Commentary: What We Know About Stemflow’s Infiltration Area

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A Commentary on

What We Know About Stemflow’s Infiltration Area
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INTRODUCTION

Stemflow represents the portion of precipitation routed by vegetation to the base of tree boles or plants stems. Van Stan and Allen (2020) (herein referred to as VS&A) is a mini review of studies that have attempted to quantify the infiltration area of stemflow once it has reached the soil surface, $I_T$. More specifically, VS&A provide an overview of: (i) the ability of vegetation canopies to funnel rainfall; (ii) the various approaches used to estimate or measure the size of $I_T$; (iii) the different soil properties that may influence the magnitude of $I_T$, and (iv) the potential for and limitations to using dye and stable isotope tracers in $I_T$ research. The objectives of this commentary are to: (i) highlight and expand upon important points raised by VS&A in order to advance the understanding of the controls regulating the size of $I_T$, and (ii) provide corrections to and clarification of prior $I_T$ results presented in VS&A.

ADVANCEMENT OF THE SCIENTIFIC UNDERSTANDING OF STEMFLOW INFILTRATION AREA, $I_T$

VS&A state the importance of stemflow in the hydrology and biogeochemistry of vegetated environments is dependent upon $I_T$ size. These authors rightfully note that there is a need for further research, especially in natural forest systems, to characterize the size of $I_T$. Previous studies (e.g., Iida et al., 2005; Chinen, 2007) have estimated the magnitude of $I_T$ using litter marks (the
displacement of leaf litter) or soil scour marks caused by the excess overland flow of stemflow. As VS&A state, litter and scour marks are difficult to interpret quantitatively as they neither represent mean nor maximum $I_T$ for a given storm. As such, litter and scour marks have little utility estimating $I_T$.

VS&A correctly state that factors, such as soil hydrophobicity, could influence stemflow infiltrability in certain environments. Nonetheless, the methodology of Herwitz (1986), in which $I_T$ values are derived by dividing the stemflow volumetric input rate by the infiltration capacity of the surface soil (i.e., the saturated hydraulic conductivity, $K_{sat}$), remains a theoretically sound approach. What is important to highlight is that in situ measurements of $K_{sat}$, as a surrogate for stemflow infiltrability in the proximal bole/stem area that include the effect of macropore flow (i.e., $K_{sat}$ measured with no tension; hydraulic head = 0 cm) are likely to be more representative of the actual infiltrability of stemflow than $K_{sat}$ measured using tension or $K_{sat}$ values derived from pedotransfer functions [e.g., ROSETTA model—Schaap et al. (2001)], which estimate soil matrix $K_{sat}$.

CRITIQUE OF REPORTED FORMULA AND FINDINGS OF PREVIOUS RESEARCH

VS&A (page 1) suggest that the following equation (Equation 1 in VS&A) is the funneling ratio derived by Herwitz (1986):

$$ F = \frac{S_T}{P \cdot I_T} $$

(1)

where $F$ is the funneling ratio (dimensionless), $S_T$ represents stemflow volume (L tree$^{-1}$), $P$ is precipitation depth (mm), and $I_T$ is the stemflow infiltration area (m$^2$ tree$^{-1}$).

The funneling ratio proposed by Herwitz (1986), however, differs from that of Equation (1) in that the basal area of the tree bole, $B$ (m$^2$), rather than $I_T$, is multiplied by $P$ in the denominator of the equation:

$$ F = \frac{S_T}{P \cdot B} $$

(2)

VS&A (page 2) also suggest “...Herwitz’s (1986) equation for $F$ employs the concept of $I_T$...”; however, Herwitz (1986) never advocated that $B$ was a surrogate for $I_T$ or that $B$ played any role in $I_T$ size. Instead, and as aforementioned, Herwitz (1986) derived $I_T$ by taking the stemflow input rate and the infiltration capacity of the surface soil into account, and the derived values of $I_T$ were markedly different than $B$.

VS&A (page 3) cite various studies supporting their claim that "there are pieces of evidence that suggest that $I_T$ is larger, 10$^{-1}$ to 10$^4$ m$^2$, than the areas assumed elsewhere, e.g., 10$^{-4}$-10$^{-1}$ m$^2$ (Iida et al., 2016; McKee and Carlyle-Moses, 2017; Carlyle-Moses et al., 2018)”. Iida et al. (2016) make no mention of $I_T$ (or stemflow) and it is unclear why this study was cited. Furthermore, the range of $I_T$ provided by Carlyle-Moses et al. (2018) is for conditions of average rainfall / stemflow input rates within mature, natural forests. They are not representative of extreme precipitation events (e.g., Herwitz, 1986) nor orchards or agricultural fields (e.g., Keen et al., 2010) where soil compaction may reduce stemflow infiltrability.

Table 1 of this commentary expands on Table 1 of VS&A to illustrate a fuller range of $I_T$ reported in the literature and provides corrections and / or clarifying statements to some of the results presented in that table. Table 1 of this commentary shows that assessments of $I_T$ under a variety of rainfall, soil, and plant morphological conditions are lacking. The majority of prior studies report the maximum extent of $I_T$ (e.g., Voigt, 1960; Pressland, 1973) or use “litter marks” or erosional soil scouring for estimating $I_T$ (e.g., Iida et al., 2005; Chinen, 2007) which simply do not provide reliable quantitative evidence of average $I_T$. Litter marks may be seasonal and are at least episodic phenomena persisting across events (e.g., Iida et al., 2005). Litter marks are not created during low intensity events (as stated by VS&A) but rather during peak periods of heavier rain with high stemflow funneling. What does emerge from Table 1 is that studies conducted thus far using in situ dye experiments and direct observations of stemflow infiltration or studies utilizing physically-based approaches such as dividing the stemflow input rate by the soil $K_{sat}$ suggest that $I_T$ associated with average rainfall and stemflow rates are limited < 1 m$^2$ tree$^{-1}$ in environments (e.g., mature, natural forests) where the soil infiltrability can be expected to have a magnitude of order of 1 x 10$^2$ or 1 x 10$^3$ mm h$^{-1}$. Additionally, the findings presented in Table 1 suggest that $I_T \geq 1$ m$^2$ tree$^{-1}$ may sometimes arise during large / extreme rainfalls and stemflow rates in these forest environments and under relatively smaller rainfall and stemflow rates in environments (e.g., agricultural plantations, orchards, agroforestry areas, and urban environments) where infiltrability is likely < 1 x 10$^2$ mm h$^{-1}$.
Empirical Extrapolation

Stemflow Rate divided by K

\[ \frac{I_f}{K} \]

\[ (Dye \ Experiment) \]

\[ \text{Direct Observation} \]

\[ \text{Herwitz (1986)} \]

\[ \text{Gonzalez-Ollauri et al. (2020)} \]

\[ \text{Carlyle-Moses et al. (2018)} \]

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\[ \text{Aboal et al. (1999)} \]

\[ \text{Durocher (1990)} \]

\[ \text{Gonzalez-Ollauri et al. (2020)} \]

\[ \text{Herwitz (1986)} \]

\[ \text{Schwärzel et al. (2012)} \]

\[ \text{Setting and study Method} \]

\[ I_f (m^2 \text{ tree}^{-1}) \]

\[ I_f \text{ Measurement type} \]

\[ \text{Additions, corrections and/or clarifications to VS&A} \]

\[ \text{FORESTS AND FOREST PLANTATIONS} \]

\[ \text{Aboal et al. (1999)} \]

\[ \text{Empirical Extrapolation} \]

Stemflow sampled for 30 trees representing 6 tree species within a laurel forest, Canary Islands. A single \( I_f \) for each species was derived by extrapolating empirical relationships put forth by Tanaka et al.; Tanaka et al. (1991; 1996). Mean basal areas of the 6 species ranged from 1.5 \( \times 10^{-3} \) to 9.1 \( \times 10^{-2} \) m².

\[ 0.277–0.722 \]

\[ \text{Range of annual maximum} I_f \text{ values for individual trees} \]

\[ \text{Addition: Not Included in VS&A} \]

\[ \text{Carlyle-Moses et al. (2016)} \]

\[ \text{Dye Experiment} \]

Juvenile pine plantation in British Columbia, Canada. Dye tracer was used at the base of nine small lodgepole pine trees (basal area range = 1.80 \( \times 10^{-3} \) to 3.14 \( \times 10^{-2} \) m²) during each of three rain events (5.9 to 16.0 mm).

\[ 0.0017 \]

\[ \text{Average} I_f \text{ value for all trees across 3 rain events} \]

\[ \text{Correction:} I_f \text{ values presented by VS&A for this reference are the tree basal area values.} \]

\[ \text{Carlyle-Moses et al. (2018)} \]

\[ \text{Stemflow Rate divided by} K_{sat} \]

Lowland tropical forest, Cambodia. \( I_f \) estimated as mean stemflow rate (0.853 L h\(^{-1}\)) divided by measured \( K_{sat} \) of 531 mm h\(^{-1}\). 130 rain events totaling 1500.9 mm.

\[ 0.0016 \]

\[ \text{Average annual} I_f \text{ value for all trees} \]

\[ \text{Addition: Not Included in VS&A} \]

\[ \text{Carlyle-Moses et al. (2018)} \]

\[ \text{Stemflow Rate divided by} K_{sat} \]

Global mature, natural forests. \( I_f \) estimated from mean stemflow rates (0.1 to 7.7 L h\(^{-1}\)) from 16 studies conducted in natural forests and the typical range of \( K_{sat} \) in mature forests (100 to > 1,000 mm h\(^{-1}\)).

\[ 0.0001–0.1 \]

\[ \text{Range of average annual or season-long} I_f \text{ values for all trees} \]

\[ \text{Addition: Not Included in VS&A} \]

\[ \text{Durocher (1990)} \]

\[ \text{Direct Observation} \]

Stemflow was measured from 14 trees within a red oak plantation that also contains sweet chestnut. Mean basal area of trees in the study plot was 3.14 \( \times 10^{-2} \) m². Measured \( K_{sat} \) of soil (micropores + macropores) averaged 713 mm h\(^{-1}\).

\[ \text{Stemflow directly infiltrated adjacent to trees due to high infiltrability of soil.} \]

\[ \text{Average season-long} I_f \text{ value for all trees} \]

\[ \text{Addition: Not Included in VS&A} \]

\[ \text{Gonzalez-Ollauri et al. (2020)} \]

\[ \text{Dye Experiment} \]

Blue dye was applied to the downslope sides of two sycamore trees in Aberdeenshire, UK using a 20-L backpack sprayer for 35 min resulting in an equivalent rainfall intensity of 45.7 mm h\(^{-1}\) to identify areas of double-funneling. It should be noted that the authors describe the precipitation at the site as being characterized by frequent, low-intensity rain events. The two trees were part of a stand of trees found on a 20.3 ± 11.6° slope. \( K_{sat} \) of the soil was 256 mm h\(^{-1}\).

\[ \text{No data} \]

\[ \text{Correction: VS&A state that, based on correspondence with the corresponding author of the article, the dye extended 1.27 and 0.63 m downslope of the two study trees. VS&A use the distance the dye extended downhill as the radius of the} I_f \text{ areas; however, the dye stained} I_f \text{ areas are clearly not circular and occupies only a fraction of the areas suggested by VS&A [see Figure 2B. of Gonzalez-Ollauri et al. (2020)].} \]

\[ \text{Herwitz (1986)} \]

\[ \text{Stemflow Rate divided by} K_{sat} \]

Stemflow measured from eight trees (basal area range = 4.9 \( \times 10^{-2} \) to 1.82 \( \times 10^{-2} \) m²) in a tropical rainforest of Australia during a 51.6 mm rainfall with a duration of 42 minutes (mean intensity = 73.7 mm h\(^{-1}\)). \( K_{sat} \) was measured at 372 mm h\(^{-1}\).

\[ 0.13–1.52 \]

\[ \text{Range of} I_f \text{ extents for individual trees for a single extreme rain event} \]

\[ \text{Clarification: During an extreme period of the storm when 11.8 mm of rain fell over 6 min (intensity = 118 mm h}\(^{-1}\)),} I_f \text{ expanded to a maximum of 3.09 m² tree}^{-1}, \text{the maximum} I_f \text{ listed by VS&A for this study.} \]

\[ \text{Schwärzel et al. (2012)} \]

\[ \text{Dye Experiment} \]

Applied 180 L of simulated stemflow over a 180-min period (60 L h\(^{-1}\)) to a single European beech tree in Germany. Used dye to determine \( I_f \). It should be noted that the non-water repellent leaf litter was removed around the tree and the soil surface was sprayed with water. \( K_{sat} \) measured in the field was 997 mm h\(^{-1}\).

\[ 0.245 \]

\[ \text{} I_f \text{ extent for a single simulated event value for an individual tree} \]
TABLE 1 | Continued

| Setting and study | Method | $I_F$ (m² tree⁻¹) | $I_T$ Measurement type | Additions, corrections and/or clarifications to VS&A |
|-------------------|--------|------------------|------------------------|--------------------------------------------------|
| Tischer et al. (2020) | *Dye Experiment* | 0.023 beech | Maximum extent of $I_T$ for one European beech and one sycamore maple tree over a 3-week period | Addition: This is a newly published study and was not available to VS&A |
| | Trunk area of one European beech (BA = 1.37 x 10⁻¹ m²) and one sycamore maple (BA = 1.40 x 10⁻¹ m²) was dye-stained in advance. Stemflow patterns and $I_F$ were visually quantified following natural rain events of < 4.2 to 7.8 mm h⁻¹ (± 23.2 mm 3 weeks⁻¹) | 0.041 maple | | |
| Voigt (1960) | *Direct Observations* | 0.25 red pine | Maximum annual extent of $I_T$ values for all trees of a given species | Correction: The 1960 paper cited by VS&A and listed in the reference list is incorrect. The proper 1960 Voigt reference is cited in this paper. |
| | Stemflow from 7 trees in each of three forest types (red pine, hemlock, and beech) was measured. Basal areas of trees ranged from an average of 1.82 x 10⁻² m² for the beechees to 4.57 x 10⁻² m² for hemlock. Rainfall conditions were not provided. | 0.44 beech | | |
| | | 0.52 hemlock | | |

**SAVANNA AND SHRUBLAND**

| Study | Method | $I_F$ (m² tree⁻¹) | $I_T$ Measurement type | Additions, corrections and/or clarifications to VS&A |
|-------|--------|------------------|------------------------|--------------------------------------------------|
| Chinen (2007) | *Erosional Scour Marks and Rills* | 0.03 | Maximum extent of $I_T$ for all trees across all rain events (maximum rain depth = 52 mm) | |
| | The extent of scour marks, including rills, were measured and assumed to be associated with stemflow produced during an intense rainfall from three tree species occupying an immobile sand dune in the Republic of Niger. The rainfall depth was 20.7 mm rainfall in which the bulk of the rain fell within 20 mm (intensity c. 60 mm h⁻¹). | | | |
| Návar (2011) | *Direct Observations* | 0.10–1.14 | Range of maximum $I_T$ extents for individual trees over 18 months | |
| | Stemflow infiltration area monitored for several Tamaulipan thornscrub shrub species and temperate tree species in northeastern Mexico over 18 months. | | | |
| Pressland (1973) | *Direct Observations* | 0.03 | Maximum extent of $I_T$ for all trees across all rain events (maximum rain depth = 52 mm) | |
| | Arid woodland, stemflow from 28 sampled trees (basal area range = 2.6 x 10⁻³ to 1.0 x 10⁻¹ m²), was found to represent 18% of rainfall with individual rainfall events ranging from 0.25 to 120 mm. | | | |
| Pressland (1976) | *Direct Observations* | No data | | |
| | Arid woodland in proximity to where the Pressland (1973) study took place. Stemflow was not measured, but stemflow infiltration was observed during rainfall events. | | | |

**AGRICULTURAL PLANTATIONS, ORCHARDS AND AGRO-FORESTRY**

| Study | Method | $I_F$ (m² tree⁻¹) | $I_T$ Measurement type | Additions, corrections and/or clarifications to VS&A |
|-------|--------|------------------|------------------------|--------------------------------------------------|
| Charlier et al. (2009) | *Model Simulation* | No data | | |
| | Simulated versus observed runoff from a banana plantation plot with an average Ksat between 67 and 75 mm h⁻¹ was estimated for 18 rain events ranging from 10.0 to 139.2 mm with mean intensities of 11.0 to 47.2 mm h⁻¹ and maximum 5-min intensities of 45.6 to 144.0 mm h⁻¹. The study evaluated if inclusion of stemflow in the models improved simulation results. | | | |
| Gómez et al. (2002) | *Stemflow Rate divided by Ksat* | 0.108 | Average $I_T$ value for three trees over 12 rain events | |
| | Stemflow measured from three mature olive trees (mean basal area of 5.3 x 10⁻² m²) in an orchard situated in Spain. $I_T$ estimated as mean stemflow rate divided by measured $K_{sat}$ of 81 mm h⁻¹. | | | |

(Continued)
**Summary** In all but a few extreme rainfall events, \( I_T < 1 \text{ m}^2 \text{ tree}^{-1} \) under average conditions for forested ecosystems. There is no compelling evidence to indicate otherwise. For agricultural and urban settings with soil compaction average \( I_T \) could be larger than 1 m\(^2\) in some cases but convincing evidence is lacking at this juncture. More work is necessary to quantify \( I_T \) for a range of ecosystems, especially different forest types.

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**TABLE 1**

| Setting and study | Method | \( I_T \) (m\(^2\) tree\(^{-1}\)) | \( I_T \) Measurement type | Additions, corrections and/or clarifications to VS&A |
|-------------------|--------|-------------------------------|-----------------------------|---------------------------------------------------|
| Keen et al. (2010) | Litter Marks | 18 to 19-year-old oil palm plantation in Malaysia. \( I_T \) determined using the litter mark method for 30 trees in which the extent of bare dark areas around the base of trees was assumed to be created by stemflow. | 6.8–11.8 | Range of maximum \( I_T \) values. No time scale provided. |
| Rashid and Askari (2014)/Rashid et al. (2015) | Litter Marks | 18 to 19-year-old oil palm plantation in Malaysia. \( I_T \) determined using the litter mark method for 30 trees in which the extent of bare dark areas around the base of trees was assumed to be created by stemflow. | 2.1 | Maximum \( I_T \) extent for any tree over 16 months |

**URBAN**

| Iida et al. (2005)* | Litter Marks | Litter mark extents for 16 trees within the University of Tsukuba campus, including Formosa sweet gum and two species of evergreen oaks, were measured in March 2005. Stemflow input rate and \( K_{sat} \) were not reported. | 0.36–1.22 (Average = 0.81) | Range (and average) of maximum \( I_T \) extents for 16 trees for a single 88.5 mm rain event |

**Summary** In all but a few extreme rainfall events, \( I_T < 1 \text{ m}^2 \text{ tree}^{-1} \) under average conditions for forested ecosystems. There is no compelling evidence to indicate otherwise. For agricultural and urban settings with soil compaction average \( I_T \) could be larger than 1 m\(^2\) in some cases but convincing evidence is lacking at this juncture. More work is necessary to quantify \( I_T \) for a range of ecosystems, especially different forest types.

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*The statements in VS&A \( I_T > 1 \text{ m}^2 \text{ tree}^{-1} \) has been reported under low rainfall intensity, 1–2 mm h\(^{-1}\) and *photographs of litter marks showing \( I_T = 0.4 \text{ to } 1.3 \text{ m}^2 \text{ tree}^{-1} \) under non-extreme precipitation conditions* cannot be derived from or substantiated by Iida et al. (2005) as the litter marks were formed during an earlier 88.5 mm rain event when the maximum intensity of 9.5 mm h\(^{-1}\) was reached, not during portions of that event with lower rain intensity. In addition, the 22-23 March, 2005 event only created limited ponding close to the tree trunk (Figure 4, Iida et al., 2005) when rain intensity was 1.5 mm h\(^{-1}\) and no litter was displaced during the entire storm, despite a maximum intensity of 6.5 mm h\(^{-1}\). As a comparison, \( I_T \) values of 0.34 and 0.30 m\(^2\) were calculated based on a maximum stemflow intensity of 1,100 cm\(^{3}\) (30\text{s}^{-1}) and average infiltration capacities of 383 and 441 mm h\(^{-1}\) for two Formosa sweet gum trees (Iida et al., unpublished data).

**Clarification:** From Figure 1 of Rashid and Askari (2014) no leaf litter can be seen. Since bare areas around the base of trees may be caused by a variety of factors (allelopathy, competition, herbicide use) and because stemflow was not measured nor were direct observations of stemflow induced overland flow made during this study, there is no definitive proof that these dark, bare areas were caused by stemflow or represent \( I_T \). \( I_T \) values provided in Table 1 of VS&A are not correct (those are the diameters at the tree base) and ranged from 18.1 to 39.2 cm with an average of 28.6 cm. Also see Table 1 footnote 7.

**Clarification:** All marks except for one indicated that \( I_T < 1 \text{ m}^2 \). The infiltration area marks generated by stemflow associated with the 2.0 mm rainfall are not to be confused with litter marks or erosional scour marks that may be formed during high stemflow funneling episodes. Also see Table 1 footnote 7.

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AUTHOR CONTRIBUTIONS

DC-M was the primary author of the manuscript and a co-originator of the commentary. SI contributed to the text and was a major contributor to the table. SG and PL contributed to the text of the paper, making several editorial changes and suggestions. SG also played a major role in the revision, reconfiguring the table into final form. BM contributed to the text and contributed to the table. KN contributed ideas to the text. AT contributed ideas to the text and contributed to the table. TT contributed to the text. DL contributed to the text, the table and was a co-originator of the commentary. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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