



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):

$$F = \frac{S_T}{P \cdot I_T} \quad (1)$$

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

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:

$$F = \frac{S_T}{P \cdot B} \quad (2)$$

VS&A (page 2) also suggest that "... 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 $10^1 m^2$, 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 $< 1 m^2 \text{ tree}^{-1}$ in environments (e.g., mature, natural forests) where the soil infiltrability can be expected to have a magnitude of order of 1×10^2 or $1 \times 10^3 \text{ mm h}^{-1}$. Additionally, the findings presented in **Table 1** suggest that $I_T \geq 1 m^2 \text{ tree}^{-1}$ 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 $< 1 \times 10^2 \text{ mm h}^{-1}$.

TABLE 1 | Stemflow infiltration areas (I_T) from previous research.

Setting and study	Method	I_T ($\text{m}^2 \text{ tree}^{-1}$)	I_T Measurement type	Additions, corrections and/or clarifications to VS&A
FORESTS AND FOREST PLANTATIONS				
Aboal et al. (1999)	<i>Empirical Extrapolation</i> Stemflow sampled for 30 trees representing 6 tree species within a laurel forest, Canary Islands. A single I_T 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 1.5×10^{-2} to $9.1 \times 10^{-2} \text{ m}^2$.	0.277–0.722	Range of annual maximum I_T values for individual trees	Addition: Not Included in VS&A
Carlyle-Moses et al. (2018)	<i>Dye Experiment</i> Juvenile pine plantation in British Columbia, Canada. Dye tracer was used at the base of nine small lodgepole pine trees (basal area range = 1.80×10^{-3} to $3.14 \times 10^{-2} \text{ m}^2$) during each of three rain events (5.9 to 16.0 mm).	0.0017	Average I_T value for all trees across 3 rain events	Correction: I_T values presented by VS&A for this reference are the tree basal area values.
Carlyle-Moses et al. (2018)	<i>Stemflow Rate divided by K_{sat}</i> Lowland tropical forest, Cambodia. I_T estimated as mean stemflow rate (0.853 L h^{-1}) divided by measured K_{sat} of 531 mm h^{-1} . 130 rain events totalling 1500.9 mm.	0.0016	Average annual I_T value for all trees	
Carlyle-Moses et al. (2018)	<i>Stemflow Rate divided by K_{sat}</i> Global mature, natural forests. I_T 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 $> 1,000 \text{ mm h}^{-1}$).	0.0001–0.1	Range of average annual or season-long I_T values for all trees	Addition: Not Included in VS&A
Durocher (1990)	<i>Direct Observation</i> 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 $3.14 \times 10^{-2} \text{ m}^2$. Measured K_{sat} of soil (micropores + macropores) averaged 713 mm h^{-1} .	Stemflow directly infiltrated adjacent to trees due to high infiltrability of soil.	Average season-long I_T value for all trees	Addition: Not Included in VS&A
Gonzalez-Ollauri et al. (2020)	<i>Dye Experiment</i> 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 $20.3 \pm 11.6^\circ$ slope. K_{sat} of the soil was 256 mm h^{-1} .	No data		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_T areas; however, the dye stained I_T 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)].
Herwitz (1986)	<i>Stemflow Rate divided by K_{sat}</i> Stemflow measured from eight trees (basal area ranged from 4.9×10^{-2} to $1.82 \times 10^{-1} \text{ m}^2$) 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	Range of I_T extents for individual trees for a single extreme rain event	Clarification: During an extreme period of the storm when 11.8 mm of rain fell over 6 min (intensity = 118 mm h^{-1}), I_T expanded to a maximum of $3.09 \text{ m}^2 \text{ tree}^{-1}$, the maximum I_T listed by VS&A for this study.
Schwärzel et al. (2012)	<i>Dye Experiment</i> 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_T . 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	I_T extent for a single simulated event value for an individual tree	

(Continued)

TABLE 1 | Continued

Setting and study	Method	I_T ($\text{m}^2 \text{ tree}^{-1}$)	I_T Measurement type	Additions, corrections and/or clarifications to VS&A
Tischer et al. (2020)	<i>Dye Experiment</i> Trunk area of one European beech ($\text{BA} = 1.37 \times 10^{-1} \text{ m}^2$) and one sycamore maple ($\text{BA} = 1.40 \times 10^{-1} \text{ m}^2$) was dye-stained in advance. Stemflow patterns and I_T were visually quantified following natural rain events of < 4.2 to 7.8 mm h^{-1} ($\Sigma 23.2 \text{ mm 3 weeks}^{-1}$)	0.023 beech 0.041 maple	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
Voigt (1960)	<i>Direct Observations</i> 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 $1.82 \times 10^{-2} \text{ m}^2$ for the beech trees to $4.57 \times 10^{-2} \text{ m}^2$ for hemlock. Rainfall conditions were not provided.	0.25 red pine 0.44 beech 0.52 hemlock	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.
SAVANNA AND SHRUBLAND				
Chinen (2007)	<i>Erosional Scour Marks and Rills</i> 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 min (intensity c. 60 mm h^{-1}).	No data	Single extreme event	Clarification: I_T was not measured, but the extent of traces of surface runoff and rills extended c. 4 to 7 m in the downslope direction of the trees. There is no mention of I_T varying from 1.12 to $4.75 \text{ m}^2 \text{ tree}^{-1}$ as indicated in Table 1 of VS&A, although it seems VS&A based their values on Figure 4 of Chinen (2007), which provides a sketch and scale of the traces of erosional scours and rills that developed during an extreme rainfall event.
Návar (2011)	<i>Direct Observations</i> Stemflow infiltration area monitored for several Tamaulipan thornscrub shrub species and temperate tree species in northeastern Mexico over 18 months.	0.03	Maximum extent of I_T for all trees across all rain events (maximum rain depth = 52 mm)	Addition: Not included in VS&A
Pressland (1973)	<i>Direct Observations</i> Arid woodland, stemflow from 28 sampled trees (basal area range = 2.6×10^{-3} to $1.0 \times 10^{-1} \text{ m}^2$), was found to represent 18% of rainfall with individual rainfall events ranging from 0.25 to 120 mm.	0.10–1.14	Range of maximum I_T extents for individual trees over 18 months	Clarification: Observed infiltration was constrained to within 0.15 m of the boles of small trees and 0.45 m of large tree boles. This suggests, taken the basal area of the trees into account, the given maximum I_T range for rain events up to 120 mm.
Pressland (1976)	<i>Direct Observations</i> Arid woodland in proximity to where the Pressland (1973) study took place. Stemflow was not measured, but stemflow infiltration was observed during rainfall events.	No data		Clarification: Stemflow infiltrated to within 50 cm of large trees (circumference $> 40 \text{ cm}$, basal area $> 1.27 \times 10^{-2} \text{ m}^2$) and to within 30 cm of small trees (circumference $< 20 \text{ cm}$, basal area $< 3.18 \times 10^{-3} \text{ m}^2$). It is not possible to derive I_T with available information, but likely on the order of that for Pressland (1973).
AGRICULTURAL PLANTATIONS, ORCHARDS AND AGRO-FORESTRY				
Charlier et al. (2009)	<i>Model Simulation</i> Simulated versus observed runoff from a banana plantation plot with an average K_{sat} 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.	No data		Clarification: Was not measured or estimated. Inclusion of stemflow improved modeling results of runoff from the plot. However, from Figures 5, 7, and 8 of Charlier et al. (2009), stemflow is shown to not be the main contributor to overland flow from the plot. Extreme example due to special morphology of banana plants (funnel like shape).
Gómez et al. (2002)	<i>Stemflow Rate divided by K_{sat}</i> Stemflow measured from three mature olive trees (mean basal area of $5.3 \times 10^{-2} \text{ m}^2$) in an orchard situated in Spain. I_T estimated as mean stemflow rate divided by measured K_{sat} of 81 mm h^{-1} .	0.108	Average I_T value for three trees over 12 rain events	Clarification: I_T average presented in this table was calculated for the three trees for the study period (12 rain events). For the largest rain event (77.1 mm) I_T for the three trees averaged $0.762 \text{ m}^2 \text{ tree}^{-1}$ (range = 0.53 to $1.12 \text{ m}^2 \text{ tree}^{-1}$).

(Continued)

TABLE 1 | Continued

Setting and study	Method	I_T ($m^2 \text{ tree}^{-1}$)	I_T Measurement type	Additions, corrections and/or clarifications to VS&A
Keen et al. (2010)	<i>Erosional Scour Marks</i> Macadamia orchard, Australia. Seven 9-year-old trees were sampled for stemflow and the erosion associated with stemflow was monitored. Total study-period rainfall depth was not provided but did include a 217 mm event with a mean intensity of 6.8 mm h^{-1} . No estimate of K_{sat} is provided; however, the authors state that the exposed soil is inherently erodible and is also subjected to erosion during harvesting.	2.1	Maximum I_T extent for any tree over 16 months	Correction: Study period was 16 months, not 18 months as reported by VS&A. Clarification: I_T was not derived, however, the authors state that it was "confined to small areas of the entire orchard." It is not entirely clear from the article, but the area of erosion from the base of the trees appears to have been 2.1 m^2 . If so, this may represent the maximum I_T per tree in the orchard.
Rashid and Askari (2014)/Rashid et al. (2015)	<i>Litter Marks</i> 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.	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 . Addition: Rashid et al. (2015) include the same I_T data as Rashid and Askari (2014). VS&A did not reference Rashid et al. (2015).
URBAN				
lida et al. (2005) [†]	<i>Litter Marks</i> 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	Correction: Litter marks occurred at the peak intensities during an 88.5 mm rain event observed on 15–16 January 2005 with maximum and mean intensities of 9.5 and 2.3 mm h^{-1} , respectively. VS&A incorrectly suggest that two rain events created the litter marks. Additionally, the DBH values 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 ([†]).
Tanaka et al. (1991) ^{**}	<i>Infiltration Area, Erosional Scour, and Vegetation Marks</i> The extent of infiltration area marks (i.e., wetted infiltration areas on the soil surface), erosional scour marks and vegetation marks were measured for 12 trees within and outside of the University of Tsukuba campus. It should be noted that intensities of stemflow and K_{sat} were not measured. DBH values provided in Table 1 of VS&A were likely derived from the diameter at tree base indicated in Figure 4 of Tanaka et al. (1991).	0.17–1.03 (Average = 0.60)	Range of maximum I_T extents derived from infiltration area mark for 7 trees for a single 2.0 mm rain event; erosional scour marks and vegetation marks based on some earlier rainfall events	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 (^{**}).

Summary In all but a few extreme rainfall events, I_T is $< 1 \text{ m}^2$ 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.

[†]The statements in VS&A " $I_T > 1 \text{ m}^2 \text{ tree}^{-1}$ has been reported under low rainfall intensity, $1\text{--}2 \text{ mm h}^{-1}$ " and "photographs of litter marks showing $I_T = 0.4$ to $1.3 \text{ m}^2 \text{ tree}^{-1}$ under non-extreme precipitation conditions" cannot be derived from or substantiated by lida 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, lida 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 $1,100 \text{ cm}^3 (30 \text{ s})^{-1}$ and average infiltration capacities of 383 and 441 mm h^{-1} for two Formosa sweet gum trees (lida et al., unpublished data).

^{**} The description "post-storm litter marks caused by infiltration excess (Tanaka et al., 1991.)" in VS&A (page 3) is not correct since Tanaka et al. (1991) did not observe any litter marks. Instead, the extent of I_T was inferred as the extent of the infiltration area marks (i.e., the area of wetted surface soil). It should be noted that I_T using this method may be overestimated due to capillarity of the surface soil increasing the wetted area in the absence of infiltration.

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 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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