



REVIEW ARTICLE

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Key Points:

- Stemflow is an important phenomenon which remains poorly understood
- Guidance on the quantification of stemflow fluxes is presented
- Directions for future research are presented and discussed

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A review of stemflow generation dynamics and stemflow-environment interactions in forests and shrublands

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Abstract Many geoscientists now recognize stemflow as an important phenomenon which can exert considerable effects on the hydrology, biogeochemistry, and ecology of wooded ecosystems and shrublands. Despite the explosive growth of stemflow research, until this review there has been no comprehensive attempt to summarize and synthesize this literature since 2003. Topical areas of substantive new knowledge in stemflow research include the following: (1) the interrelationships among stemflow and meteorological conditions, especially within individual rain events; (2) the dynamic interplay between stemflow and canopy structure; (3) stemflow and the cycling of solutes and transport of particulate matter; (4) stemflow and its interactions with canopy fungi and corticolous lichens; and (5) stemflow-soil interactions. Each of these five topical areas of substantive new stemflow research is summarized and synthesized, with areas of future research opportunities discussed. In addition, we have reviewed the parameters which can be used to describe stemflow and critically evaluate their utility for different purposes. This review makes a call for scientists studying stemflow to utilize common metrics in an effort to increase the cross-site comparability of stemflow studies. Capitalizing on the insights of prior research, exciting research opportunities await hydrologists, biogeoscientists, and forest ecologists who will conduct studies to deepen our knowledge of stemflow which will enable a better and more accurate framing of stemflow in the larger context of watershed hydrology and biogeochemistry.

1. Introduction

Thirty-two years have passed since *Parker* [1983] published his literature review of throughfall and stemflow in the nutrient cycles of forests (see glossary for key terms, Appendix A) and 12 years since *Levia and Frost* [2003] published their review article on stemflow in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. Recognizing the complexity of water flux and the importance of stemflow in the hydrologic cycle of forests (Figure 1), another review specifically focusing on some stemflow studies in Japan was published by *Ikawa* [2007], while *Johnson and Lehmann* [2006] focused on the double funneling of stemflow above ground and below ground. In addition, *Levia et al.* [2011a] reviewed some past throughfall and stemflow work and identified some future directions for stemflow research. While there have been significant advancements in our understanding of stemflow over the last 12 years, there has been no comprehensive attempt to chronicle, analyze, and evaluate this corpus of research. Indeed, a total of 460 works with “stemflow” as a topic have been published according to Web of Science between 2003 and 2014 (as of 8 January 2015), whereas *Levia and Frost* [2003] cited a total of 199 papers in their stemflow review paper which sought to examine stemflow research from as early a point as possible. The 460 papers published with stemflow as the topic constitutes 21.2% of the 2168 articles published in the same period with “forest hydrology” as the topic (as of 8 January 2015). Significant advances have been made in a number of key areas of stemflow research, including stemflow-soil interactions, the effects of lichens and other epiphytes on stemflow, and a deeper understanding on the influence of weather on stemflow. Perhaps, most notably, stemflow has been put on the “radar screen” of many scientists in the geoscience community over the past 12 years. This is particularly noteworthy because it has precipitated an increase in the breadth and diversity of stemflow publications and confirmation of its importance to the hydrology and biogeochemistry of wooded ecosystems.

The primary emphasis of this review article is on stemflow research since 2003, with earlier work incorporated where applicable and warranted. *Levia and Frost* [2003] synthesized and examined many of the biotic and

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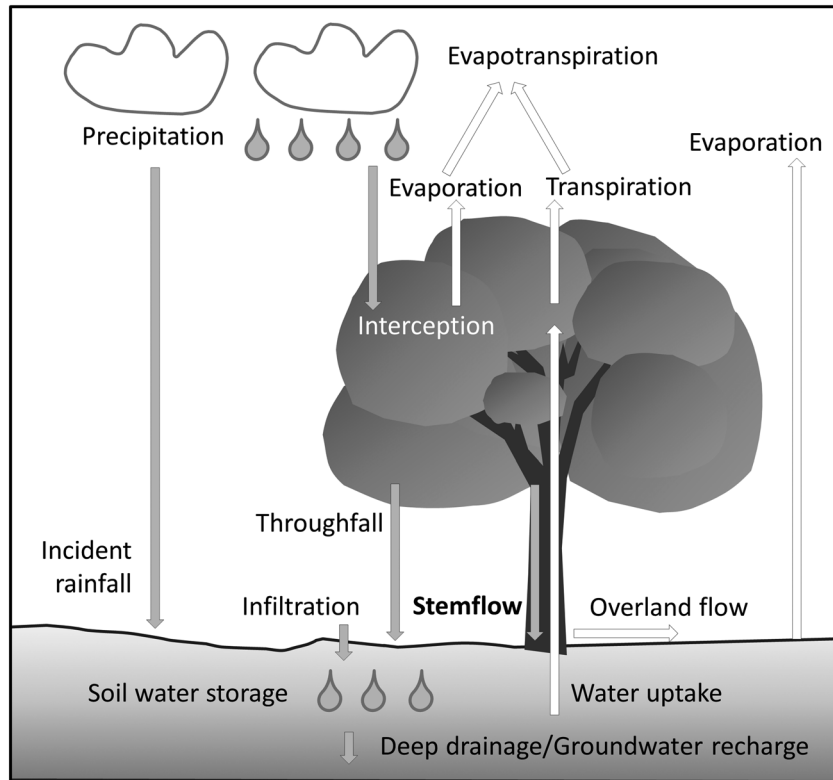


Figure 1. The hydrologic cycle of wooded ecosystems.

abiotic factors that affect stemflow yield in forests and agricultural ecosystems. They also identified areas in need of further research. The current review builds upon the knowledge gleaned from this earlier review and subsequent work. Rather than simply comparing species with different canopy traits or the effects of various meteorological conditions on stemflow generation, the intention of this paper is to highlight, explore, and evaluate areas of significant advancement of stemflow research in the past 12 years. With the dramatic increase of stemflow studies conducted in recent years, this review focuses on stemflow generated by trees and woody shrubs in an effort to keep the length manageable, although references to stemflow from crops are included where they enhance our understanding of stemflow generation processes. Figure 2 displays the major sections of this paper, along with some key subsections, which represent topical areas of substantive new knowledge that are critically reviewed.

2. Quantifying Stemflow Fluxes

To quantify stemflow water fluxes, usually, only a few trees per stand are sampled and results are scaled up to the whole stand. For stemflow measurement, collectors, or collars, are usually wrapped in a spiral or ring around a tree trunk and connected to a collection bin. They are often made of flexible tubing, urethane mats, tarpaulin, or aluminum and plastic foil which are fastened to the tree trunk (Figure 3). Silicon sealant between the trunk and collector is applied to achieve water tightness. The most common shortcoming in the planning phase is that maximum stemflow rates are sometimes underestimated, and hence, installed collectors are too small to adequately capture high stemflow volumes.

Sampled trees in a forest should represent the full range of species and diameter classes. The simplest way of scaling up stemflow volume from a representative group of sample trees is to calculate mean stemflow volume (S_T in L) and multiply it by the total number of trees per unit area (e.g., per hectare of a forest). The stemflow percentage per incident precipitation ($S_{(\%P)}$) is then calculated as

$$S_{(\%P)} = \frac{\left(\frac{S_T \times N_{\text{trees}}}{A}\right) \times 100}{P} \quad (1)$$

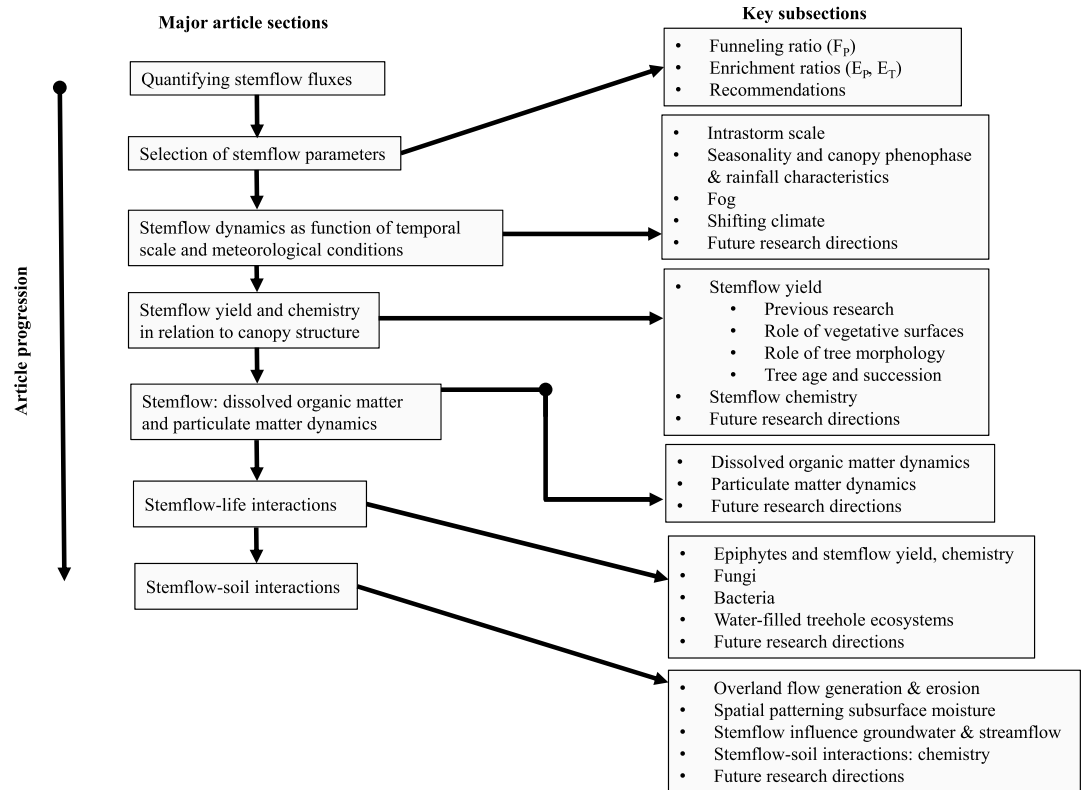


Figure 2. A schematic depicting the major sections of this review article which demonstrate topical areas of substantive new knowledge in stemflow research. Several key subsections that stem from the major sections of this review are also depicted.

where S_y is mean (or median) stemflow of all sampled trees (L), N_{Trees} is the number of trees per area, A is the area (m^2), and P is precipitation (mm). Preferably, P should be measured above the canopy or in open areas adjacent to the forest under study. As precipitation amount and intensity can vary widely over short distances, monitoring rainfall in several open areas around the forest being studied is recommended. The area to which equation (1) refers to depends on the purpose of the study. In forests it is usually per hectare, but in arid environments, or for other isolated trees, it should be the projected crown area instead. Regardless of the study purpose, the area over which stemflow inputs (water and solutes) are computed and expressed must be specifically stated to ensure proper interpretation of results.

As stemflow volumes can differ between species and diameter size class, $S_{(%P)}$ should be weighted by the number of trees per group:

$$S_{(%P)} = \frac{\left(\sum_{i=1}^k \frac{(S_{y,i} \times N_{Trees,i})}{A} \right)}{P} \times 100 \quad (2)$$

where k is the number of groups of species or of trunk diameter ranges.

Solute fluxes are calculated as the product of stemflow volume and solute concentration per tree. The mean or median flux of all sampled trees, or per group of sampled trees, is multiplied by the respective number of trees per area. Fluxes calculated per group are added.

Stemflow can be recorded on different time scales: event, daily, weekly, biweekly, or monthly basis with bulk collector bins or, alternatively, on a within-event basis with tipping-bucket collectors. For stemflow chemistry, samples can be taken from bulk collectors or sequential bins. Further details of stemflow volume measurement and stemflow sampling for chemistry were summarized by *Levia and Frost [2003]*.



Figure 3. Examples of stemflow collectors as used by (top left) *Germer et al.* [2010] in Rondônia, Brazil, (middle left) *Levia et al.* [2010] in northeastern USA (photo courtesy N. Finger), (bottom left) *Levia et al.* [2015] for saplings in Thuringia, Germany, and (top right and bottom right) *Iida et al.* [2012] in Tsukuba Experimental Forest, Japan (photos courtesy K. Nanko and S. Iida).

3. Selection of Stemflow Parameters

Results are often reported using the raw data of stemflow volumes or stemflow concentrations. This, however, restricts the comparability to other studies with trees of different ranges of DBH (diameter at breast height, 1.37 m). Stemflow water fluxes, chemical concentrations, and solute fluxes can be reported in multiple other ways depending on the aim of a study and data availability (Table 1). Tables 2a and 2b and equations (1) and (2) (section 2) serve as a ready reference for the equations utilized to quantify stemflow. It is important to note that each method of expressing stemflow inputs has inherent strengths and weaknesses (Table 1). Awareness of the utility and restrictions of each parameter is critical to ensure that future studies meet their intended goals. While all listed parameters are useful in one context or another, restrictions are not obvious for all of them. Two parameters without obvious restrictions according to Table 1 include (1) stemflow water flux in terms of percentage of incident rainfall ($S_{(\%P)}$) and (2) contribution of solute fluxes by stemflow to total flux (stemflow + throughfall) per hectare. Stemflow water flux, as a percentage of incident rainfall ($S_{(\%P)}$), is the most commonly reported stemflow parameter. It reflects how much of incident rainfall reached the forest floor by stemflow. It is often reported together with throughfall percentage of incident rainfall and can be used with rainfall and throughfall data to calculate precipitation interception. The percentage of stemflow indicates how relevant this flow path is for water fluxes in different forest types. It provides an indication as to whether stemflow needs to be considered in future water cycling studies in respective forest types. But, caution should be taken if tree age or stocking density from the forest to be studied differs considerably from that which values exist in the literature for the same species. It must also be emphasized that a low percentage of stemflow (in relation to incident precipitation) should not automatically preclude a further examination of stemflow. This is because

Table 1. Overview of Parameters That Can Be Used to Report Stemflow Water and Chemical Fluxes, the Data Required to Calculate Them, and Possible Utility and Restrictions of Applying Each Parameter (P = Precipitation, S = Stemflow, T = Throughfall, C = Concentration, N = Number of Trees, B = Basal Area, K = Canopy Area, and I = Infiltration Area)

Parameter	S Volume per Tree	C_S	P Depth	C_P	T Depth	C_T	N_{Trees} per Hectare	B per Hectare	K	I	Notable Use(s)	Notable Restriction(s)
<i>S Water Flux in Terms of</i>												
Volume per tree ($S \text{ yield} - S_T$)	X										<ul style="list-style-type: none"> compare trees (e.g., in terms of morphology influence) gauge temporal dynamics of tree species 	<ul style="list-style-type: none"> P intensity changes can have different effects on S yield for different trees, and hence, morphology effects might get obscured no comparison over wide DBH range possible as size of tree affects collecting area and, hence, stemflow yield volumetrically expressed canopy storage is unsuitable for the use in hydrologic models
Volume per unit P depth ($S \text{ rate} - S_R$)	X		X								<ul style="list-style-type: none"> compare trees (e.g., in terms of morphology influence and rainfall intensity) gauge temporal dynamics of tree species express canopy storage in terms of unit P depth compare trees over a wide range of DBH in terms of (e.g., morphology influence and rainfall intensity) gauge temporal dynamics of tree species over a wide range of DBH 	<ul style="list-style-type: none"> no comparison possible for differing rainfall depths among trees as rainfall depth directly influences stemflow depth
Depth per unit basal area ($S \text{ depth} - S_D$)	X							X			<ul style="list-style-type: none"> get information about relevance of S in stand for hydrological fluxes (e.g., for interception estimation) if data are collected on event or within-event basis, it can be used to estimate canopy storage and model interception 	None
% of incident P ($S_{\%P}$)	X		X				X				<ul style="list-style-type: none"> input for soil hydrological interpretation or modeling compare funneling of S among trees of different canopy structure, age, and stand position (i.e., edge, interior) examine the effects of variable rainfall intensities on P funneling examine the effects of differing meteorological conditions (e.g., wind speed and wind direction) on S funneling 	<ul style="list-style-type: none"> not possible to draw conclusions of maximum wetting front depth in soil because infiltration area does not equal tree basal area ratios calculated from monthly or annual sums of P and S average out extremes; hence, event or daily data should be used to provide the full range of possible funneling ratios
Funneling ratio per basal area (F_{PB})	X		X					X			<ul style="list-style-type: none"> input for soil hydrological interpretation or modeling compare funneling of S among trees of different canopy structure, age, and stand position (i.e., edge, interior) examine the effects of variable rainfall intensities on P funneling examine the effects of differing meteorological conditions (e.g., wind speed and wind direction) on S funneling 	<ul style="list-style-type: none"> not possible to draw conclusions of maximum wetting front depth in soil because infiltration area does not equal tree basal area ratios calculated from monthly or annual sums of P and S average out extremes; hence, event or daily data should be used to provide the full range of possible funneling ratios

Table 1. (continued)

Parameter	S Volume per Tree	C _S	P Depth	C _P	T Depth	C _T	N _{Trees} per Hectare	B per Hectare	B per Tree	K	I	Notable Use(s)	Notable Restriction(s)
Funneling ratio per infiltration area (f_P)	X		X						X		X	<ul style="list-style-type: none"> compare S funneling for trees with different life histories 	<ul style="list-style-type: none"> as rainfall intensity influences funneling ratios and is dynamic within particular events, ratios should only be calculated for long periods of constant rainfall intensities; short, variable rainfall intensities are more useful for laboratory experiments to compare P funneling across a range of P intensities under controlled conditions the infiltration area depends on soil hydraulic conductivity, P intensity, and P duration > decreased comparability of S generation between individual P events and forests
S Chemical Concentration in Terms of Average concentration per event or tree		X										<ul style="list-style-type: none"> compare S concentrations among trees or stands 	<ul style="list-style-type: none"> comparison to other studies is restricted as concentrations are also influenced by S volumes, which depend on P size (among many other factors) and can vary widely, even for trees of same species and similar DBH
Volume-weighted-mean per event for all collectors	X											<ul style="list-style-type: none"> study S concentration in relation to event characteristics; seasonal dynamics 	<ul style="list-style-type: none"> seasonal differences in event sizes might influence seasonal concentration differences
Volume-weighted-mean per collector for a period	X											<ul style="list-style-type: none"> compare S concentrations among trees 	<ul style="list-style-type: none"> for the spatial heterogeneity, conclusions are only possible if differences in concentrations but not in fluxes are of interest
Concentration-based enrichment ratio of volume-weighted mean S concentration per event compared to P concentration	X											<ul style="list-style-type: none"> compare enrichment among sites and tree DBH classes 	<ul style="list-style-type: none"> a comparison of sites with different ranges of rainfall size and intensity is difficult because they can influence the degree of concentration enrichment
S Chemical Flux in Terms of Deposition per tree	X											<ul style="list-style-type: none"> compare trees of similar DBH (e.g., in terms of morphology) 	<ul style="list-style-type: none"> no comparison of morphological effects over wide DBH range
												<ul style="list-style-type: none"> access temporal dynamics of tree species compare trees of the same species for influence of DBH 	<ul style="list-style-type: none"> P intensity changes can have different effects on S yield and concentration for different tree species, and hence, morphology effects might get obscured

Table 1. (continued)

Parameter	S Volume per Tree	C _S	P Depth	C _P	T Depth	C _T	N _{Trees} per Hectare	B per Hectare	B per Tree	K	I	Notable Use(s)	Notable Restriction(s)
Deposition per hectare	X	X						X	X			<ul style="list-style-type: none"> compare forests of the same species and tree density with different solute concentrations in precipitation and/or different dry deposition loads between P events 	<ul style="list-style-type: none"> no relevance without information about total flux (S + T) per stand comparisons of forests with different species are only possible between study sites with similar rainfall characteristics and atmospheric deposition loads None
Contribution to total flux (S + T) per hectare	X	X	X		X	X		X	X			<ul style="list-style-type: none"> acquire information about the respective importance of S, T to stand level chemical fluxes 	
Enrichment ratio per basal area compared to P flux (E _{PB})	X	X	X	X				X	X			<ul style="list-style-type: none"> obtain information of possible hot spots of chemical fluxes of single trees or shrubs in open areas input for hydrochemical models 	<ul style="list-style-type: none"> not useful for comparison of flux inputs by stemflow to the forest floor for areas with different precipitation solute concentrations or dry deposition rates comparisons in relation to tree morphology are only possible between study sites with similar rainfall characteristics and atmospheric dry deposition loads
Enrichment ratio per basal area compared to T flux (E _{TB})	X	X			X	X			X			<ul style="list-style-type: none"> acquire information of possible hot spots of chemical fluxes in forests input for hydrochemical models compare trees of differing size and morphology 	<ul style="list-style-type: none"> infiltration area does not equal tree basal area comparisons of enrichment ratios in relation to tree morphology are only possible between study sites with similar rainfall characteristics and atmospheric deposition loads
Enrichment ratio per canopy area compared to P flux (E _{PK})	X	X	X	X						X		<ul style="list-style-type: none"> to evaluate effectiveness to increase nutrient inputs to the rooted area presuming that horizontal canopy area corresponds to the belowground rooting area of single trees or shrubs in dry environments compare trees of differing size and morphology 	<ul style="list-style-type: none"> S might not spread over the whole projected canopy area but be restricted to the infiltration area; hence, heterogeneity below the canopy is neglected
Enrichment ratio per infiltration area compared to P flux (E _{PI})	X	X	X	X							X	<ul style="list-style-type: none"> obtain information of possible hot spots of chemical fluxes of single trees or shrubs in open areas 	<ul style="list-style-type: none"> comparisons of enrichment ratios in relation to tree morphology are only possible among study sites with similar rainfall characteristics and atmospheric deposition loads the infiltration area depends on soil hydrologic conductivity and P intensity and duration == > decreased

Table 1. (continued)

Parameter	S Volume per Tree	C _S	P Depth	C _P	T Depth	C _T	N _{Trees} per Hectare	B per Hectare	B per Tree	K	I	Notable Use(s)	Notable Restriction(s)
Enrichment ratio per infiltration area compared to T flux ($E_{T,I}$)	X	X			X	X					X	<ul style="list-style-type: none"> input for hydrochemical models in forest stands, obtain information about the importance of internal nutrient cycling in relation to external input compare trees of differing size and morphology 	<ul style="list-style-type: none"> comparability of S fluxes between individual P events and forests comparisons of enrichment ratios in relation to tree morphology are only possible between study sites with similar rainfall characteristics and atmospheric deposition loads the infiltration area depends on soil hydrologic conductivity and P intensity and duration \Rightarrow decreased comparability- of S fluxes between individual P events and forests comparisons of enrichment ratios in relation to tree morphology are only possible between study sites with similar rainfall characteristics and atmospheric deposition loads

stemflow is a localized point input and the volumes of water funneled down the tree trunk can be significant for studies seeking to examine the effects of stemflow on hydrology, ecology, and biogeochemistry (dissolved, particulate, and microbial) in the proximal area of tree trunks. A comparison of stemflow flux in relation to the stemflow plus throughfall fluxes (and not to rainfall fluxes) is also a useful measure since it includes the relevance of stemflow to solute and particulate matter fluxes in different forest types.

In addition, three other parameters (defined in Tables 2a and 2b) of particular use in Table 1 include (1) stemflow funneling ratio per basal area (F_{PB}) [Herwitz, 1986], (2) stemflow enrichment ratio per basal area compared to rainfall flux (E_{PB}) [Levia and Herwitz, 2000], and (3) stemflow enrichment ratio per basal area compared to throughfall flux (E_{TB}). Even though the basal area of tree trunks does not equal the infiltration area at the soil surface, these ratios are advantageous because they rely on easily measurable data.

3.1. Stemflow Funneling Ratio (F_{PB})

The stemflow funneling ratio is an indispensable parameter to compare stemflow amounts and production processes across forest types and DBH ranges, regardless of geographic location, as well as a variable for input for hydrological models. F_{PB} values (Tables 2a and 2b) exceeding 1 indicate that outlying portions of a tree's crown contribute to stemflow. A number of studies have quantified F_{PB} values at storm, seasonal, and annual time scales [e.g., Aboal et al., 1999; Carlyle-Moses and Price, 2006; Li et al., 2008; Levia et al., 2010]. With increasing temporal integration from daily to annual values, one can expect that the variability of F_{PB} to decrease, as high values from extreme events, with high stemflow intensities are averaged out over time. Annual mean funneling ratios for different forest types ranged from 3 to 37 (Table 3a). Funneling ratios at the seasonal scale were reported to range from 7 to 26 for some deciduous tree species in Canada [Carlyle-Moses and Price, 2006]. Storm level F_{PB} averaged between 24 and 153 for semiarid shrub species in China [Li et al., 2008]. For individual trees, F_{PB} values can exceed 100 [Herwitz, 1986] or be around 1 for larger trees [Germer et al., 2010]. This effect of temporal scale on funneling ratios emphasizes the need for future studies to always report means and ranges of event, seasonal-, and annual-based funneling ratios.

While F_{PB} has been examined in relation to tree size [Germer et al., 2010], rainfall intensity [Levia et al., 2010], and rainfall thresholds [Li et al., 2008], among other factors, the authors propose that a concerted effort to couch stemflow results in the context of F_{PB} would be a fruitful endeavor, allowing researchers to readily compare results with other studies and achieve meaningful cross-site comparisons. Such comparisons, however, need to carefully address possible differences of rainfall characteristics between sites, as these can influence funneling ratios in addition to tree architecture.

Table 2a. Key Parameters and Equations to Understand and Quantify Stemflow (S) Fluxes

Parameter	Description	Equation
Stemflow yield (S_Y)	Stemflow volume per tree	S_Y
Stemflow rate (S_R)	Stemflow volume per unit precipitation depth (P)	$S_R = \frac{S_Y}{P}$
Stemflow depth (S_D)	Stemflow in mm per unit basal area (B)	$S_D = \frac{S_Y}{B}$

3.2. Stemflow Enrichment Ratios ($E_{P,B}$ and $E_{T,B}$)

The stemflow enrichment ratio is a flux-based ratio which seeks to quantify the extent to which trees concentrate solutes (and particulates) at the tree base (Tables 2a and 2b). Similar to the $F_{P,B}$, $E_{P,B}$ as reported in the past is a beneficial parameter to examine which factors control the transport and flux of solutes and particulates to the tree base. It also indicates how relevant stemflow can be for forest nutrient cycling compared to open areas where nutrient input is restricted to rainfall and dry deposition. Nevertheless, we also propose a stemflow enrichment ratio that is related to throughfall instead of rainfall fluxes ($E_{T,B}$) (Tables 2a and 2b). This variant of the enrichment ratio would provide information about the heterogeneity of nutrient input to the forest floor, thereby providing additional insights into the importance of stemflow in relation to both $E_{P,B}$ and biogeochemical cycling as a whole within a particular forest. Stemflow $E_{P,B}$ values are highly variable for a given solute or particulate, fluctuating widely as a function of many factors, including precipitation solute and particulate concentrations, dryfall, and meteorological conditions (e.g., rain intensity and wind direction) that are influenced by geographic locality as well as individuality in tree canopy architecture and the life history of individual trees [e.g., *Levia*, 2003a; *André et al.*, 2008a; *Germer et al.*, 2012; *Zhang et al.*, 2013]. K^+ $E_{P,B}$ values from *Carya glabra* Mill. (pignut hickory) during winter, for example, averaged 580 [*Levia and Herwitz*, 2000], whereas a K^+ $E_{P,B}$ value of 1230 was reported for tree species in the Amazon rainforest [*Germer et al.*, 2012].

The authors purport that both the $E_{P,B}$ and $E_{T,B}$ ratios would serve as a useful cross-site comparator for stemflow studies; however, possible differences in rainfall characteristics and rainfall chemistry as well as atmospheric deposition must be taken into account across sites and seasons. Future studies of stemflow chemistry should include an analysis of both variants of the flux-based enrichment ratio, $E_{P,B}$ and $E_{T,B}$. To ensure the robustness of the $E_{P,B}$ and $E_{T,B}$ values and increase the viability of interstudy comparisons, care must be taken to ensure that an adequate number of trees are sampled within a given study to overcome the marked variability associated with stemflow concentrations and fluxes which result in highly variable tree-to-tree enrichment ratio values. In addition, the enrichment ratios should be examined as a function of both abiotic and biotic factors which can exert a detectable effect on stemflow chemistry. The inclusion of these two enrichment ratios will enhance the comparability among stemflow studies and permit the community to better understand the processes that affect stemflow chemistry and evaluate the role of stemflow in forest or shrubland nutrient cycling at different locations. To date, several studies have couched some of their results using the $E_{P,B}$ ratio [e.g., *Levia*, 2003a; *André et al.*, 2008a; *Germer et al.*, 2012; *Zhang et al.*, 2013]. Future stemflow studies would be enhanced by following suit and building upon the database of $E_{P,B}$ ratios encapsulated in work to date as well as calculating $E_{T,B}$ ratios.

3.3. Stemflow Parameters: Some Insights and Recommendations

Stemflow is often neglected because it is believed to contribute just a minor fraction of total fluxes of water and nutrients in forests [*Levia and Frost*, 2003; *Parron et al.*, 2011]. Is this really true? And can we deduce that

Table 2b. Key Parameters and Equations to Understand and Quantify Water and Solute Redistribution by Stemflow (S)^a

Parameter	B (Basal Area)	K (Canopy Area)	I (Infiltration Area)
Funneling ratio (F_P) ^b	$F_{P,B} = \frac{S_Y}{P \times B}$	--	$F_{P,I} = \frac{S_Y}{P \times I}$
Enrichment ratio (E_P) compared to P (precipitation) flux ^c	$E_{P,B} = \frac{S_Y \times C_S}{P \times B \times C_P}$	$E_{P,K} = \frac{S_Y \times C_S}{P \times K \times C_P}$	$E_{P,I} = \frac{S_Y \times C_S}{P \times I \times C_P}$
Enrichment ratio (E_T) compared to T (throughfall) flux	$E_{T,B} = \frac{S_Y \times C_S}{T \times B \times C_T}$	--	$E_{T,I} = \frac{S_Y \times C_S}{T \times I \times C_T}$

^a C_S , C_P , and C_T are chemical concentrations in stemflow, incident precipitation, and throughfall, respectively. P and T are depth equivalents of precipitation and throughfall, respectively.

^bOriginally defined by *Herwitz* [1986] per unit trunk basal area.

^cOriginally defined by *Levia and Herwitz* [2000] per unit trunk basal area.

Table 3a. Overview of Funneling Ratios and Stemflow Chemical Flux Contribution to Total Flux (Stemflow (S) + Throughfall (T)) for Different Research Sites

Research Station/Location	Forest/Soil Type	S % of Incident Rainfall	Funneling Ratio per Basal Area	S Chemical Fluxes Contribution to Total Flux per ha (%)								Reference
				N _{tot}	DON	NO ₃	NH ₄	K	Mg	Ca		
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest-primary inceptisol	1	3	2	3	1	1	2	1	2	<i>Hofhansl et al.</i> [2012] ^a	
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest-secondary inceptisol	1	3	1	1	0	3	3	3	2	<i>Hofhansl et al.</i> [2012] ^a	
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest-primary ultisol	1	3	3	4	5	3	6	6	3	<i>Hofhansl et al.</i> [2012] ^a	
Central Africa	Rain forest with low density of ectomycorrhizal trees	2	5	1				2	2	2	<i>Chuyong et al.</i> [2004] ^b	
Yunnan, China	Montane evergreen forest	2	8	7		9	13	4	5	4	<i>Liu et al.</i> [2003] ^b	
Central Africa	Rain forest with high density of ectomycorrhizal trees	2	8	2				3	2	3	<i>Chuyong et al.</i> [2004] ^b	
Montseny, Spain	Holm oak sheltered from pollution	3	11			2	2	3	3	0	<i>Rodrigo et al.</i> [2003] ^b	
Zululand, South Africa	Eucalyptus plantation-Dukuduku	4	14	7	6	6	7	12	19	22	<i>Dovey et al.</i> [2011] ^a	
Zululand, South Africa	Eucalyptus plantation-Kwambonambi	5	23	4	4	2	5	11	12	12	<i>Dovey et al.</i> [2011] ^a	
Montseny, Spain	Holm oak exposed to pollution	5	23			6	5	6	7	7	<i>Rodrigo et al.</i> [2003] ^b	
Black Forest, Germany	Beech stand	6	13			6	12	21	19		<i>Berger et al.</i> [2009] ^b	
Ile-Ife, Nigeria	Secondary lowland rainforest	7	22			10		10	15	12	<i>Oziegbe et al.</i> [2011] ^b	
Gran Sabana, Venezuela	Primary forest (tall)	8	20	13				18	11	18	<i>Dezseo and Chacon</i> [2006] ^b	
Rancho Grande / Rondônia, Brazil	Tropical open forest	8	27			51	12	28	19	18	<i>Germer et al.</i> [2012] ^b	
Island of Zealand, Denmark	Beech stand	10	32			10	26	10			<i>Pilegaard et al.</i> [2003] ^b	
Pradres, Spain	Holm oak forest	14	37			11		11	41	15	<i>Bellot and Escarré</i> [1991] ^b	

^aCalculated from data requested from authors that were used in publications but not as a list of values.

^bCalculated from published values.

nutrient fluxes by stemflow are low for forests with stemflow water fluxes less than 5% of incident rainfall? During the last decade there was a great increase in stemflow studies that reported nutrient fluxes at the stand level for stemflow, throughfall, and rainfall together with tree basal areas per stand. Before the last decade, enrichment ratios in stemflow studies were mostly related to concentration enrichments [e.g., *Moreno et al.*, 2001; *Johnson and Lehmann*, 2006]. But now it is possible, for the first time, to compare several forest stands by their stemflow flux enrichment ratios in relation to rainfall (E_{PB}) and throughfall (E_{TB}).

We calculated funneling and enrichment ratios for published studies that reported water and nutrient fluxes of rainfall, throughfall, and stemflow as well as related total tree basal areas (Tables 3a and 3b). Studies in a montane evergreen forest or a rainforest with high density of ectomycorrhizal trees resulted in only 2% of rainfall that reached the forest floor by stemflow, but stemflow water fluxes per basal area were 8 times higher than rainfall on an equivalent area [*Liu et al.*, 2003; *Chuyong et al.*, 2004]. As expected, this difference between stemflow percentage and funneling ratio is greater for forests with higher stemflow percentages of incident rainfall (Table 3a). The share of stemflow nutrient fluxes to total fluxes (stemflow + throughfall) also tends to increase with increasing percentages of incident rainfall; it is, however, more heterogeneous and seems to depend on chemical species and site (Table 3a). But again, for a montane evergreen forest with only 2% stemflow of incident rainfall, stemflow contributed around 10% of mineral nitrogen [*Liu et al.*, 2003]. Such a high contribution by stemflow should not be ignored in nutrient flux studies. For sites with stemflow percentage of incident rainfall greater than 5%, stemflow contribution was

Table 3b. Overview of Basal Area and Enrichment Ratios (Calculated From Flux Sums per Year or Study Period) in Terms of Rainfall (E_{PB}) and Throughfall (E_{TB}) for Different Research Sites

Research Station/Location	Forest/Soil Type	Basal Area per Hectare (m ²)	Enrichment Ratio in Terms of Rain (E_{PB})							Reference
			Enrichment Ratio in Terms of T (E_{TB})							
			N _{tot}	DON	NO ₃	NH ₄	K	Mg	Ca	
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest- primary inceptisol	33	6	18	1	3	37	5	7	<i>Hofhansl et al.</i> [2012] ^a
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest- secondary inceptisol	31	3	5	0	6	40	12	5	<i>Hofhansl et al.</i> [2012] ^a
La Gamba/Puntarenas, Costa Rica	Tropical lowland rainforest- primary ultisol	33	3	4	5	3	51	20	8	<i>Hofhansl et al.</i> [2012] ^a
Central Africa	Rain forest with low density of ectomycorrhizal trees	32	13				89	16	31	<i>Chuyong et al.</i> [2004] ^b
Yunnan, China	Montane evergreen forest	26	31		63	77	186	57		<i>Liu et al.</i> [2003] ^b
Central Africa	Rain forest with high density of ectomycorrhizal trees	27	17				156	25	44	<i>Chuyong et al.</i> [2004] ^b
Montseny, Spain	Holm oak sheltered from pollution	27	9		4	6	120	22	1	<i>Rodrigo et al.</i> [2003] ^b
Zululand, South Africa	Eucalyptus plantation- Dukuduku	29	44	82	26	25	113	465	167	<i>Dovey et al.</i> [2011] ^a
Zululand, South Africa	Eucalyptus plantation- Kwambonambi	22	19	19	10	17	76	92	96	<i>Dovey et al.</i> [2011] ^a
Montseny, Spain	Holm oak exposed to pollution	22			29	30	433	87	68	<i>Rodrigo et al.</i> [2003] ^b
Black Forest, Germany	Beech stand	47			30	26	29	34	37	<i>Berger et al.</i> [2009] ^b
Ile-Ife, Nigeria	Secondary lowland rainforest	32			14	24	181	71		<i>Berger et al.</i> [2009] ^b
Gran Sabana, Venezuela	Primary forest (tall)	40	17		34		887	116	363	<i>Oziegbe et al.</i> [2011] ^b
Rancho Grande / Rondônia, Brazil	Tropical open forest	30	39		129		1382	125	74	<i>Oziegbe et al.</i> [2011] ^b
Island of Zealand, Denmark	Beech stand	31			34		36	53	43	<i>Dezseo and Chacon</i> [2006] ^b
Pradres, Spain	Holm oak forest	38			25		497	428	78	<i>Bellot and Escarré</i> [1991] ^b
					33		66	179	47	

^aCalculated from data requested from authors that were used in publications but not as a list of values.

^bCalculated from published values.

commonly between 10 and 20% of total fluxes (Table 3a). In a tropical open rainforest, nitrate contribution by stemflow was greater than 50% of total nitrate flux to the forest floor [*Germer et al.*, 2012]. These enrichment ratios were calculated for annual fluxes and are useful for a general comparison of forests. As the funneling efficiency is affected by rainfall intensities and timing of peak rainfall, funneling ratios can vary widely between events [*Dunkerley*, 2014a]. Therefore, ratios should be calculated on event basis, and mean (or median) ratios as well as ranges or variances should be reported.

As explained above, nutrient enrichment ratios per basal area can be expressed in terms of rainfall (E_{PB}) or throughfall (E_{TB}) fluxes. While reporting E_{TB} ratios is useful for comparisons of spatial heterogeneity of fluxes in forests or plantations, calculations of E_{PB} are useful for studying nutrient funneling efficiency of single trees under comparable atmospheric deposition loads and rainfall characteristics, in particular rainfall intensity, amount, and chemistry (Table 1). Often, however, stemflow enrichment ratios have been calculated in terms of rainfall for forests, because throughfall was not measured or because it was defined initially by *Herwitz* [1986] only in relation to rainfall [e.g., *Germer et al.*, 2012]. Commonly, both stemflow and throughfall are enriched in nutrients, which could lead to an overestimation of spatial heterogeneity in nutrient fluxes if enrichment ratios are only related to rainfall. For instance, potassium enrichment ratios in terms of throughfall (E_{TB}) were lower for all studies than enrichment ratio in terms of rainfall (E_{PB} , Table 3b).

The same is true for calcium and magnesium for most studies. Such a general statement is, however, not possible for all four listed nitrogen species. Nevertheless, nitrogen enrichment can be 10 times higher for stemflow compared to throughfall even when stemflow percentage of incident rainfall is just 1% [Hofhansl *et al.*, 2012].

To conclude, we point out that low stemflow percentages of incident rainfall do not imply that their share in total water or nutrient fluxes of forest is low. And, even if it is low compared to total fluxes, stemflow may still generate hot spots of fluxes. Nevertheless, the conditions under which hot spots of water or nutrient fluxes influence overall ecosystem balances remain inadequately understood (section 8).

4. Stemflow Dynamics as a Function of Temporal Scale and Meteorological Conditions

4.1. Intrastorm Stemflow Dynamics

4.1.1. Stemflow Hydrology

Building upon earlier insights of intrastorm stemflow generation by *Durocher* [1990], three key studies have added to our knowledge of stemflow production within discrete rain events [*Reid and Lewis*, 2009; *Germer et al.*, 2010; *Levia et al.*, 2010]. *Reid and Lewis* [2009] recorded stemflow at 5 min intervals over a 3 year period in 120 year old coastal forest dominated by redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) in northwestern California. They documented the intrastorm interplay among evaporative processes, bark water storage, and rainfall partitioning. The thick fibrous bark of redwood and Douglas fir is favorable for bark water storage, which would likely diminish stemflow production. In fact, these two coniferous species were estimated to have bark water storage capacities of 10–15 mm, with only small areas of the tree trunk contributing to stemflow [*Reid and Lewis*, 2009]. This impacts intrastorm dynamic storage of the canopy which has ramifications for canopy drainage during and after rain events [*Reid and Lewis*, 2009]. It is likely that the concept of dynamic storage, as espoused by *Reid and Lewis* [2009], has a detectable impact on the timing of intrastorm stemflow generation. Even though stemflow was <5% of the precipitation, stemflow was observed for as long as 48 h after any rain in some cases [*Reid and Lewis*, 2009]. For babassu palms (*Orbignya phalerata* Mart.), stemflow continued for as long as 11 h after a rain event [*Germer et al.*, 2010]. For redwood and Douglas fir, it is possible that the prolonged input of stemflow is a function of both tree size and the higher bark water storage capacity (which would keep the preferred flow paths wetter over longer time periods) as well as the alteration in dynamic storage with time. In contrast, the storage of intercepted water in canopy soil (i.e., aboveground soil on trees) of babassu palm accounted for the protracted production of stemflow after a rain event [*Germer et al.*, 2010].

Tree size and bark water storage capacity were also found to be among the key factors controlling stemflow intrastorm generation and totals from deciduous species in the eastern United States [*Levia et al.*, 2010]. *Levia et al.* [2010] witnessed a marked synchronicity between rainfall inputs and stemflow generation for temperate deciduous tree species at the intrastorm scale once the bark water storage capacity of preferred flow channels was reached. Mean 5 min stemflow production was roughly 5 times larger for American beech than yellow poplar [*Levia et al.*, 2010]. Intrastorm 5 min F_{PB} values declined sharply with more intense rain for both tree species but were larger for smooth-barked American beech than the rougher-barked yellow poplar [*Levia et al.*, 2010]. Thus, stemflow production at the intrastorm scale is governed by some of the same factors (both canopy structure and meteorological conditions) as the event scale. In contrast to temperate forests, intrastorm F_{PB} values of babassu palms increase with rainfall intensity [*Germer et al.*, 2010].

While *Levia et al.* [2010] focused on the effects of tree size and canopy structure on intrastorm stemflow production, wind-driven rainfall on the same set of trees was the focus of a paper by *Van Stan et al.* [2011]. *Van Stan et al.* [2011] observed that wind-driven rainfall can augment stemflow production within particular storm events. They reported the occurrence of preferential stemflow when the predominant wind direction was from the east to north-northeast at their particular study site. Moreover, there was interspecific variation in stemflow generation between co-occurring deciduous species due to differences in crown position and geometry [*Van Stan et al.*, 2011]. The greater vertical canopy depth of American beech led to more efficient rainfall interception during windy conditions and augmented stemflow production as compared to the shallower and more horizontally oriented canopy of yellow poplar [*Van Stan et al.*, 2011].

Crown exposure, as determined from unshaded crown projection area, which varies with wind direction, was also reported to be a key factor explaining tree-to-tree differences in stemflow production [Iida *et al.*, 2011]. Levia [2004] also found that bi-hourly intrastorm stemflow volumes differed for trees as a function of meteorological conditions. In winter, intrastorm stemflow inputs were the largest when precipitation inputs were synchronized with higher wind speeds [Levia, 2004].

Dunkerley [2014b] conducted a laboratory experiment to investigate stemflow production on the woody parts of trees (branches and boles) in relation to rainfall intensity and event profile. He observed that simulated events of variable intensity produced larger peak stemflow fluxes than events with rainfall of constant intensity; moreover, stemflow fractions of P were larger if peak rainfall intensities were greater in the earlier portion of an event. The main finding is that the temporal variation of rainfall intensity at the intrastorm scale is a key control affecting stemflow fraction, rather than mean rainfall intensity itself [Dunkerley, 2014b].

4.1.2. Stemflow Chemistry

Within-event stemflow chemistry has received less attention than intrastorm stemflow hydrology. Sources of stemflow solutes and particulates are dry deposition washoff, canopy leaching, and incident precipitation. The extent to which any of these three sources comprise the total stemflow input is a function of geographic location, proximity to industrial sources, climate, and tree species composition, among others. Examining stemflow chemistry within discrete storm events, Levia *et al.* [2011b] found that stemflow exhibited the same exponential decay in solute concentrations as throughfall [e.g., Hansen *et al.*, 1994; Germer *et al.*, 2007], substantiating an earlier study on stemflow by Kazda [1990]. Moreover, building on the earlier work of Kazda [1990], Levia *et al.* [2011b] found that the steady state solute input reached after the washoff of dry deposited materials was not constant. The initiation of new flow paths within the canopy after the initial washoff period, as a storm wets up and saturates new surfaces, was observed to raise the magnitude of the steady state solute input [Levia *et al.*, 2011b] since these newly wetted surfaces will now contribute to canopy leaching. This process indicates that stemflow inputs are dynamic within discrete rain events and that the timing and magnitude of stemflow inputs are variable, with implications for hot spot and hot moment theories, as espoused by McClain *et al.* [2003], with the chemical character of stemflow drainage changing with time and tree species [Levia *et al.*, 2012].

Kubota and Tsuboyama [2003] examined changes in the isotopic composition of stemflow within discrete precipitation events. They found that stemflow $\delta^{18}\text{O}$ revealed remarkable variation within particular storms, sometimes decreasing progressively and other times decreasing and then increasing near the end of storms. The observed decreases in $\delta^{18}\text{O}$ were ascribed to the Rayleigh distillation process [Kubota and Tsuboyama, 2003]. The increase of $\delta^{18}\text{O}$ in some events was hypothesized to be the result of differences in the source of the vapor mass [Kubota and Tsuboyama, 2003]. Higher-magnitude, more intense storms were found to deplete stemflow $\delta^{18}\text{O}$ more than longer-duration storms [Kubota and Tsuboyama, 2003], suggesting that the intrastorm profile and timing of rain and its intensity could exert a detectable effect on the isotopic signature of stemflow. Approximately 70% of the stemflow samples examined were enriched in $\delta^{18}\text{O}$ [Kubota and Tsuboyama, 2003]. Another source of variability of the isotopic composition of stemflow that should be taken into account is pre-event canopy moisture [Allen *et al.*, 2014]. This is to say that the residual moisture held within the bark, which differs among tree species and age, likely impacts the isotopic signature of stemflow.

4.2. Stemflow Seasonality: Role of Canopy Phenophase and Rainfall Characteristics

4.2.1. Stemflow Hydrology

Canopy state has been found to be a critical predictor of stemflow amount with stemflow production being greater in a leafless state for various tree species [e.g., Helvey and Patric, 1965; Levia and Frost, 2003; André *et al.*, 2008b; Staelens *et al.*, 2008a, 2011]. This appears to be contrary to the trend for some shrub species where the presence or absence of leaves did not affect stemflow amounts [e.g., Martinez-Meza and Whitford, 1996]. Within the leafed or leafless period, precipitation type can affect stemflow yield. Winter stemflow generation from leafless deciduous trees was affected by precipitation event type (e.g., rain, rain-to-snow and snow-to-rain) [Levia, 2004]. Even with similar durations, magnitude, and intensities, different types of precipitation events can produce drastically different stemflow amounts [Levia, 2004]. For instance, a rain and snow-to-rain event with similar characteristics produced stemflow volumes that differed by a factor of 4.2 [Levia, 2004].

Mean stemflow F_{PB} values were the least for snow events (0.3), intermediate for rain events (13.9), and highest for rain-to-snow events (22.5) [Levia, 2004].

The threshold for stemflow generation differs as a function of canopy state. In a European beech stand, the threshold for stemflow generation was 1.9 mm and 2.5 mm for leafless and leafed canopy states, respectively [Staelens *et al.*, 2008a]. Likewise, André *et al.* [2008b] observed that the rainfall threshold for stemflow initiation was higher for the leafed period than the leafless period, while the stemflow rate was higher in the leafless period. Moreover, the water storage on the aboveground surfaces of trees did not differ significantly between the two periods [André *et al.*, 2008b]. This highlights the importance of bark storage to stemflow production which is consistent with prior research of Herwitz [1985] who showed that bark water storage was much larger than that of foliar surfaces. The proportion of total water storage by foliar and woody surfaces was even higher for woody surfaces under simulated windy conditions [Herwitz, 1985]. The threshold of rainfall depth needed to generate stemflow increased with the seasonally variable ratio between cumulative potential evaporation in the antecedent dry period occurring before a particular rain event and the volume of rainfall of the prior event [André *et al.*, 2008b].

Muzyło *et al.* [2012] showed marginally higher stemflow amounts in the leafless period as opposed to the leaf period for a downy oak (*Quercus pubescens* Willd.) forest in the eastern Pyrenees Mountains. These forests experience a unique mountainous Mediterranean climate with distinct wet and dry seasons and especially large differences in precipitation characteristics between seasons. They categorized precipitation events into four groupings: low-intensity short, low-intensity long, high-intensity short, and high-intensity long events. Stemflow was greater for longer events in the leafless period compared to the leafed period regardless whether it was low or high intensity [Muzyło *et al.*, 2012]. In contrast, the opposite was found for short events where the stemflow fraction of incident precipitation was less in the leafless period than the leafed period for both low- and high-intensity storms [Muzyło *et al.*, 2012]. In semiarid areas of Central Texas, USA, rainfall intensity was observed to affect stemflow yields for Ashe juniper (*Juniperus ashei* Buchholz), a drought-tolerant evergreen shrub [Owens *et al.*, 2006]. They found that stemflow was of minor importance for low-intensity storms (<12.5 mm in 24 h) and notable for high-intensity storms (>25 mm in a short time) [Owens *et al.*, 2006]. Yang *et al.* [2008] also observed that stemflow amount and percentage of P per unit crown area increased for two shrub species (*Salix psammophila* C. Wang et Chang Y. Yang and *Artemisia sphaerocephala* Krasch) with maximum rain intensity in Mu Us sandy land area of northwestern China. Stemflow accounted for almost 8% of rainfall for *S. psammophila* and approximately 3% for *A. sphaerocephala* in relation to canopy area [Yang *et al.*, 2008].

Stemflow yield decreased with maximum hourly rainfall rate on an event basis in European beech [Staelens *et al.*, 2008a], likely due to the increased probability of drip as stemflow channels are overloaded [Staelens *et al.*, 2008a; Levia *et al.*, 2010]. Larger hourly vapor pressure deficits corresponded with lower stemflow inputs under European beech, whereas wind speed appeared to have no detectable effect on stemflow amount at the event level [Staelens *et al.*, 2008a]. André *et al.* [2008b] noted that higher wind speeds during storms led to an increase in stemflow rate and lowered the rainfall threshold for stemflow generation, especially in the leafless season, for a mixed species stand of European beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.). Other studies have found some similar trends with wind [e.g., Xiao *et al.*, 2000] or rainfall amount or rate on event-based stemflow production [e.g., Manfroi *et al.*, 2004].

In a Bornean tropical lowland forest dominated by convective rainfall and limited seasonality, for instance, four-fifths of all stemflow generated occurred in storms > 20 mm [Manfroi *et al.*, 2004]. For individual trees, an average correlation coefficient of 0.92 was observed between storm rainfall amount and the volume of stemflow generated [Manfroi *et al.*, 2004]. It is likely that stemflow fractions observed were partly influenced by the intrastorm rainfall intensity profile, and the temporal variability thereof, that can exert a considerable influence on stemflow yield [Dunkerley, 2014b]. In fact, Dunkerley [2014b] suggested that a primary reason for larger stemflow fractions of P from trees during the dormant season may be attributable to more moderate rainfall intensities associated with frontal weather systems (as opposed to summer convective storms) which are less likely to overcome drop adhesion forces and convert branchflow and stemflow to throughfall.

4.2.2. Stemflow Chemistry

Working in a mixed beech-oak stand of the Belgian Ardennes, André *et al.* [2008a] employed mixed linear models to examine the effects of rain volume and the duration of the antecedent dry period on net

stemflow ion fluxes with respect to tree size. For both leafed and leafless canopy states, net stemflow ion fluxes were found to increase with rain volume and the length of the antecedent dry period [André *et al.*, 2008a]. Rates of dry deposition were much higher in the leafless period than the leafed period [André *et al.*, 2008a]. Also working in Belgium, Staelens *et al.* [2007] documented that stemflow ion concentrations and ion deposition fluxes were higher in the leafless period than the leafed period for most ionic species. They attributed the higher fluxes in the leafless period to both the generation of larger stemflow volumes in the absence of leaves and higher stemflow concentrations under leafless conditions, which, presumably, is partly attributable to high dry deposition onto the leafless crowns of trees. As expected, the high contribution by stemflow to total annual fluxes of H^+ in the leafless period stemflow corresponded with the low pH of stemflow compared to rainfall during this period [Staelens *et al.*, 2007]. In total, stemflow accounted for 9–19% of solute inputs to the soil for typical ions, such as Na^+ , K^+ , Ca^{2+} , NH_4^+ , and almost two-fifths (38%) of H^+ [Staelens *et al.*, 2007]. It is important to note that total stemflow fluxes are likely to vary for events that occur in leafed, leafless, emergent, or senescent canopy conditions [Staelens *et al.*, 2007]. In a Costa Rican lowland tropical rainforest, the net stemflow flux was largely attributed to canopy exchange processes rather than atmospheric dryfall [Hofhansl *et al.*, 2012]. In addition, both rainfall magnitude and duration were cited as significant factors controlling stemflow chemistry in these tropical lowland forests [Hofhansl *et al.*, 2012].

4.3. Stemflow in Relation to Fog

Fog inputs represent a critical source of water for some ecosystems [e.g., Dawson, 1998; Vasey *et al.*, 2012]. Interrelationships between fog and stemflow received further attention over the past decade. Hildebrandt *et al.* [2007] found that stemflow water inputs in Omani cloud forests enveloped in fog constituted a mean of 34% of net precipitation. The high stemflow amounts were attributable to the steep branching angles of the vegetation as well as the low-intensity rainfall rates and small drop sizes that are indicative of fog events [Hildebrandt *et al.*, 2007]. In Australian tropical rainforests, stemflow production was observed to increase with altitude (from 2–3% of gross precipitation inputs at lower sites to 11% at a higher site) [McJannet *et al.*, 2007]. They ascribed this increase to high stem density (2019 stems ha^{-1}) and low leaf area index (LAI) at this highest elevation site (1560 m), which would lead to more cloud interception and the coalescence of fog on aboveground woody surfaces. In a Hawaiian tropical montane cloud forest, morphological differences in canopy structure as well as high stem densities (150 stems per $400 m^2$) of *Psidium cattleianum* (strawberry guava) at an invaded forest site were also implicated in the very high stemflow production (29% of rainfall) as compared to native forest site dominated by *Metrosideros polymorpha* ('ohi'a lehua) with 54 stems per $400 m^2$ [M. Takahashi *et al.*, 2011]. Bruijnzeel *et al.* [2011] also observed increased stemflow fractions in tropical montane cloud forests with increased elevation and lower LAI values. They concluded that a better understanding is needed between cloud water interception and wind-driven precipitation. It would be advantageous to examine such stemflow inputs using the F_{PB} ratio to improve our understanding of the relationship between fog duration, thickness, and droplet size on stemflow inputs to the forest floor. Fog also has been documented to affect the chemistry of stemflow. On the island of Hokkaido in Japan, Lyobe *et al.* [2003] noted that the presence of fog dampened the differences in electrical conductivity between throughfall and stemflow that were plainly evident in the absence of fog.

While fog can generate appreciable stemflow quantities in some forests, canopy structure is of importance as well. In contrast, to studies that have observed large stemflow inputs in relation to foggy conditions, Pryet *et al.* [2012] found stemflow inputs less than 1% of gross precipitation along the windward slope of Santa Cruz Island in the Galapagos. They ascribed the low stemflow inputs to the bountiful epiphyte coverage on the forest canopy and less than favorable canopy structure [Pryet *et al.*, 2012]. In particular, the sample trees had subhorizontal branching patterns which would divert stemflow away from the trunk and detaching bark [Pryet *et al.*, 2012].

4.4. Stemflow and Shifting Climate

Winter is an important season for the ecology of forested ecosystems [Campbell *et al.*, 2005] which is being affected by climate change [Campbell *et al.*, 2009; Groffman *et al.*, 2012]. Groffman *et al.* [2012] have noted substantial changes in the hydrology and biogeochemistry of northeastern forests in the U.S. during winter based on decades of monitoring and experimentation at the Hubbard Brook Experimental Forest in

New Hampshire, USA. Most notably, climate change has reduced the duration and depth of the snowpack which increases the likelihood of soil freezing and the export of nitrate, phosphate, and base cations from the watershed and causing an asynchrony in early spring between leafing and the canopy demand for nutrients and microbial activity in the soil [Groffman *et al.*, 2012]. Such changes are not unique to the northeastern United States as climate change has tangible effects on forest ecosystems around the globe [Bonan, 2008, 2011; Intergovernmental Panel on Climate Change, 2014]. It is certainly plausible that precipitation changes will have an effect on stemflow yield and chemistry. Ice storms, for example, which have a detectable effect on watershed-scale nitrogen cycling [Houlton *et al.*, 2003], also have been shown to damage trees and increase nitrate leaching from damaged crowns which, in turn, could also affect stemflow chemistry from damaged trees.

Stemflow amounts have been observed to change as a function of precipitation type [Levia, 2004]. Snow-to-rain events also have been reported to leach greater quantities of some cations and anions, such as K^+ , Ca^{2+} , Mg^{2+} , and NO_3^- , than either rain or rain-to-snow events [Levia, 2003a, 2003b]. Variable interception efficiencies of different hydrometeors and different intrastorm air temperature profiles which can alter contact time with the corticular surface may partly explain the observed differences [Levia, 2003a]. Therefore, a decrease in snow events and an increase in snow-to-rain events would increase stemflow leaching. Snowmelt-induced stemflow is partly affected by the meteorological conditions and microclimatic variables at the storm scale [Levia and Underwood, 2004]. Differences in canopy albedos, canopy snow storage, radiative fluxes, and sensible and latent heat fluxes between snow-covered, partially snow-covered, and snow-free canopies that develop as the intercepted snow ripens and melts [e.g., Leonard and Eschner, 1968; Nakai *et al.*, 1999; Lundberg and Koivusalo, 2003] can affect stemflow yield among rain and mixed precipitation events [Levia and Underwood, 2004].

4.5. Stemflow Dynamics as a Function of Temporal Scale and Meteorological Conditions: Evaluation and Future Directions

A better understanding of the relationship between fog and stemflow yield could be achieved, especially in regard to droplet size and droplet size distributions. Some of this work could draw on recent research by Park *et al.* [2013] examining the role of woven meshes with differing coatings of varying roughness topography and wetting characteristics on fog collection efficiencies. How does fog droplet size affect adherence to plant surfaces? Do fog droplets coalesce differently on foliage and bark surfaces? Do fog droplet size distributions that are right skewed lead to a faster onset of stemflow than those skewed to the left? Such questions are important and will provide a more holistic understanding of the water cycle in ecosystems dominated by fog. The use of phase Doppler particle analyzers can permit answers to these questions.

It is clear that more work is needed to better understand the effects of climate change on stemflow hydrology and chemistry. Given the complexity and multifaceted nature of climate change, such research should focus on both the direct and indirect impacts of climate change on stemflow. Two examples of direct effects of climate change on forest ecosystems would be a decrease in the incidence of snow events or an increase in the duration of the leafed period. As documented above, both are expected to affect stemflow hydrology and chemistry. Work completed to date on the possible effects of climate change on stemflow hydrology and chemistry [Levia, 2003b] has signified that further investigation into the interactions between climate change and stemflow are justified. Further research is needed to examine the direct effects of climate change across the different types of wooded ecosystems.

The indirect effects of climate change on forests include dieback from insect attack, fire caused from drier conditions, or an increased frequency of ice storms. The effects of these stressors, and others, are inadequately understood. Insects, forest fires, or ice storms and the synergistic effects among them lead to an increase in the number of standing dead trees in forests. Bearup *et al.* [2014], for example, demonstrated the unprecedented dieback of vast expanses of forest throughout the western United States in a relatively short period of time as a result of mountain pine beetle infestations which alter forest transpiration and interception and presumably throughfall and stemflow amounts. Stemflow hydrology and chemistry from standing dead trees is just beginning to be understood [Watters and Price, 1988; Frost, 2011; Frost and Levia, 2014]. Varying states of mortality have been found to have a substantial impact on stemflow amounts [Frost and Levia, 2014]. Stemflow chemistry also varies significantly among different live, moribund, and standing dead trees [Frost, 2011]. Rainfall threshold for stemflow was lower for live and

stressed trees than standing dead trees [Frost and Levia, 2014]. On a precipitation event basis, stemflow volumes from live and stressed trees was approximately 60 times larger than from standing dead trees [Frost and Levia, 2014]. What is the impact of individual stressors on stemflow hydrology and chemistry? What are the synergistic effects of a combination of these stressors on stemflow hydrology and chemistry? As such, further work needs to examine the effects of climate change on stemflow chemistry. It will be difficult to disentangle the confounding effects of changes in weather, species shift, and the increased stress from insects, fire, drought, and other stressors, but we need to better understand the effects of climate change on stemflow hydrology and chemistry. The use of isotopes [after Allen *et al.*, 2014] may be a fruitful approach to better understand the source, routing, and transport of stemflow through the canopy.

5. Stemflow Yield and Chemistry in Relation to Canopy Structure

5.1. Stemflow Yield

5.1.1. Previous Research

Earlier work on the effects of canopy structure on stemflow yield and chemistry is summarized by Levia and Frost [2003], although a few key studies deserve particular mention. Herwitz [1987] examined the flow of water over branches of different tropical tree species under simulated rainfall. Among other findings, he concluded that the relationship between branchflow yield and branch inclination angle shifts from linear to logarithmic as branches wet and become saturated under high-intensity rainfall [Herwitz, 1987]. In arid environments, Martinez-Meza and Whitford [1996] observed a variation in stemflow yield from shrubs of different ages with different stem angles. For *Flourensia cernua* DC, they found that the largest stemflow yields were from branches inclined $> 45^\circ$ [Martinez-Meza and Whitford, 1996]. It also has long been observed that rougher-barked trees produced less stemflow than smoother-barked trees [e.g., Voigt, 1960; Levia and Frost, 2003; Xiao and McPherson, 2011]. Barbier *et al.* [2009] provide a review of precipitation partitioning with respect to some coniferous and deciduous tree genera in temperate and boreal forests in relation to several aspects of canopy structure, largely bark roughness, and stand level canopy structural metrics, (e.g., basal area). Readers interested in species-specific comparisons for temperate and boreal tree species are referred to this review.

5.1.2. Role of Vegetative Surfaces

Stemflow has been observed to be disproportionately generated in the upper portion of the canopy [Hutchinson and Roberts, 1981]. An initial study by Levia and Wubbena [2006] suggested that this may be partly due to lower bark water storage capacities in the upper canopy where bark tends to be thinner. But higher stemflow production might also be attributable to higher branch inclination angles in the upper canopy for some tree species as well as the greater exposure of the upper canopy in forests.

Levia and Herwitz [2005] reported that bark water storage capacities, which can amount to hundreds of liters of water for individual trees, differed significantly among three co-occurring deciduous tree species (*Quercus rubra* L. (northern red oak), *Betula lenta* L. (sweet birch), and *Carya glabra* Mill. (pignut hickory)). The statistically significant higher mean normative bark water storage capacity for northern red oak ($\sim 0.67 \text{ mL cm}^{-3}$) as compared to sweet birch ($\sim 0.44 \text{ mL cm}^{-3}$) was largely due to the smoother (and thinner) bark of sweet birch [Levia and Herwitz, 2005].

Van Stan and Levia [2010] quantified the bark microrelief of trees across small, medium, and large diameter classes of both American beech and yellow poplar. As expected, the overall trend was that smooth-barked American beech out produced the stemflow production of the rougher-barked yellow poplar [Van Stan and Levia, 2010]. Correspondence analysis for these tree species revealed that stemflow yield is more similar within a given tree species than between them and that tree size exerts a considerable effect on stemflow production within a certain species, almost certainly as a result of differences in bark microrelief and bark water storage capacities with tree age [Levia *et al.*, 2010]. For a mixed oak/beech forest in Belgium, however, André *et al.* [2008b] found that stemflow rates were not significantly affected by tree size. Actual stemflow yield is, of course, a result of many interacting factors from both biotic (e.g., bark texture [Barbier *et al.*, 2009] and dynamic water storage capacity [Reid and Lewis, 2009]) and abiotic (e.g., wind speed) realms [Levia *et al.*, 2010]. Thus, stemflow can be negatively correlated with ecological diversity indices [Krämer and Hölscher, 2009] when the proportion of tree species with less favorable canopy structural characteristics for stemflow production outnumber those species with favorable canopy architectures.

It is worth noting that stemflow yields are not simply affected by bark microrelief but also the orientation of bark furrows. For example, a rough bark species with linear furrows can channel stemflow effectively, but rough bark with overlapping ridges or that is detached from the trunk can inhibit stemflow yield (see *Crockford and Richardson* [2000], *Levia and Herwitz* [2005], and *Schooling* [2014] for further discussion). Thus, bark microrelief is one factor affecting stemflow yield, while bark morphology with particular regard to the sizes, shapes, depths, and frequencies of furrows and ridges is also important for stemflow production. Appendix B details technology useful to quantify bark microrelief and canopy structure.

5.1.3. Role of Tree Morphology

For tall *Stewartia* (*Stewartia monadelphica*) in Japan, *Liang et al.* [2009a] found that meteorological factors were largely inconsequential in affecting stemflow production and that canopy structure was the key factor in accounting for differences in stemflow generation; specifically, the upward thrust branches and smooth bark of *Stewartia* were reported to account for high stemflow amounts (12% of rainfall). The downslope tilting of tree trunks was believed to lead to asymmetric stemflow drainage which accounted for disproportionately large stemflow amounts on the downslope side of the tree than the upslope side [*Liang et al.*, 2009a]. This finding agrees with that of *Gersper and Holowaychuk* [1971] who found that trunk lean also altered stemflow inputs to the soil, leading to larger organic C inputs but lower exchangeable Ca and Mg on the high stemflow input side of the tree. Leaf surfaces promoted water drainage to the inclined branches [*Liang et al.*, 2009a]. In subtropical forests of Okinawa, Japan, *Xu et al.* [2005] found that mean stemflow production values constituted 30.9% of incident rainfall. Besides wind-driven rain during typhoons, they attributed the extraordinarily high stemflow amounts to the inclined branches and concave leaf morphology of the dominant species, *Castanopsis sieboldii* [*Xu et al.*, 2005].

Llorens and Domingo [2007] provide a review of precipitation partitioning in Mediterranean environments. Average relative stemflow ($S_{\%P}$) from trees for precipitation ranging from 200 to 1600 mm was approximately 3% of incident rainfall in Mediterranean areas but was highly variable, with a coefficient of variation of 111% [*Llorens and Domingo*, 2007]. The largest stemflow input from trees was 12% of precipitation [i.e., *Domingo*, 1992; *Domingo et al.*, 1994; *Bellot and Escarré*, 1998] as reported in *Llorens and Domingo* [2007]. Stemflow production values from shrubs were larger (20–40%) in some cases and lower (4–7%), differing as a function of shrub canopy morphology [*Llorens and Domingo*, 2007]. The tiny amount of rain needed to produce stemflow in shrubs is a likely reason for large stemflow inputs by some species [*Llorens and Domingo*, 2007].

For Mediterranean shrub species, *Garcia-Estringana et al.* [2010] found that stemflow yield (mL plant^{-1}) correlated to biomass as well as fresh stem biomass, basal diameter, height, and canopy projection area, among others. Interestingly, there was no significant correlation between stemflow yield and branch inclination angle. Other factors such as branch rigidity, leaf insertion angle, and pubescence influenced stemflow amounts when expressed as a percentage of incident rainfall on the orthogonal projected area of the canopy [*Garcia-Estringana et al.*, 2010]. These findings underscore the different scales of canopy structure, ranging from microscale to stand scale. *Yang et al.* [2008] observed that stemflow volume was positively correlated with branch number, crown volume, and branch angle for shrub species in China. While our understanding of stand-scale canopy structure metrics on stemflow has increased greatly, further work at the microscale is necessary.

5.1.4. Effects of Tree Age and Forest Succession

In a field experiment conducted with ten isolated European beech saplings, *Levia et al.* [2015] found that the primary factors governing stemflow yield were the amount of woody biomass (expressed as a woody to foliar biomass ratio, using dry weights) and branch number per unit projected crown area and mean branch inclination angle. This study controlled for tree size to uncover the canopy structure metrics that actually govern stemflow amount. Saplings with straighter boles, less foliage per unit projected crown area, more branches and woody biomass per unit projected area, and slightly higher mean branch inclination angles (39.3° versus 30.2°) produced an average of almost twice the stemflow as saplings in the lower stemflow producing group [*Levia et al.*, 2015].

A drastic reduction of stemflow funneling ratios, from 81.3 to 30.0, was witnessed for Japanese cypress for 9 year compared to 12 year old trees [*Murakami*, 2009]. The difference was attributed to a change in canopy cover and closure [*Murakami*, 2009]. He speculated that the change in canopy cover could have led to lower stemflow yields due to less favorable branching inclination angles and higher bark water

storage capacities. He further hypothesized that the change in canopy structure was an adaptive mechanism to combat dry summers and enhance the probability of survival. Other research investigating tree-to-tree variability of stemflow, in this case for Japanese cedar (*Cryptomeria japonica* D. Don), found that trees with higher crown lengths (i.e., a larger numbers of branches) produced greater stemflow quantities than those trees with lower crown lengths [Iida et al., 2010]. Of course, such results have direct implications for stemflow yield with tree age as the length and angle of branches change with tree age. For Moso bamboo (*Phyllostachys pubescens* (Carriere) J. Houz.) in Japan, Shinohara et al. [2013] found that stemflow quantities were low from newly emerged bamboo plants, attributing the observed decrease in stemflow to the presence of wax on the plant stem.

In a succession experiment in Japan spanning 17 years, a monospecific stand of *Pinus densiflora* Sieb. et Zucc. (Japanese red pine) was transformed to a mixture of red pine, *Quercus myrsinaefolia* Blume (evergreen oak), and *Eurya japonica* Thunb. (evergreen theaceous tree) [Iida et al., 2005a]. The 75% reduction of red pine triggered a significant increase in stemflow which was attributed the more sharply inclined branches, smoother bark, and hydrophobic leaves of the evergreen oak and theaceous trees as compared to the red pine [Iida et al., 2005a]. The lower bark water storage capacity of the oak and theaceous trees was cited as a key reason for the decreased canopy water storage capacity and, presumably, increased stemflow amounts [Iida et al., 2005a]. In a reforested landscape of Southern Ontario, Buttle and Farnsworth [2012] found that stemflow decreased as a percentage of incident precipitation for older red pine stands as compared to younger red pine stands, although the difference was very slight (~1%).

Experimental thinning of Aleppo pine plantations in Spain was found to progressively increase throughfall and decrease stemflow amounts [Molina and del Campo, 2012], indicating that thicker stand densities promote stemflow but decrease throughfall in these plantations. For a *Hopea odorata* forest plantation in Malaysia, stemflow was correlated with tree height, diameter, crown area, and crown depth for one plot but not for the other, underscoring the complex relationship between canopy structure and stemflow yield [Siti Aisah et al., 2012]. In fact, a multiple-regression analysis revealed that the only canopy structure metric that was useful for predicting stemflow was crown depth [Siti Aisah et al., 2012]. As is the case for temperate forests [Price and Watters, 1989; Siegert and Levia, 2014], Manfroi et al. [2004] demonstrated the importance of the understory trees in producing stemflow in lowland tropical forests. They reported that trees with 1–5 cm DBH produced 57.5% of the total stemflow volume, whereas the corresponding percentages for trees 5–10 cm DBH were 22.4% [Manfroi et al., 2004]. Canopy trees > 10 cm DBH accounted for 20.1% of the total stemflow volume [Manfroi et al., 2004]. Macinnis-Ng et al. [2014] noted large differences in canopy storage capacity between primary (3.5 mm) and secondary (0.62 mm) forests in Panama which may partly account for the threefold difference in stemflow production between the two forest types (0.9% of rainfall for primary and 3.2% for secondary forests). Such results demonstrate the need to report stemflow results for fixed DBH classes for understory trees. It would be useful, as recommended by Germer et al. [2010], to calculate and relate the F_{PB} for several smaller DBH classes such as > 1 cm, > 5 cm, and > 10 cm to better frame the contribution of understory trees to total stemflow production at the stand level (i.e., both canopy and understory trees).

In a birch forest of northern Japan, K. Takahashi et al. [2011] found that stand level stemflow increased with tree diameter but decreased with stand leaf mass. This is consistent with past research [e.g., Levia and Frost, 2003]. Generally speaking, larger trees produce more stemflow than smaller trees but that is not the whole story. Bark morphology and microrelief, branch inclination angles, and canopy area can change as a function of age within and among tree species. For rain events in which the preferred flow channels along the branches and tree stems are saturated, larger trees will generate more stemflow than smaller trees, but for more moderate events the medium size trees, with canopy codominance, will produce greater quantities of stemflow than smaller more sheltered trees or larger trees with unsatisfied bark water storage capacities [Levia et al., 2010; Van Stan and Levia, 2010].

Along with changes in stemflow dynamics that are engendered by changes in species composition of forests through succession or reforestation, it is important to be cognizant of how changes in land cover type and land use, from forest to agriculture, alter stemflow production. Båse et al. [2012] found that soybeans planted in the Amazon Basin have stemflow yields that account for 9% of incident precipitation, whereas that of native forest was < 1%. Interception was substantially greater for soybean fields than for native

forests [Bäse *et al.*, 2012]. They argued that regional water balance models should examine the shift in precipitation partitioning which corresponds to land use and land cover change. Siles *et al.* [2010] found that stemflow fractions of incident rainfall (10.6% versus 7.2%) were larger for coffee cultivated in an agroforestry system than in monoculture, with corresponding respective funneling ratios of 68 and 48. They attributed this finding to the shading of overstory trees which resulted in coffee plants with larger stems and branches which, in turn, increased woody surface area and raised the potential for stemflow production. Further, the shaded coffee plants in the agroforestry system had a lower LAI which also appeared to foster greater stemflow yields. Less foliage was also shown to increase stemflow for European beech saplings [Levia *et al.*, 2015].

5.2. Stemflow Chemistry

Remarkably little work has been accomplished hitherto on the interrelationships between canopy structure and stemflow chemistry. Levia and Herwitz [2002] found that branch inclination angle did, in fact, have a detectable effect on stemflow leachate chemistry. Branches inclined at 20° above the horizontal had significantly higher base cation fluxes in branchflow than branches inclined at 5° or 38° [Levia and Herwitz, 2002]. It was concluded that the 20° branch achieved the optimal balance between drop capture and branchflow volume and a long enough residence time of the intercepted precipitation on the branch surface to increase leachate concentrations and fluxes. Levia and Herwitz [2005] also linked solute flux from canopy trees to bark microrelief and morphology. Even though the bark of northern red oak was not smooth, the linear configuration of its bark furrows and branching geometry promoted stemflow generation and higher solute fluxes than sweet birch or pignut hickory. In contrast, the rough bark surface of pignut hickory inhibited stemflow production with its forking bark ridges which led to significantly lower stemflow solute fluxes [Levia and Herwitz, 2005]. André *et al.* [2008a] found that the product of the tree trunk circumference and tree height explained a high proportion of the tree-to-tree variation in stemflow chemistry between sessile oak and European beech except for oak in the leafed period. Together, rain volume, length of the antecedent dry period, and tree size explained almost three-fourths of the variation in stemflow chemistry [André *et al.*, 2008a]. In tropical lowland forests of Costa Rica, Hoffmans *et al.* [2012] also found that species and tree specific characteristics, such as trunk diameter and tree height, as well as plant area index were significant factors governing stemflow chemistry.

While the prior section has demonstrated the notable effects of succession on stemflow hydrology, it is likely that invasion of forests, grasslands, or prior agricultural lands by other plant species (native or exotic) would also alter stemflow chemistry. In fact, Chiwa *et al.* [2010] reported that invasion of former agricultural land by Moso-bamboo (*Phyllostachys pubescens*) significantly altered the biogeochemical cycling of base cations, N and S, Cl⁻, and SiO₂. Prior work from plant ecologists indicates that forest fragmentation (and the consequent increase in perimeter to area ratios) will favor invasion by nonnative species [e.g., Yates *et al.*, 2004; Rojas *et al.*, 2011]. Tree species composition can also change from fire suppression programs. In eastern Kentucky, a species shift from oak dominated woodlands to red maple as a result of fire suppression efforts was also found to alter biogeochemical cycling [Alexander and Arthur, 2010]. Specifically, they reported that stemflow was 2–3 times larger for red maple than chestnut or scarlet oak and its corresponding solute fluxes accounted for much higher winter net nitrification rates (5–13 times) in soils underneath red maples [Alexander and Arthur, 2010].

5.3. Future Research

The imbalance of this section of the review in favor of canopy structure and stemflow yield reflects the scant level of knowledge as to how canopy structure affects stemflow chemistry. Three key areas where further work is most needed to better understand the interplay between canopy structure and stemflow chemistry are (1) dissolved organic matter (DOM) character in relation to PAI (plant area index, m² m⁻²), branch inclination angle, trunk lean, crown asymmetry, and woody surface area; (2) the chemical character of particulate matter (PM) in stemflow as a function of PAI, branch inclination angle, trunk lean, crown asymmetry, and woody surface area; and (3) the effects of plant surface characteristics (both foliar and woody) on stemflow chemistry. Moreover, fine-scale canopy architectural models, derived from lidar, according to the methods of Côté *et al.* [2012], may be coupled with stemflow chemistry measurements to better understand and harness the insights that could be gained from high-resolution lidar imagery.

Table 4. Concentrations of Iodine, Dissolved Labile Bromine, Beryllium, and Dissolved Organic Carbon in Rain, Throughfall, and Stemflow at the Plynlimon Experimental Catchment in Mid-Wales, United Kingdom^a

Concentration	Precipitation		Throughfall		Stemflow	
	Mean	Range	Mean	Range	Mean	Range
Iodine ($\mu\text{g L}^{-1}$)	1.55	0.4–10.5	5.46	1.2–33.3	8.16	1.4–42.0
Dissolved labile bromine ($\mu\text{g L}^{-1}$)	15.6	1–128	110.7	22–600	148.2	24–475
Beryllium ($\mu\text{g L}^{-1}$)	0.02	≤ 0.05 –0.24	0.01	≤ 0.05 –0.13	0.02	≤ 0.05 –0.17
Soluble reactive phosphorus ($\mu\text{M L}^{-1}$)	0.33	< 0.05 –19.26	0.73	< 0.05 –6.61	2.12	< 0.05 –18.61
Dissolved organic carbon (mg-C L^{-1})	0.69	0–4.2	11.40	0.9–214	19.15	1.6–128

^aConsolidated and adapted from Neal [2003] and Neal *et al.* [2003, 2005, 2007a, 2007b].

As mentioned above, Garcia-Estringana *et al.* [2010] found that leaf pubescence influences stemflow. What other features of the phyllosphere and cortisphere affect stemflow? Juniper and Jeffree [1983] published a classic text on plant surfaces which could help provide insights into the influence of plant surfaces on stemflow generation processes. With advances in microscopy, the time has come to better couple microscale (or even nanoscale) features to stemflow generation processes. This dovetails well with the intersection of particulates, microbes, and microrelief and morphology of the bark that are likely to affect stemflow chemistry as well as stemflow production. The biology of plant surfaces plays a critical role in the formation of droplets on foliar surfaces [Rosado and Holder, 2013] and the flow of water over branch surfaces [Herwitz, 1987], thereby affecting throughfall and stemflow generation.

We currently lack a sufficient understanding of the dynamics of pollutant transport along vegetative surfaces and their possible entry into the soil, and possibly groundwater, via stemflow. This will require a deeper knowledge of the fluid dynamics and chemical physics of stemflow revealing how solutes are leached and both solutes and particulates transported over the bark surface via stemflow. Such investigations should examine the presence of chromatographic effects that are likely to lead to the differential transport of particulates along branches and down the tree stem. Mathematical models should be utilized to approximate the transport of solutes and particulates over smooth and rough bark surfaces to determine which pollutants are likely to remain on vegetative surfaces and which may be mobilized and transported to the soil and the groundwater reservoir. Once a fundamental mechanistic understanding of pollutant transport along vegetative surfaces is attained, then further work can examine differences among tree species to better manage forests.

6. Stemflow: Dissolved Organic and Particulate Matter Dynamics

6.1. Dissolved Organic Matter Dynamics

Interspecific differences in the stemflow chemistry of inorganic nutrient ions have long been observed and reaffirmed in the literature [e.g., Mahendrappa, 1974; Herwitz, 1991; Fujinuma *et al.*, 2005; Levia *et al.*, 2011b; Hofhansl *et al.*, 2012]. As such, this section mostly focuses on dissolved organic matter chemistry of stemflow, except in a few instances where new findings have led to valuable research insights, as in the case of iodine, bromine, neutral sugars, or herbicides, for example.

Concentrations of solutes are not always higher in stemflow than throughfall and can vary depending on whether the mean or maximum concentrations are expressed. Mean iodine, dissolved labile bromine, soluble reactive phosphorus, and dissolved organic carbon (DOC) concentrations were higher in stemflow than throughfall or rainfall at the Plynlimon experimental site in mid-Wales, UK [Neal *et al.*, 2003, 2005, 2007a, 2007b] (Table 4). Whereas maximum iodine, soluble reactive phosphorus, and beryllium concentrations were higher in stemflow than throughfall, throughfall had higher maximum dissolved labile bromine and dissolved organic carbon concentrations than stemflow [Neal, 2003; Neal *et al.*, 2003, 2005, 2007a, 2007b] (Table 4). Iodine concentrations in stemflow were positively and linearly related with dissolved organic carbon concentrations [Neal *et al.*, 2007a]. Stemflow dissolved labile bromine concentrations were positively and linearly correlated with stemflow chloride concentration [Neal *et al.*, 2007b].

Atmospheric pollution exacts a terrible toll on some forested environments. Studies which lead to an enhanced knowledge of the cycling of pollutants can be useful to mitigate the deleterious effects of pollutant stressors on

wooded ecosystems. *Stidson et al.* [2004] examined trichloroacetic acid (CCl_3COOH) concentrations and fluxes in dry deposition, rainwater, throughfall, stemflow, and litterfall from Sitka spruce and larch in Scotland. They found stemflow concentrations of trichloroacetic acid concentrations, taken at 2-weekly sampling intervals, ranged from 0.23 to $2.8 \mu\text{g L}^{-1}$ and did not exhibit significant variations throughout the year. Trichloroacetic acid concentrations in stemflow did not differ significantly from throughfall [*Stidson et al.*, 2004]. Mean annual stemflow fluxes of trichloroacetic acid ranged from 90 to $110 \mu\text{g m}^{-2}$ among the Sitka spruce plots and were $60 \mu\text{g m}^{-2}$ for the larch plot [*Stidson et al.*, 2004]. They did not observe any significant differences in trichloroacetic acid fluxes between the forest edge and interior.

Additional research has sought to improve knowledge of the cycling of other pollutants, such as heavy metals and herbicides, by stemflow. Such work is important in determining whether stemflow mitigates or exacerbates pollutant cycling and loads in forested environments. In Spain, as one would expect, stemflow fluxes of heavy metals (Cu, Pb, Mn, V, Zn, Ni, and Cd) in two holm oak forests were significantly higher at an exposed site than a sheltered site [*Avila and Rodrigo*, 2004]. At the exposed site, stemflow fluxes of metals were highest for Mn and lowest for Ni and Cd [*Avila and Rodrigo*, 2004]. Experimental work involving the application and cycling of four herbicides (metolachlor, terbuthylazine, prosulfocarb, and isoproturon) in European beech forests of Germany has demonstrated that stemflow had higher pesticide concentrations than the rain water and was detectable over longer periods of time [*Bernhardt and Ruck*, 2004]. Metolachlor and terbuthylazine were found in stemflow for at least 14 days longer than in rainwater [*Bernhardt and Ruck*, 2004]. It should also be mentioned that stemflow can cycle radionuclides. Recent work by *Kato et al.* [2012] revealed that stemflow fluxes of ^{137}Cs were 120Bq m^{-2} beneath Japanese cypress and just 30Bq m^{-2} under Japanese cedar [*Kato et al.*, 2012]. Fluxes of ^{131}I were also much larger than ^{137}Cs under Japanese cypress (2430Bq m^{-2}) than Japanese cedar (530Bq m^{-2}) [*Kato et al.*, 2012]. Further work should examine the interaction of pollutants and radionuclides with bark surfaces and their transport and fate via stemflow. Some other work has sought to better understand stemflow in urban environments, as exemplified by *Livesley et al.* [2014] who examined the effects of canopy density and bark type on stemflow generated by eucalypt street trees.

Knowledge of the concentrations of micronutrients in stemflow, such as boron, and neutral sugars is key to better understand the ecophysiology of forest ecosystems. Volume-weighted mean boron concentrations in stemflow from virgin fir (*Abies firma*) trees in Japan was $2.04 \mu\text{M}$ with a range of 0.10– $12.2 \mu\text{M}$ [*Shigihara et al.*, 2008]. The mean volume-weighted stemflow boron concentration doubled those of throughfall ($0.87 \mu\text{M}$) and was more than double that of rainfall or fog water ($0.45 \mu\text{M}$) [*Shigihara et al.*, 2008]. All measured neutral sugars also had stemflow concentrations, listed parenthetically, that greatly exceeded those of throughfall, rainfall, or fog water, including L-rhamnose ($4.73 \mu\text{M}$), D-mannose ($6.66 \mu\text{M}$), and D-glucose ($6.60 \mu\text{M}$), [*Shigihara et al.*, 2008]. The sums of concentrations of neutral sugars were 1.50, 5.10, and $24.4 \mu\text{M}$ for rainfall, throughfall, and stemflow, respectively [*Shigihara et al.*, 2008]. Data on the removal of neutral sugars from trees via stemflow are important as they may affect the microbial biosynthesis of sugars in the soil or, possibly, on the bark surface by corticolous epiphytes and microbes. Sugar biosyntheses were affected by soil type and its inherent diversity of microbial communities [*Derrien et al.*, 2007].

Much work has been devoted to the study of DOC in forests over the last decade due to the importance of DOC to the biogeochemistry of forests [e.g., *Liu and Sheu*, 2003; *Cigliasch et al.*, 2004; *Levia et al.*, 2012]. It is well known that DOC, for instance, can affect the complexation and solubility of toxic elements, such as aluminum and mercury in forests [*Driscoll et al.*, 1988]. Stemflow DOC concentrations in jack pine, aspen, and spruce boreal forests ranged between 36.6 and 64.2mg L^{-1} [*Moore*, 2003]. The stemflow DOC concentrations collected under aspen were roughly half those collected under either coniferous forest type [*Moore*, 2003]. The stemflow DOC flux, however, was slightly larger under aspen (0.7g m^{-2}) than jack pine (0.6g m^{-2}) but over 3 times greater than under spruce (0.2g m^{-2}) due to the much higher stemflow volumes produced by aspen than either conifer [*Moore*, 2003]. Likewise, *Hamdan and Schmidt* [2012] also observed lower stemflow DOC concentrations under deciduous relative to coniferous forest cover in British Columbia. Stemflow DOC deposition to the forest floor was also higher under Douglas fir than bigleaf maple [*Hamdan and Schmidt*, 2012]. For Chinese fir plantations, secondary hardwood stands, and natural hardwood stands in central Taiwan, *Liu and Sheu* [2003] found that mean stemflow DOC concentrations and fluxes in the Chinese fir plantation (30.8mg L^{-1} and $132.4 \text{kg ha}^{-1} \text{yr}^{-1}$) were larger than either of the secondary hardwood stand (10.0mg L^{-1} and $15.3 \text{kg ha}^{-1} \text{yr}^{-1}$) or the natural hardwood stand (7.2mg L^{-1}

and $6.7 \text{ kg ha}^{-1} \text{ yr}^{-1}$). At the same study site, Wang *et al.* [2004] reported the carboxylic acid content (meq g^{-1}) of stemflow from a Chinese fir plantation as well as natural and secondary hardwood forests in Taiwan for two discrete precipitation events. They found that the values for humic polymers and fulvic acids ($\text{MW} > 1000$) from all three forest types ranged from 0.29 to 1.53 meq g^{-1} and 0.14 to 0.98 meq g^{-1} , respectively, with the values being higher for the hardwood forests compared to the Chinese fir plantations. Thus, the compounds cycled vary with tree species.

Mature forests in northwestern Amazonia (located on a floodplain, low terrace, high terrace, and sedimentary plains) exhibited wide variability in stemflow DOC concentrations, ranging from 775–1317 $\mu\text{mol L}^{-1}$ [Tobón *et al.*, 2004]. Variation in DOC stemflow concentrations was attributed to storm duration, storm intensity, and the length of the antecedent dry period [Tobón *et al.*, 2004]. They found that the solute concentrations of stemflow increased with increasing length of the antecedent dry period and during periods of feeding by canopy frugivores [Tobón *et al.*, 2004]. The mean ratio of DOC concentration in stemflow to rainfall ranged from 2.5 to 4.7 indicating that the canopy is a source of DOC [Tobón *et al.*, 2004]. Among the four forest types, DOC fluxes ranged from 2.82 to $6.14 \text{ kg ha}^{-1} \text{ yr}^{-1}$ [Tobón *et al.*, 2004]. DOC fluxes were larger for the floodplain and low terrace forests compared to forests occupying the high terrace or sedimentary plain [Tobón *et al.*, 2004]. Similarly, DOC concentrations in stemflow from red mangrove forest control plots of Belize (i.e., unfertilized) were substantially greater than those in the incident rainfall for both fringe and dwarf zones of the mangroves [Wanek *et al.*, 2007]. Thus, DOC dynamics differ considerably for both tree species and forest type.

There is also a seasonal dimension to DOC cycling in forests. Comparing the dissolved organic matter dynamics between native Cerrado and *Pinus caribaea* plantations in savannas of Brazil, Ciglasch *et al.* [2004] found that stemflow DOC concentrations were much greater than those in throughfall, ranging between 13 and 53 mg L^{-1} . A substantial proportion of DOC was believed to be leached from the tree trunk, with an increase in tree height corresponding to an increase in DOC leaching [Ciglasch *et al.*, 2004]. This may partly explain the larger DOC leachate quantities in the *P. caribaea* plantation as compared to the Cerrado vegetation. Roughly three-fourths of DOC constituting the hydrophilic fraction was observed at the start of the rainy season in the *P. caribaea* plantation, as compared to latter stages of the rainy season when most of the DOC was composed of the hydrophobic fraction [Ciglasch *et al.*, 2004]. This makes sense given the fact that stemflow has a high proportion of hydrophobic compounds [Qualls and Haines, 1991; Ciglasch *et al.*, 2004], likely stemming from the fact that wood leaches soluble lignin degradation byproducts with large proportions of hydrophobic compounds [Guggenberger *et al.*, 1994; Ciglasch *et al.*, 2004]. For clonal eucalypts in the Congo, Laclau *et al.* [2003a] also found differential DOC dynamics between wet and dry seasons with DOC concentrations in stemflow being somewhat higher during the rainy (5.0 mg L^{-1}) than the dry season (4.7 mg L^{-1}). Stemflow was even reported to account for high variability in soil solution chemistry for these clonal eucalypts in Congo [Laclau *et al.*, 2003b].

Levia *et al.* [2012] investigated DOC and DOM dynamics at the intrastorm, seasonal, and annual time scales in American beech and yellow poplar forests of the eastern United States. Whereas there was an exponential decay in stemflow DOC concentrations within particular events for American beech, stemflow DOC concentrations remained relatively constant for yellow poplar [Levia *et al.*, 2012]. SUVA_{254} , which denotes UV absorbance at 254 nm, can be useful for indicating the aromaticity of DOM. SUVA_{254} values were observed to increase in stemflow from both American beech and yellow poplar as a storm event progressed [Levia *et al.*, 2012]. Conversely, the $\text{E}_2:\text{E}_3$ ratios, comparing UV absorbance at 250 nm and 365 nm, generally decreased as a storm progressed, suggesting that different compounds are being transported by stemflow to the forest floor at different times [Levia *et al.*, 2012]. As expected, DOC fluxes via stemflow were much higher for American beech than yellow poplar, owing to the voluminous stemflow production of beech [Levia *et al.*, 2012]. Yellow poplar had higher SUVA_{254} and $\text{E}_2:\text{E}_3$ ratios than American beech during leafed and leafless periods as well as on an annual scale, likely the result of interspecific differences in bark morphology and overall canopy structure [Levia *et al.*, 2012].

6.2. Stemflow Particulate Matter Dynamics

Some work has sought to calculate dry deposition of particulates and canopy exchange rates to better model canopy and watershed budgets [e.g., Likens *et al.*, 2002; Staelens *et al.*, 2008b; Talkner *et al.*, 2010;

Hansen *et al.*, 2013]. In many cases, throughfall and stemflow were lumped together to account for a net throughfall (and stemflow) flux [e.g., Likens *et al.*, 2002; Staelens *et al.*, 2008b; Chiwa *et al.*, 2010]. These studies have provided useful insights into the varying importance of dry deposition and canopy exchange (as a proxy for ion leaching or uptake) processes. The emphasis of these studies, however, has been the atmospheric deposition of ions and the calculation of dry deposition and canopy exchange via modeling. Other studies have separated throughfall and stemflow inputs [e.g., Staelens *et al.*, 2007], or just focused on stemflow [Levia *et al.*, 2011b], and reported specific values for stemflow ionic fluxes for leaching and dry deposition components. There has not been an emphasis on the cycling of PM via stemflow *per se*. This is to say that the direct collection and quantification of PM and its transport via stemflow remains poorly understood. It should be noted, however, that PM has been quantified in throughfall as a result of insect infestations (as reviewed by Michalzik [2011]).

Research on PM dynamics in stemflow is critically important to achieve a better understanding of the bidirectionality of biosphere-atmosphere interactions and the transport and fate of atmospheric deposition on elemental cycling in forests. Research in Slovakia has documented that stemflow concentrates particulates derived from atmospheric pollution to hot spots around tree stems [Klučiarová *et al.*, 2008]. Stemflow also has been reported to effectively transport *Vitis* pollen on grapevines in English vineyards [Turner and Brown, 2004]. Moreover, because PM can trigger the formation of secondary aerosols [Cape, 2008] and possibly decrease cuticular photosynthesis [Pfan and Aschan, 2001], there is a real need to understand the interactions between PM and stemflow. Levia *et al.* [2013] quantified the particulate matter diameter distributions for stemflow in European beech forest in Germany under both leafed and leafless conditions. Based on a total sample size of 10,035 individual particulates in stemflow, the mean diameter (± 1 standard deviation) of stemflow particulates in the leafed and leafless periods were $4.4 \pm 5.4 \mu\text{m}$ and $3.5 \pm 3.5 \mu\text{m}$, respectively [Levia *et al.*, 2013]. The diameter distributions of particulates in stemflow were significantly skewed to the right, with greater skew in the leafless period than the leafed period (skewness values of 18.1 and 10.7, respectively) [Levia *et al.*, 2013], thereby indicating the importance of canopy phenology for the cycling of particulates in forests.

6.3. Future Work for Stemflow Dissolved Organic and Particulate Matter Dynamics

While a number of studies, as cited above, examine the dissolved organic carbon dynamics and flux of stemflow within a variety of forest types, future work is necessary to better understand the chemical character of DOM in stemflow. Fluorescence spectroscopy, as described by Cory *et al.* [2011], would be a useful tool to uncover the chemical character of DOM and POM in stemflow. Stemflow EEMs (excitation-emission matrices) for different tree species among precipitation events of different synoptic classification as well as intrastorm EEMs would undoubtedly shed light on the effects of tree species and overarching climate forcings on stemflow chemistry. It would also be of interest and importance to examine the variation of tree location with respect to edge versus interior on DOM character. Prior work has shown that edge effects can have a differential impact on throughfall chemistry [e.g., Devlaeminck *et al.*, 2005], but does this hold true for stemflow and what impact might it have on DOM character of stemflow? A recent study on the acid neutralization capacity of stemflow of yellow poplar in a fairly rural site in the eastern United States has shown that edge trees have a statistically significant higher acid neutralization capacity than yellow poplar trees in the forest interior [Shiklomanov and Levia, 2014]. The authors contend that the observed buffering capacity is location specific and that the effective scavenging and interception of atmospheric particulates could very well lead to a lower acid neutralization capacity of edge trees in urban areas. Thus, the increased aerosol capture by edge trees may enhance or diminish acid neutralization capacity depending on the site location and the land uses of surrounding areas. To what extent does the increased capture of dry deposition of edge trees affect the dissolved organic carbon concentration and DOM character of stemflow as opposed to that for trees in the interior? Answers to such questions could lead to better management of forest fragments in urban areas, allowing forest managers to enhance ecosystem services of forest fragments in urban areas.

Besides the empirical work of Neal and colleagues examining the stemflow chemistry of iodine, bromine, beryllium, among other solutes, as summarized here, further work needs to compare and contrast work at the Plynlimon experimental catchment with other forest types in other areas. Boron would also be of great interest for further study given the findings of Shigihara *et al.* [2008] as reviewed in the prior section.

Researchers are encouraged to better our understanding of boron by examining its cycling in other forest types. The pioneering work of *Shighihara et al.* [2008] on neutral sugars is important to better understand the nutrition and carbon cycling of forest and plantations. A large data gap exists on stemflow chemistry of neutral sugars and the factors that govern its transport and cycling. To what extent do insect outbreaks or other stressors exert on stemflow cycling on neutral sugars? *Michalzik* [2011] summarizes the effects of insect stressors on biogeochemical cycling, especially via throughfall, but how is stemflow chemistry altered by insect infestations? The answers to such questions will allow researchers to better highlight possible effects of climate change-induced or man-made forest conversion on forest biogeochemistry.

While our understanding of intrastorm dynamics of stemflow water and solute inputs has increased in the past decade, the intrastorm transport of particulate matter is unknown. Particulate matter in stemflow exhibits a large range in diameter [*Levia et al.*, 2013]. Might the particulates with larger diameters have a higher residence time in the canopy? What might this mean for the chemistry of stemflow within events? How could an improved understanding of intrastorm particulate matter dynamics inform hot spot and hot moment theories of biogeochemistry?

The event scale has been the traditional temporal scale of analysis for many stemflow studies. Here again, particulate matter dynamics at the event scale are completely unknown. Particulate matter is critically important for elemental budgeting. Studies which examine stemflow and particulate matter at the event scale could help close the existing data gap on the amount and chemical character of particulate matter being transported to the forest floor via stemflow. To what extent do wind speed and direction affect particulate transport and chemistry in stemflow? Answers to such questions would greatly enhance our knowledge of forests and biogeochemistry by improving the land surface parameterizations which represent the hydrology and biogeochemistry components of climate models that examine the effects of climate change on terrestrial ecosystems.

It would be useful to characterize the DOM in stemflow in relation to canopy structure using spectral methods and help inform theories of hot spots and hot moments [after *McClain et al.*, 2003] in forests. Such work could build on initial efforts of *Levia et al.* [2012]. Exceedingly little work has examined the nature and dynamics of PM in stemflow. The diameter distributions of PM in stemflow from European beech have been quantified in leafed and leafless periods in east central Germany [*Levia et al.*, 2013], demonstrating the detectable effects of canopy state (and structure) on PM transport. However, little else is known. One could formulate a number of potentially important questions regarding the dynamic interactions between bark structure and stemflow chemistry. For example, what is the interplay between bark surface chemistry and PM movement down the tree stem? Does the presence of bark furrows and capillary action affect the transport of pollutants differentially? Does differential surface tension, as a function of bark microrelief, lead to a fractionation of organic molecules? Is there preferential elution of pollutants, or other chemical species, from tree bark? How might this change with tree age and change in bark structure? NMR spectroscopy may prove useful to examine the chemical character of PM in stemflow [*Bischoff et al.*, 2014]. The variety of plant surfaces is as vast as the number of tree species. In a study examining PM deposited on plant leaves and the epicuticular wax of the leaves themselves in Polish cities, it was discovered that the size of PM was generally larger on leaves than in the epicuticular wax [*Dzierzanowski et al.*, 2011]. Do bark surfaces accumulate a greater or lesser number of larger PM size classes than leaves? What effect might this exert on stemflow chemistry? Additional research isolating the effects of the cortisphere on stemflow chemistry is clearly warranted, especially in relation to the pH of incident precipitation and in the presence/absence of epiphytes which alter canopy structure.

7. Stemflow-Life Interactions

7.1. Stemflow Yield and Chemistry in Relation to Epiphytes

7.1.1. Epiphytes and Stemflow Yield

Some of the earlier work on the effects of epiphytes on the hydrology (and biogeochemistry) of forests is summarized in *Pypker et al.* [2011]. Over the past decade, in various types of forested ecosystems, it has been (re)affirmed that epiphytes tend to decrease stemflow yields [e.g., *Fleischbein et al.*, 2005; *Pypker et al.*, 2006; *Ponette-González et al.*, 2010]. In the Pacific Northwest, for example, *Pypker et al.* [2006] observed that the surface roughness of epiphytic lichens and bryophytes covering the branches of old-growth

Douglas fir significantly increases canopy water storage capacity by obstructing branchflow, decreasing the probability of rain splash loss and lengthening the time needed for the canopy to undergo a full wetting/drying cycle. As such, the presence of epiphytic lichens and bryophytes has a detectable and significant influence on canopy interception and stemflow generation processes. Similarly, the proportion of intercepted water constituting stemflow decreased with increasing coverage by vascular epiphytes for tropical montane forests in Ecuador [Fleischbein *et al.*, 2005] and Mexico [Ponette-González *et al.*, 2010]. Increases in nonvascular epiphyte coverage also led to decreased stemflow amounts in forests of Costa Rica [Hölscher *et al.*, 2003]. While the presence of epiphytes can reduce stemflow yield, higher stemflow production of smaller cacao trees (as compared to larger cacao trees) was assumed to be a driving force for the different bryophyte assemblages found on different sized cacao trees [Ariyanti *et al.*, 2008].

7.1.2. Epiphytes and Stemflow Chemistry

The diversity and physiological ecology of epiphytes is beyond the scope of this review. Interested readers are referred to several treatises on the ecology of epiphytes [e.g., Barkman, 1958] and lichens [Kershaw, 1985; Nash, 1995]. The stemflow chemistry hypothesis, developed by Hauck and Runge [1999] and then elaborated upon in Hauck [2003], posits that epiphytic lichen abundance is greater on dieback-affected trees due to needle loss and decreased interception of some atmospherically derived elements, such as S, H, and K, which lead to less enriched stemflow as compared to live trees with greater interception losses and higher stemflow solute concentrations. This hypothesis is significant because it crystallizes the relationship between stemflow and lichen diversity. Subsequent research focused on specific elements, such as Mn, which are leached in larger quantities via stemflow and appeared to exert a detectable effect on lichens [e.g., Levia and Herwitz, 2000; Hauck and Paul, 2005; Hauck *et al.*, 2006].

Hauck and Paul [2005] witnessed decreasing epiphytic lichen abundance with increased exposure to Mn from the tree bark and/or stemflow for sites across Europe as well as both western and eastern North America. Further research noted that some epiphytic cyanolichens species (*Lobaria pulmonaria*, *Nephroina helveticum*, and *Leptogium saturnium*) are highly sensitive to intermittent stemflow inputs of Mn, which affect their physiology [Hauck *et al.*, 2006]. The diversity of epiphytic lichens was found to be greater on lime (*Tilia platyphyllos*) than holm oak (*Quercus ilex*) in Central Italy [Loppi and Frati, 2004]. This may partly be due to the higher concentrations of Mn in the bark and stemflow of holm oak [Loppi and Frati, 2004], which have been observed to decrease lichen diversity for other species [Hauck and Paul, 2005; Hauck *et al.*, 2006], as well as lower winter light levels in the evergreen holm oak [Loppi and Frati, 2004]. A review of the chemical factors which partially govern epiphytic lichen diversity, including stemflow leachates, is given in Hauck [2003].

LaGreca and Stutzman [2006] found that the occurrence of the invasive lichen *Lecanora conizaeoides* in eastern Massachusetts corresponds with both acidophilic and photophilic environments on the boles and branches of host trees. Since *L. conizaeoides* was most abundant on the upper portions of dead white cedar trees which produce little to no stemflow, it seems as if stemflow is not a major factor in the lichen colonization of dead white cedar trees. Nevertheless, it is very likely that stemflow plays a major role in the colonization of bark surfaces by acidophilic lichen species in Europe where deposition loads of N and S are substantially larger [Hauck *et al.*, 2002]. The relationship between stemflow nitrate concentrations and lichen diversity on trees is less well understood [Hauck, 2003], while stemflow does not appear to be a primary source of K for *Hypogymnia physodes* [Hauck and Gross, 2003]. Mitchell *et al.* [2005] investigated the effects of nitrogen pollution on epiphytic lichen and bryophytes for six sites in Scotland and another in the Lake District. Stemflow chemistry and bark pH were determined to be related to species through a redundancy analysis, differing for low N deposition sites in coastal and inland locations as well as for high N deposition sites [Mitchell *et al.*, 2005]. Further, redundancy analysis revealed that bark pH and NH_4^+ concentration of stemflow drainage accounted for the widest diversity of epiphytic species among study locations [Mitchell *et al.*, 2005]. Leith *et al.* [2008] found that stemflow elevates the N concentration in the tissue of epiphytic bryophytes. These bryophytes use nitrogen in stemflow for their metabolic needs, with a preferential sequestration of ammonium by the canopy as compared to nitrate [Leith *et al.*, 2008].

Stemflow pH showed strong positive correlation with bark thickness and a negative correlation with bark smoothness [Fritz *et al.*, 2009]. Thus, smooth and thinned bark species, like European beech, have low stemflow pH values [Falkengren-Grerup, 1989]. This is likely partly due to the fact that thinner bark has a

lower water holding capacity, lower residence time of stemflow on the surface, and lower cation exchange capacities in comparison to rougher bark. Epiphytic lichen and bryophyte species diversity exhibited the closest association with outer bark pH, tree vitality, and stemflow pH [Fritz *et al.*, 2009].

Hölscher *et al.* [2003] found that old-growth, early-successional, and midsuccessional forests exhibited large variation in nutrient transport via stemflow, with K fluxes measuring 5% of total flux in old-growth forests, 17% in early successional forest, and 26% in midsuccessional forests, respectively. These noteworthy differences were attributed to variation in canopy structure and epiphyte abundance [Hölscher *et al.*, 2003]. Specifically, nonvascular epiphyte layers were most developed in old-growth forests, whereas leaf areas were largest in midsuccessional forests and the leaves were the most nutrient laden in the early successional forests [Hölscher *et al.*, 2003]; nonetheless, the total stemflow nutrient inputs were not significantly different among the three forest types. This led Hölscher *et al.* [2003] to believe that epiphytes likely exerted a small effect on nutrient inputs via stemflow in these forests of Costa Rica.

7.1.3. Fungi

While investigations into interrelationships among the canopy, fungi, and stemflow or throughfall are not new [e.g., Bandoni, 1981; Mackinnon, 1982], a rich corpus of work has developed over the last decade. Earlier work by Mackinnon [1982] found conidia of many hyphomycete species in stemflow, encompassing six genera as well as some which were unknown. Gönczöl and Révay [2004] discovered that almost all stemflow samples from 13 different trees of several species in Hungary contained conidia of fungi. The conidia of *Trinacrium* spp. were especially common in the stemflow samples collected [Gönczöl and Révay, 2004]. During intense rain events, stemflow even contained conidiomata with developing conidia [Gönczöl and Révay, 2004]. Stemflow was observed to transport massive numbers of fungal spores to the soil, with hundreds to thousands of conidia being found in just several milliliters of stemflow water in some cases [Gönczöl and Révay, 2004]. Sridhar *et al.* [2006] reported that stemflow is a mechanism to spread asexual fungal conidia and propagules and thereby subscribes to the “aqueous film” theory espoused by Bandoni and Koske [1974], which posits that fungal spores may be transported along water films of wetted vegetative surfaces. This agrees with experimental work of Magyar and Révay [2009] who also concluded that stemflow was a mechanism for transport of fungal spores, especially from March to July. Fungal spores have even been observed in bark furrows during dry periods [Magyar, 2008]. It is possible that water held by capillary action and surface tension in the bark furrows is utilized by the fungi and that this temporary storage site for fungal spores could accentuate stemflow inputs of spores when it does rain. Moreover, Karamchand and Sridhar [2008] stated that canopy fungi are able to satisfy nutritional needs via stemflow and throughfall.

Of the 14 different tree species studied, Sridhar and Karamchand [2009] found that fungal species diversity was greatest in stemflow from *Ficus benghalensis* (28 species), whereas the conidial output in stemflow was highest from *Tectona grandis* (526 per 10 mL). The least number of fungal species (seven species) was found in stemflow of a couple co-occurring tree species (*Careya arborea* and *Odina wodier*) [Sridhar and Karamchand, 2009]. *Mangifera indica* was observed to have the lowest conidial input via stemflow (48 per 10 mL) [Sridhar and Karamchand, 2009]. The lowest species diversity of fungi in stemflow, according to the Simpson and Shannon diversity indices, were observed for *Eucalyptus tereticornis* [Sridhar and Karamchand, 2009]. Working on coniferous and deciduous trees in Hungary, Révay and Gönczöl [2011] found that the variety of both fungal species and their conidia was higher from twig surfaces of conifers than deciduous trees; they ascribed this difference to the rougher bark structure of the conifers as compared to the deciduous trees. It is also possible that this finding is partly the result of lower stemflow volumes produced by coniferous tree species which would lead to less mechanical disturbance effects as well as lower exposure to toxic solutes in stemflow. On the other hand, nutrients available to canopy fungi would lead one to expect great diversity with higher stemflow production [Karamchand and Sridhar, 2008]. It is currently unclear which interpretation (or both) may be correct for given forest types or tree species. The fact that Sridhar and Karamchand [2009] found the conidia of aquatic hyphomycetes from streams in water draining from the canopy supports earlier work by Ando and Tubaki [1984] and others. This finding may be partially explained by the monsoonal conditions of India where the canopies are wet for long durations [Révay and Gönczöl, 2011]. Examples of aquatic hyphomycetes found in stemflow and throughfall were *Anguillospora crassa* and *A. longissima* [Sridhar and Karamchand, 2009].

Working across four nations (Germany, Hungary, Romania, and Sweden) over a 2 year period, *Gönczöl and Révay* [2006] found conidia (both stauroconidia and scolecoconidia) of 62 hyphomycetes species in stemflow and throughfall from samples harvested from 25 different trees. Stauroconidia were observed to occur with a substantially greater frequency than scolecoconidia [*Gönczöl and Révay*, 2006]. Summer stemflow from the genus *Fagus* contained the greatest diversity of fungal species [*Gönczöl and Révay*, 2006]. This would be expected since fungal species should be more abundant during the summer months under more favorable temperature conditions. In addition, a variety of unknown or undetermined conidia was also observed in stemflow and throughfall [*Gönczöl and Révay*, 2006]. *Gönczöl and Révay* [2006] contend that evidence is mounting for the vast biogeographic distribution of a group of “arboreal aquatic hyphomycetes” [after *Carroll*, 1981], which dwells in the forest canopy of many different tree species.

7.1.4. Bacteria

Several decades ago, *Tarrant et al.* [1968] speculated that the significantly greater stemflow nitrate concentrations from coniferous trees in monospecific or mixed forests relative to other tree species, and larger stemflow ammonium concentrations from alder compared to other forest types, in Oregon might be attributable to differences in the number (and diversity) of nitrifying and ammonifying bacteria inhabiting the foliar and bark surfaces. Remarkably little research has been conducted in the intervening years to shed light on this speculation. *Ceccherini et al.* [2008] acknowledged that the interplay between stemflow and microbial communities in the soil is inadequately understood. The ammonia-oxidizing bacteria inhabiting the bark of 60 year old Corsican pine (*Pinus nigra* Arn. ssp *laricio*) in Central Italy were similar to those dwelling in the soil in the proximal area of the tree trunk receiving stemflow input but different from soil microbes inhabiting soil with a higher pH 150 cm from the tree bole [*Ceccherini et al.*, 2008]. Two hypotheses were suggested to account for the similarity of ammonia-oxidizing bacteria on the bark of the pine trees and the soils adjacent to the tree trunk: (1) stemflow transported the bacteria to the subsurface which then inhabited the soils in the proximal area of the tree trunk and (2) the bacteria inhabiting the wetted bark areas of high acidity also dwell in the highly acidic soils at the tree base [*Ceccherini et al.*, 2008]. Despite an early study based on a single alder tree suggesting that stemflow probably did not appear to have a detectable effect on soil microbial composition near the tree trunk (except for molds and *Streptomyces* bacteria) [*Bollen et al.*, 1968], it will be difficult to examine whether one or both of *Tarrant et al.*'s [1968] hypotheses are correct until a better understanding of the physicochemical dynamics of stemflow is achieved. Such an improved understanding would necessitate the ability to model and predict the Brownian noise and fluid dynamics of stemflow (laminar and turbulent flow) on bark surfaces of tree species with varying microrelief and spatial orientation and configuration of the bark morphology.

7.2. Water-Filled Treehole Ecosystems

In contrast to the paucity of work examining stemflow-bacteria interactions, a number of prior studies have examined the effects of stemflow on treehole communities, usually from a treehole ecosystem perspective involving mosquitoes. Previous research has sought to better understand the role of stemflow on treehole mosquitoes by examining stemflow's effect on larval development, population dynamics, and bacterial abundance [e.g., *Carpenter*, 1982; *Walker et al.*, 1991]. The following two studies represent the incremental advance in knowledge which seeks to disentangle the complexities of the interplay between stemflow and treehole mosquitoes.

Verdonschot et al. [2008] found that stemflow nutrient inputs to treehole ecosystems spawned increased bacterial production 1 day after rainfall, thereby suggesting that during the “connected phase,” when stemflow was produced on the crown and bole of American beech, stemflow created favorable conditions for the proliferation of microbes. The effect of stemflow on DOC concentrations of treehole water was unclear, sometimes leading to increases and other times decreases [*Verdonschot et al.*, 2008]. The mixed results were ascribed to differences in meteorological conditions and the unevenness of stemflow inputs on the tree boles [*Verdonschot et al.*, 2008]. Meteorological conditions can account for large disparities in stemflow production, even from the same tree [*Levia and Frost*, 2003] which is related, in part, to the dilution of treehole water reservoirs. To better understand the role of stemflow on mosquitoes dwelling in treeholes, *Kaufman and Walker* [2006] designed a laboratory experiment to parse the effects of (1) stemflow dilution via flushing of metabolites as stemflow mixes with treehole water and (2) stemflow

nutrient additions on mosquito production. They concluded that it appears as if the main effect of stemflow was to enhance nutrient additions to *Ochlerotatus triseriatus* Say. (eastern treehole mosquito) larvae, rather than dilution of toxic compounds [Kaufman and Walker, 2006].

7.3. Some Future Stemflow-Life Interaction Research Opportunities

Several important areas where sufficient knowledge is lacking and which future research should address include the following: (1) microbial (fungal and bacterial) species composition in stemflow across ecoregions; (2) the individual, collective, additive, and synergistic effects of microbes on stemflow chemistry; (3) variations in microbial compositions in relation to phenophase; and (4) the linkages between bark microrelief and microbial community composition, especially in relation to elemental cycling. The studies cited above indicate that there is a wide array of fungal species that dwell in the forest canopy and are detectable in stemflow drainage. It is likely that different combinations of microbial communities will exert differential effects on biogeochemical cycling via stemflow. Without prior knowledge of the microbial composition of these species across ecoregions with different wooded ecosystems, it will not be possible to understand if microbes exert additive or synergistic influences on stemflow chemistry. Does microbial species composition change on bark surfaces as a function of phenophase? If so, to what extent does it affect the leachate chemistry from bark tissue for snow-covered and snow-free canopies? These questions, among many others, will greatly advance knowledge of forest biogeochemistry and the role that stemflow plays within the larger context.

Bark provides a diverse substrate for a variety of microorganisms, epiphytic lichens and bryophytes, and roots (adventitious and apogeotropic). Life in the "cortisphere" is dynamic and complex [Pfanzen and Aschan, 2001], and hydrologists and biogeochemists are just beginning to scratch the surface on the interactions between stemflow and the organisms that dwell within and on corticular surfaces. Yarranton [1967] reported different lichen species inhabiting the "humps" and "hollows" of the bark surfaces. What is the effect on stemflow chemistry of these epiphytic corticolous lichens, fungi, and bacteria that differentially dwell within and on the bark surface? How does the fluid dynamics of stemflow on trees with varied bark microrelief affect the microbial species composition, and, in turn, how does that influence the solute and particulate flux in stemflow? The authors encourage interdisciplinary research among the hydrological, biogeochemical, and microbial ecological communities to answer some of these compelling questions and elucidate our understanding of the cortisphere on forest hydrology and biogeochemistry.

8. Stemflow-Soil Interactions

Since Levia and Frost's [2003] review on stemflow, in general, and Johnson and Lehmann's [2006] review focusing on stemflow and root-induced preferential flow in particular, great advances in understanding how soil hydrology is impacted by stemflow have been achieved. To summarize the numerous new articles, achievements are reported separately for processes on the soil surface, water movement through the soil and groundwater recharge, interaction with streamflow, and their impact on soil and water chemistry.

8.1. Overland Flow Generation and Erosion

Herwitz [1986] concluded that stemflow in a tropical rainforest resulted in significant infiltration-excess overland flow by comparing stemflow rates with soil infiltration capacity. Recently, Cattani et al. [2007] found through a modeling study that stemflow from fully developed banana plants combined with the soil management practice of furrowing increased overland flow volume threefold compared to bare soil, when the infiltrability was lower than 100 mm h^{-1} . At the same experimental station but another plantation, Charlier et al. [2009] found better model performance for runoff from a 3000 m^2 banana plot when stemflow was added into the hydrologic model. This was particularly true for low flow. In a Japanese cypress plantation forest, Miyata et al. [2009] speculated that higher runoff coefficients were attributable to the spatial concentration of stemflow around the tree base and throughfall drip points, although they did not specifically study the relationship between stemflow and runoff. Iida et al. [2005b] observed and published a photograph of infiltration-excess water ponding on the soil surface around a Formosa sweet gum (*Liquidambar formosana* Hance) tree during a rainfall event with a maximum intensity of 6.5 mm h^{-1} . But the timing, extent, and depth of stemflow-induced overland flow and their relations to rainfall characteristics are still needed. Although Abrahams et al. [2003] found that overland flow was generated in

a desert shrubland under creosotebush, for which 6.7% of the rainfall per canopy area reaches the ground as stemflow, the degree to which rainfall, throughfall, and stemflow were the driving forces of overland flow was not assessed. In addition, the authors are unaware of any study that tackles the question as to whether the hydrophobicity of the organic layer on the soil surface influences the generation of overland flow by stemflow.

Stemflow-induced soil erosion was inferred from soil erosion and litter marks next to trunks for different biomes: tropical rainforest (Australia) and an oil palm plantation (Malaysia), temperate broadleaf forest (Japan), and dry savanna (Republic of Niger) [Herwitz, 1986; Tanaka *et al.*, 1996, 2004; Iida *et al.*, 2005b; Chinen, 2007; Rashid *et al.*, 2015]. Recently, it had been communicated that erosion is a serious problem in Macadamia orchards of southeast Australia [Keen *et al.*, 2010]. The authors calculated erosion from soil surface maps generated at monthly intervals over 16 months by laser scanning the distances from a fixed platform to the soil surface. For the study period, 6.5 mm m⁻² of soil was eroded per year. Stemflow from the Macadamia trees averaged 7% per rainfall over the canopy area. The serious nature of the soil erosion problem even prompted the government of New South Wales, Australia, to publish a video explaining that Macadamia varieties with different canopy structures that produce substantially less stemflow should be planted in order to reduce erosion [NSW Department of Primary Industries, 2011]. In contrast, for corn and sorghum, Bui and Box [1992] found that erosion resulting from stemflow was negligible compared to that from throughfall.

8.2. Spatial Pattern of Soil Moisture, Preferential Flow, and Subsurface Flow

Once stemflow infiltrates into the soil, water percolation can be dominated by matrix flow or preferential flow along macropores for small and large stemflow rates, respectively. Large stemflow fluxes can lead to soil saturation of both the topsoil [Germer, 2013] and the soil-bedrock interface [Liang *et al.*, 2007; Taucer *et al.*, 2008; Liang *et al.*, 2011].

Preferential flow through macropores has been reported decades ago [Crabtree and Trudgill, 1985]. The combination of stemflow and root-induced preferential flow was described as “double-funneling of trees” by Johnson and Lehmann [2006]. For desert shrubs, experiments with dye tracer sprinkled on the soil surface next to trunks showed that preferential flow was taking place next to roots [Martinez-Meza and Whitford, 1996; Li *et al.*, 2009; Jian *et al.*, 2014]. Recently, it was reported that the same is true for tall *Stewartia monadelphica* [Liang *et al.*, 2011] and beech trees in temperate regions [Schwärzel *et al.*, 2012]. For young babassu palms (*Attalea speciosa* Mart.), however, rainfall was funneled via its fronds directly to its subterranean stems at 25–50 cm soil depth [Germer, 2013]. By using two dye tracers of different colors, Liang *et al.* [2011] were able to distinguish between preferential flow that was due to throughfall or stemflow. The degree of preferential flow pattern heterogeneity was higher for small rainfall events, while larger rainfall led to more uniform flow in upper soil layers [Li *et al.*, 2009]. The depth of the wetting front increased logarithmically, however, with rainfall amount [Li *et al.*, 2008]. Below different desert shrubs, the wetting front was substantially deeper at the shrub base than between shrubs, while lateral flow was greater for particular shrubs with higher funneling ratios [Zhang *et al.*, 2013; Jian *et al.*, 2014]. In order to account for preferential flow along roots in a hydrological model, Liang *et al.* [2009b] applied a variable source term in relation to soil layers. Including stemflow yielded more realistic results, as shown earlier by Tanaka *et al.* [1996] who included stemflow in his model as a concentrated input to the infiltration soil surface area around the trunk. As might be expected response times of soil moisture increases were reduced and more realistic when a variable source term for water input to different soil layers was included [Liang *et al.*, 2009b].

An increasing number of studies have shown that stemflow-induced preferential flow along roots affects the spatial patterning of soil moisture of desert shrubs [Li *et al.*, 2008; Wang *et al.*, 2011] and dry, temperate mixed forest [Návar, 2011], for example. For stemflow from babassu palms in an agroforestry system, preferential flow along roots was not a dominant process, probably due to the lack of secondary growth of palm roots [Germer, 2013]. For oil palms (*Elaeis guineensis*) that have similar forms as babassu palms, an inverse estimation of soil hydraulic properties was performed using the model HYDRUS-2D/3D [Rashid *et al.*, 2015]. The authors found a tendency of higher infiltration rates as well as higher porosity and organic matter content but lower water content and bulk density in the top 10 cm of soil for stemflow compared to throughfall areas. This led to higher modeled saturated hydraulic conductivity and saturated water content

next to palm stems compared to distal locations. It, however, remains unknown if these spatial differences also exist at lower soil depths and therefore whether these soil hydraulic differences can lead to quicker deep percolation of stemflow than throughfall. As shown by *Liang et al.* [2007] soil moisture patterns due to stemflow can be influenced by topography, resulting in a greater soil moisture increase downslope of tree trunks. Through a modeling study of spatial soil moisture patterns in a corn field, *Bruckler et al.* [2004] found that the differences in the spatial distribution of soil moisture were diminished during dry periods due to heterogeneous root distribution. This is consistent with greater temporal water content variability within compared to between rows of corn and soybean fields that was attributed to greater rainfall funneling and water consumption in rows [*Logsdon et al.*, 2010]. Similar results were found for numerical experiments showing that increasing root activity had the potential to reduce or the effect of uneven water input by throughfall [*Guswa*, 2012]. In contrast, for tall *stewartia* (*Stewartia monadelphica*) growing on a hillslope, high soil water content depletion after rainfall for areas with high stemflow input could be attributed predominately to drainage instead of evapotranspiration [*Liang et al.*, 2014]. The authors also found higher soil water depletion for areas with high stemflow water input and for a period with stemflow compared to one without stemflow water inputs.

As stemflow can create patterns of soil moisture, it is obvious that vegetation disturbance or clearing can lead to a decrease of soil moisture heterogeneity due to decreased localized water input by stemflow. This hypothesis was proven to be true through comparisons of semiarid sites of intact and disturbed multistemmed evergreen shrubs (*Larrea divaricata*) [*Cecchi et al.*, 2006]. *Liang et al.* [2011], however, found little change in bypass flow frequency for a period before and after intercepting stemflow of *stewartia* trees but a decrease of saturation zone generation at the soil-bedrock interface. This corresponds with a significant reduction of subsurface flow that was collected at a trench of > 50 cm depth (no maximum depth mentioned) in a karst region of Texas with soils of shallow gravelly clays and loams after the removal of the juniper vegetation and, hence, a shift from localized input by stemflow to uniform rainfall input [*Taucer et al.*, 2008].

8.3. Stemflow Influence on Groundwater and Streamflow

One of the most interesting questions is whether the spatial heterogeneity of soil moisture due to stemflow and subsequent preferential flow can lead to localized hot spots of deep drainage [*Tanaka*, 2011]. In a mass balance study performed in a Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) stand, *Taniguchi et al.* [1996] found high chloride concentrations in subsurface water compared to rainfall and throughfall and concluded that subsurface water and, hence, groundwater recharge were influenced by stemflow that had even higher chloride concentrations. This was corroborated by a modeling study in the same red pine stand by *Tanaka et al.* [1996]. In a modeling study for a banana plantation, drainage was 6 times higher under banana rows than between rows due to stemflow [*Sansoulet et al.*, 2008]. Besides stemflow, the study also indicated, however, that heterogeneous root distribution needs to be accounted for to avoid drainage overestimation. This was done in a numerical throughfall study that found that throughfall variability always led—regardless of the net effect—to localized concentrated groundwater recharge, which might be important to understand the potential impact of stemflow on runoff chemistry [*Guswa*, 2012].

Evidence that localized concentrated groundwater can have a significant effect on groundwater or streamflow chemistry is still lacking. In contrast, *Astel and Matek* [2010] found that stemflow had no effect on streamflow chemistry, the latter being largely influenced by bedrock chemistry. The end-member mixing analyses by *Inamdar et al.* [2013] did demonstrate the presence of stemflow in stream water but could not prove any significant effect of stemflow on streamflow chemistry, as the principal component analysis resulted in a two-dimensional mixing space where stemflow was primarily localized between throughfall and litter leachate.

8.4. Stemflow-Soil Interactions: Chemistry

The fact that stemflow can influence soil chemistry was documented earlier [*Johnson and Lehmann*, 2006] and reaffirmed over the following years. Higher pH values next to trunks relative to distal locations were reported by *Ceccherini et al.* [2008] for a pine forest in Central Italy and by *Hamdan and Schmidt* [2012] for Douglas fir and bigleaf maple in British Columbia. The latter authors also documented higher base saturation and concentrations and contents of NO₃-N and contents of total N and S. For a desert shrub in

a sandy desert of central Asia, salinity and nutrient contents of the soil next to the shrub center were higher than farther away [Li *et al.*, 2011]. The authors also showed that the nutrient concentration was especially high within 20 cm of the shrub main root. A recent study in a Canarian laurel forest by Aboal *et al.* [2014] pointed out that soil chemistry around tree trunks influenced by stemflow not only was significantly different from soil influenced by throughfall but also depended on tree species. They found, however, only few significant correlations between stemflow and soil chemistry next to trunks. Therefore, it is not clear whether soil chemistry differences between tree species were due to the impact of stemflow or were induced by nutrient cycling from the respective trees. Stemflow-induced soil chemical heterogeneity due to industrial pollution was found in the vicinity of a steel factory in Slovakia with heavy metal concentrations above the detection limit only near stems [Klučiarová *et al.*, 2008]. Higher heavy metal content and lower pH in soil next to the trunk base than distal soils were also documented for a beech stand in Świętokrzyskie Mountains (Poland) with pollution impacts from Ostrava-Karviná Industrial Basin (Czech Republic) [Józwiak *et al.*, 2013]. Likewise, Fantozzi *et al.* [2013] reported stemflow-induced increased concentrations of Al, Fe, Mg, Cu, Pb, and Cd in topsoil in urban areas but not in the extra urban control site. For isolated trees in a savanna ecosystem of South Africa, stemflow was suggested to be a primary mechanism for the enrichment of Zn, Mo, As, and Se in soils adjacent to tree trunks in comparison to the open [Mills *et al.*, 2012]. It, however, remains difficult to distinguish whether and to what degree soil chemical heterogeneity was influenced by stemflow, throughfall, and litterfall [Vorobeichik and Pishchulin, 2009]. If heterogeneous solute input by stemflow is included in hydrochemical models, then the expected increase of that solute in the soil next to the tree trunk can be simulated as shown for aluminum by Nikodem *et al.* [2010]. In contrast, Sansoulet *et al.* [2007] could simulate increased leaching of fertilizer due to high stemflow water fluxes from banana plants. The leaching under the banana stem was 5 and 10 times higher than for greater distances from the stem for N and K, respectively [Sansoulet *et al.*, 2007].

8.5. Evaluation and Future Direction

Concentrated water input to the soil by stemflow triggers different flow paths of water on or in the soil. Whether it is overland flow, preferential flow through macropores or matrix flow depends not only on soil characteristics but also on the plant that generated the stemflow. Most importantly, the plant also impacts the stemflow-induced patterns of soil moisture and also of soil chemistry. Therefore, future research should address the following questions: (1) Under which circumstances are the concentrated water and nutrient inputs supplied by stemflow (a) utilized by the plant and (b) leading to hot spot and hot moment development of soil microbial activity? (2) Under what combination of soil, vegetation, and climatic conditions could stemflow be a driver for localized deep percolation and groundwater recharge, potentially impacting groundwater chemistry? (3) Does the preferential flow along roots really facilitate quick deep percolation beyond the rooting zone compared to matrix flow with slower water percolation?

While some recent studies have found increased pollutant loads in soils near tree trunks (as cited above), there is an urgent need to better understand the transport and fate of pollutants scavenged and intercepted by the forest canopy. Future studies should assess the relationship of bark properties and stemflow funneling on heavy metal concentrations in soil next to trunks. Do tree species with higher stemflow pollutant concentrations but lower stemflow volumes transport larger pollutant loads to forest soils than tree species with lower stemflow pollutant concentrations but higher stemflow volumes? It would be also interesting to find minimum air pollution intensities for which elevated heavy metal soil concentrations can be found next to tree trunks.

What role do extreme events play in stemflow-soil interactions? Specifically, how might more intense thunderstorms affect stemflow-soil interactions compared to an increased incidence of hurricanes or typhoons that is forecasted with climate change? It is likely that these two types of extreme events will differentially affect stemflow-soil interactions since thunderstorms are of short duration and high intensity while hurricanes and typhoons are of long duration and variable intensity (ranging from low to high intensity over the course of an event). Studies examining the role of extreme events in stemflow-soil interactions could supply important insights for quantifying frequency and volume of localized groundwater recharge and into the flushing of particulate matter from the cortisphere by stemflow, which, in turn, could impact the chemistry of stemflow inputs to the soil and groundwater.

9. Conclusion

Our knowledge of stemflow and its importance to wooded ecosystems has greatly increased in recent years. It is probable that the number of studies examining stemflow will further increase in the coming years as more scientists recognize its importance in the hydrologic and biogeochemical cycles of wooded ecosystems. Capitalizing on the insights of prior research, exciting research opportunities await hydrologists, biogeoscientists, and forest ecologists who will conduct studies that develop a better understanding of the dynamic interactions between stemflow and canopy life and stemflow and vadose zone hydrology and chemistry. Such work will undoubtedly utilize current and new technologies to definitively link the microbial ecology of the cortisphere with stemflow and trace the transport and fate of atmospheric aerosols through the canopy and the vadose zone. Other work will likely delve into the chemical physics of stemflow along branches and stems to uncover the mechanism of leaching and its dynamic interplay with fungi, bacteria, other corticolous organisms, and intercepted aerosols. Together, such efforts will better frame stemflow in the larger context of watershed hydrology and biogeochemistry, leading to a better formulation of the hot spots and hot moments of watersheds.

Appendix A: Glossary of Some Specialized Key Terms in Stemflow Studies

basal area- cross sectional area occupied by tree trunks or stems. Basal area is utilized in the calculation of stemflow funneling and enrichment ratios (see text, sections 3.1 and 3.2). Basal area is a useful metric to characterize wooded ecosystems and is often expressed in $\text{m}^2 \text{ha}^{-1}$ for site characterizations.

canopy leaching- the removal of a substance from a plant surface by an aqueous solution [Tukey, 1970]. The aqueous solution is throughfall or stemflow, originating from rainfall or snowmelt. Canopy leaching is a process engendered by passive diffusion via differences in concentration equilibria and gradients of substances between intercepted water and the plant surface.

canopy structure- defined by Parker [1995] as “the organization in space and time, including the position, extent, quantity, type, and connectivity, of aboveground components of vegetation.” Canopy structure constitutes microscale features, such as the texture and morphology of bark surfaces, to more macroscale features such as changes in canopy phenophase (i.e., leafed, leaf fall, leafless, and leafing conditions) occurring with different seasons to lateral rain shadows created by the three-dimensional geometry among neighboring trees of differing heights.

cortisphere- the bark surface and life dwelling in and on the bark substrate. The term was coined by Pfanz and Aschan [2001]. The cortisphere is a rich and diverse ecosystem for fungi, bacteria, epiphytic lichens and bryophytes, and insects, among others.

diameter at breast height (DBH)- the diameter of a tree trunk at 1.37 m (USA) or 1.30 m (Europe) above the ground. Many allometric equations predicting various aspects of canopy structure are based on DBH. Tree DBH is often used in the calculation of basal area, ignoring a possible increase of tree diameter toward the soil surface.

dry deposition- atmospherically derived materials intercepted by plant surfaces between precipitation events. A variety of substances are intercepted by plant surfaces, including particulates of widely variable diameters. Dry deposited materials are washed from plant surfaces by stemflow and throughfall, thereby affecting throughfall and stemflow chemistry.

fungal conidia- singular form is conidium. Fungal conidia are asexual reproductive spores.

hot spots and hot moments theory- espoused by McClain *et al.* [2003], hot spots and hot moments refer to the spatial and temporal aspects of disproportionate rates and reactions of biogeochemical reactivity in certain places at certain times. McClain *et al.* [2003] primarily focused on hot spots and hot moments of coupled terrestrial-aquatic systems. For a larger discussion of hot spots and hot moments, interested readers are referred to their article which couches these theories more broadly. With particular regard to stemflow, the theory of hot spots and hot moments is a useful construct to examine stemflow hydrology and biogeochemistry, especially since stemflow has been long documented to differentially affect near-stem areas.

precipitation interception- the catch of hydrometeors by aboveground plant surfaces. Rain and snow intercepted by plant surfaces are partitioned into throughfall, stemflow, and interception. Intercepted water is stored on and within the canopy and subsequently evaporated and returned to the atmosphere. Some intercepted water is routed to the forest floor in distinctly different ways as throughfall and stemflow (Figure 1). The extent to which a particular plant species partitions intercepted water into throughfall, stemflow, and interception is partly governed by canopy structure and partly governed by abiotic factors such as meteorological conditions and climate.

projected crown area- on the scale of individual trees, the horizontal area occupied by a tree's crown. This metric is often calculated via ground-based measurements of crown radii in different directions to account for asymmetry in crown shape. Projected crown area may also be calculated from photogrammetric analysis of airborne imagery as well as ground- or aerial-based lidar. Projected crown area is affected by a suite of factors, including light availability, competition from neighboring trees, and individual tree life history.

stemflow- the water that drains over the exterior of a plant stem or tree trunk. Stemflow originates from rainfall (or snowmelt) that is intercepted by the branches and stems/trunks of plants and from throughfall droplets that are released from foliar surfaces and are subsequently intercepted by a branch. Stemflow is a localized point input of water, solutes, and particulates at the base of a tree trunk or plant stem.

stemflow infiltration area- area around a tree trunk where stemflow infiltrates and has the capability of changing water storage and soil chemistry.

throughfall- intercepted water that passes directly through the canopy (free throughfall) or is caught by aboveground plant surfaces and subsequently routed to the forest floor (release throughfall). The terms free throughfall and release throughfall were coined by *Dunkerley* [2000]. Release throughfall can occur as canopy drip or smaller splash droplets. Free throughfall is chemically identical to the gross incident precipitation, whereas release throughfall exhibits chemical enrichment from canopy leaching and dry deposition washoff.

Appendix B: New Technology for the Measurement of Bark Microrelief

While it has long been known that smooth-barked trees generate larger stemflow volumes than their rough-barked counterparts [e.g., *Horton*, 1919; *Voigt*, 1960; *Brown and Barker*, 1970], technological advances permitting the quantification of bark microrelief in a precise, reproducible, and efficient manner were necessary to definitively investigate the linkages between stemflow yield and bark morphology. The LaserBark™ automated tree measurement system was co-invented at the University of Delaware by John Van Stan, Matthew Jarvis, and Delphis Levia [*Van Stan et al.*, 2010]. A primary purpose of the LaserBark system is to give researchers high-resolution measurements of bark microrelief. The LaserBark system, consisting of a laser rangefinder and carriage assembly, provides an accurate, fast, precise, and reproducible global measurement of bark microrelief [*Van Stan et al.*, 2010]. A second generation prototype LaserBark system employs Bluetooth technology and measures distances from the carriage assembly to the tree bark surfaces at a 0.1° resolution. The bark microrelief metric, calculated from readings of the LaserBark, is defined as the ratio of bark area to cross-sectional area of the tree stem [*Van Stan and Levia*, 2010]. *Legates et al.* [2014] illustrated the utility of wavelet analysis to examine the spatiality of bark microrelief from LaserBark readings. Together, it is possible to have the global measurement of bark microrelief based on the bark microrelief metric as well as a more detailed picture of the variation of bark microrelief over the circumference of the tree from wavelet analysis. As such, wavelet analysis is particularly promising as a methodological tool to precisely couple bark microrelief with both the chemophysical processes which govern stemflow leaching and the presence (or absence) or certain corticolous epiphytes and microbes.

B1. Use of Other Technologies to Quantify Other Elements of Canopy Structure

The use of lidar in quantifying forest canopy structure has been well studied [e.g., *Lim et al.*, 2003; *Parker et al.*, 2004; *Tesfamichael et al.*, 2010; *Côté et al.*, 2012]. As discussed in *Levia et al.* [2015], abundant opportunities exist to pair spatially explicit canopy structural information, derived from combining lidar with fine-scale architectural models of trees as espoused by *Côté et al.* [2012], with measurements of stemflow yield and chemistry. Such work would provide new insights into the effects of canopy structure on stemflow that were not possible until relatively recently. How does total woody surface area and orthogonally projected area

influence stemflow chemistry? Is it the woody surface area which catches and drains stemflow or the total surface area which most strongly governs stemflow chemistry? To what extent is stemflow production affected by the overlap among branches? Future work which blends lidar technology with stemflow has the potential to yield insights into forest hydrology and biogeochemistry. Fine-scale lidar also could be used for high-resolution stem scans which would be useful to map bark microrelief along the vertical profile of tree stems.

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