Advanced Review

Throughfall drop size distributions: a review and prospectus for future research

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Throughfall is the dominant input of water to forests. Throughfall drop size and the distribution thereof are important because of their influence on the forest water balance, soil erosion, and, possibly, biogeochemical cycling. However, our inadequate understanding of throughfall drop size distributions has hampered progress in the identification of direct and indirect linkages between throughfall inputs and the biogeochemistry and physiological ecology of forests. This review provides a snapshot of our current understanding of throughfall drop size distributions by tracing the historical development of throughfall drop size studies and examining the determinants of throughfall drop size. The theory and methods of drop size studies also are reviewed to consolidate our collective knowledge of throughfall drop size distributions to date. Some of the gaps in our current knowledge, among many, include: (1) the effects of snowmelt on throughfall drop size; (2) the role and extent to which different canopy phenophases affect throughfall drop size; and (3) the extent to which throughfall drop size affects the chemistry of and biogeochemical cycling within forest soils. Closing these knowledge gaps will likely lead to the better conceptualization of rainfall partitioning processes and more definitive linkages between the cause-and-effect relationships between throughfall and soil erosion, forest biogeochemistry, and plant physiological ecology, for example. © 2017 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

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INTRODUCTION

Trees are important modulators of biosphere–atmosphere interactions, affecting atmospheric carbon dioxide concentrations, surface energy fluxes, the hydrologic cycle, and biogeochemical cycling.[1,2] The multi-faceted nature of trees' impacts on the surrounding environment is complicated and confounded by species-specific traits, such as canopy architecture and leaf habit that can alter soil moisture status and soil microbial communities,[3,4] as well as phenoseason[5] and exogenous stressors.[6,7] In this paper, we specifically focus on one aspect of this complex puzzle, seeking to better understand how the scientific literature to date captures and characterizes our collective understanding of rainfall partitioning with specific regard to throughfall drop size.

Vegetation partitions incident rainfall into interception loss, throughfall, and stemflow. The throughfall component may be divided into free and release throughfall,[8] with release throughfall subsequently further subdivided into splash throughfall and canopy drip[9,10] (Figure 1). Free throughfall is considered as the portion of throughfall which at no

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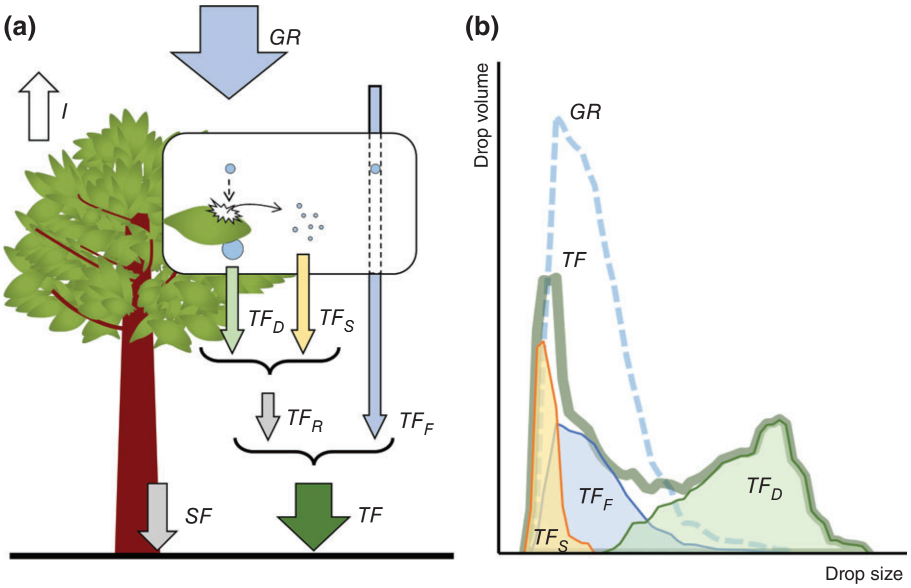

FIGURE 1 | Schematic diagram of throughfall drop component separation and drop size distribution of the different throughfall components. (a) GR, gross rainfall; I, interception; SF, stemflow; TF, throughfall; TF_F, free throughfall, TF_R, release throughfall; TF_D, canopy drip; TF_S, splash throughfall. The sum of TF_D and TF_S equals TF_R. TF equals the sum of TF_F and TF_R. The box details the interaction of different throughfall types with the canopy. Please note that the dashed line for TF_F denotes that it passes through the canopy without ever contacting any vegetative surface. (b) The drop size of the different throughfall types and GR in relation to drop volume.

point comes into contact with any canopy surfaces, thus maintaining a drop size distribution (DSD) identical to that of open precipitation.[11] Splash throughfall is often categorized as droplets <1.5 mm in diameter (although this value is not fixed) and is generated by momentum transferred into the canopy by rainfall,[10] wind,[12] or from the redistribution of intercepted water in the canopy.[13] Canopy drip is comprised of throughfall droplets with diameters >1.5 mm.[10,14] The diameter of canopy drip is partly governed by its routing along vegetative surfaces, meteorological conditions, canopy state, and the biophysical characteristics of the plant surface, among other factors (e.g., Refs 10, 14–17).

A comprehensive understanding of throughfall generation and DSD is of critical importance to the forest water balance because it affects the amount of water reaching the forest floor. It is likely that throughfall DSD also exerts a detectable influence on forest soil chemistry (e.g., pH as well as organic matter breakdown and cation exchange capacity) and its functional ecology with particular regard to the spatial patterning of soil moisture and microbial biogeochemistry, although these have yet to be examined. Moreover, throughfall processes, modifying the kinetic energy of incident precipitation, may affect soil erosion and slope stability.[9,18–25] The purpose of this review paper is to critically evaluate past work on throughfall drop size and to map new research directions that will advance our current understanding of throughfall drop generation and DSD. After an initial primer on the theory and lexicon of throughfall drop size studies, the next section of this review traces the evolution of throughfall drop size measurement methods. Another section reviews the biotic and abiotic determinants of throughfall drop size. The final section critically reviews the literature and identifies knowledge gaps in our current understanding, thereby setting an agenda for future research on throughfall drop size. This review draws from studies around the world published in both English and Japanese. This is particularly noteworthy as there are a number of throughfall drop studies that have been published in Japanese over the past several decades that are inaccessible to most readers.

A PRIMER ON THROUGHFALL DROP SIZE STUDIES: THEORY AND LEXICON

Representative Parameters of Throughfall Drop Size Distributions

DSD is an important concept in the analysis of rainfall and throughfall drops since the diameter of drops is so variable, changing as a function of many factors, including rainfall intensity,[26,27] rainfall type,[28] and throughfall type.[10] Given the inherent variability

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in throughfall drop size, the aggregate number and volume of drops in discrete drop classes is necessary to construct throughfall DSDs. Two types of DSDs have been widely used: the first is based on drop number density, $N(D)$ ($\mathrm{mm^{-1}\ m^{-3}}$), and the second on drop relative volume, $V(D)$ (dimensionless)[29] (Figure 2). They are calculated as:

$$N\left(D_j\right)=\sum_i^{N_j}\frac{1}{A\cdot v_i\cdot \Delta t\cdot \Delta D_j} \tag{1}$$

$$V\left(D_j\right)=\frac{\sum_i^{N_j}V_i}{V_{\text{total}}} \tag{2}$$

where N_j is the number of the drops in a drop diameter class j, A the sampling area ($\mathrm{m^2}$), v_i the velocity of a respective drop i ($\mathrm{m\ s^{-1}}$), Δt the sampling time (s), ΔD_j the class range of drop diameter (mm), V_i the volume of a respective drop i, and V_{total} the total volume of all drops. In studies with natural rainfall, $N(D)$ has been generally calculated by using the drop terminal velocity equations (e.g., Refs 30–33), while $V(D)$ has been generally used in throughfall studies because throughfall drops do not always reach terminal velocity.[16,18,34]

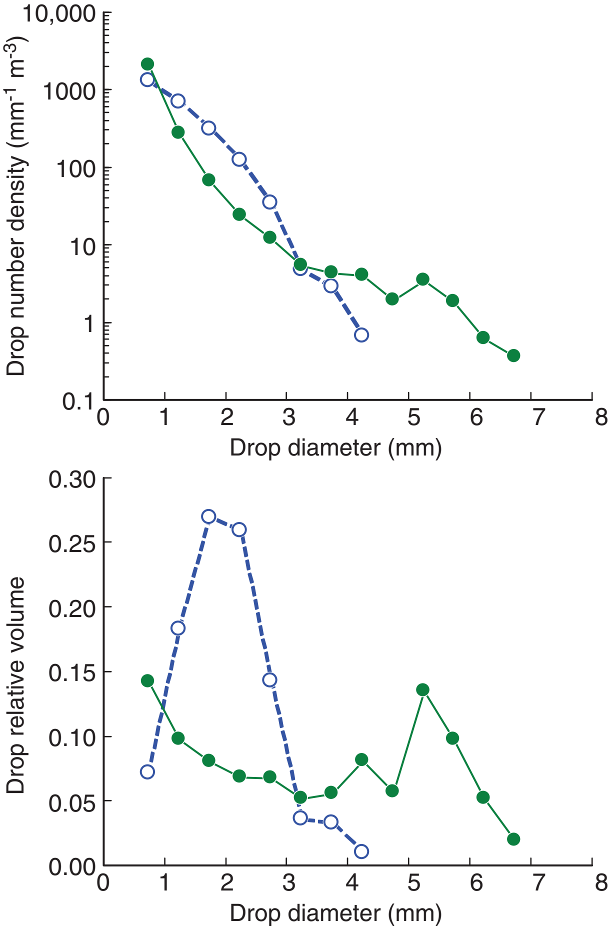

FIGURE 2 | Example of drop size distribution of open rainfall and throughfall based on drop number density, N(D) and drop volume ratio, V(D) observed in 1-h with 14.7 mm $\mathrm{h^{-1}}$ rainfall intensity. The dashed blue and bold green lines indicate open rainfall and throughfall, respectively. (Data source: K. Nanko, Ref 10.)

Rainfall and throughfall diameter distributions are positively skewed, which accounts for the common use of maximum drop diameter (D_{MAX}, mm), median volume drop diameter (D_{50}, mm), and median drop volume (v_{50}, $\mathrm{mm^3}$) as they better quantify and characterize the non-normal distribution. D_{50} is a widely used index representing both open rainfall (e.g., Refs 35–39) and throughfall (e.g., Refs 10, 15, 29, and 34), while v_{50} is used for the Calder[40] two-layer stochastic model to estimate canopy interception loss.

Characteristics, Prediction and Usage of Throughfall Drop Size Distribution

Throughfall has a distinct DSD compared to open rainfall (Figure 2); whereas open rainfall has a unimodal DSD, throughfall has a bimodal DSD.[10,41] First, for a given time period, the total number of throughfall drops is less than that for open rainfall due to interception loss, storage, and partitioning of incident rainfall by the canopy.[10,42–44] Second, due to canopy drip, the number of larger throughfall drops (>3.0 mm) is higher than that for open rainfall. Throughfall categorized as canopy drip usually comprises more than half of the total volume of throughfall, and thus D_{50} is usually higher than 2–3 mm. For open rainfall, these larger raindrops are rare and the volume percentage is low and only observed at high rainfall intensities; for example, a 3 mm D_{50} value is observed at a rainfall intensity >100 mm $\mathrm{h^{-1}}$.[15,35] Third, the relative volume of smaller drops (<1.0–1.5 mm) increases because of splash throughfall. The impact of larger drops onto foliage generates splash droplets,[45] especially when open rainfall is of higher intensity and strong winds jostle foliage during rain storms.[10] The generation process of these splash droplets have been studied in agronomic contexts[45–47] and in relation to forest canopy interception loss.[48]

To determine the throughfall DSD, it is necessary to know both the DSD and relative volume percentage for each throughfall component (i.e., free, splash, drip)[49] (Figure 1). With this objective, a couple of models have been developed. One approach used the combination of the DSDs of free throughfall and canopy drip,[50,51] while a second approach by Nakaya et al.[52] added the splash throughfall component. Frasson and Krajewski[53] developed a physical process-based rainfall interception model, where throughfall DSD was estimated considering splashing, drop breakup, and drop detachment. In all these models, the DSD of free throughfall is estimated by the Marshall and Palmer[26] distribution, a widely used exponential relation between raindrop size and drop number density related to rainfall intensity, or a general gamma relation.[27] Both showed that higher rainfall intensity generated higher drop number density totals for each diameter class, and larger raindrops. The DSD of canopy drip is empirically estimated as a normal distribution based on $V(D)$. The application of mean, range, and standard deviation of drop diameter are the values used to estimate the DSD.[50–52] Last, the DSD of splash throughfall is empirically estimated as an exponential distribution[52] or Weibull distribution[54,55] based on $N(D)$.

Predictions of throughfall DSD are important because they are used to estimate throughfall kinetic energy for soil erosion studies (e.g., Refs 15, 21, and, 43). In fact, much of the mid-twentieth century research on the DSD of open rainfall was motivated by the need to mitigate soil erosion. This study focused on both the determination of the terminal velocity and erosive potential of precipitation[30,31,35] as well as radar calibration and validation studies to establish an empirical relationship between drop size and rainfall intensity.[26,56] Chapman[18] published the first known study to understand the role of the tree canopy on soil erosion. His work ultimately corrected the generally held assumption that tree canopies muted the erosive power of rainfall in forests. He found that throughfall drops had a consistently larger median size than open precipitation. This finding was later substantiated by others (e.g., Refs 9, 11, 19, 43, and 57). Readers specifically interested in throughfall DSD and throughfall kinetic energy in relation to soil erosion are referred to Nanko et al.,[21] Geißler et al.,[24] and Goebes et al.,[58] among others whose calculations of throughfall kinetic energy assume that the fall height of release throughfall is equal to the canopy height from which the droplets detach.[20,50,52,59–61]

In addition to its application to soil erosion studies, throughfall DSD is useful to estimate canopy interception loss. A two-layer stochastic model of rainfall interception,[13,40] based on the original stochastic interception model,[62] accounts for the gradual wetting of a vegetation canopy by raindrops and water dripping from an upper canopy layer onto a lower one.[63] The stochastic model estimates maximum canopy storage from v_{50} and raindrop kinetic energy to impact leaves. The maximum canopy storage decreased with the increase of median drop volume.[13,64] The throughfall DSD is used to calculate the median volume drop diameter of throughfall impacting lower layers of the canopy.

THROUGHFALL DROP SIZE MEASUREMENT METHODS

The temporal evolution of drop size measurement methods of direct relevance to throughfall DSDs is depicted in Figure 3. The first known study to describe raindrop size[65] utilized slate sheets with a 1-inch (25.4 mm) grid drawn on them to examine the size and distribution of naturally occurring rainfall. Lowe[65] observed the irregular distribution of drop diameters within a given event, as well as the tendency of large drops to break into smaller droplets upon impact. Another early effort to quantify rainfall drop size emerged from a desire to confirm whether tropical raindrops actually reached 1 inch in diameter.[66] Wiesner[66] employed the paper staining method, whereby paper is treated with a water reactive dye, and then exposed to falling rain. The drop size of a particular hydrometeor is then calculated from the diameter of the dye stain and the thickness of the paper.[30,31,35,66] Mihara[67] quantified drop size by the glass plate method, whereby a glass plate is exposed to falling rain. Raindrops intercepted by the glass plate are then later absorbed by stain paper with a water reactive dye in a laboratory. Compared with the paper staining method, the glass plate method permitted the measurement of larger raindrops, which presumably remain intact due to surface tension, as opposed to the paper staining method, which sometimes generated splash droplets at impact. The glass plate method also allowed for the measurement of smaller droplets than the flour pellet method devised by Bentley.[68] In contrast to paper staining methods, this method relied upon a container of sifted flour being exposed to rainfall for a known period of time. Raindrops impacting the flour surface create flour pellets. Pellets generated in this manner are then dried and sorted via a sieve set. Pellet size can be related to raindrop size through a calibration function, where drops of a known size are generated and the resultant pellets were measured.[68] Additionally, Fuchs and Petrjanoff[69] described the oil method, in which water drops are collected in a low-density immiscible liquid-like oil. The oil envelops the drop, preventing both evaporation of and condensation onto the drops. Due to the high surface tension

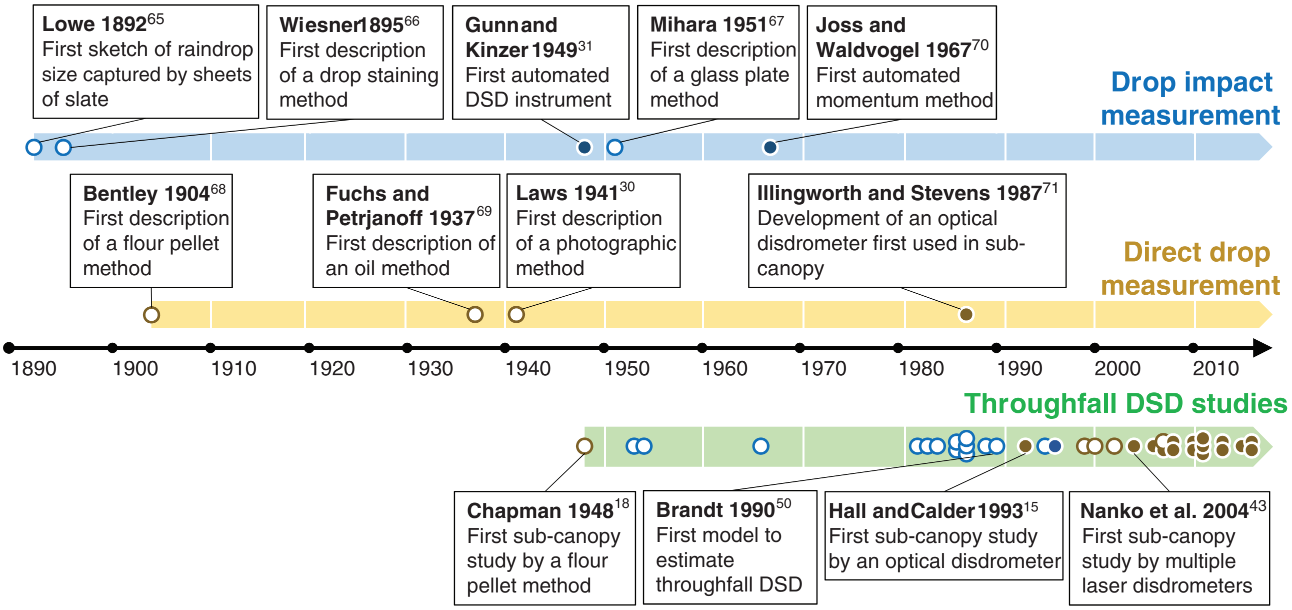

FIGURE 3 | Historical evolution of throughfall drop size distribution (DSD) studies related to the development of raindrop measurement methods. Open and filled circles indicate manual and automated sampling methods, respectively. Please note that this figure highlights certain key studies and does not attempt to identify every study by name. The numbers in the top right of each box correspond with its number in the reference list. The clustering of circles is intended to demonstrate the increase of throughfall DSD studies from 1980 onwards.

forces, the drops form spherical shapes, from which the diameters can be measured with a microscope or other device.[72] These methods provided a low cost, reasonable measurement of raindrop size, although there were inherent issues with sample preparation, drop size calibration, sample timing, and limited temporal resolution.

To remedy the deficiencies of these earlier methods, automated methods of drop size and velocity measurement were developed in concert with technological advances in meteorology. One early automated method involved using a camera and shutter apparatus to sequentially measure the fall of a hydrometeor across a calibrated background to determine fall speed, with the drop itself being captured via the flour pellet or oil immersion method.[30] A second device exploited the naturally occurring electrical charge on hydrometeors. Gunn[73] developed an instrument consisting of two insulated induction rings, separated by a meter, and connected to an oscillograph. When a drop possessing a charge passed through the first ring, a pulse was sent to the oscillograph. Once the drop passed through the second ring, a second pulse was recorded. The two pulses record the time it took for the drop to pass 1 m. The drop then impacted the oscillograph paper reel, allowing the diameter to be recorded along with the velocity. These methods were later replaced by the advent of the disdrometer, an instrument that measures the DSD and velocity of hydrometeors. Both impact and optical disdrometers are manufactured, although impact disdrometers are not suitable for throughfall measurements (as discussed below).

The manual and early electronic methods allowed researchers to approximate the diameter and terminal velocities of hydrometeors. These datasets were used to generate early tables of raindrop size and kinetic energy. Armed with the information about drop sizes of hydrometeors from these earlier studies, new methods were developed that electronically recorded raindrop impact to quantify drop size and distribution. These impact methods relied upon either hydrometeors impacting the ground or a membrane connected to a transducer.[74] The impacting energy of the hydrometeor provided an estimate of the kinetic energy of the drops (and by extension drop size) on the basis of either a voltage output or a sound file.[70,74] The impact disdrometer is commonly used in meteorological observations, as it can be reasonably assumed that open precipitation is falling at terminal velocity (e.g., Refs 30–32, and 75), allowing the standard calibration equations to be employed. However, the impact disdrometer is invalid for measuring throughfall drops because canopy drip from a low canopy layer may not always achieve terminal velocity.[76]

Optical disdrometers are the latest development in drop size measurement methods and are in wide use today at airports, monitoring sites, and research grade meteorological stations.[10,71,77–79] Optical disdrometers rely on either camera technologies, infrared, or laser sensors. They accurately measure both diameter and velocity from the attenuation of a light source.[79] Because the optical disdrometer directly measures diameter and velocity, it is well-suited for the quantification of throughfall drop size where drops may not reach terminal velocity. Readers particularly interested in the development of methods, monitoring, and modeling of DSD of open rainfall are directed to a recent review by Kathiravelu et al.[80]

DETERMINANTS OF THROUGHFALL DROP SIZE

Role of Plant Surfaces

The biophysical examination of plant surfaces is not new. Robert Hooke, more than three centuries ago, described the presence of leaf hairs on nettle (*Urtica dioica*), an herbaceous plant, in his treatise *Micrographia*. Later, de Bary[81] provided the first classification of plant surface waxes and Albert Chinball transformed our understanding of leaf wax chemistry in the 1930s (e.g., Refs 82 and 83).[84] Then, with the advent of chromatographic techniques and electron microscopy, plant scientists achieved huge strides in our understanding of the plant surfaces.[84] More recently, hydrologists have started to couple the biophysical characteristics of leaf surfaces with their water repellency and throughfall inputs.[85] The linking of the hydrophobicity of plant surfaces with throughfall is of critical importance in understanding the influence of different plant species on throughfall drop size. Interested readers are referred to the review by Rosado and Holder[85] on the development, theory, measurement, and importance of leaf water repellency.

Recognizing that throughfall inputs are affected by leaf hydrophobicity,[86,87] Nanko et al.[29] found that throughfall drop size was smaller beneath tree species with more hydrophobic foliar surfaces. In fact, specific experiments demonstrated that the degree of foliar hydrophobicity determines droplet contact angle, whereas droplet contact diameter and contact length are more influenced by leaf roughness, inclination, and geometry.[9,17,29,45,88] A wide range of leaf traits, therefore, directly and/or indirectly affect throughfall drop size (Table 1). Hall and Calder[15] even found that interspecific differences in leaf shape, orientation, and surface characteristics trumped rainfall intensity in the determination of throughfall drop size comparing broadleaved and coniferous trees (*Eucalyptus camaldulensis* (river red gum), *Tectona grandis* (teak) and *Pinus caribaea* (Caribbean pine)). Nanko et al.[10] attributed differences among DSDs of a few tree species (*Quercus acutissima* (sawtooth oak), *Chamaecyparis obtusa* (Japanese cypress) and *Cryptomeria japonica* (Japanese cedar)) to the fact that intercepted water was better able to coalesce on oak leaves than more hydrophobic conifer needles. Leaf pubescence, which can also affect hydrophobicity, is another factor affecting throughfall drop size.[17,45,59]

For nine different tree species—*Castanopsis sieboldii* (Itajii chinkapin), *Schima liukiuensis* (Chinese guger tree), *Daphniphyllum teijsmannii* (Japanese daphniphyllum), *Elaeocarpus japonicus*, *Cinnamomum doederleinii* (cinnamon), *Machilus thunbergii* (Japanese bay tree), *Ternstroemia gymnanthera* (cleyera), *Distylium racemosum* (evergreen witch hazel), and *Ilex liukiuensis* (holly)—the median throughfall drop size was similar for both adaxial (3.2–4.5 mm) and abaxial foliar surfaces (3.3–5.0 mm).[89] Intraspecific differences in leaf traits did not appear to affect throughfall drop size in a notable manner.[89] Similarities in throughfall drop sizes between adaxial and abaxial surfaces may be partly attributable to likenesses in water contact angles with the foliar surface. Indeed, Nanko et al.[29] reported that maximum throughfall drop diameter was partially affected by droplet contact angle, whereas the range of throughfall DSD was impacted by droplet contact length and contact diameter at leaf hanging points. Moreover, differences in throughfall drop sizes among species were attributed to varying leaf characteristics, such as leaf size and shape.[15] Similarly, throughfall drop size was observed to change as a function of leaf roughness, leaf inclination, and leaf geometry.[29]

Herwitz[90] observed that branch surfaces were much more efficient at retaining intercepted droplets than leaf surfaces, especially when already wetted or under windy conditions.[91] Intercepted water on branches was found to drain to the bottom of the branch and efficiently channel that water as stemflow. Sometimes, an irregularity in the canopy can cause the branchflow to become detached, likely as large throughfall droplets (although Herwitz[90] did not measure the diameter of such droplets). Branch inclination angle was a key factor controlling raindrop capture and its entrainment as branchflow.[90] In contrast, foliar surfaces encounter more drop-on-drop impacts as rain and release throughfall from above are intercepted as the water tends to stay on the adaxial surface—this agitation minimizes drop

TABLE 1 | Listing of Canopy Structural and Plant Surface Variables That Likely Affect Throughfall Drop Size

Canopy Structure Variables	
Tree species (and diversity thereof)	Broadleaved versus coniferous
	Deciduous versus evergreen
Canopy phenophase	
Tree/canopy metrics	Tree size
	Projected crown area[1]
	Crown thickness
	Height to first branch
	Height to first live branch
	Branch count
	Branch inclination angle
	Trunk lean
	Woody: foliar surface area ratio
Leaf geometry	Leaf area
	Leaf inclination angle
	Leaf margin/tip shape[2]
	Leaf thickness
	Leaf rigidity
	Needle length
	Needle density
	Petiole characteristics[3]
Plant area index	Number of canopy layers[4]
3D canopy geometry	
Distance from forest edge	Wind effects, extent of fetch
	Sun exposure
	Increased dry deposition
Plant Surface Variables	
Interspecific/intraspecific differences[5]	
Foliar surface wettability/hydrophobicity	Surface roughness
	Trichome type and density
	Epicuticular wax[6]
	Leaf/needle age
	Presence/absence of spider webs between leaves/needles
Bark surface wettability/hydrophobicity	Bark microrelief
	Bark texture and spatial variation thereof
	Bark thickness
	Bark chemistry[7]
	Presence/absence of epiphytes, bryophytes
	Presence/absence of adventitious roots
	Presence/absence of surface irregularities[8]
	Rate of dry deposition (change in surface tension)

(*continued overleaf*)

[1] Crown width, crown height, crown length.
[2] Serrate, dentate, incised, etc.
[3] Length, inclination angle, rigidity.
[4] Single versus multi-storied.
[5] Among and within tree species.
[6] Thickness, chemistry.
[7] Suberin content, for example.
[8] From insects/spiders/disease.

size and interception storage capacity of leaf surfaces.[90]

As previously demonstrated for throughfall volume and canopy interception,[90] there are a number of plant surface variables that can influence throughfall drop size (Table 1). It is probable that there is a mutual interaction among various canopy structure and plant surface variables. For instance, canopy phenophase should impact leaf age, trichome density, photodegradation of epicuticular waxes, and the hydrophobicity of foliar surfaces. The disentanglement of these interactive effects is necessary to understand whether the interplay among any given set of variables is additive, countervailing, or synergistic with respect to throughfall DSDs.

Role of Canopy Structure

As would be expected, there are interspecific differences in throughfall drop size values. Throughfall D_{50} values ranged around 2.0–3.0 mm at the lower end to 6.0 mm at the upper end (Table 2). Throughfall drop size maximum (D_{MAX}) ranged between 2.6 mm for *C. obtusa*[34] (Japanese cypress) and 10.0 mm for multi-layered forest.[102] However, many studies reported a D_{MAX} values between 6.0 and 8.0 mm for a variety of vegetation types (Table 2; Table S1, Supporting Information). Even within a single study, large differences in the median throughfall drop size were observed between two tropical tree species, differing by almost a factor of 2 between *P. caribaea* (Caribbean pine, 2.3 mm) and *T. grandis* (teak, 4.2 mm).[15] The main canopy structure characteristics affecting DSD are listed in Table 1.

TABLE 2 | Abbreviated Summary of Maximum Diameter (D_{MAX}) and Median Volume Drop Diameter (D_{50}) of Throughfall Beneath Some Plant Species in Previous Studies

Species	Measuring Method[1]	Rainfall[2]	D_{50} (mm)[3]	D_{MAX} (mm)[3]	References
Acacia mangium (brown salwood)	Oil	N	3.8	NA	92
Betula ermanii (Erman's birch)	Disdro-L	N	3.9[4]	NA	52
Chamaecyparis obtusa (Japanese cypress)	Disdro-L	N	2.5, 3.9[4]	6.0, 7.4[4]	93
C. obtusa	Disdro-L	Sm	1.5–3.6	5.2–7.0[4]	76
C. obtusa	Disdro-L	N	4.0[4]	NA	52
C. obtusa	Disdro-L	Sp	4.7	7.1[4]	29
C. obtusa	Disdro-L	Sm	1.0–4.4[4]	2.6–6.7[4]	34
C. obtusa	Disdro-L	N	1.8–2.1	4.5–6.1[4]	10
Cissus antarctica (kangaroo vine)	Mass	Sp	3.9[5]	NA	9
Cryptomeria japonica (Japanese cedar)	Disdro-L	N	1.9–2.9	5.1–7.3[4]	10
C. japonica	Disdro-L	N	3.8[4]	NA	52
C. japonica	Disdro-L	Sp	5.1	7.1[4]	29
C. japonica	Glass	N	NA	6.4	19
Dipterocarpaceae (mixed lowland tropical tree species)	Filter	N	5.5	6.8	94
Elaeocarpus grandis (blue marble tree)	Mass	Sm	5.2[5]	NA	9
Eucalyptus camaldulensis (river red gum)	Disdro-O	Sm	2.8	<5.5[6]	15
Eucalyptus populnea (poplar box)	Mass	Sp	6.3[5]	NA	9
Fagus crenata (Japanese beech)	Disdro-L	Sp	5.2	6.8[4]	29
Fagus sylvatica (European beech)	Flour	Sm	1.6–2.5	NA	95
Fatsia japonica (Japanese aralia)	Filter	Sp	5.0	<7.0[6]	11
Larrea tridentata (creosote bush)	Flour	Sm	1.6	<5.0[6]	96
Liriodendron tulipifera (yellow poplar)	Disdro-L	N	3.3–5.7[7]	5.6–7.0	14
Machilus thunbergii (Japanese bay tree)	Filter	Sp	4.4[8]	NA	89
Malus pumila (common apple)	Filter	N	2.0[6]	4.1	57
Melaleuca quinquenervia (broadleaved paperbark)	Mass	Sp	5.8[5]	NA	9
Nothofagus moorei (Antarctic beech)	Mass	Sm	4.2[5]	NA	9
Nothofagus obliqua (roble beech)	Filter	N	2.2[6]	<5.4[6]	97
Olea europaea (common olive)	Oil	Sm	1.4[6]	<8.0[6]	98
Picea abies (Norway spruce)	Filter	N	4.4	<7.3[6]	99
P. abies	Filter	N	<1.7[6]	<3.9[6]	97
Pinus caribaea (Caribbean pine)	Disdro-O	Sm	2.3	<5.5[6]	15
Pinus densiflora (Japanese red pine)	Glass	N	NA	5.8	19
P. densiflora	Glass	Sp	NA	4.6	19
P. densiflora	Disdro-L	Sp	3.7	6.2[4]	29
P. densiflora	Flour	N	2.8–3.6	<8.0[6]	18
Pinus massoniana (Chinese red pine)	Oil	N	3.5	NA	92
Pinus thunbergii (Japanese black pine)	Disdro-M	N	1.6[6]	5.0	42
P. thunbergii	Filter	N	NA	5.5	100
Platanus occidentalis (American sycamore)	Filter	N	4.3	<7.3[6]	99
Quercus acuta (Japanese evergreen oak)	Disdro-L	Sp	4.1	5.0[4]	29
Quercus acutissima (sawtooth oak)	Disdro-L	N	1.9–3.6	5.8–7.6[4]	10
Quercus dentate (daimyo oak)	Glass	Sp	NA	6.3	19

(*continued overleaf*)

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TABLE 2 | Continued

Species	Measuring Method[1]	Rainfall[2]	D_{50} (mm)[3]	D_{MAX} (mm)[3]	References
Quercus rubra (northern red oak)	Filter	N	3.3[6]	<6.5[6]	97
Sassafras tzumu (Chinese sassafras)	Oil	N	4.1	NA	92
Schima liukiuensis (Chinese guger tree)	Filter	Sp	3.8[7]	NA	89
Tectona grandis (teak)	Disdro-O	Sm	4.2	<5.5[6]	15
Tsuga heterophylla (western hemlock)	Filter	N	2.3[6]	<5.4[6]	97
Tsuga sieboldii (southern Japanese hemlock)	Glass	Sp	NA	5.0	19
Zea mays (maize)	Filter	Sm	5.1[6]	NA	101

NA, not available.

Please see Table S1 for the expanded version of this table, which includes tree, bush, and flower species to represent different vegetation types.

[1] Flour, flour pellet; Filter, filter paper; Glass, glass plate; Mass, estimated diameter of drips from water mass; Disdro-O, optical disdrometer; Disdro-M, microphone disdrometer; Disdro-L, laser disdrometer.

[2] N, natural rainfall; Sm, rainfall simulator; Sp, spray experiment.

[3] Range indicate min–max from different seasons, rainfall events, meteorological conditions, sites, forest ages, or measuring points in same species.

[4] Newly calculated from observed data.

[5] Mean of five replicates with every 50 or 100 drips.

[6] Calculated from figures and/or tables of drop size distributions.

[7] The diameter of the respective cumulative volume percentiles for 95%.

[8] Mean of adaxial and abaxial sides of 30 leaves with 10–15 drips.

Canopy phenophase and the corresponding changes in plant area index are an essential canopy structural variable that can affect throughfall drop size (Table 1). Nanko et al.[14] found that canopy state (i.e., presence/absence of foliage) was one of the most important factors controlling throughfall DSD. The top three most influential factors (based on boosted regression trees analysis) affecting D_{50} was foliation state, air temperature, and wind speed.[14] This is because of the mutually interacting effects among meteorological conditions, plant surface morphology, and canopy structure. D_{50} was substantially larger in the unfoliated period than the foliated period. This could be due to the fact that water adhesion to branches is stronger than foliar surfaces. Nanko et al.[14] suggested that water channeled along the underside of branches of leafless tree crowns is detained for longer spans of time with lower evaporation rates and more viscous branchflow. This likely increases contact time and larger drops only fall when momentum transfer or gravitational forces outweigh the adhesion forces keeping the drop *in situ*. Many of us may know this anecdotally from a walk in the park during winter or summer—just after rain, larger drops hit us in winter than in summer!

Canopy thickness has a detectable effect on throughfall drop size. Canopy thinning, as simulated by the pruning of branches, increased the volume proportion of large throughfall drops[16] and increased D_{50},[49] suggesting the capture and re-interception of throughfall drops from above.[16,44] This pattern was more pronounced for saturated canopies.[16] Goebes et al.[17] also assumed that increase in crown width led to increase in throughfall drop sizes. D_{50} was observed to be the largest at the crown periphery, decreasing with distance to the tree trunk.[34,49] Similar results were found for maize whereby the differential and patchy obstructive capacity of the canopy led to an increase in D_{50}.[44] Moreover, thicker canopies tended to increase the probability of splash droplet formation, which led to a reduction in throughfall drop size.[16,49] Accordingly, throughfall kinetic energy is negatively correlated with crown length.[16,61] The erosive potential of throughfall drops was able to be satisfactorily estimated using just two canopy structural variables, namely plant height and plant canopy area,[103] although plot level tree species richness was found to affect throughfall kinetic energy.[104]

Role of Meteorological Conditions

On the whole, less work has been done to know the effects of meteorological conditions on throughfall drop sizes than the influence of either canopy structure or the morphology of plant surfaces. Antecedent moisture levels in the canopy can affect throughfall drop sizes. Herwitz[90] found that vegetative surfaces that were already wetted detained a greater proportion of incident rain than dry surfaces, thereby reducing splash losses. In support of this observation, a canopy in the wetting stage (as opposed to saturation) had a lower volume proportion of large throughfall drops.[16] Thus, as a canopy wets-up some intercepted water is devoted to filling the canopy storage capacity (after Rutter et al.[105]) and some is invariably lost to splash but less water is likely to become canopy drip until the interception storage capacity is reached. Of course, there is a continuum on the probability that a throughfall drop will be released as splash or drip with the latter probability increasing as the canopy approaches saturation.

Empirical evidence demonstrates that rainfall intensity is not the most important factor affecting throughfall drop size.[11,14,18,19,41,100,106] This is primarily due to the fact that higher rainfall intensities increase the splash component of throughfall which have smaller drop sizes.[10,45,52] For both D_{50} and D_{MAX} of canopy drip, Nanko et al.[14] found that rainfall intensity ranked last or next to last in its relative influence on drop size, thereby ranking lower than canopy state, air temperature, and host of other factors. For multi-layered tree canopies, the low effect of rainfall intensity on throughfall drop size is reduced further as splash droplets from intense rain is recaptured by branches and foliage lower in the canopy.[16] It is important to note that a species-specific effect exists for impact of rainfall intensity and canopy drip. For example, high rainfall intensities were observed to lower throughfall drop sizes for sawtooth oak but had only a negligible effect on Japanese cedar and Japanese cypress.[10] In fact, some studies applied a constant DSD for released throughfall independent of rainfall intensity to estimate throughfall kinetic energy[50,52,59,60] and canopy interception.[13,63]

Increases in wind speed have been found to reduce throughfall drop sizes for both coniferous and deciduous tree species under foliated conditions.[10] Strong winds essentially dislodge intercepted water from vegetative surfaces, albeit to a much greater extent for foliar surfaces than woody surfaces,[91] by concurrently dislodging intercepted water and promoting the genesis of smaller-sized splash droplets and diminishing canopy drip.[10] For D_{50} of canopy drip, wind speed was found to be the third most influential factor after the presence/absence of foliage and air temperature.[14] In the special case of unfoliated conditions, wind speeds between 3 and 5 $\mathrm{m\ s^{-1}}$ actually increased canopy drip drop size,[14] likely due to the accumulation and subsequent detachment of branchflow. Little work has investigated the effects of wind direction of throughfall drop sizes under field conditions. It could be that certain wind directions have the highest wind speeds which could alter throughfall DSD. Nanko et al.,[14] however, found that wind direction did not seem to have a significant influence on D_{50} or D_{MAX} of canopy drop, although it did impact the drop volume ratio of canopy drip.

Air temperature and vapor pressure deficit appear to be effective meteorological factors, which can influence throughfall drop size. Larger canopy drip could be caused by higher surface tension and higher viscosity of intercepted water due to lower air temperature and higher water storage capacity due to lower vapor pressure deficit.[14]

Fog represents an interesting case with regard to canopy drip generation processes. The occult deposition of water droplets onto aboveground vegetative surfaces through coalescence and their subsequent release from the canopy is useful to consider due to the impact of frequently occurring fog and persistent cloud shading on the hydrology and ecology of some ecosystems.[107–110] Precipitation augmentation via fog interception and throughfall release is partially dependent on the leaf surface wettability and leaf inclination as these are two important determinants of canopy drip diameter.[29,87]

KNOWLEDGE GAPS IN THROUGHFALL DROP SIZE DISTRIBUTIONS: FUTURE RESEARCH DIRECTIONS

Overview

As detailed in this review, we have learned a great deal about some of the factors that affect throughfall drop size. It is clear that throughfall drop size is governed by a suite of mutually interacting factors that change both spatially and temporally at different scales. Biotic factors, such as tree species and leaf morphology (e.g., Refs 9, 15, 29, and 104), as well as abiotic factors involving weather conditions (e.g., Ref 10) both affect throughfall drop size. Despite the great deal of progress in throughfall drop size studies, there are a number of areas in which present knowledge is weak and where our understanding is insufficient. Closing these knowledge gaps will likely lead to the better conceptualization of rainfall partitioning processes and more definitive linkages (both direct and indirect) between the cause-and-effect relationships between throughfall DSD and the biogeochemistry and functional ecology of forests. This section identifies certain areas and avenues for future work so that a comprehensive understanding of throughfall in the hydrologic and biogeochemical cycle of forested ecosystems can be achieved for better stewardship of forest resources.

Effect of Plant Surfaces on Throughfall Drop Size

An entire literature exists on plant surfaces and water repellency of foliage (see Ref 85). On the level of individual plants, future work needs to quantify and

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assess the effects of varying bark morphologies on throughfall drop size. One would expect throughfall DSDs to differ between smooth- and rough-barked trees. But, how do throughfall DSDs differ, if at all, between tree branches with linear furrows or those with curvilinear overlapping structures or those with irregular detaching bark? Does the residence time of throughfall differ among tree species with differing bark structures? How might that influence drop size? Does longer residence time on some bark surfaces equate to larger or smaller throughfall DSDs? Given the apparent importance of leafless tree crowns in altering throughfall drop sizes,[14] it would be prudent to commission further studies that specifically examine differing bark structures and morphologies on throughfall drop sizes.

On the level of foliar and woody surfaces, the effects of the phyllosphere and cortisphere on throughfall drop size are largely unknown. Using confocal, light, and scanning-electron microscopy, it is possible to characterize the biophysical surfaces of both leaves/needles and bark. Such biophysical characterizations are not new in the bioimaging community (e.g., Ref 84), but may be used in a fruitful manner by hydrologists to examine the effects of plant surfaces on throughfall droplet genesis and DSDs. Bioimaging of plant surfaces has been successfully employed in other contexts to examine both ant locomotion in tropical canopies[111] and particulate matter dynamics in terrestrial solutions.[112] So, with respect to throughfall, do hairs on the abaxial surface of leaves alter throughfall drop size? If so, to what extent? How does the density of leaf hairs and their thickness affect throughfall drop size? Do water droplets detained on foliage of amphistomatous species have higher or lower water contact angles and drop sizes? Does the presence of particulate matter on foliage with different hair densities or types alter the surface tension of detained droplets? How does the surface roughness of bark at the scale relevant to drop formation influence throughfall drop size? Because bark morphology also changes vertically for any given tree, attention must also be paid to the vertical change of throughfall drop size. Do fractures in foliar or woody surfaces affect throughfall droplet size? Thus, hydrologists can utilize bioimaging techniques to better understand throughfall droplet genesis and DSDs.

We also contend that X-ray photoelectron spectroscopy could be used in conjunction with bioimaging techniques to advance throughfall droplet studies by simultaneously investigating surface chemistry, often related to degree of water repellency and biophysical structure. Do differences in the surface chemistry and biophysical structure of the phyllosphere and cortisphere have a detectable effect on throughfall DSD? What role do epicuticular waxes and hydrophobic substances (like suberin) play in throughfall drop size? Comparing two species with similar surface chemistries but different biophysical structures (and *vice versa*) would permit one to pinpoint the differential effects of surface chemistry and bark structure on throughfall DSD. Both foliar and woody surfaces of many tree species should be examined to link throughfall DSDs to plant traits. This would help demystify some species-specific idiosyncrasies and permit forest or plant functional type models of throughfall DSD.

As surface chemistry and biophysical structure of the phyllosphere and cortisphere changes with stress initiated by insects, fire, ice storms, drought (or other stressor), how does the throughfall DSD respond? Does throughfall DSD change with type and severity of stressor? Which stressors most affect throughfall DSD and how does that affect soil moisture status and fine root development? With the advent of the optical disdrometer and of low cost minirhizotron microscopes, the work of Ford and Deans[113] can be greatly amplified, to determine if, in fact, fine root development mirrors throughfall hot spot locations.

A definitive coupling between throughfall drop size and forest biogeochemical cycles is needed to provide some meaningful conclusions on the effects of throughfall DSD on the genesis of hot spots and the spatial variability thereof, and their corresponding impact on the hydrology and biogeochemistry of the soils. Throughfall collectors should be positioned under optical disdrometers to examine the effects of throughfall DSD on throughfall chemistry to assess the potential for hot spot development. Ideally, such an experiment would employ 100 disdrometers over similar soils with 50 disdrometers coupling throughfall DSD with chemistry and the other 50 examining soil moisture and biogeochemical reactivity in the soil. This way one could parcel the effects of throughfall DSD on chemical input from the canopy and then its impact on the hydrology and biogeochemistry of the soils. Microbial assessments of the soil also could be made as there are no known studies that have linked throughfall DSD with the diversity and functional ecology of soil microbes. The aqueous samples collected should be analyzed by traditional inductively-coupled plasma-mass spectrometry (ICP-MS), fluorescence spectroscopy, isotopes, ^{13}C-nuclear magnetic resonance (C-NMR), and time of flight secondary ion mass spectrometry. This would permit a thorough database on the chemistry

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of throughfall inputs, their relation to DSD, and their impact on hot spot development. While deployment of 100 disdrometers is no small feat, it would allow for a sufficient sample size to provide some meaningful conclusions on the effects of throughfall DSD on fundamental questions relating to the genesis of hot spots and the spatial variability thereof.

Finally, further work needs to be conducted to investigate the existence and magnitude of intraspecific variation of throughfall DSDs. This is especially true with tree age over the course of years as the bark morphology[114] and branch inclination angles[115] change. What species have the largest intraspecific variation? What accounts for the observed variation? Differences in woody surfaces, foliar surfaces, or both? Answers to these questions are important for age distribution management of forests, especially if certain tree ages are found to affect carbon cycling or soil erosion more so than others.

Canopy Structure and Throughfall Drop Size

The study by Nanko et al.[14] showed the effect of canopy state on throughfall drop size. However, it was based on just a single tree species (*Liriodendron tulipifera* L., yellow poplar), which begs the question of whether the presence or absence of foliage significantly affects the throughfall DSD beneath other tree species. Logic dictates that the substantial differences between the biophysical structure and morphology of foliar and woody surfaces would lead to differential throughfall DSDs between foliated and unfoliated states across tree species. Future work is necessary to qualify and quantify the effect of foliage and woody surfaces on throughfall drop size. As such, do other phenophases besides fully leafed and leafless, such as leaf emergence and leaf senescence, exert a differential effect on throughfall drop sizes? Which phenophase produces the largest and smallest throughfall droplets? We make a call for studies that examine the influence of phenophase on throughfall DSDs.

Branch inclination angle was observed to influence the flowpath of intercepted water on branches,[90] and leaf inclination changes in canopy drip size were mathematically estimated.[87] But precisely how does branch inclination angle affect throughfall drop size, if at all? Is there a correlation between woody area index and throughfall DSD? Are there threshold angles at which there are marked shifts in throughfall drop size? How do branch angle and wind interact to affect throughfall drop size? Suffice it to say, future studies are necessary to answer these and many other questions regarding the interactions between branch angle and throughfall drop size. Such studies should take advantage of coupling light detection and ranging technologies (LiDAR), destructive sampling, and optical disdrometers to provide quantitative answers to these and other questions.

Furthermore, spatial variation of throughfall DSD has not been considered without foliage. For leafed trees, Nanko et al.[34] estimated the spatial variation of throughfall drop size under an isolated Japanese cypress tree in an indoor rainfall simulator. Crown length above the measuring point influenced throughfall DSD, whereas the analysis was insufficient to detect the determinant of the spatial variation of throughfall drop size. The spatial variation and distribution of throughfall drop size, both in the leafed and leafless periods, is important information to consider in relation to the distributions of fine roots in the soil,[113] mosses and lichens,[116] water uptake and percolation fluxes,[117] bacterial communities tolerant to moisture stress,[118] surface runoff generation,[76] and splash detachment rates on bare forest floors.[21]

Meteorological Conditions and Throughfall Drop Size

Hydrometeors inherently differ with respect to their interception efficiencies.[119] Rain, for instance, has a higher interception efficiency than sleet. One would expect there to be different throughfall drop sizes and DSDs of free and release (splash and drip) throughfall for different hydrometeors. Studies that quantify throughfall drop size of different hydrometeors are necessary. Of particular interest, is the throughfall DSD for snowmelt-induced canopy drip and how throughfall drop size varies under different snowmelt-induced scenarios. For example, how do snowmelt-induced throughfall drop sizes vary with air temperature? What is the impact of wind and vapor pressure deficit? And, are snowmelt-induced throughfall drop sizes constant over the course of a snowmelt event or do they differ? If so, how? Answers to such questions are important to the development of a more holistic understanding of soil moisture recharge and the possible development of hot spots of biogeochemical reactivity. Given that the routing of canopy drip in tree crowns is complex[120,121] and the fluxes of meltwater in forests during snowmelt is highly variable, even for homogenous deciduous forest stands,[122] it is probable that a better understanding of throughfall drop sizes of snowmelt-induced canopy drip could help to explain the dynamism of vadose zone moisture during episodes of snowmelt and the snow ablation season.

New research needs to examine the effects of differences of intrastorm characteristics on throughfall DSD, particularly with respect to the number of wetting/drying cycles with a given rain event, the number and duration of rainfall lapses during an event, solar radiation inputs, vapor pressure deficit, and wind speed and direction. How are throughfall drop sizes affected by variable lapses in rainfall during a discrete rain event, if at all? Are wind gusts more important than mean wind speeds in altering throughfall drop size? Does the influence of wind speed and direction change over the course of an individual rain event? Do increases in evaporative demand during rain events, due to fluctuations in vapor pressure deficit, impact throughfall drop size? Some findings from Nanko et al.[14] suggest that vapor pressure deficit exerts some influence on throughfall drop size between foliated and unfoliated periods but further research is necessary to see if this observation holds for different tree species during other times of the year.

CONCLUSION

The study of throughfall DSDs is a nascent subject of study. The first known paper to examine throughfall drop size beneath vegetation was conducted in 1948 in an effort to better understand soil erosion processes. Only in the last decade, there has been a dramatic increase in the number of throughfall drop size studies, which have been mostly motivated by a desire to better calculate the kinetic energy of throughfall for soil erosion modeling. Some recent studies, however, have sought to better understand the role of plant surfaces, canopy structure, or meteorological conditions on throughfall DSDs. While a great deal has been learned from these recent studies, we make a call to the broader hydrological sciences community to employ disdrometers in their research to answer many of the unknown questions raised in this review (see section *Knowledge Gaps in Throughfall Drop Size Distributions*: *Future Research Directions*). It is our hope that further research into throughfall DSDs will permit a better understanding of the direct and indirect effects of throughfall drop size on the hydrology, biogeochemistry, and functional ecology of forest ecosystems.

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