

The influence of emergent trees on rainfall distribution in a cacao agroforest (Sulawesi, Indonesia)

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Abstract

Emergent trees may have an influence on the volume and the spatial distribution of water input into agroforestry stands and may thus affect water availability for the main crops. Our goal was to analyze the influence of such trees on rainfall distribution in a cacao agroforest area in the rainforest margin zone of Central Sulawesi, Indonesia. The emergent trees studied belong to the species *Bischofia javanica* (Phyllanthaceae) and were 15 m high remnants from the natural forest. A set of 96 throughfall gauges was systematically distributed underneath canopies of cacao only, and underneath canopies of cacao plus emergent trees (cacao plus trees). From an earlier study we knew that stemflow can safely be estimated with less than 1% of gross precipitation (P_g).

Median throughfall tended to be lower in gauges underneath cacao plus trees than under cacao only ($p \leq 0.1$), and the estimated rainfall interception loss was 4% and 16% of P_g in cacao only and cacao plus trees plots, respectively. This difference was most likely caused by a tree-induced enhancement of the canopy water storage capacity and an increase in canopy roughness. Underneath the canopy of emergent trees (cacao plus trees), throughfall exceeded gross precipitation east of the tree stems (113%) and was significantly lower ($p \leq 0.05$) west and north of the tree stems (67–77% of P_g). Significant effects of trees on throughfall did not extend beyond their canopy area. We assume that wind-driven rain was stripped out east of the stems causing an increase in throughfall, while rain-shadow effects led to a decrease in throughfall west and north of the tree stems. Thus, at our study site emergent trees tended to reduce rain water input, and produced clear spatial patterns in throughfall distribution. A reduced water availability may lead to reduced cacao bean yields in times of water scarcity but a more complete assessment of the hydrological function of shade trees in agroforestry systems may also reveal positive influences of shade trees on cacao trees. Such an advanced analysis of hydrological functions still remains to be done.

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Keywords: *Bischofia javanica*; *Theobroma cacao*; Throughfall; Rainfall interception

Introduction

Cacao is the second most important tropical cash crop and can be cultivated in shaded agroforestry systems as well as in open monocultures. Shaded systems are preferable from the viewpoint of nature conservation as indicated by a study in Sulawesi,

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Indonesia, where completely unshaded cacao systems harbored a significantly lower number of species such as birds and butterflies compared to shaded cacao systems (Schulze et al., 2004). On the other hand, net revenues from cacao increase with decreasing tree cover (Steffan-Dewenter et al., 2007). Experimental studies dealing with the effects of trees on water distribution and availability in cacao cultivation systems are largely lacking. A modelling study revealed that bean harvest in cacao is strongly influenced by water availability (Zuidema et al., 2005). Due to an increased rainfall interception loss, trees may reduce the water input and availability in cacao cultivation. Additionally, trees may also effectuate spatial patterns in throughfall distribution, thereby favoring some cacao plants and being disadvantageous for others.

Under given meteorological conditions, rainfall interception is mainly controlled by stand structural characteristics such as leaf area and canopy roughness. In a comparison of differently managed forest stands in Sulawesi, which among others included agroforest stands, interception increased significantly with increasing tree height (Dietz et al., 2006). In a multiple regression, leaf area index and tree height explained 81% of the observed variability in interception among twelve stands. The three agroforest stands included in the study were characterized by relatively low tree height and relatively low rainfall interception rates. The variation in interception and the spatial variability in throughfall within these agroforest stands were considerable, probably due to differences in tree cover and structure.

The variation of throughfall within a cacao agroforest stand may be induced by the associated emergent trees, which may have similar effects as the more often studied isolated or widely separated trees in open woodlands or savannah-type ecosystems. In the latter, spatial patterns of throughfall during wind-driven rainfall were detected, with areas of increased throughfall upwind and areas of reduced throughfall downwind (David et al., 2006; Gómez et al., 2001; King and Harrison, 1998; Samba et al., 2001; Xiao et al., 2000). The upwind concentration areas underneath the crown were ascribed to accumulation of dripping, while the depletion areas have been attributed to rain-shadow effects (David et al., 2006). It is, however, difficult to predict whether and to what extent results from emergent trees in open woodlands also hold for cacao agroforests. The cacao plants themselves can also have big crowns and large leaf areas, which may significantly influence interception and throughfall distribution patterns.

The present study was conducted in an upland region of Central Sulawesi, Indonesia, where cacao cultivation has more than doubled in the last two decades. In the vicinity of remaining old-growth forest, cacao is grown under the canopy of remnant trees from the natural

forest. This form of cultivation has been proposed by the Lore Lindu National Park authorities for the management of buffer zones bordering the fully protected core zone (Helmi, 2005) and may also occur in other areas close to natural forests. Similar stand structural patterns with some scattered emergent trees above shrubs or small trees can also be encountered on farms where fruit trees are mixed into coffee or cacao fields. The objective of our study was to reveal the influence of emergent trees on rainfall interception and distribution within a cacao agroforest.

Methods

Study site

The study was conducted in the margin zone of the Lore Lindu National Park in Central Sulawesi, Indonesia, in the vicinity of the village of Toro (1.5014°S, 120.0355°E) (Fig. 1). Toro is situated about 110 km south of Palu and is surrounded by mountain chains in three directions (Fig. 2). Our study stand is located at 952 m a.s.l. on an eastward facing slope (inclination 20.6°). In some parts of the stand, cacao occurs with little or no cover of trees, in other parts the cacao plants are cultivated under trees remaining from natural forest. The stand comprised 1706 stems per hectare, which were mostly cacao plants, while stem density of emergent trees was relatively low. The cacao trees had a mean diameter (at 1.3 m height) of 7.9 cm and were on average 4.1 m high. The mean diameter of emergent trees was 25.6 cm and they reached an average height of 14.7 m (Dietz, pers. comm.). The tree species diversity in such stands may be considerably high but species endemic in Central Sulawesi are often lacking (Gradstein et al., 2007). In our plot, the tree species *Bischofia javanica*

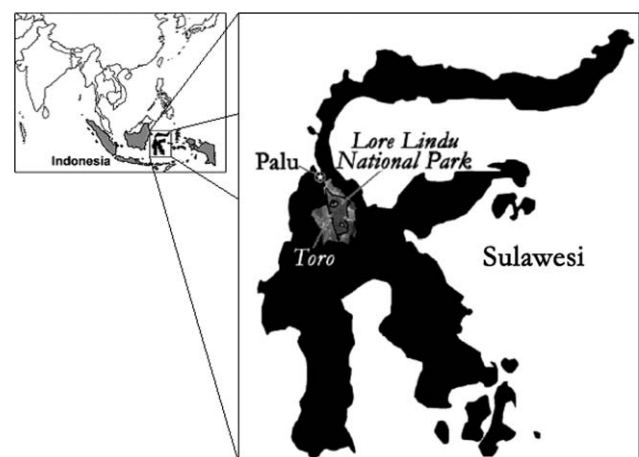


Fig. 1. Location of Sulawesi in the Indonesian archipelago and location of Toro village, which is surrounded by the Lore Lindu National Park.

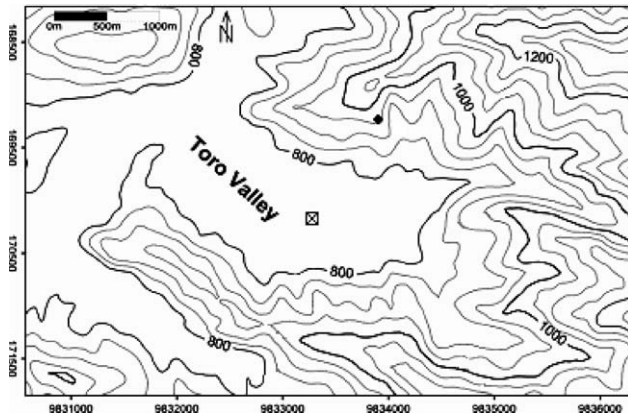


Fig. 2. Topographic map of the Toro valley (UTM 51 S) showing positions of the automatic weather station (☒) and the study plot (●).

Table 1. Rainfall characteristics over 1 year (April 2004–2005) at the valley bottom close to the village of Toro (805 m.a.s.l.; Kreilein et al., unpublished data).

Number of days observed	366
Number of days $P_g > 0.2$ mm	218 (60%)
Number of rain storms	526
Number of rain storms with precipitation > 0.2 mm	282 (54%)
Gross precipitation, P_g (mm)	1828
Average rain storm precipitation amount (mm)	6.5
Average rain storm duration (h)	1.9
Average rainfall intensity, \bar{R} (mm h^{-1})	3.4

(Blume), Phyllanthaceae (formerly Euphorbiaceae, current taxonomic family according to a personal communication by P. Kessler), was quite frequent. The annual mean temperature measured at an automatic weather station on the bottom of the Toro Valley was 23.1 °C and the annual rainfall total was 1812 mm (Kreilein et al., unpublished data). This station was unfortunately malfunctioning at the time of study. Rainfall intensities at this station are usually relatively low (Table 1), which is also true for daily averages of wind speed (1.03 m s^{-1}). Higher annual rainfall volumes were recorded at the slopes of the surrounding mountains (Dietz et al., 2006), which is due to orographic uplift of air masses. An analysis of wind patterns for Central Sulawesi revealed that the coastal region of Palu is dominated by a land–sea breeze circulation transporting air masses from a northern direction into the Palu Valley (Gunawan, 2006). Continuing along the bottom of the valley, this sea breeze reaches far inland until it is uplifted at the edges of mountains, e.g. at the edges of the Toro Valley. Resulting from these patterns of air movement and orographic rainfall formation, locations on the slopes of the Toro Valley are likely to receive rainfall from varying wind directions according to their exposition.

From this follows that our study plot receives rainfall from an eastern direction, which is confirmed by the observations made during field work.

Throughfall sampling

Incident rainfall was measured on an open field adjacent to the plot using five bulk samplers. The gauges were attached to a bamboo tower at a height of 5 m, had an orifice of 295 cm^2 each and a vertical rim of 3.5 cm height. A table tennis ball was placed in each of the funnels to reduce evaporation from the gauges. Rainfall as well as throughfall volumes were measured daily from 22 May to 16 July 2006 (56 days). Throughfall was collected with 96 similar gauges installed 100 cm above ground. Three ‘cacao plus tree’ plots and three ‘cacao only’ plots were equipped with 16 samplers each. Starting at a central point, transects in every cardinal direction (north, east, south and west) were equipped with four rain gauges at a distance of 2 m. On the ‘cacao plus tree’ plots, an emergent tree of the species *B. javanica* was located in the centre of the plot, and no further trees other than cacao occurred within a radius of 8 m. On ‘cacao only’ plots there was no tree in the centre and no other trees than cacao on the plot (201 m^2). The *B. javanica* trees on the ‘cacao plus tree’ plots had a dbh between 20 and 27 cm, were 12–19 m high and their canopy radius was 4.2 m on average. Stemflow in this stand, including *B. javanica* and cacao, had been measured before, and was less than 1% of gross precipitation (Dietz et al., 2006). We therefore did not repeat stemflow measurements.

Statistical analyses

Medians and interquartile ranges (IQR, 25–75%) are reported as measures of central tendency and dispersion. Pair-wise comparisons among groups were conducted with the non-parametric Wilcoxon rank sum test. The standard level of significance was $p \leq 0.05$. The statistical analyses were conducted using SAS software (SAS Institute Inc., Cary, NC, US; version 8.2).

Results

During the measurement period of 56 days, a total number of 27 days with rain events were recorded and the gross precipitation (P_g) summed up to 466 mm. Daily rainfall sums ranged from 0 to 73 mm, with a median of 11 mm per rainy day.

Median throughfall tended to be higher in samplers underneath ‘cacao only’ (96% of P_g) than in samplers under ‘cacao plus trees’ (84% of P_g ; $p \leq 0.1$). Considering the low stemflow rates in the plot (Dietz et al., 2006),

one can estimate the rainfall interception with 4% and 16% of P_g in ‘cacao only’ and ‘cacao plus trees’ plots, respectively. Interquartile ranges were quite similar for throughfall sums throughout the entire study period (60% of P_g underneath ‘cacao only’, 57% of P_g underneath ‘cacao plus trees’) indicating a high spatial variability in both plot categories. On a daily basis, the IQR of throughfall was higher in gauges underneath ‘cacao only’ than in gauges underneath ‘cacao plus trees’ on 74% of all days (Fig. 3). IQRs of daily throughfall in both plot categories did not correlate with daily rainfall volume, and neither could the differences be explained by rainfall volume. The frequency distribution of throughfall gauge catch in the ‘cacao only’ plots shows an almost equal distribution ranging from 30% to 180%

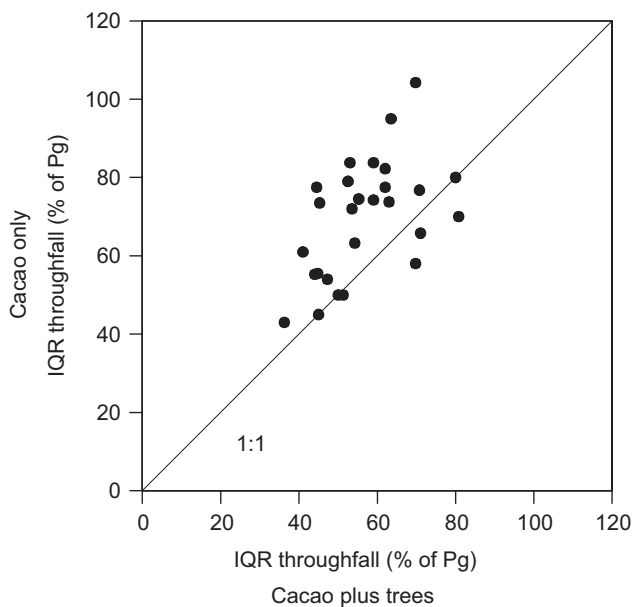


Fig. 3. Interquartile ranges (IQR; 0.25–0.75) of throughfall (percentage of gross precipitation, P_g) for samplers underneath cacao only and samplers underneath cacao plus trees.

of throughfall without a clear peak (Fig. 4A). In contrast, the frequency distribution in the ‘cacao plus trees’ plots resembles a normal distribution with a peak in the class of 60–90% throughfall (Fig. 4B).

In the ‘cacao plus tree’ plots, the position of the sampling gauges significantly influenced the volume of collected throughfall. High throughfall values were recorded east of the tree stems, especially in samplers 2 m distant from the tree trunk (119% of P_g ; Fig. 5). Low values were e.g. recorded west of the tree trunk in 4 m distance (59% of P_g). Averages of the 2 and 4 m eastern collectors had a significantly ($p \leq 0.05$) higher gauge catch (113%) than those of collectors placed west (71%) and north (67%) of the stem. The southern collectors (73%) only tended to differ from the ones located east of the stem ($p \leq 0.1$). The influence of the trees did not seem to extend further than ~4 m from the trunk (Fig. 5), which nearly corresponds to the average tree crown radius (4.2 m). No such patterns of throughfall distribution were found underneath cacao only.

Discussion

We estimated a rainfall interception loss of 16% of P_g where the ground was covered by tree and cacao canopies, which is very close to the average (18%) of three agroforest plots in the region studied by Dietz et al. (2006). Our estimation is also close to values obtained in agroforest stands in Costa Rica, where 15% and 16% were reported from cacao associated with *Erythrina poeppigiana* and *Cordia alliodora* trees, respectively (Imbach et al., 1989). In contrast, we estimated a rainfall interception loss of 4% in samplers positioned under cacao canopies only. A comparatively low value of 1% was found for a cupuaçu (*Theobroma grandiflorum*) monoculture in central Amazonia by Schroth et al. (2001). Thus, there is a tendency towards increased rainfall interception through associated trees,

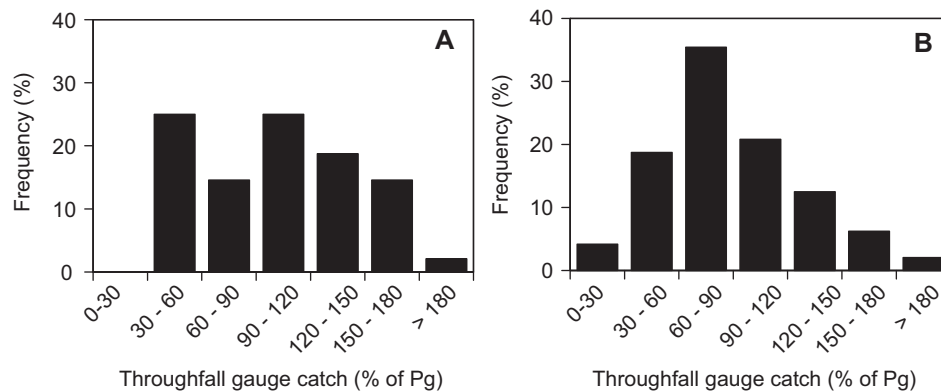


Fig. 4. Frequency distribution of throughfall gauge catch in percentage of gross precipitation (P_g); displayed are sums per gauges for the entire study period. (A) Gauges on cacao plots only; (B) gauges on cacao plus trees plots, $n = 48$ per category.

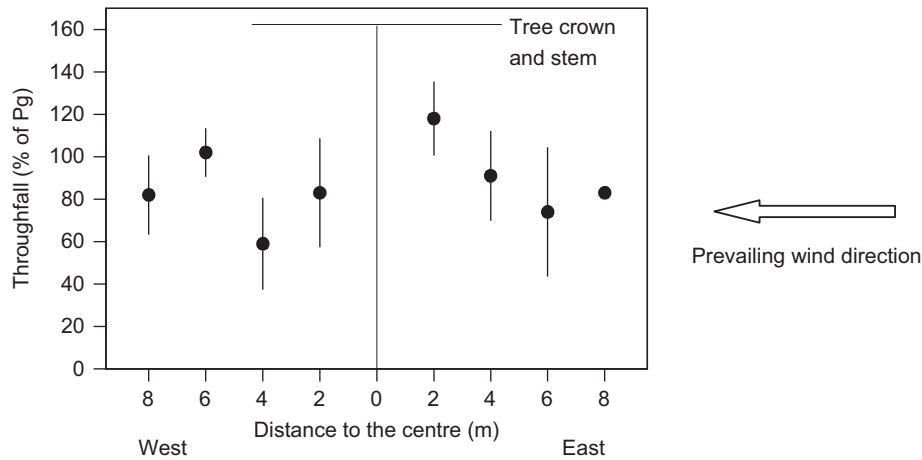


Fig. 5. Throughfall as percentage of gross precipitation (Pg) in varying distances to the stem centre of an emergent tree (*Bischofia javanica*) over cacao, in west–east direction (medians and interquartile range, $n = 3$). Prevailing wind direction was east.

which may be due to additional canopy water storage capacity provided by the trees and an increased canopy roughness.

The cacao plant itself has a comparably extensive canopy cover and has, due to its capacity to form a shade canopy, a relatively high leaf area. We assume that under the climatic conditions prevailing in our study region, a rough and high canopy might be of greater importance for rainfall interception loss than leaf area. Dietz et al. (2006) found that 81% of the variation in rainfall interception among twelve stands of the region ranging from agroforest to natural forest was explained by leaf area and tree height. Based on regression analysis, tree height was much more influential (63%) than leaf area (18%). A comparable conclusion can be drawn from an analysis of satellite images which aimed at predicting regional interception patterns in Central Sulawesi (Nieschulze et al., 2009): A measure of canopy roughness, the so-called local maxima, yielded high coefficients of determination when compared to ground-based measurements. A possible explanation is that under the prevailing conditions in our study region the canopy may not completely dry up between subsequent rainfall events, and the actual water storage at the start of rainfall is thus lower than the potential. This assumption is backed by measurements of surface wetness in a natural forest of Sulawesi, where surfaces remained wet for long periods after individual rainfall events (Dietz et al., 2007). We do not have such measurements in cacao cultivation systems but personal observations also suggest that cacao leaves remain wet for long periods after rainfall. Tall associated trees then may increase the range of the vertical distribution of leaves and other canopy components contributing to the canopy water storage, thus leading to a higher canopy roughness and a more effective energy exchange with the atmosphere. This may cause a comparatively high rainfall interception loss. In contrast, cacao

has a relatively uniform canopy with supposedly low roughness, and consequently a low rainfall interception loss.

In our study, the emergent trees influenced the spatial distribution of throughfall. Beneath the tree canopy we found an increase of throughfall volumes east of the stem, which corresponds to the prevailing wind direction. Throughfall values were much lower west, north and south of the stem. The area of influence did not extend beyond the canopy area. In studies of isolated or widely separated trees in open woodlands or savannah-type ecosystems, comparable patterns have been frequently observed (Dancette and Poulain, 1969; David et al., 2006; Gómez et al., 2001; King and Harrison, 1998; Samba et al., 2001; Xiao et al., 2000). Non-random spatial variability of throughfall during wind-driven rainfall, with areas of rainfall concentrations upwind and areas of reduced rainfall downwind, was consistently demonstrated in these studies. The upwind concentration areas were ascribed to accumulation of dripping, while the depletion areas have been attributed to rain-shadow effects (David et al., 2006). Thus, similarities between the above-mentioned ecosystems and the studied cacao agroforest are apparent, which is partly due to the low interception of cacao plants. Conflicting observations were made with respect to the distance of accumulation and depletion areas to the stem. Voigt (1960), Ford and Deans (1978) and Herwitz (1987) reported higher throughfall amounts near stems than under the crowns' edges, while Aussenac (1970), Swank (1972), Johnson (1990) and Beier et al. (1993) observed the opposite. Such patterns may be highly species specific. In case of the leeward rainfall depletion area, e.g. David et al. (2006) stated that the latter extended beyond the crown's edge. The spatial expansion of both rainfall concentration and depletion areas may also be determined by tree height, rainfall inclination angle and wind speed.

Our data suggest that emergent trees in the study stand had an influence on rainfall distribution. Non-sheltered cacao plants and those in windward direction from a stem underneath a tree canopy (in this case east) received more water than those standing in other directions (west, north and south). From the database and modelling results presented by Zuidema et al. (2005), one can also deduce that the average rainfall in our study region is less than optimal for cacao bean harvest. Furthermore, our study area is frequently affected by below-average annual rainfall during El Niño events (Gunawan, 2006). Thus, with a focus on water input and cacao yield the role of shade trees in such cultivation systems could be critical. Nonetheless, for an overall evaluation of the role of shade trees in the hydrological cycle of cacao cultivation, more processes have to be studied, including whole plant transpiration, soil water resource partitioning and hydraulic redistribution (see also Smith et al., 2004) as well as an assessment of drought effects. Shade trees will most likely also increase stand-level transpiration and thereby reduce water availability for cacao trees. On the other hand, shade trees can probably mitigate negative effects of droughts and low rainfall. Shading reduces evaporative demand on cacao trees and may thus reduce stress of cacao plants during low-rainfall periods. If shade and cacao trees differ in vertical water uptake depth competition for soil water competition would largely be avoided. By deep rooting and resource uptake shade trees may even transport nutrients, and by hydraulic redistribution also water, to upper soil layers, which are then also available for uptake by cacao trees. Such a comprehensive analysis of the hydrological function of shade trees in cacao cultivation systems still remains to be done.

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