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Throughfall, stemflow and interception loss in *Grewia optiva* and *Morus alba* in north west Himalayas

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Abstract: The study examined and compared the throughfall, stemflow and canopy interception in *Grewia optiva* and *Morus alba* tree stands in western Himalayas. Incident precipitation on tree can be partitioned into throughfall, stemflow and interception which have significant contribution in water balance in forest ecosystems. Total 39 rainfall events were studied for analyzing rainfall partitioned components in 5 years old plantations of *G. optiva* and *M. alba* in Dehradun, India. Maximum and minimum rainfall depth per event recorded during the study period was 1.01 mm and 121.70 mm respectively. Plastic funnels were fitted with the trees to trap the stemflow and plastic buckets were used to collect the throughfall. Average stemflow, throughfall and interception were 2.5%, 86.7% and 10.8% of total incident rainfall for *G. optiva* whereas, for *M. alba* it was 8.6%, 76.4% and 14.7% respectively. The funneling ratio for the entire rainfall events was found more than 1 for both the trees. The characteristics nature of the tree canopy in *M. alba* resulted in unique stemflow yield in comparison to *G. optiva*. *M. alba* funneled almost 3.5 times more stemflow than *G. optiva*. The proportion of rainfall partitioned components varied for both the trees due to their distinguished morphological characteristics. Results clearly show that interception loss varies with tree species type and contributes a significant proportion of incident rainfall towards catchment water balance.

Key words: Interception, rainfall, stemflow, throughfall, tree canopy.

Introduction

Rainfall (R) on vegetation can be partitioned in Stemflow (SF), Throughfall (TF) and Interception loss (I). Stemflow is that part of rainfall which runs down to the ground via twigs, branches and stem whereas, throughfall drips down through the canopy to ground. The remaining part, 'Interception' remains with the canopy and later on lost by the process of evaporation. Thus, SF and TF are combined termed as net rainfall which flow as runoff after meeting the infiltration demand of the soil. Apart from soil types and soil factors, runoff from different forest types varies significantly due to variation in vegetation. In different forest ecosystems, studies on rainfall partitioned components are important to quantify different environmental flows. Surface and sub-surface runoff originated from dense forest ecosystem is primarily the outcome of net rainfall i.e. SF and TF. This surface and sub-surface runoff maintains the water flow in river, replenish the groundwater. Hence, the SF and TF have vital role to play in sustaining the forest and aquatic ecosystems. The water balance equation of rainfall falling on vegetation can be written as:

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$$R = SF+TF+I$$

Several studies have been done before to quantify the rainfall partitioned components from different forest type. It has been found from the studies that TF is the major component in most of the vegetation types. These rainfall partitioned components were affected by various climatic factors and tree architecture. Interception loss varies among vegetation types and also among species of particular vegetation. Interception also depends on different biotic and abiotic factors such as rainfall amount, intensity, duration, wind direction, hydrophobicity of tree parts, canopy volume, ambient temperature, etc.

In wooded ecosystem, SF and TF are most important which account about 70–90% of the incident rainfall and rest goes as interception loss (Alvarez-Sánchez *et al.* 2016; Levia & Frost 2003). When rainfall occurs, leaves, twigs, branches and stem of tree take part in formation of stemflow path. Herwitz (1986) developed funneling ratio (F) to account the effect of biotic abiotic-factors. Funneling ratio is defined as,

$$F = \frac{V}{B * P}$$

Where, V is stemflow volume, B is the trunk basal area and P is precipitation depth. *F* value >1 indicates that tree canopy is contributing greater stemflow volume than stemflow expected solely from trunk basal area. Whereas, *F* value <1 indicates tree canopy has not reached to storage capacity during low magnitude rainfall or stemflow converted into throughfall due to canopy structure. Stemflow increases with increase in precipitation amount. When rainfall amount reaches to a threshold, canopy storage capacity gets saturated and stemflow paths get overloaded. At this stage, stemflow starts transforming into throughfall. Wind speed and its direction effects in stemflow yield rate. Some researchers found stemflow yield increases with increase in wind speed (Xiao *et al.* 2000). Higher wind speed wets more canopy area, thus increases stemflow yield. Tree species have distinguished morphological properties and age of tree affect on bark characteristics (Levia & Frost 2003). Tree species having smooth bark such as *F. grandifolia* and *F. sylvatica* L. (European beech) yields stem flow at lower precipitation amount than species with rough bark such as *Q. rubra* or *Liriodendron tulipifera* L. (yellow poplar) due to lower storage capacities and resistance to stemflow path (Van Stan & Levia 2010). Tree branches inclined concavely yields more stem flow than species with branches horizontal or nearly horizontal (Herwitz 1987). Tree leaves with concave orientation; funnel more proportion of the precipitation to its petiole and subsequently to the stem (Crockford & Richardson 2000).

Throughfall is not uniform throughout underneath of canopy cover. Where canopy density is thick and incident rainfall amount is small, throughfall discharge is less in comparison to places having thin canopy cover. The reason attributed to high interception by thick canopy (Bouten *et al.* 1992; Cantu´ Silva & Okumura 1996). Apart from rainfall amount, throughfall amount also depends on wind condition and rainfall intensity. In some places under canopy, the throughfall intensity can be more than rainfall intensity due to accumulation of water from different branches and drips down as throughfall. Rainfall intensity was found to reduce the coefficient of variation (CV) of throughfall volume (Weiqing *et al.* 2007) while increase in wind speed in certain trees is found to enhance throughfall voulme in windward direction (Herwitz & Slye 1995). The objective of the study was to measure and compare the rainfall partitioned components in plantation of 5 years old *Grewia optiva* and *Morus alba* during the monsoon season in North West Himalayas.

Materials and methods

Study area

The study was conducted at Selakui Research farm of Indian Institute of Soil and water Conservation (IISWC), Dehradun, India with geographical location 30º27'22"N latitude and 77º52'39"E longitude. Dehradun is located in Doon Valley on the foothills of Himalayas. The mean elevation of the research farm varies from 543 to 518 m above mean sea level. The average (1956–2003) annual rainfall of the study area is 1625 mm with subtropical climate. About 80% of the annual rainfall occurs in between Mid-June and Mid-September. The region also experiences winter rainfall. About 127 mm of rainfall (S.E. ± 9.6 mm) occurs during winter season (December to February). Occurrence of high intensity storms exceeding 100 mm h^{-1} is very common during monsoon season which causes heavy soil erosion (on an average, at least one event per year). Longterm mean maximum and minimum temperature recorded in May and January are 37.2 °C and 3.8 °C, respectively.

Description of tree species

Three trees each of *G. optiva* and *M. alba* with 5 × 5 m spacing having healthy canopy were identified in this study from five years old plantations of existing agroforestry systems. Both the tree species have distinguished morphological characteristics i.e. canopy architecture, leaf size and branch orientation, etc. *M. alba* widely known as white mulberry is a short lived and small to medium in size. White mulberry is basically native to China. However, it is now widely cultivated and acclimatized in tropical to temperate climate. This tree is deciduous in temperate regions, but in tropics it is grown as evergreen. It is widely produced to feed silkworms for commercial production of silk whereas, *G. optiva* locally known as bhimal is a deciduous tree with spread crown, widely used for fresh fodder purpose.

Measurement of rainfall and throughfall

Selakui research farm is equipped with a meteorological station. The distance from the meteorological station to study plot was approximately one kilometer. However, there was variation in rainfall observed within the farm. Keeping the above rainfall variation in mind, a standard non-recording type rain gauge was installed in open space nearby the study site to record each rainfall event. It was assumed that when one rainfall spell stopped and at least for next one hour there was no rain, considered as one exclusive rainfall event. Five buckets with 0.275 m diameter were kept randomly under each tree for collecting throughfall. Average volume of throughfall from each tree was calculated for each rainfall event from that water accumulated in buckets. Average volume of throughfall for each species was calculated from the three sample trees of the species. Average depth of throughfall from each species corresponding to rainfall event was calculated by dividing the average throughfall volume data with bucket top cross section area.

Canopy projection area (CPA)

Stemflow depth is the ratio of stemflow volume to CPA (Shachnovich *et al.* 2008). CPA was measured by projecting the edges of the crown to a horizontal surface (Delphis & Levia 2004). The crown radius is the distance between the centers of the tree bole to the edge of the crown. In this study, eight directional crown radii were measured and average of the radii was used to calculate the CPA of each tree using formula of a circle.

Stemflow and interception loss measurement

Plastic funnel was used in this study to trap, divert and collect the stemflow coming down the tree bole (Fig. S1). Based on the diameters of the tree bole, the size of the funnel was chosen (Fig. S2). The funnel was cut twice with knife in such a way so that it can be fitted with circular tree bole at suitable tree height where all the stemflow water passes through. The first cut was made at a distance vertically down from the funnel upper circular area and the second cut was made transversely of the upper separated cut. Proper care has been taken in sealing the contact area between the fitted funnel and tree bole. The juncture of fitted funnel and tree bole is sealed with suitable adhesive and tape. Before fitting the funnel with tree bole, a circular hole was made near to the base of the cut funnel to connect a flexible plastic pipe with one end at the funnel and the other with a clean plastic container for collecting the stemflow water. Another similar finished funnel was installed over the lower funnel surrounding the tree bole to hinder the throughfall falling on lower funnel. Proper monitoring was made to see that the upper funnel should not be in contact with the tree bole otherwise a portion of the stemflow will be lost from the contact area during the stemflow trapping process. In this way, stemflow volume was collected for each rainfall event. Stemflow volume recorded for each rainfall event from each tree converted to equivalent stemflow depth by dividing CPA of the tree. Interception loss was calculated after subtracting throughfall and stemflow depth from incident rainfall. All the data i.e. rainfall, throughfall and stemflow was recorded during 17th July to 4th October, 2013 at daytime.

Results

Species morphological properties

The height and diameter at breast height (dbh) of *G. optiva* trees selected for the study ranged from 5.0–6.0 m and 8.2–10.0 cm, respectively, whereas for *M. alba*, it ranges from 3.5–4.5 m and 7.0–9.3 cm, respectively. Mean height directional crown diameter of *M. alba* and *G. optiva* trees varies from 3.4–4.0 and 3.8–4.3 m respectively.

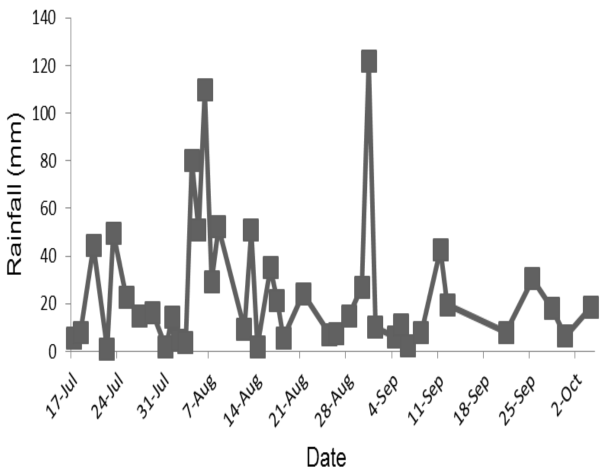

Fig. 1. Date wise recorded rainfall.

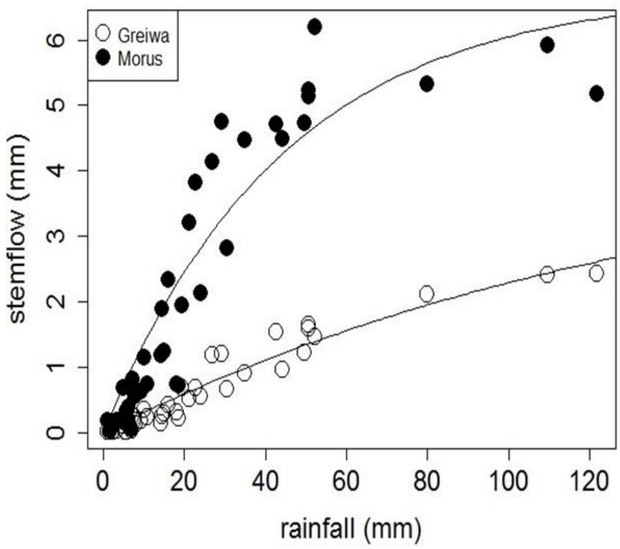

Fig. 2. Fitted model corresponding to observed stemflow.

The average crown diameter of *M. alba* and *G. optiva* trees was calculated as 3.22 m and 4.0 m, respectively. Leaf area of mature *M. alba* leaf is 1.5–2 times larger than *G. optiva* tree leaf.

Recorded Rainfall

Total 39 rainfall events were studied during monsoon 2013 (Fig. 1). Gross rainfall occurred during that period was 997.8 mm with average and median depths of 25.6 and 16.0 mm, respectively. Minimum and maximum rainfall events recorded was 1.0 and 121.7 mm, respect-tively. There were twenty six, seven and six rainfall events having magnitude of less than 25 mm, 25 to 50 mm and more than 50 mm, respectively. As the rain gauge used for measuring rainfall was non-recording type, there was no information available related to duration and intensity of those rainfall events. The experi-mental site was located within 300 m distance from the farm research building; onset and cessation of rainfall spell were easily observed with naked eye during the daytime. The CPA of *M. alba* and *G. optiva* was calculated as 8.14 m^2 and 12.56 m^2, respectively.

Rainfall partitioning

Variation of stemflow with rainfall for *G. optiva* and *M. alba* is shown in Fig. 2 indicating that stemflow increases with the rainfall. Average stemflow was 2.5% and 8.6% of total incident rainfall for *G. optiva* and *M. alba*, respectively (Table 1). Graphical exploration revealed that stemflow depth has a nonlinear relation with the total rainfall. Hence, different non-linear regression models were tried and finally, the following model (Eq. 1) proved to be the best fitted one. The model was validated with the help of different residual diagnostics.

$Y = a * (1 - e^{-bx})$ Eq. 1 Where Y is the stemflow (mm), x is the rainfall depth and a, b are the parameters to be estimated. In case of *G. optiva*, value of ‘a’ and ‘b’ was 4.56 and 0.007 with standard errors 1.01 and 0.002, respectively; whereas for *M. alba* value of ‘a’ and ‘b’ was 6.75 and 0.02 with standard errors 0.70 and 0.004, respectively.

In support to the previous studies (Ahmed *et al.* 2015; Xiao *et al.* 2000), our results also indicate more rainfall generated more SF, ranging for *M. alba* from 0.04 mm (2.4% of R) to 6.20 mm (11.8% of R) and in *G. optiva* from 0.01 mm (0.2% of R) to 2.43 mm (2% of R). Both *G. optiva* and *M. alba* yielded stemflow even in 1 mm rainfall depth. This signifies that the threshold value of rainfall depth for yielding stemflow was below 1 mm for both the trees. The rate of increase of stemflow is not uniform. Fig. 2 shows that stemflow yield rate increases at a pace both for *G. optiva* and *M. alba* up to rainfall depth less than equal to 52 mm. As rainfall depth exceeds 52 mm, stemflow generation rate was almost static to rainfall depth for both the trees. The funneling ratio corresponding to the rainfall event is shown in Fig. 3. It showed that funneling ratio (F) for all the rainfall events is greater than 1 for the both the trees under this study. Higher value of ‘F’ indicates more tree

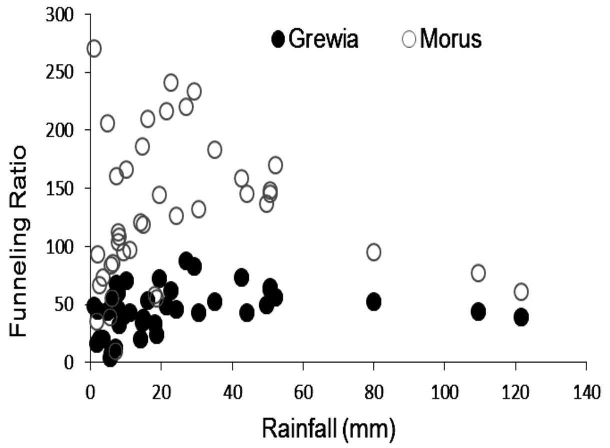

Fig. 3. Funneling ratio corresponding to rainfall.

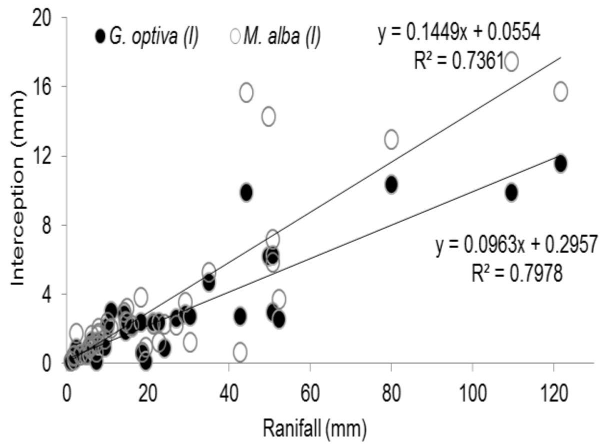

Fig. 5. Interception and rainfall relationship.

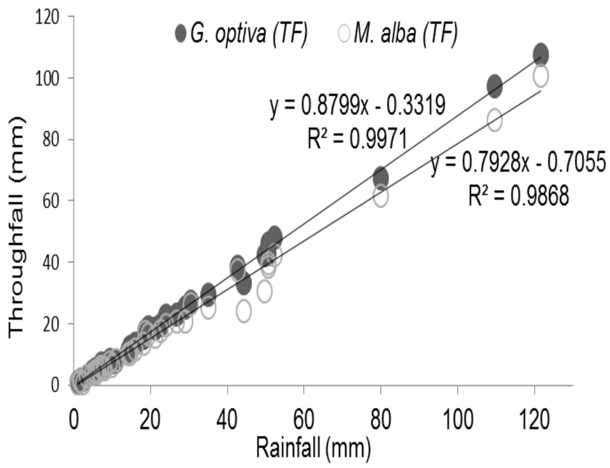

Fig. 4. Throughfall and rainfall relationship.

canopy is taking part in stemflow yield. Season-long funneling ratios of several deciduous tree species typically ranges from 7 to 26 (Carlyle-Moses & Price 2006); albeit funneling ratio for individual tree may exceed 100 (Herwitz 1986). Maximum and minimum value of 'F' calculated for *G. optiva* was 87 and 4 whereas, for *M. alba* it was 270 and 10, respectively. It signifies more tree canopy in *M. alba* is participating in stemflow yield than *G. optiva*. Moreover, likewise in Fig. 2, 'F' was almost static or declining in trend when precipitation depth exceeds 52 mm. The reason can be attributed to saturation and overloading of the stemflow paths at rainfall depth 52 mm which causes the transformation of excess stemflow into throughfall.

Results showed *M. alba* yields approximately 3.5 times more stemflow than *G. optiva*. Fig. 4 shows the variation of throughfall over rainfall for *G. optiva* and *M. alba*. Throughfall increases with the increase with the rainfall. Maximum and minimum throughfall recorded for *G. optiva* was 107.72 mm (88.5% of R) and 0.84 (83.2% of R) mm whereas for *M. alba* 100.82 mm (82.8% of R) and 0.60 mm (24.5% of R), respectively. Average throughfall was 21.43 mm (86.7% or R) and 18.91 mm (76.4% of R) for *G. optiva* and *M. alba,* respectively (Table 1). A strong positive linear relationship was observed between the throughfall and rainfall depth (R^2 value almost equal to 0.99) for *G. optiva* and *M. alba*. Results showed *G. optiva* yields somewhat more throughfall than *M. alba* which is non-significant (throughfall depth does not varies significantly depending on the species $P > 0.05$). Fig. 5 shows the variation of interception by both the trees with rainfall. Interception loss also increases with the rainfall. Though interception is positively correlated with rainfall, it is highly variable. Average interception loss was calculated for *G. optiva* was 2.68 mm (10.8% of R) and for *M. alba* 3.64 mm (14.7% of R) (Table 1). Maximum and minimum interception loss was calculated for *G. optiva* was 11.55 mm (9.5% of R) and 0.12 mm (0.6% of R) and for *M. alba* it was 17.46 mm (15.9% of R) and 0.15 mm (14.8% of R).

Discussion

Interspecific differences in average stemflow, throughfall and interception loss were observed in this study between *G. optiva* and *M. alba*. On an average *M. alba* yielded 3.5 times more stemflow than *G. optiva* whereas, 1.13 times more throughfall was recorded in *G. optiva*. Higher interception loss was calculated in *M. alba,* almost 1.36 times than *G. optiva*. Interspecific morphological canopy characteristics played a major role for these differences. Tree architecture in tropics can be represented by 23 tree architectural models (Tomilnson 1983). *Grewia optiva* fits best with Roux's tree architectural model, whereas architecture of *M. alba* can be described best with Attim's model. Roux's architecture is defined with amonopodial orthotropic trunk, branches are plagiotropic, leaf ordered spirally on the trunk and branches, flowering is variable, but mainly lateral on the branches. In contrast, Attim's model is determined by axes with continuous growth, differentiated into a monopodial trunk and equivalent branches; branching takes place either continuously or diffusely. Flowering is always lateral and does not affect shoot construction.

Canopy architecture plays an important role in higher stemflow yield in *M. alba*. It is observed that the upward concave branching pattern of *M. alba* is the prime reason for enhanced stemflow yield compared to *G. optiva*. Most of the branches of *M. alba* extended in the upward direction in concave orientation. This branching architecture enhances formation of continuous stemflow path and results in more stemflow yield. In case of *G. optiva*, most of the branches extended in the upward direction rather in convex pattern and droop outwards. Therefore, approximately inner half of branches close to the stem play roles in stemflow generation and transportation. The stemflow generated in the other outer half could not reach to main stem of the tree and drops down in the form of throughfall. These results are supported well by similar findings of Herwitz (1987). Total number of branches in both the trees was almost equal. However, the ratio between total effective length of the branches for *M. alba* and *G. optiva* for stemflow generation and transportation was calculated approximately 1.5 which proves the effect of branch orientation in stemflow yield variation.

The other reason which causes more stemflow yield in *M. alba* than *G. optiva* is the orientation and size of leaves. Average surface area of most of the leaves of *M. alba* is 1.5–2.0 times greater than *G. optiva* leaves. Most of the tip of the leaves of *M. alba* is inclined upward whereas, tip of leaves of *G. optiva* is drooping downward. However, it was observed that leaves in lower branches in *M. alba* drooping downward and not contributing in stemflow yield. Hence, rainfall falling on leaves of *M. alba* drain water to their respective petiole and ultimately funneled to the stem, whereas downward drooping leaves of *G. optiva* contributes more to throughfall. Similar results have also been reported by Crockford and Richardson (2000).

The bark flakes on the way to stemflow path acts as barrier and break the continuity of the stemflow paths. It acts as a drip point and has greater influence on potential stemflow to throughfall conversion (Crockford & Richardson 2000; Gupta & Usharani 2009). In this study, both the trees are having no apparent bark flake extruding from its body. Hence, the effect of tree barks on stemflow yield can be nullified in this study. The tree morphological factors mentioned above which were found less favorable for lower stemflow yield in *G. optiva*, the same is responsible for higher throughfall yield in *G. optiva*.

It was observed that canopy density and area of the matured leaves of *M. alba* is higher than *G. optiva* which could be attributed to greater interception in *M. alba*. Leaf Area Index (LAI) was not quantified in this study due to lack of LAI meter facility. Apart from tree species, branch and leaf orientation, there are several other biotic factors which effect the rainfall partitioned components i.e. hydrophobicity of the bark surface, leaf area index (LAI), canopy length and openness etc. which is to be taken into consideration for in-depth study.

Abiotic factors that affect rainfall partitioned components over space and through time are related to meteorological conditions. Most of the researchers have correlated the rainfall partitioned components with respect to rainfall amount (André *et al.* 2008; Clements 1972). However, several other abiotic factors i.e. storm intensity and duration, wind speed and direction affect the rainfall partitioned components. Increasing storm intensities have been reported to decrease stemflow yields as flowpaths become overloaded and entrained as throughfall (Levia & Frost 2003). Xiao *et al.* (2000) reported that stemflow yield increases with wind speed in isolated trees. However, apart from the rainfall amount, other abiotic factors were out of scope of this present study.

In different deciduous forest across the world, the stemflow was found as low as 0.5% in Georgia, USA (Bryant *et al.* 2005) and maximum up to 6.4% in NW Italy (Mosello *et al.* 2002). According to the review made by Johnson and Lehmann (2006), the average stemflow ranges to 0.1–22% of the incident rainfall in the precipitation range of 600–7100 mm yr^{-1}. In our study, the average stemflow was 2.5% for *G. optiva* towards mid end and 8.6% for *M. alba* towards high end of the reported range of stemflow. In natural forests, average throughfall values reported as low as 27% (matorral) and as high as 96% (African moist forest) of incident rainfall (Levia & Frost 2006). In this study, the average throughfall was measured 76.4% for *M. abla* and 86.65% for *G. optiva* which falls with high end of reported throughfall range. In most of the watershed based water balance study, the variation in interception by tree canopies is often neglected. However, this study showed a significant amount of incident rainfall, which is on average 10.8% for *G. optiva* and 14.7% for *M. alba,* returned to atmosphere through evaporation process. Hence, interception by tree canopies (forest types) must be accounted for precise water balancing in a forest dominated watershed.

Maximum height of both types of experimental trees is close to 10 m and both throughfall is major component of the incident rainfall. However, TF generated from *G. optiva* is comparatively more than *M. alba.* Sufficient energy is present in thoughfall to cause splash erosion after beating the canopy. Hence, sufficient ground cover must be managed especially for *G. optiva* to protect the soil beneath the tree canopy from splash erosion. Net rainfall increases with the increase in rainfall amount. The study area gets considerable amount of rainfall in summer and winter season in the form of isolated storms. The thirsty forest floor gets revegetated through stemflow and throughfall generated from those storms.

Besides, part of the rainfall which falls on ground just beneath the tree canopy as net rainfall can be stored in soil sub-strata to palliate water shortage during lean period. In this study, the average net rainfall from the trees ranged approximately between 85–89% of the incident rainfall. In general, only overland runoff results from rainfall is only considered during designing soil moisture conservation techniques. However, it is clear from this study that before designing of soil moisture conservation structures or techniques, the net rainfall component must be considered apart from overland runoff for the success of the soil moisture conservation structures.

Conclusions

In this study, rainfall partitioned components i.e. throughfall, stemflow and interception loss from *G. optiva* and *M. alba* were studied. The proportion of rainfall partitioned components from both the trees were in the order, throughfall> interception loss>stemflow. The threshold value for yielding throughfall and stemflow for both trees was found below 1 mm. Stemflow and interception loss was found higher in *M. alba* whereas in case of throughfall it was vice versa. *M. alba* yielded significantly more stemflow than *G. optiva*. It was observed that distinguished tree morphology was responsible for variation in the proportion of the rainfall partitioned components. Study shows interception loss from different vegetation types should be considered distributed from different vegetation types for water budgeting in catchment scale. Net rainfall amount was found more than 85% of the incident rainfall. Hence, adequate groundcover is suggested beneath the tree canopy to check splash erosion and *in-situ* harvesting of net rainfall can mitigate soil moisture demand of trees during lean period.

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Supporting Information

Additional Supporting information may be found in the online version of this article.

Fig. S1: Stemflow collection system.

Fig. S2: Digitized branch and leaf orientation in *G. optiva* and *M. alba.*