.2. Field monitoring

Gross rainfall (*Pg*) and throughfall (*Tf*) were measured for almost 13 months from November 2013 to December 2014. The *Pg* value was continuously recorded by one automatic tipping-bucket rain gauge (*Waterlog H-340*, 20 cm diameter, resolution of 0.24 mm) connected to a datalogger *Waterlog H-500 XL* supplied by a 12 V battery and a solar panel (Figure 1c). The tipping-bucket was installed 1.5 m above the ground and in a clearing area with no obstacles in a distance of at least twice the difference between the height of the obstacle and the height of the collecting area (Mota *et al.*, 2017). The system was set to register the rainfall amount every 5 minutes.

Similar to Park and Cameron (2008) and to Siegert et al. (2016) that used hand-crafted rain gauges made with bottles and plastic funnels, we measured throughfall with hand-crafted rain gauges (Figure 1d) consisting of a 195 $cm^2$ area funnel connected by a 1 cm diameter orifice to a 5 L volume container. On 8 November 2013, 8 gauges were installed on a 3-m radius circular area. The delimitation of the plot was made as to enclose a representative portion of the forest, including trees of different sizes and species. In order to further investigate the spatial variability of *Tf*, on 15 April 2014, additional 20 gauges were installed in the plot. The gauges were numbered according to their position in the plot (Figure 1b). All gauges were placed below the canopy and 40 cm above the soil surface (Figure 1d). Even though there might be a significant interception by understory vegetation, we ensured that no understory vegetation covered the collecting area of the *Tf* gauges. Throughfall amounts were measured on a bi-weekly to monthly basis, resulting in 3 periods of measurement in 2013 and 20 periods in 2014.

The plot (28 $m^2$) has 39 individual trees. The tree species encountered in the plot were: caixeta (*Tabebuia cassinoides*); cajujo (*Clethra scabra*); camboatã (*Matayba elaeagnoides*); canela-guaicá (*Ocotea puberula*); capororoca (*Myrsine coriacea*); cedro (*Cedrela fissilis*); guamirim-branco (*Myrtaceae sp* 1); guamirim-vermelho (*Myrtaceae sp* 2); jerivá (*Syagrus romanzoffiana*); maria-mole (*Guapira opposita*); pessegueiro-bravo (*Prunus myrtifolia*); vassourão-branco (*Vernonanthura discolor*); voadeira (*Ilex brevicuspis*); xaxim (*Dicksonia sellowiana*) and xaxim-espinhento (*Cyathea phalerata*).

### 2.3. Time stability of throughfall spatial patterns

The persistence in time of *Tf* spatial distribution was investigated through a time stability plot, which is the same method used in many other interception studies (e.g. Gómez et al., 2001; Germer et al., 2005; Keim et al., 2005; Manfroi et al., 2006; Shachnovich et al., 2008; Zimmermann et al., 2008; Gerrits et al., 2010). Following this method, the *Tf* value obtained at each gauge was normalized for each measurement period,

$$\delta_{t,j} = \frac{Tf_{t,j} - \overline{Tf_t}}{\sigma_t} \quad (1)$$

where $\delta_{t,j}$ is the normalized throughfall at time $t$ for gauge $j$; $Tf_{t,j}$ is the throughfall measured at gauge $j$ at time $t$; $\overline{Tf_t}$ is the mean throughfall of all the points at time $t$; and $\sigma_t$ is its standard deviation. In the time stability plot, the gauges were sorted in ascending order of average normalized throughfall,

$$\overline{\delta_j} = \frac{1}{d}\sum_{i=1}^{d} \delta_{t,j} \qquad (2)$$

where $\overline{\delta_j}$ is the mean normalized throughfall for gauge $j$; and $d$ is the number of the measurement period.

### 2.4. Canopy Parameters

Three indices were calculated in order to characterize the canopy cover: LAI; CCF; and NOC at each $Tf$ gauge. The CCF and LAI were estimated from digital photographs taken at each of the 28 $Tf$ gauges. Photographs were taken with a digital Canon Power Shot S5 IS camera which was set for a 3264 x 3448 resolution. For each photograph capture, the camera was mounted on a leveled platform placed 25 cm above the soil surface, with the lens placed at the center point of the gauge and directed towards the zenith (Figure 2a, b). Before taking each photograph, the shutter speed velocity was set according to the light conditions to avoid information loss due to overexposure, following Llorens and Gallart (2000). During the summer, the photographs were preferably not taken close to midday.

The post-processing of the photographs consisted on the following steps: (i) the images were converted to black-and-white (Figure 2d), where the black pixels indicate the presence of vegetation cover (foliage and branches) and the white pixels indicate the canopy openness; (ii) to avoid radial distortion, the central circle of each photograph was extracted with diameter equal to 50% of the diagonal; (iii) in each cropped image the large gaps between tree crowns were selected and the total number of pixels contained in these large gaps were counted; and (iv) the remaining pixels (representing the crown projection area) were separated between the gaps within the crown (remaining white pixels) and the vegetation cover (black pixels).

The sensitivity of canopy cover indices to the size of the circle extracted from each photograph was analyzed by changing its radius from 25 to 10% of the diagonal in 1% increments. The standard error was then calculated as a measure of the variation of the obtained indices values. The final values of LAI and CCF used in this study were the average of all the obtained values.

### *2.4.1. Canopy Cover Fraction*

The value of CCF was determined as the ratio between black pixels (*Nb*) and the total number of pixels ($T_p$):

$$\mathrm{CCF} = \frac{Nb}{T_p} \tag{3}$$

### *2.4.2. Leaf Area Index*

The LAI value was calculated by considering the difference between the open area within the crown (crown porosity) and the open area between the trees (Pekin and Macfarlane, 2009):

$$\mathrm{LAI} = -\frac{f_c \ln(\Phi)}{k} \tag{4}$$

where $f_c$ is the crown cover; $\Phi$ is the crown porosity; and $k$ is a light extinction coefficient at the zenith, which was assumed in this study as 0.5. This value is the same value that Macfarlane et al. (2018) used for Jarrah forest (eucalypt forest). Since this parameter only changes the magnitude of the estimated value of LAI, and our focus was on its variability in time and space, we expected the choice of this value not to strongly affect the main conclusions of the present paper. The $f_c$ is the relationship between the gaps between crowns ($g_L$) and the total number of pixels in the photo ($T_p$),

$$f_c = 1 - \frac{g_L}{T_p} \tag{5}$$

The crown porosity ($\Phi$) is defined as the proportion of the ground area covered by the vertical projection of foliage and branches within the perimeter of the crowns of individual plants (Walker and Tunstall, 1981),

$$\Phi = 1 - \frac{f_f}{f_c} \tag{6}$$

where $f_f$ is the fraction of foliage cover, defined as the proportion of ground area covered by the vertical projection of foliage and branches (fraction of black pixels):

$$f_f = 1 - \frac{g_T}{T_p} \quad (7)$$

where $g_T$ is the number of pixels representing gaps (total number of white pixels).

*2.4.3. Number of overlapping crowns*

To estimate the projected crown area, the radius of the vertical projection of each canopy was measured in 8 directions 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° following Shinzato et al. (2011). The NOC value above each $Tf$ gauge was estimated by using the projected crown area of all trees whose canopies were entirely or partly inside the 28-m² circular area (Figure 1b). Therefore, only $Tf$ gauges placed inside this area were considered in this analysis (20 of 28 $Tf$ gauges). At each $Tf$ gauge we counted the maximum NOC above the collecting area of each gauge.

# 3. RESULTS AND DISCUSSION

## 3.1. Gross rainfall and throughfall measurements

During the period from November 2013 to December 2014 the total gross rainfall at the Araponga catchment was 1622 mm (monthly rainfall is shown in Figure 3). The maximum 5-min rainfall rate ($I_{5max}$) ranged from 14.3 to 100.4 mm h$^{-1}$. In March and June 2014, extreme rainfall events occurred. The observed rainfall of these two months was significantly higher than the mean monthly rainfall amount of the previous 35 years (Figure 3).

Throughfall was measured with 8 $Tf$-gauges during 10 periods and with 28 $Tf$-gauges during 13 periods. During 5 of them, not all $Tf$ gauges were operated due to clogging, overflow, or another problem that made the measurement unreliable. Those issues occurred in five out of the 23 periods, with the number (proportion) of $Tf$ gauges with some of the mentioned problems equal to 2 (7%), 2 (7%), 4 (50%), 7 (25%) and 28 (100%). Two of those periods, one in March and the other in June

2014, in which the majority of *Tf* gauges were completely full, were eliminated from further analysis. By eliminating these two larger events, we expect the long-term average *Tf* reported in this study to be somewhat lower than the total, since in large events the proportion of rainfall that reaches the soil as *Tf* is generally high.

As reported in many studies, we found that storm-total *Tf* is linearly related to *Pg* (Figure 4a). The relative *Tf* (expressed as percentage of *Pg*) of each period ranged from 49% to 103%, corresponding to 71% of *Pg* for the entire 13-month period (Figure 4c and 4d) which is similar to the values in the literature. In a review of interception studies conducted in Brazilian forests, Giglio and Kobiyama (2013) showed that the reported values of long-term relative *Tf* in the Atlantic Forest varied between 47.6 and 97.4%.

The *Tf* distribution is heterogeneous in time (Figure 4) and space. This high variation among *Tf* gauges is one of the characteristics of highly heterogeneous forests, in which the complex canopy structure enables the water movement through several possible pathways. There was no clear seasonality pattern in our data (Figure 4b, d).

### 3.2. Throughfall spatial patterns

The spatial distribution of *Tf* in this study is clearly heterogeneous (Figure 5). This heterogeneity is typical of tropical rainforests, as shown in other studies (Oliveira and Dias, 2005; Souza et al., 2007; Scheer, 2009; Souza and Marques, 2010; Diniz et al., 2013; Lorenzon et al., 2013; Avila et al., 2014; Gasparoto et al., 2014; Tonello et al., 2014). It can be also observed that the *Tf* distribution varies among the events. This fact indicates that the spatial distribution of *Tf* depends on the storm characteristics and therefore corroborates that it is not solely controlled only by the canopy characteristics (e.g. Gómez et al., 2001; Germer et al., 2005; Manfroi et al., 2006; Shachnovich et al., 2008; Zimmermann et al., 2008; Gerrits et al., 2010).

The dependency of the measured plot mean *Tf* on the number of *Tf* gauges was investigated with the analysis of the coefficient of variation of the average *Tf* ($CV_{comb}$) using all possible combinations of *Tf* gauges (Figure 6a). The high heterogeneity of the studied forest leads to a $CV_{comb}$

over 5% when the number of analyzed *Tf* gauges is lower than 20 (Figure 6a). We found that the coefficient of variation (CV) of the *Tf* measurements of the 28 *Tf* gauges was independent of total gross rainfall (inset of Figure 6a).

The temporal stability of the spatial distribution of *Tf* suggested the existence of preferential paths for the water movement in the forest canopy (e.g., gauges 5.2 and 4.6 in Figure 6b). However, some *Tf* gauges (e.g., gauges 4.5, 6.4 and 6.5) presented a high variation among the monitoring periods (Figure 6b). Mean normalized *Tf* was significantly different than zero (t-test at the 5% significance level) in 10 of the 28 *Tf*-gauges. Mean normalized throughfall was consistently lower than plot-averaged *Tf* in 6 of them (*Tf* gauges in red in Figure 6b) and consistently higher in 4 of them (*Tf* gauges in blue in Figure 6b).

### 3.3. Canopy parameters

In a preliminary observation of the photographs before any digital processing, it was already clear that the forest canopy is heterogeneous among the monitoring points. The mean values of LAI and CCF during the monitoring period ranged from 4.2 to 6.8 $m^2/m^2$ and from 85 to 96%, respectively (Figure 7a and Figure 7c). These values were much more variable at some points throughout the year than at others (e.g., gauge 2.3 and 2.4 in Figure 7 ). Even though the LAI and CCF were slightly lower in winter (Figure 7c,d), the seasonal variation was much less pronounced than that among the *Tf* gauges. While it is expected a significant correlation between canopy cover (LAI and CCF) and *Tf* in a highly seasonal or relatively less dense forests, we suppose that the smaller variability of canopy cover in denser evergreen forests is not sufficient to account for the high temporal variability observed in *Tf*.

### 3.4. Relationship between throughfall and canopy parameters

The time-averaged LAI and CCF for each *Tf* gauge were not significantly related to relative *Tf* (results not shown). We used the 60-mm threshold to separate the events into two classes, the lower and the upper half in terms of total *Pg*. The NOC seems to be related to the throughfall distribution in the plot for periods with *Pg* lower than 60 mm (Figure 8a,c). The relative *Tf* was smaller (higher) in regions with a higher (lower) NOC (Figure 8a,c) for those smaller events (i.e. *Pg* < 60 mm). This result may be a consequence of the higher *Sc* in locations with higher number of overlapping crowns. The variation of the *Sc* in space (Figure 8b) confirms this hypothesis, suggesting a relationship between this parameter and the pattern of *Tf* spatial distribution for periods with *Pg* < 60 mm (Figure 8c).

Figure 8d does not show a clear relation of *Tf* at each *Tf* gauge with NOC (for the periods with a higher amount of gross rainfall (*Pg* > 60 mm). The higher *Tf* amount under a higher NOC in periods with *Pg* > 60 mm indicates that in this situation the canopies may act like a funnel, forming preferential pathways with a high number of dripping points. Despite of those notable visual patterns, the relationship between relative *Tf* and the number of overlapping canopy layers was very weak, even for events with *Pg* < 60 mm (Figure 8e,f).

Although we did not find any significant relationship between *Tf* and the canopy cover indices, the canopy cover may influence the *Tf* variation among events. Indeed, the standard deviation of the normalized *Tf* was positively related to the CCF and LAI and the NOC above each *Tf* gauge (Figure 9). It indicates that *Tf* at locations with less canopy cover has a lower variability among rainfall events than under dense canopy. Therefore, locations with a higher number of overlapping canopy layers are more likely to have a higher *Sc* (as shown in Figure 8) and a higher number of preferential pathways, which leads to large *Tf* variability depending on the rainfall characteristics.

## 4. CONCLUSIONS

In this study we explored the relationship between canopy cover and *Tf* in a Subtropical Atlantic Forest in Brazil. We proposed the use of the number of overlapping crowns above each gauge as a measure of canopy structure and compared it to the CCF and LAI. Confirming previous research, we found that the vegetation plays an important role in rainfall redistribution in this forest as there was throughfall persistency in time at some points which received consistently less or more *Tf*. However, we did not observe any satisfactory relationship between *Tf* and canopy cover indices (CCF, LAI and NOC above each *Tf* gauge). Instead, we found that the *Tf* variation among rainfall events at each *Tf* gauge was positively related to the CCF (time-averaged CCF for each *Tf* gauge), LAI (time-averaged LAI for each *Tf* gauge) and NOC above each *Tf* gauge.

Those results indicate that locations with a higher number of canopy layers have a higher potential for creating preferential pathways, which will lead to large *Tf*-variability depending on the rainfall characteristics. Additionally, we were able to establish a connection between NOC and the *Tf* spatial distribution for periods with lower amounts of *Pg*. It suggests that for lower events *Sc* is the major control of the amount of rainfall reaching the soil. The results obtained in this study show the difficulty of using canopy cover indices (LAI, CCF and NOC) to represent the spatial redistribution of rainfall by the vegetation in highly heterogeneous forests.

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**Data availability statement**

Throughfall data is available in the supporting information. Canopy cover data is available from the corresponding author upon.

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