Influence of canopy architecture on stemflow in agroforestry trees in Western Himalayas

Akram Ahmed[1,*], J. M. S. Tomar[2], Harsh Mehta[2], N. M. Alam[2] and O. P. Chaturvedi[2]

[1]Indian Grassland and Fodder Research Institute, Jhansi 284 003, India
[2]Central Soil and Water Conservation Research and Training Institute, 218 Kaulagarh Road, Dehradun 248 195, India

Rainfall event on a tree can be partitioned into throughfall, interception loss and stemflow. In this study, stemflow was measured for 39 rainfall events in 5-year-old plantations of 3 trees each, belonging to *Morus alba* and *Grewia optiva* in Dehradun, India. Diameter of selected *Morus* and *Grewia* trees varies from 7 to 9.3 and 8.12 to 10 cm respectively, whereas height varies from 4 to 4.5 and 5.5 to 6.5 m respectively. The minimum and maximum rainfall events recorded during the study period were 1.01 and 121.70 mm per day respectively. When the rainfall magnitude was less than or equal to 50 mm and more than 50 mm, stemflow volume from *Morus* was approximately 2.72 and 1.85 fold higher respectively, compared to *Grewia*. Maximum stemflow volume recorded for *Morus* and *Grewia* was 48,065 and 30,633 ml with respect to rainfall magnitude of 109.58 and 121.70 mm respectively. The generation of higher stemflow volume in case of *Morus* is due to concave orientation of branches and leaves. Results showed that a significant amount of nutrients leached from *Grewia* and *Morus* through stemflow process.

Keywords: Canopy architecture, interception loss, rainfall, stemflow, throughfall.

In forest ecosystems, partitioning of rainfall (R) is an important hydrologic process which impacts the overall water-balance partitioning. Rainfall on trees is partitioned into three components, i.e. stemflow (SF), throughfall (TF) and interception loss (I). The water balance equation can be written as

$$R = TF + SF + I.$$

Stemflow is the portion of rainfall which is drained from the branches and leaves of a tree and runs down towards bole or stem of that tree. Throughfall is the component of rainfall which passes down through the canopy or is obstructed by the canopy and gradually drips down through it[1]. A part of the combined SF and TF infiltrates into the soil and the rest goes out of the field by the process of run-off and evaporation. The amount of infiltration and run-off depends on the rainfall amount, duration and intensity. Apart from the stemflow and throughfall, the rest of the rainfall is termed as interception loss which is held by the canopy and gradually lost by the process of evaporation[2]. Among the rainfall components, the major portion of rainfall in forest ecosystem is throughfall, which varies from 70% to 80% among different forest tree species[3]. Proportion of the rainfall partitioned components depends on climatic factors and canopy properties[4–6]. The climatic factors include rainfall amount, intensity, duration, wind speed and its temporal distribution, whereas canopy properties are canopy structure, leaf area index (LAI), leaf branch properties, etc. Interception loss has a reciprocal relationship with rainfall intensity. Levia *et al.*[7] showed that SF volume depends on tree species, crown size, leaf shape and orientation, branch angle and bark roughness. Rainfall amount is an important factor for increasing stemflow volume[8,9]. Stemflow yield increases with precipitation and reaches its maximum level for a particular rainfall intensity until all stemflow contributing areas take part in stemflow yielding process. After a particular rainfall intensity, stemflow yield or volume decreases as defined flowpaths of stemflow get overloaded and stemflow is converted into throughfall[10]. Stemflow rate increases with rainfall intensity and reaches a threshold level at which increase in rainfall intensity does not increase stemflow rate. A part of the stemflow falls on the ground while flowing down the stem. This phenomenon is known as stem dripping, which is influenced by bark roughness. More bark roughness causes more stem dripping. Tree species and age often define the bark morphology for water absorption and significantly affect stemflow yield[10]. Tree species with smooth bark such as *Fagus grandifolia* and *F. sylvatica* L. (European beech) generate stemflow at lower precipitation in comparison to species with rough bark such as *Quercus rubra* L. or *Liriodendron tulipifera* L. (yellow poplar) due to lower storage capacity and resistance to stemflow path[2,11]. Tree branches having more inclination generate more stemflow with respect to the species having horizontal or nearly horizontal branches[12]. Tree leaves concave in orientation, funnel more proportion of the precipitation to their petiole and subsequently to the stem[4]. Many studies have been conducted around the

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*For correspondence. (e-mail: akrambckv@gmail.com) world related to nutrient cycling through stemflow. The concentration of different ions varies according to the tree, tree size, age, season of the year and intensity of rainfall, etc. Nutrient concentration is generally low in high-intensity rainfall events[13]. Levia and Herwitz[14] found higher concentration of K^+ and Mn^{2+} in stemflow trapped from *Carya glabra* Mill. Stemflow trapped from rough-barked trees had higher concentration of nutrient than smooth-barked trees[15].

The objective of the present study was to measure and compare stemflow and nutrient flux through stemflow in plantations of 5-year-old *Grewia optiva* and *Morus alba* during the rainy season. The main focus of this research is to study how tree architecture plays a role in stemflow generation process.

Materials and methods

Study area

The study was carried out at Selakui Research Farm of Central Soil and Water Conservation Research and Training Institute (CSWCRTI), Dehradun, India, located approximately 20 km west of Dehradun city (Figure 1). The geographical location of the study plot is 30°27′22.21″N lat. and 77°52′39.45″E long., and elevation varies from 543 to 518 m amsl. Climate of the region at the farm site is subtropical with an average (1956–2003) annual rainfall of 1625.3 mm. About 80% of the total annual rainfall is received in 80 rainy days during the monsoon season between mid-June to mid-September. On an average, rainfall of 127.3 mm (standard error 9.57 mm) is also experienced during winter season (December to February). Occurrence of high-intensity storms exceeding 100 mm h^{-1} is a common feature during the monsoon season, leading to severe erosion problems (on an average, at least one event per year). Long-term mean maximum temperature of 37.2°C and mean minimum temperature of 3.8°C have been recorded in May and January respectively.

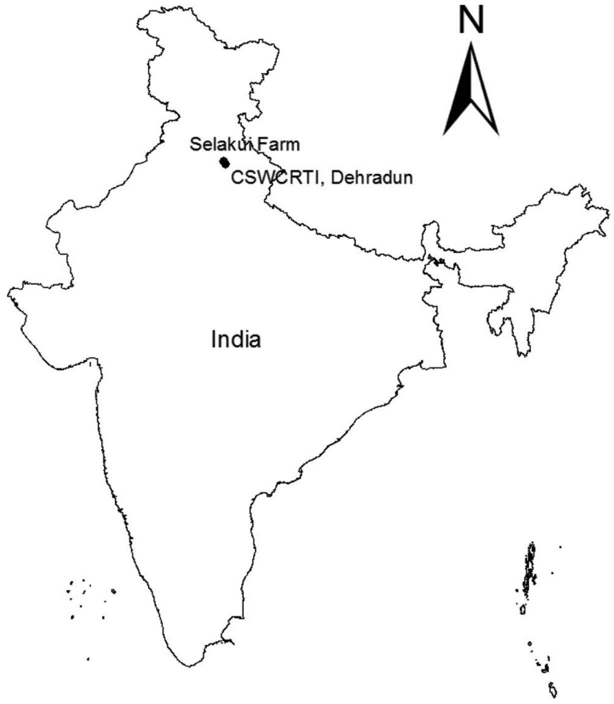

Figure 1. Location of the study area.

Selection of tree species

Three trees each of *G. optiva* and *M. alba* with 5 m × 5 m spacing were selected for this experiment from the plantations. Trees having healthy canopy were selected for the experiment. These two tree species were chosen due to their discriminant canopy architecture, leaf size and branch orientation. Average stemflow volume from *Grewia* and *Morus* was used for comparison of stemflow yield from these trees. *Morus*, widely known as white mulberry, is short-lived and small to medium in size. White mulberry is basically native to China. However, it is now widely cultivated and acclimatized in other countries as well. It is widely produced to feed silkworms for commercial production of silk. *Grewia*, locally known as bhimal, is a deciduous tree with its crown spread, widely used for fodder purpose.

Stemflow and rainfall measurement

Collar made of plastic funnel was used to trap and measure stemflow coming down the tree bole. The size of the funnel was selected based on the diameter of the trees. Each funnel was cut twice to fit it to the tree. First, the funnel was cut at the end of its upper widespread area. Then, the upper separated part was cut transversely and fitted to the tree at an apparently circular shaped area near at the base of the tree. The contact area between the tree and funnel was sealed with the help of adhesive and cellotape. Before fitting the funnel to the tree, a hole was made at the bottom of the cut funnel to connect a pipe to one end of the funnel and the other to a clean plastic container for collecting the stemflow water. To obstruct the throughfall falling on the funnel fitted to the tree bole, a similar funnel was fitted in the opposite direction over the first funnel. Figure 2 shows the instrumentation for measuring the stemflow. Due to rainfall variation observed between the meteorological station and the study site, a standard non-recording-type rain gauge was installed in the open space near the study site to measure rainfall. All the data on rainfall and stemflow were recorded during daytime. When one rainfall spell was over and there was no rain at least for the next 1 h, it was considered as an exclusive rainfall event. At the end of each rainfall event, rainfall depth and stemflow volume were recorded. Proper attention was given to make sure that the upper funnel and tree body are not in contact. Otherwise, a portion of the stemflow will be lost along the contact area.

Stemflow sample collection

Water sample from stemflow storage container corresponding to five rainfall events during the study period was collected in clean plastic water bottles for measuring nutrient flux in stemflow. Subsequently, chemical analysis was done in the laboratory. Concentration of exchangeable ions, i.e. Ca, Mg, Na, Cl and HCO_3 in stemflow water was measured for *Grewia* and *Morus* using standard method. The pH values of the samples were measured using a pH meter.

Results and discussion

Characteristics of selected tree species

The height and diameter at breast height (dbh) of *Grewia* trees selected for the study range from 5 to 6 m and 8.2 to 10 cm respectively, whereas for *Morus*, it ranges from 3.5 to 4.5 m and 7 to 9.3 cm respectively. Mean crown diameter of *Morus* and *Grewia* trees varies from 3.4 to 4 and 3.8 to 4.3 m respectively. Leaf area of mature *Morus* leaf is 2–2.5 times larger than *Grewia* tree leaf. Figure 3 shows the canopy architecture, stem and leaf orientation of *Morus* and *Grewia*.

Figure 2. Instrumentation for measuring stemflow.

Rainfall recorded

A total of 39 rainfall events were studied from 17 July to 4 October 2013. Gross rainfall recorded during that period was 997.79 mm. Minimum and maximum rainfall events recorded were 1.01 and 121.70 mm respectively. There were 26, 7 and 6 rainfall events having magnitude less than 25, 25–50 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 experimental site was located within 250 m from Selakui farm research building. Therefore, onset and offset of rainfall spell were easily observed with naked eye during daytime.

Stemflow volume

Maximum and minimum stemflow volume recorded for *Morus* was, 48,065 and 336 ml respectively, whereas for *Grewia* it was 30,633 and 174 ml respectively. The rainfall and average stemflow volume for *Morus* and *Grewia* are given in Table 1. Figure 4 shows the variation of stemflow with rainfall for *Grewia* and *Morus*. Different

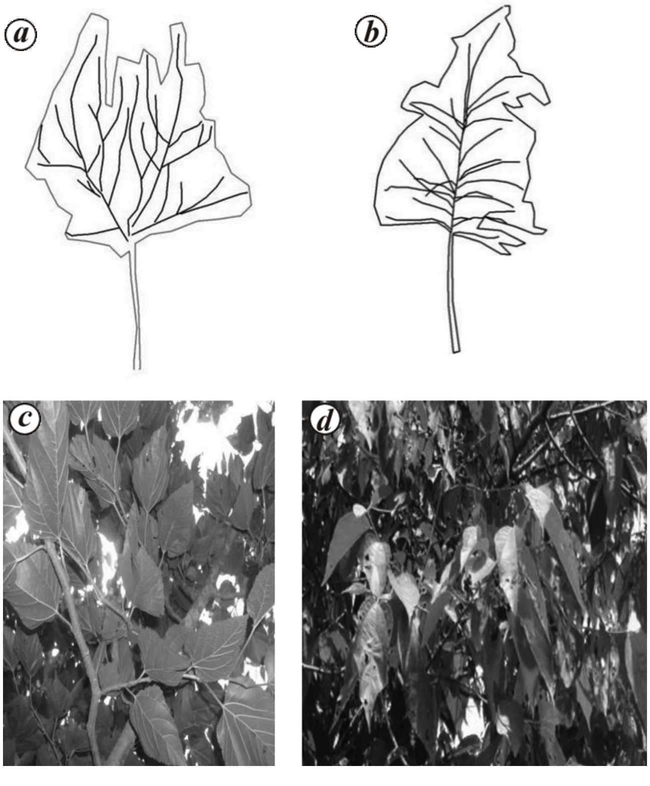

Figure 3. Canopy structure (***a***, ***b***) and leaf orientation (***c***, ***d***) of *Morus* and *Grewia*.

Table 1. Average stemflow data for *Grewia* and *Morus* with rainfall

		Stemflow (ml)	
Date (2013)	Rainfall (mm)	*Grewia*	*Morus*
17, 18, 20, 22, 23, 25, 27, 29, 31 July; 1–8, 12–14, 16–18, 21, 25, 26, 28, 30, 31 August; 1, 6, 8, 11, 12, 21, 25, 28, 30 September; 4 October	7.92, 5.56, 44.22, 49.69, 1.01, 22.74, 15.16, 16, 1.68, 14.15, 4.80, 3.45, 80.01, 50.70, 109.58, 29.14, 52.22, 9.35, 50.79, 1.85, 35.04, 21.31, 5.64, 24.09, 7.07, 7.24, 14.91, 26.95, 121.70, 10.02, 2.44, 7.75, 42.70, 19.46, 7.83, 30.49, 18.19, 6.32, 18.61	1655, 1256, 18,654, 17,534, 293, 8762, 3183, 5433, 174, 1846, 1336, 436, 26,661, 20,863, 30,412, 15,266, 22,245, 2398, 20,360, 531, 14,653, 8360, 930, 9640	5100, 2570, 36,451, 38,500, 1350, 31,150, 15,600, 19,075, 336, 9675, 3600, 1427, 46,543, 41,797, 48,065, 38,625, 47,564, 5060, 42,572, 977, 36,362, 26,152, 2672, 31,260, 3925, 6615, 10,015, 33,702, 47,456, 6050, 930, 4560, 38,362, 21,500, 4975, 18,750, 3070, 19,460

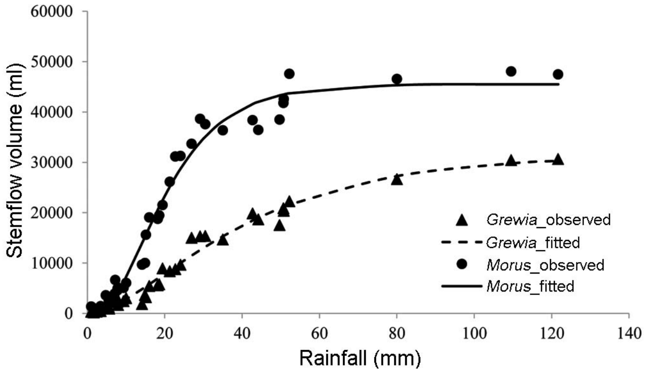

Figure 4. Fitted model corresponding to observed stemflow yield.

nonlinear regression models were used for fitting the stemflow data. Among them, Chapman model fitted best with the observed data both for *Grewia* and *Morus* (Figure 3). The model can be represented by the following equation

$$Y = a * (1 - e^{-bx})^c,$$

where Y is the stemflow (ml), x the rainfall depth (mm) and a–c are parameters to be estimated. Table 2 provides the Chapman model parameters. André *et al.*[9] observed more stemflow generation with respect to increased rainfall amount. Both *Grewia* and *Morus* responded to stemflow volume even in 1 mm rainfall depth. This signifies that the threshold value of rainfall depth for stemflow generation was below 1 mm for both the trees. However, the preceding rainfall event had accelerated the stemflow generation process. For example, rainfall event magnitude of 1.01 mm generated more stemflow compared to the event of 1.68 mm. This may be due to the previous day heavy rainfall event (49.69 mm). Similarly, rainfall event magnitude of 4.8 mm generated more stemflow both in *Grewia* and *Morus* in comparison to 5.56 mm rainfall event. This may be because the 5.56 mm rainfall event occurred at higher intensity and short duration compared to 4.8 mm event. Hence stemflow paths may get overloaded and some of the stemflow might be converted into throughfall. Similar observations have been documented by Levia and Frost[10]. Rate of increase of stemflow volume is not uniform with respect to rainfall magnitude, as shown in Figure 4. It clearly discriminates four regions in stemflows versus rainfall fit in case of *Morus*, i.e. from rainfall magnitude of 1.01 to 3.45 mm (region A), 3.45 to 10.02 mm (region B), 10.02 to 29.14 mm (region C) and 29.14 to 121.70 mm (region D) respectively. Rate of increase of stemflow volume in region A was less in comparison to region B. Rate of increase of stemflow volume was found highest in region C and the curves flattened in region D. The intensity corresponding to the rainfall depth of 29.14 mm in case of *Morus* signifies the beginning of overloading of stemflow path. The excess stemflow transformed into throughfall from that point onwards. In case of *Grewia*, region D was absent. This may be attributed to discontinuous stemflow path discussed in the next section.

Role of canopy architecture

Tree architecture in the tropics can be described by 23 tree architectural models[16]. *Grewia* fits best with Roux's tree architectural model, whereas *Morus* fits best with Attim's model. Roux's architecture is determined with a monopodial orthotropic trunk, branches are plagiotropic, leaf arranged 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[17]. Trunk canopy architecture plays an important role in higher stemflow yield in *Morus*. Upward concave branching pattern of *Morus* is the main reason for enhanced stemflow yield compared to *Grewia* (Figure 3 *a* and *b*). The branches of both the trees were digitized from their photographs. Most of the branches of *Morus* extended in the upward direction in

Table 2. Chapman model parameters for *Grewia* and *Morus*

	Grewia				*Morus*			
Parameter	Estimate	Standard error	Approx. 95% confidence limit		Estimate	Standard error	Approx. 95% confidence limit	
a	31,347.3	1290	28,731.1	33,963.6	45,507.2	1137.3	43,200.6	47,813.9
b	0.0332	0.00386	0.0253	0.041	0.0844	0.00862	0.0669	0.1019
c	1.9112	0.1986	1.5084	2.3141	3.2775	0.5005	2.2625	4.2924

Table 3. Average concentration of different nutrients

	Stemflow (mg/l)		
Nutrient	*Grewia*	*Morus*	Incident rainfall (mg/l)
Ca	21.34	9.22	0.13
Mg	12.72	5.54	0.11
Na	7.00	3.07	0.08
HCO_3	9.02	3.97	0.06
Cl	3.58	1.60	0.04
pH	6.24	6.28	6.56

Table 4. Average amount of nutrients returned back to the soil

	Stemflow (kg/ha)		
Nutrient	*Grewia*	*Morus*	Incident rainfall (kg/ha)
Ca	3.02	2.91	1.11
Mg	1.80	1.75	1.44
Na	0.99	0.97	0.75
HCO_3	1.28	1.25	0.58
Cl	0.51	0.50	0.22
pH	6.24	6.28	6.56

concave orientation. This branching architecture enhances continuous stemflow path formation and results in more stemflow generation. In case of *Grewia*, most of the branches extended in the upward direction rather in convex pattern. In this orientation, branches droop outwards. Therefore, approximately half of the length of branches plays a role in stemflow generation and transportation. The other outer half of the branches contributes in throughfall. These results are supported well by similar findings of Herwitz[12]. The other reason which may cause more stemflow yield in *Morus* than *Grewia* is the orientation of leaves. Most of the leaves of *Morus* drain the precipitation water to their petiole and ultimately to the stem, whereas the drooping of leaves to outward side in *Grewia* contributes more to throughfall (Figure 3 *c* and *d*). Similar results have also been reported by Crockford and Richardson[4].

Mean nutrient concentration in stemflow water

Concentration of various nutrient elements was found higher in stemflow than incident rainfall. While coming in contact with the tree parts such as leaves, branches, etc. nutrients from the tree parts are dissolved into the rainwater[18,19]. However, a part of the nutrients in stemflow is contributed by the airborne particles trapped by the trees[20,21]. In this way, some amount of nutrients return back to the soil through stemflow. Concentration of nutrient elements in stemflow water varies from tree to tree and seasons of the year[22]. Vitousek and Sanford[23] showed that concentration of nutrient elements in stemflow water was more in the dry season than rainy season due to the presence of more dust particles in the tree stand. Five samples of stemflow water from *Grewia* and *Morus* as well as incident precipitation were collected on 20, 29, 31 July and 6 and 11 August for assessing their chemical composition. Table 3 shows the average concentration of nutrient elements. Concentration of Ca was found higher in stemflow water in this study and in the order Ca > Mg > HCO_3 > Na > Cl for both the trees. Similar findings were reported in other studies[22,24,25], where concentration of Ca in stemflow was higher than the other elements, except K. It was also found that concentration of nutrient elements in stemflow water was found more in *Grewia* than *Morus* (Table 3). The pH value of stemflow water and rainfall showed slightly acidic nature. Table 4 shows the average amount of nutrients returned back to the soil via stemflow and precipitation. *Grewia* returned more nutrients via stemflow than *Morus* during the study period.

Conclusion

In this study we compared the stemflow yield and nutrient flux in stemflow of *G. optiva* and *M. alba*. *Morus* yielded substantially more stemflow in comparison to *Grewia*. This may be due to the favourable branching pattern and leaf orientation in *Morus*. *Grewia* leaches more nutrient in stemflow compared to *Morus*. It was also found that stemflow yielded both for *Grewia* and *Morus* even in less than 1 mm rainfall depth. Findings of the present study also show that stemflow plays an important role in nutrient cycling process by returning nutrients back to the soil.

1. Ahmadi, M. T., Attarod, P., Marvi, R. M. M., Rahmani, R. and Fathi, J., Partitioning rainfall into throughfall, stemfow, and inter-

ception loss in an oriental beech (*Fagus orientalis* Lipsky) forest during the growing season. *Turk. J. Agric. For.*, 2009, **33**, 557–568.

2. Carlyle-Moses, D. E. and Price, A. G., Growing-season stemflow production within a deciduous forest of southern Ontario. *Hydrol. Process*., 2003, **20**, 3651–3663.
3. Bryant, M. L., Bhat, S. and Jacobs, J. M., Measurements and modeling of throughfall variability for five forest communities in the southeastern US. *J. Hydrol.*, 2005, **312**, 95–108.
4. Crockford, R. H. and Richardson, D. P., Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrol. Process*., 2000, **14**, 2903–2920.
5. Deguchi, A., Hattori, S. and Park, H., The influence of seasonal changes in canopy structure on interception loss: application of the revised Gash model. *J. Hydrol.*, 2006, **319**, 80–102.
6. Staelens, J. *et al.*, Rainfall partitioning into throughfall, stemflow, and interception within a single beech (*Fagus sylvatica* L.) canopy: influence of foliation, rainevent characteristics, and meteorology. *Hydrol. Process*., 2008, **22**, 33–45.
7. Levia, D. F., Vanstan, J. T., Mage, S. M. and Kelley-Hauske, P. W., Temporal variability of stemflow volume in a beech–yellow poplar forest in relation to tree species and size. *J. Hydrol.*, 2010, **380**, 112–120.
8. Clements, J. R., Stemflow in a multi-storied aspen community. *Can. J. For. Res.*, 1972, **2**, 160–165.
9. André, F., Mathieu, J. and Ponette, Q., Influence of species and rain event characteristics on stemflow volume in a temperate mixed oak–beech stand. *Hydrol. Process*., 2008, **22**, 4455–4466.
10. Levia, D. F. and Frost, E. E., A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *J. Hydrol.*, 2003, **274**, 1–29.
11. Van Stan, J. T. and Levia, D. F., Inter- and intraspecific variation of stemflow production from *Fagus grandifolia* Ehrh. (American beech) and *Liriodendron tulipifera* L. (yellow poplar) in relation to bark microrelief in the eastern United States. *Ecohydrology*, 2010, **3**, 11–19.
12. Herwitz, S. R., Raindrop impact and water flow on the vegetative surfaces of trees and the effects on stemflow and throughfall generation. *Earth Surf. Proc. Landforms*, 1987, **12**, 425–432.
13. Tukey Jr, H. B., The leaching of substances from plants. *Annu. Rev. Plant Physiol.*, 1970, **21**, 305–324.
14. Levia, D. F. and Herwitz, S. R., Physical properties of water in relation to stemflow leachate dynamics: implications for nutrient cycling. *Can. J. For. Res.*, 2000, **30**, 662–666.
15. Levia, D. F. and Herwitz, S. R., Interspecific variation of bark water storage capacity of three deciduous tree species in relation to stemflow yield and solute flux to forest soils. *Catena*, 2005, **64**, 117–137.
16. Tomilnson, P. B., Tree architecture: new approaches help to define the elusive biological property of tree form. *Am. Sci.*, 1983, **71**, 141–149.
17. Hallé, F., Oldeman, R. A. A. and Tomilnson, P. B., *Tropical Trees and Forests: An Architectural Analysis*, Springer-Verlag, New York, 1978.
18. Chuyong, G. B., Newbery, D. M. and Songwe, N. C., Rainforest input throughfall and stemflow of nutrients. *J. Biogeogr.*, 2004, **76**, 73–91.
19. Parker, G. G., Throughfall and stemflow in forest nutrient cycle. *Adv. Ecol. Res.*, 1983, **13**, 57–103.
20. Bruijnzeel, L. A., *Hydrology of tropical montane forests: a reassessment. Land Use Water Resour. Res.*, 2001, **25**, 1–1.18
21. Muoghalu, J. I. and Oakhumen, A., Nutrient content of incident rainfall, throughfall and stemflow in a Nigerian secondary lowland forest. *Appl. Veg. Sci.*, 2000, **3**, 181–188.
22. Ndakara, E. O., Throughfall, stemflow and litterfall nutrient flux in isolated stands of *Persea gratissima* in a moist tropical rainforest region, Southern Nigeria. *Online J. Phys. Env. Sci. Res*, 2012, **1**, 5–14.
23. Vitousek, P. M. and Sanford, R. L., Nutrient cycling in moist tropical forest. *Annu. Rev. Ecol. Syst.*, 1986, **17**, 137–167.
24. Ling-Hao, Li. and Peng, L., Throughfall and stemflow nutrient depositions to soil in a subtropical evergreen broad-leaved forest in the Wuyi Mountains. *J. Env. Sci.*, 1998, **10**, 426–432.
25. Pathak, P. C. and Singh, J. S., Nutrients in precipitation components for pine and oak forests in Kumaun Himalaya. *Tellus B*, 1984, **36**, 44–49.

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