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Three Fundamental Challenges to the Advancement of Stemflow Research and Its Integration into Natural Science

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Perspective

Three Fundamental Challenges to the Advancement of Stemflow Research and Its Integration into Natural Science

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Abstract: Plant canopies divert a portion of precipitation to the base of their stems through "stemflow", a phenomenon that influences the canopy water balance, soil microbial ecology, and intrasystem nutrient cycling. However, a comprehensive integration of stemflow into theoretical and numerical models in natural science remains limited. This perspective examines three unresolved, fundamental questions hindering this integration, spanning the canopy to the soil. First, the precise source area within the canopy that generates stemflow is undefined. Thus, we asked, "whence stemflow?" Current common assumptions equate it to the entire tree canopy, a potentially misleading simplification that could affect our interpretation of stemflow variability. Second, we asked what are the various conditions contributing to stemflow generation—beyond rain, to dew and intercepted ice melt—and could the exclusion of these volumes consequently obscure an understanding of the broader implications of stemflow? Third, we explored "whither stemflow?" This question extends beyond how much stemflow infiltrates where, into what uptakes it and from where. Addressing these questions is constrained by current observational and analytical methods. Nevertheless, by confronting these challenges, the stemflow research community stands to make significant strides in comprehending this unique hydrological component and situating it within the broader context of natural science.

Keywords: forest hydrology; ecohydrology; rainfall partitioning; cryosphere; ecology; biogeochemistry

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1. Introduction

The canopy of any plant can intercept precipitation, capturing and channeling a portion of it across the labyrinthine network of leaves and branches towards the ground at its base. This "stemflow" is therefore generated by herbaceous plants in grasslands [1,2], croplands [3,4], rangelands [5], and forest understories [6–8], as well as woody plants in shrublands [9–11], savannas [12], and forests [11,13,14]. Across vegetation types and climatic regions, physical conditions have been identified where stemflow can represent significant fractions of the total precipitation, in some cases exceeding 50% of the total rainfall across the canopy [3,14,15]. As a result, the arrival of stemflow to near-stem soils can provide important or negligible inputs of water, solutes, and suspended organisms belowground. Despite its prevalence and potential significance, stemflow research has historically occupied a niche position within the broader realm of hydrology.

Pioneering work on stemflow dates to the 19th century, notably by forester Carl Eduard Ney. To Ney, canopy water budgets relying exclusively on throughfall (precipitation that drips through gaps and off the canopy) seemed overly erroneous [16]. His 1893 treatise, *On Forests and Springs [Der Wald und die Quellen]*, stated "that there is no doubt, even in pine trees . . . some of the water that initially remains on the leaves and twigs subsequently runs down the tree trunks. This source of error is of the most crucial importance for our question". When Ney attempted to measure stemflow from a beech tree, he was overwhelmed by the unexpectedly voluminous stemflow, which overflowed his collection bins. This increased Ney's concern about stemflow's significance in the canopy water balance. However, just as Ney was gaining momentum, the outbreak of the Franco-Prussian War interrupted his pioneering stemflow study. When he returned, many of his notes on stemflow had been lost [17,18], and another study had beaten his to the presses [19]. Still inspired, Ney persevered in his exploration of stemflow alongside a burgeoning community of foresters through rain, snow, mixed-phase, and dewy conditions [16,20–24].

Nevertheless, as the 20th century dawned, bringing substantial advances in forest hydrology [25,26], fundamental questions about stemflow's role in hydrology and the wider realm of natural science lingered [18]—and stemflow remained a niche interest, often overlooked in canopy water balance measurements [27] or large-scale hydrological modeling [28,29]. After the marked ecohydrological advancements of the following century, natural scientists today still grapple with stemflow on a fundamental level [30], even asking, "should I measure it or not?" Since stemflow cannot be measured everywhere (at least not yet), under what circumstances does stemflow merit attention, and which specific processes within these circumstances are most influenced by stemflow? To unravel the long-standing mysteries of stemflow and guide future research activities, stemflow must be woven into the tapestry of broader theory, for it is at the nexus of broader theory and a researcher's nuanced experience that the most compelling and motivational hypotheses about stemflow's relevance and connections to natural science will emerge.

In discussing stemflow's enduring esoteric nature, we realized that we have each developed playful terms to describe stemflow when engaging new students. Van Stan dubs stemflow the "hipster hydrologic flux", while Pinos calls it the "homeless hydrologic flux". Both monikers hint at stemflow's elusive place in theoretical or numerical hydrological models.

While there is a clear need for this integration, the stemflow community has certainly not been idle. Today, this growing community is rich with empirical observations, as showcased in the comprehensive reviews that synthesize and evaluate stemflow hydrological and biogeochemical data across drylands [10,31], croplands [3,32,33], shrublands [15,34], and forests—both natural [13,15,35,36] and urban [37–39]. Many of these reviews offer a global-scale perspective on the topic [10,11,13,14,34]. Notably, much of these data have been accumulated in the recent decade, reflecting a recent and growing interest in stemflow. Amidst the burgeoning interest, a question looms: Why is stemflow research still limited in its integration with broader natural science? Here, this question is explored by spotlighting and discussing three central challenges (Figure 1) that might be complicating such an integration.

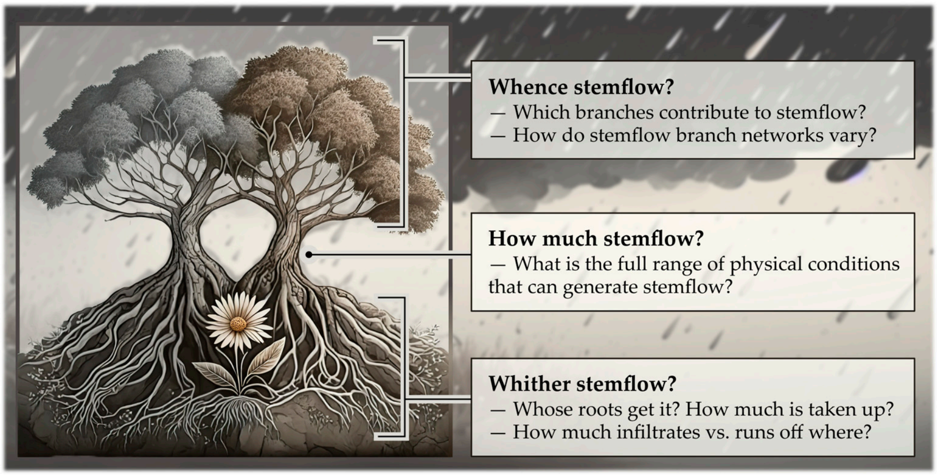

Figure 1. Conceptual illustration depicting the fundamental challenges to advancing and integrating stemflow research into broader natural scientific theory. These three questions span the entire vertical space between stemflow's origins (whence stemflow?) and its fate (whither stemflow?), including the range of physical conditions under which stemflow may be generated. Figure designed using Adobe Firefly (generative AI, Adobe Inc., San Jose, CA, USA) by the authors.

2. Whence Stemflow?

Where does stemflow come from? Where do the *boundaries* of the stemflow-generating system lie, which our ecohydrology community aims to study? While one can confidently assert the intuitive argument that "not every branch in a tree's canopy contributes to stemflow", empirical evidence supporting this argument is lacking. To the best of our knowledge, prior stemflow studies that have sought mechanistic explanations linking canopy architecture and stemflow generation have relied on metrics encompassing the entirety of the tree canopy (see discussions of canopy structural and form metrics in reviews [10,14,15] and applications in recent work [40,41]). Even studies that employed direct, destructive sampling of sapling branches to characterize canopy morphology reported results from the entirety of the tree canopy [42]. Stemflow studies are limited, yet also empowered, by current forest hydrology theory, and these studies have yielded valuable insights. We do not question their results (for their uncertainties have been reported to current scientific standards and are high). Indeed, many of our own past publications suffer from the same limitation (not cited here to avoid self-citation). Rather, we aim to share the perspective that our community's current mechanistic understanding of stemflow ignores a crucial and potentially transformative piece of the puzzle.

As the vegetation canopy intercepts precipitation, it is imperative to discern which branches actively contribute to stemflow and which do not. This subtle distinction is pivotal for contextualizing and interpreting stemflow observations within a broader theoretical context. Regarding interpretation of stemflow observations, delimiting the boundary of a system enanbles robust inferences about the causal relationships between the system's internal components and its emergent output, i.e., understanding the relationship between the stemflow "watershed" and the consequent stemflow flux. Without a clear boundary, many conflicting variables may cloud one's interpretation (and likely has). By constraining the stemflow-generating canopy boundary, we can therefore improve interpretative clarity. This enhanced clarity can open the door to revolutionize our understanding and prediction of stemflow's ecohydrological roles at both the individual and stand scales, potentially uncovering new dynamics previously obscured by broader, canopy-wide metrics. Such nuanced insights could refine our ecological models (i.e., what stemflow-reliant epiphyte communities colonize where in the canopy) and, where stemflow represents a significant portion of precipitation supply, could inform forest management strategies and conservation efforts. As we move forward, innovative methodologies, perhaps leveraging advancements in remote-sensing or real-time monitoring, could pave the way for these more granular observations, ushering in a new era of precision in stemflow research.

Stemflow watershed boundaries are also critical for contextualizing our empirical observations, which consist of volumes (L tree^{-1} storm^{-1}). By predominantly considering the entire canopy area in our calculations, the derived stemflow yields (mm storm^{-1}) can be under-represented. We argue that if stemflow originates from a smaller portion of the canopy area, its yield can be significantly larger than reported values. Such discrepancies have positioned stemflow values at the brink of what some may deem "negligible" enough to ignore (often <5% of total rainfall [13,43]). This potential underestimation might have cascading ecohydrological implications. First, omitting or underestimating stemflow's significance in canopy water budgets can introduce biases in our assessments of other individual hydrological processes (such as throughfall, evaporation, and canopy water storage) and consequently the accuracy of hydrologic models [14,44]. This could lead to flawed water budget estimations and consequently skew our understanding of the broader water dynamics in vegetated ecosystems. Secondly, by not accurately gauging stemflow's portion in gross precipitation, we might inadvertently downplay its importance in biogeochemical cycling, soil moisture replenishment, and the sustenance of certain epiphytic and ground-layer communities that rely heavily on stemflow as a water source [30,45–47].

Consider the following scenario in an urban environment: A tree row stretches along a bustling city street, characterized by managed mature trees with nearly uniform characteristics and an average projected canopy area of 100 m^2 tree^{-1}. An ecohydrologist with a special interest in urban environments is intrigued by the potential stormwater ecosystem services provided by such urban tree rows. (The significance of urban tree rows in mitigating stormwater runoff, enhancing water quality, and thereby potentially alleviating the burden on urban drainage systems is currently thought to strongly merit attention [37,48]). The scientist is undecided regarding the relevance of stemflow to the project. They are aware that stemflow, while seemingly a small component, might play a larger role in directing and concentrating rainwater around the tree base. For the purposes of the project, a benchmark is set: if stemflow accounts for >5% of the total rainfall received by the tree, it is deemed significant and warrants a more detailed investigation. After 25 mm of rain falls on the city, the researcher diligently collects data and finds that each tree, on average, produced a stemflow volume of 100 L. Employing the traditional calculation methods, stemflow yield is 1 mm or 4% of the 25 mm storm. At first glance, stemflow seems negligible. However, what if only a fraction of the canopy, say 40% (or 40 m^2), generates stemflow? With this information, stemflow yield from its actual drainage area becomes 2.5 mm, jumping to 10% of gross rainfall, far exceeding the benchmark set for relevance in the study.

After recognizing the relevance of stemflow, the ecohydrologist now poses the curious question: what if these trees are, like many other urban trees, planted in small sidewalk openings, with compacted soils, and surrounded by impervious surfaces? The decision to ignore stemflow might, thereby, ignore a source of runoff and potential nutrients. We deliberately selected this urban context, for the potential overattribution of this stemflow to interception loss could cause greater errors than simply enlarging the ecoservice estimation of canopy-related stormwater reductions. In urban settings, where precision can have implications for stormwater management practices, design of green infrastructure, and urban water policy, such nuances can be critical. As the thought experiment suggests, a mere shift in perspective—accurately identifying stemflow source areas—can drastically alter our conclusions and subsequent decisions.

3. How Much Stemflow Is There?

Stemflow observations are primarily collected during rainfall events worldwide; however, stemflow can be generated under a wider range of conditions. The research community has acknowledged the importance of these other conditions and has dedicated some effort to their study. Stemflow observations from fog or cloud deposition in forests have been reported across geographically diverse settings, including the Middle East [49], South America [50], the South Pacific [51,52], and Asia [53]. But, the stemflow generated from condensation [5,16,54], the melt of intercepted ice and snow [55–57], and mixed precipitation [58] has very rarely been reported (citations provided are the only studies known to the authors) but it may occur more often than assumed. Acquiring this type of data poses a significant challenge due to the complexity of the instruments required, their maintenance, and the demanding conditions for achieving fine-resolution field monitoring.

Regarding condensation, dew-related stemflow from smaller plants with canopies well suited to dew collection may generate additional water supplies at volumes relevant to water needs [5,54,59,60]. In arid landscapes, dew (and fog) harvesting by vegetation can be important for survival and in community-level plant interactions [59,60]; however, even in more humid settings, plants have been observed to generate dew-related stemflow [5,54]. Shure and Lewis [54] estimated an additional ~1 L m^2 $night^{-1}$ of dew-related stemflow for *Ambrosia astemisiifolia* (common ragweed) in humid temperate conditions (NJ, USA). The canopy morphological adaptation of ragweed for dew collection enables additional stemflow inputs, potentially providing a niche advantage as an invading weed, especially "during dry periods when soil moisture becomes a serious limiting factor" [54]. Condensation drainage as stemflow was unexpectedly significant (interquartile range of ~0.5–1.0 L m^{-2} per dew event) for another herbaceous plant in humid subtropical conditions (GA, USA), *Eupatorium capillifolium* (dogfennel) [5], where it too was hypothesized to play a role in competition among rangeland plants and aid the expansion of this weed, to the detriment of cattle.

While the significance of dew-related stemflow in smaller plants is emerging, the scenario is markedly different for larger flora. For larger shrubs and trees, the only data available (from Ney in 1893 [16]) suggest that condensation-related stemflow is modest, if not negligible. However, it is essential to recognize that even modest contributions of condensation to bark water storage can significantly impact stemflow generation. The large inter-storm variability observed in the amount of rainfall required to initiate stemflow from study trees [44] could, in part, be influenced by the degree to which condensation has filled bark pore spaces. For instance, rainstorms following night-time condensation events might lead to a more rapid generation of stemflow (and consequently a greater fraction of stemflow per gross rainfall). Misinterpreting the correlation between water fluxes (rain vs. stemflow yield regressions [44]) could result from this, leading to inferred bark water storage capacity estimates being lower than the actual value. Recent research underscores the importance of pre-event filling and emptying of bark water storage through humidity-related mechanisms [61,62]. This emphasizes the need to investigate the role of dew and condensation contributions, which may be just as crucial as hygroscopic water, to bark water storage in larger plants. Thus, a holistic understanding of all moisture sources and their interactions in shaping stemflow dynamics is sorely needed. Still, how many smaller plants in how many other settings likely generate (and benefit) from this rarely sought for water input? How much of this water do they generate and what functions might it play in their ecological niche?

In areas experiencing icy precipitation, the dynamic interplay between a tree's internal heat—bolstered by thermal transfer from the ground—and its bark albedo presents a significant, yet often overlooked, mechanism for the genesis of stemflow. In fact, current snow models assume no intercepted snow melts from the canopy below freezing [63]. Still, a thermal gradient at the interface between tree bark and any accumulated ice or snow can facilitate the localized melting of intercepted icy precipitation, even when ambient temperatures remain below freezing [55]. Based on limited observations on this subject, it is estimated that snowmelt-related stemflow may reach 5–10% of the incident precipitation [55,57], inputting concentrated meltwaters at the stem base. During ice storms that swathe trees in a thick sheath of ice, the melt likely initiates at the ice–bark boundary. Given the encasement, this meltwater becomes entrapped, with the ice acting as a natural funnel, ensuring the meltwater's primary drainage is down the stem and to the tree's base.

While this peculiar phenomenon has been serendipitously observed (and appreciated) by internet naturalists (https://imgur.com/hgemi5E (accessed on 22 December 2023); also available in the Supplemental Materials), it has not been formally studied to the best of our knowledge. An improved accounting of this (potentially) ~10% of intercepted snow (which can represent dozens of mm in snow-water equivalents [64]) may refine our understanding of forest hydrology during winter months.

Finally, maybe we are also missing a meaningful amount of stemflow in the rain? There are few studies reporting stemflow observations under high (or extreme) rainfall conditions [65]; yet, many vegetated ecosystems now face increasing intensities under hydrologic intensification [66–68]. Some trees, generally reported to be low stemflow generators under standard conditions, may generate significantly more stemflow during episodes of intense or extreme rainfall [69]. The storage capacity of tree bark, typically sufficient to intercept and gradually release water during normal rainfalls, can be quickly exceeded during downpours [70]. When this happens, the sheer volume of water inundating the tree canopy could bypass traditional interception pathways (i.e., low or no flow resistance) and be funneled directly down the stem, substantially increasing stemflow volumes. Could the hydrological intensification effects of climate change, in reducing the magnitude of rainfall interception [70], increase the magnitude of stemflow? If so, stemflow research would gain increased prominence within the natural sciences in a warming world.

This phenomenon suggests that our current understanding of stemflow may be based on a limited spectrum of rainfall conditions. Of course, it may be that many studies do not report stemflow values during extreme events as the intense volume of water often surpasses the collection capacity of standard gauges or exceeds the recording limits of automated monitoring systems (a challenge faced by the first empirical stemflow study that persists to this day). If these intense rainfall events, though perhaps less frequent, contribute significantly to the overall volume of stemflow over time, then our models and predictions could be underestimating the true role of stemflow in forest hydrology. To gain a comprehensive understanding, researchers focused on rainfall events should prioritize stemflow monitoring and analysis during these extreme events (with caution due to the potential risks extreme weather poses), ensuring we are not missing critical data points in the broader narrative of stemflow dynamics.

4. Whither Stemflow?

Where does stemflow at the soil surface actually go? Traditional methods of measuring and monitoring stemflow typically redirect its course—diverting it from the bark surface—at breast height into a collection bin or through a tipping bucket (see photographs in reviews [14,15]). While such practices are necessary to achieve various research objectives, they inadvertently obscure the natural path of stemflow after it drains from the tree stem to the surface. This leaves those interested in stemflow's relevance and role in broader natural processes with a myriad of intriguing questions surrounding its ultimate fate and ecological impact. How much stemflow infiltrates under which conditions? Which, if any organism, benefits from stemflow? Is stemflow a self-sustaining mechanism where a tree effectively waters itself, or does it serve broader ecological functions? And, does the setting (e.g., urban, plantation, and natural forest) influence the answer to these questions?

In natural forest settings, preferential infiltration of stemflow along coarse roots and macropores has been documented using geophysical methods, like ground-penetrating radar and electrical resistivity tomography [71,72], high-resolution spatiotemporal monitoring via soil volumetric water content probes [73,74], tracing dyes [73,75,76], and a combination of these approaches [71,73]. Even in agriculture, such as with potatoes, similar deep infiltration patterns have been observed [4]. Despite this growing but limited knowledge of stemflow's underground pathways in natural forests, the beneficiaries of stemflow-related soil moisture remain largely unknown. Under undisturbed soil conditions, it is plausible that a tree rarely, if ever, directly benefits from its own stemflow, for the soil of a natural forest can have a dense network of roots from trees and understory vegetation [47,77]—a scenario that suggests intense competition for soil water resources. This phenomenon, root closure, implies that stemflow, once it infiltrates the ground, could be swiftly appropriated by nearby vegetation. In contrast, within urban landscapes where trees are solitary figures against a concrete backdrop and their root networks are isolated [78,79], a tree might be more reliant on its stemflow, as evidenced by Smith et al. [80]. Paradoxically, stemflow may be less available in an urban setting due to altered soil characteristics, which might impact the infiltration dynamics and water availability (see our earlier discussion regarding urban stemflow in Section 2).

Saving the most speculative and thought-provoking topic of this perspective until the end: if plants take up their stemflow, might this uptake vary with a plant's developmental stage? Juvenile trees, with more shallow and localized root systems, may be more adept at harnessing their own stemflow. Then, as trees mature and their roots expand laterally and vertically, they may become less dependent on their stemflow. Alternatively, stemflow from one tree could benefit nearby juveniles and other herbaceous understory plants (influencing understory plant patterns [81]) or nonvascular vegetation, like the bryophytes often observed on the base of trunks and the surrounding area. In smaller plants, particularly those rooted in the parched soils of arid regions (e.g., nebkha), stemflow may assume a more critical role [82]. Plants that capture dewfall as stemflow, like those discussed in our previous section, might employ stemflow as a survival mechanism to avoid xylem cavitation during drier seasons or conditions, maximizing every possible source of moisture.

Finally, the journey of stemflow likely not only satisfies the water needs of plants but also provides hydration to a diverse array of detritivorous macrofauna [83] that aid in litter decomposition [84], soil microbial communities [46] that perform key nutrient cycling functions [85], lichens [86], and canopy fauna [87–90]. Ultimately, understanding the fate of stemflow and its interactions in the plant–soil system demands a multidimensional approach, factoring in the ecological context and the unique life history of study plants.

5. Conclusions

To take full advantage of the creative opportunities afforded us by this perspective format—and inspired by the first stemflow observer being a poet and naturalist (Carl Eduard Ney)—we conclude with a poem.

*On Springs in the Forest**
*[*The opposite of Ney's 'Der Wald und die Quellen']*

The water cycle is built drip-by-drip,
by the ways that we encounter it.
On land our senses, literal,
study states and flows, terrestrial.
From the heavens, be it sky or space,
we also sense by GOES and GRACE.

But some water, the plants still hide,
between our Earthen and Heavenly eyes.
In branches aloft, mysteries abide,
where stemflow's secrets still reside.

Like, whence really comes this rivulet—
which branches might deliver it?
'Tis not from all that stemflow springs.
To fathom this, one must have wings:
either sprouted from our imagination
or through technological innovation. . .
though, perhaps the best wings spring from their collaboration.

And, what's its range of physical conditions—
is sub-zero stemflow mere speculation?
Might there be a bark–energy interplay
that challenges what we think today,
bathing stems in melt or the dawn's dewy display?

Then, whither does this water go—
is it destined for the roots below?
If so, who grasps its fleeting tide?
The tree, its neighbors, or a weed beside?
What portion drains past into the deep?
And does all this change, site by site, week by week?

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16010117/s1, Video S1: Ice melt-induced stemflow underneath a layer of ice surrounding a tree.

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