Rainfall interception and redistribution by a common North American understory and pasture forb, *Eupatorium capillifolium* (Lam. dogfennel)

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Abstract. In vegetated landscapes, rain must pass through plant canopies and litter to enter soils. As a result, some rainwater is returned to the atmosphere (i.e., interception, I) and the remainder is partitioned into a canopy (and gap) drip flux (i.e., throughfall) or drained down the stem (i.e., stemflow). Current theoretical and numerical modelling frameworks for this process are near-exclusively based on data from woody overstory plants. However, herbaceous plants often populate the understory and are the primary cover for important ecosystems (e.g., grasslands and croplands). This study investigates how overstory throughfall ($P_{T,o}$) is partitioned into understory I, throughfall (P_T) and stemflow (P_S) by a dominant forb in disturbed urban forests (as well as grass- and pasturelands), *Eupatorium capillifolium* (Lam., dogfennel). Dogfennel density at the site was 56,770 stems ha^{-1}, enabling water storage capacities for leaves and stems of 0.90±0.04 mm and 0.43±0.02 mm, respectively. Total $P_T:P_{T,o}$ was 71% (mMedian $P_T:P_{T,o}$ per gauge was 72%(, 59-91% interquartile range)). P_S data were highly skewed, where mean $P_S:P_{T,o}$ per plant was 36.8%, but the median was 7.6% (2.8%-27.2% interquartile range) and total over the study period was 7.9%. P_S variability (n = 30 plants) was high ($CV > 200\%$) and may hypothetically be explained by fine-scale spatiotemporal patterns in $P_{T,o}$ (since no plant structural factors explained the variability). Occult precipitation (Mmixed dew/light rain events) occurred during the study period, revealing that dogfennel can capture and drain dew to their stem base as P_S. Dew-induced P_S may help explain dogfennel's improved invasion efficacy during droughts (as it tends to be one of the most problematic weeds in the southeastern US's improved grazing systems). Overall, dogfennel's precipitationrainfall partitioning differed markedly from the site's overstory trees (*Pinus palustris*), and a synthesis of currentdiscussion of the limited literature suggests that these differences may exist across vegetated ecosystems. Thus, more research on herbaceous plant canopy interactions with precipitation is merited.

Key words: Rain, throughfall, stemflow, canopy water storage, stem water storage, evaporation.

1. Introduction

Precipitation (P_g) across most of the global land surface will interact with plant canopies. Precipitation-canopy interactions during storms result in three general hydrologic processes; one which returns water to the atmosphere (interception) and two others that route water to the surface (throughfall and stemflow). Interception is the evaporation of droplets splashing against (Dunkerley, 2009), or stored on, canopy surfaces, like leaves (Pereira et al., 2016), bark (Van Stan et al., 2017a, and epiphytes (Porada et al., 2018). Depending on the vegetation and storm conditions, interception can be small per unit area (David et al., 2006) or return half the annual precipitation to the atmosphere (Alavi et al., 2001). In this way, canopy interception can evaporatively cool regions (Davies-Barnard et al., 2014), recycle moisture to generate nearby storms (Van der Ent et al., 2014), and reduce stormwater runoff to save millions of dollars (US) in stormwater infrastructure costs (Nowak et al., 2020~~19~~). Throughfall is the water that drips to the surface through gaps or from canopy surfaces, while stemflow is the water that drains down plant stems. The portion of precipitation that drains as throughfall versus stemflow is also highly variable depending on vegetation and storm conditions: ranging annually from 10-90% for throughfall and <1-60% for stemflow (Sadeghi et al., 2020~~19~~). Since throughfall and stemflow reach the surface at different locations, they differentially interact with subsurface hydrological and biogeochemical processes—having been implicated in fine-scale patterns in soil physicochemistry (Gersper and Holowaychuk, 1971), microbial community composition (Rosier et al., 2015; 2016), N-cycling functional genes (Moore et al., 2016), and metazoan community composition (Ptatscheck et al., 2018). Accurate accounting for each of these precipitation partitioning fluxes is, therefore, necessary for the accurate prediction of atmospheric and surface hydro-biogeochemical processes.

Current theoretical and numerical modeling frameworks for canopy precipitation partitioning (see review by Muzylo et al. (2009)), are almost exclusively based on observations beneath woody plants, like forests and shrublands (Sadeghi et al., 2020~~19~~). In forests, the past 150 years of research has primarily targeted dominant overstory trees (Ebermayer, 1873; Van Stan and Gordon, 2018). However, herbaceous plants commonly dominate forest understories and can be abundant beneath shrublands (Jiménez-Rodríguez et al., 2020; Lajtha and Schlesinger, 1986; Specht and Moll, 1983). As a result, our current understanding of "net" precipitation (as measured beneath woody overstory canopies) is not representative of the actual precipitation that reaches the surface (or litter layer: Gerrits and Savenije, 2011) beneath the understory. Herbaceous canopies are relevant to precipitation partitioning in more than the one-third of the global land surface represented by forests; they also cover 27% and 11% of the global land surface in grasslands and croplands, respectively (Alexandratos and Bruinsma, 2012; Suttie et al., 2005). It is unlikely that current knowledge on precipitation partitioning based on woody vegetation is applicable to herbaceous vegetation, since they differ in many hydrologically-relevant morphological features: smaller height, the lack of bark structure, and presence of other stem features (like trichome hairs or desiccated leaves), etc. This raises unanswered and little-researched, questions that must be addressed to include herbaceous plants in precipitation partitioning theory, e.g.: How do these significant morphological differences affect canopy and stem water storage capacities? Do herbaceous plants also favor throughfall generation, like woody plants, or do they more efficiently drain precipitation to their stem bases (and, thereafter, their shallow roots)? In fact, several long-standing (and hitherto unanswered) calls for greater research on the precipitation partitioning of non-woody plants (rooted in detailed observations) have been made (Price

71 et al., 1997; Price and Watters, 1989; Verry and Timmons, 1977; Yarie, 1980). These are general questions identified

72 by the community; but, in this study we focus on: How is overstory throughfall ($P_{T,o}$: Figure 1) partitioned into

73 understory interception, throughfall (P_T: Figure 1) and stemflow (P_S: Figure 1) by a dominant forb in disturbed urban

74 forest understories (as well as grass- and pasturelands), *Eupatorium capillifolium* (Lam., dogfennel)?

75   Very little is known about how understory plants partition $P_{T,o}$ into understory P_T and P_S (Figure 1). Overstory

76 stemflow is currently assumed to bypass the understory and litter layers (Carlyle-Moses et al., 2018); however, this

77 assumption, particularly regarding the bypass of litter, has rarely been tested (Friesen, 2020) and overstory stemflow

78 has been observed to runoff for long distances away from the stem (Cattan et al., 2009; Keen et al., 2010). We do not

79 investigate interactions between the understory and overstory stemflow in this study, because stemflow from this study

80 site is negligible (<0.2%: Yankine et al., 2017). Most observations of precipitation partitioning beneath any plant

81 besides overstory woody plants have been done on maize (Zheng et al. (2019) and references therein) and other cash

82 crops (Drastig et al. (2019) and references therein), which leave plants of forest understories, grasslands or

83 pasturelands relatively unresearched. Even the few studies on forest understory interception, P_T, and P_S

84 overwhelmingly focus, again, on woody plants (González-Martínez et al., 2017; Price and Watters, 1989), limiting

85 net precipitation observations beneath understory herbaceous plants to ferns (Verry and Timmons, 1977) and

86 nonvascular plants (Price et al., 1997). These scant observations, however, indicate that precipitation partitioning by

87 non-woody understory plants is hydrologically relevant, as they can store as much water as woody plants (Klamerus-

88 Iwan et al., 2020), evaporate significant portions of $P_{T,o}$ (Coenders-Gerrits et al., 2020) and redistribute 7-90%

89 of event $P_{T,o}$ as P_S (Sadeghi et al., 2020). For our study on dogfennel, we hypothesized that, compared to past

90 research on woody plants, dogfennel stems and leaves (i) can store a hydrologically relevant amount of rainwater (i.e.,

91 within the range of water storage capacities reported for woody plants: (Klamerus-Iwan et al., 2020), (ii)

92 significantly reduce net rainfall flux to the surface (i.e., $P_T + P_S \ll P_{T,o}$), and (iii) redistribute a substantial portion of

93 $P_{T,o}$ to the surface via P_S (i.e., P_S will often "funnel" more rainwater per storm to the soils surrounding stems than P_T,

94 $P_{T,o}$ or P_g over the same area).

95 **2. Materials and methods**

96 **2.1. Study site and study plant description**

97 The study site, Herty Pines, is a forest fragment in Statesboro, Georgia, USA (Figure 2a), at Georgia Southern

98 University's main campus (32.430 N, -81.784 W, 65 m A.S.L.). Climate is subtropical (Köppen *Cfa*) where mean

99 monthly temperatures (1925-2014) for July range from 21-33°C and winter months are generally mild, i.e., the lowest

100 mean January temperature is 3.5°C (University of Georgia, 2019). Mean annual precipitation is 1,170 mm y^{-1} and

101 precipitation occurs almost exclusively as rain, relatively evenly spread over the year. The overstory is dominated by

102 *Pinus palustris* (longleaf pine) and overstory rainfall partitioning for this site has been reported (Mesta et al., 2017;

103 Van Stan et al., 2018; Yankine et al., 2017). Trunk diameter at breast height (DBH) was relatively consistent across

104 all trees in the study plot, 49.7 cm (mean) with an interquartile range of 36.2-55.7 cm. Mean tree height was 30.4±4.5

105 m and was derived from terrestrial lidar (terrestrial lidar methods identical to Van Stan et al., 2017a). Stand density

106 was 223 trees ha^{-1} with ~~12.6~~50.4 m^2 ha^{-1} of basal area. Dogfennel, our study plant, was particularly dominant along

107 the forest edge. Dogfennel is a forb of the Asteraceae family, native to (and widespread across) North America (Van

108 Deelen, 1991; Wunderlin and Hansen, 2003). Although dogfennel behaves as an annual plant throughout much of its

109 North American range, it can behave as a perennial in the southern US by overwintering as a rosette, typically from

110 January to March, before re-growing from a taproot in the spring, typically in April (Macdonald et al., 1994;

111 Macdonald et al., 1992). Dogfennel can be abundant in disturbed forest understories, particularly pine forests

112 (Brockway et al., 1998) and pastures (Figure 2b). In the study pine forest, dogfennel stem density was 56,770 stems

113 ha^{-1} along the stand edge. In pasturelands, dogfennel can reach this stem density within a single season and, if left

114 unmanaged, dogfennel densities have been measured as high as 74 stems m^{-2}, or ~740,000 stems ha^{-1} (Dias et al.,

115 2018). The growth habit of dogfennel results in "clumps" of stems. Dogfennel density was estimated in ten 10x10 m

116 plots by counting the stems clump^{-1} for 3 randomly-selected clumps in each plot. For each plot, the mean stems clump^{-1}

117 ^{1} were multiplied by the number of clumps plot^{-1}. Finally, all stems plot^{-1} were summed and scaled to 1 ha. Three

118 dogfennel clumps were randomly selected for throughfall and stemflow monitoring. Within these three clumps, 30

119 individual dogfennel stems were randomly selected for stemflow monitoring. Individual plant attributes—canopy

120 radius [cm], stem radius [cm], leaf angle at the stem [degrees from vertical] at various canopy heights (1.00, 1.25,

121 1.50, 1.75, 2.00 m), and relative location within the clump, interior (I), middle (M), or exterior (E)—were measured

122 for each stemflow-instrumented plant (Table 1). Canopy and stem radii were determined manually with a tape

123 measure, where canopy radii were the mean of measurements from eight directions (N, NE, E, SE, S, SW, W, and

124 NW) and stem radius was determined by a single manual measurement at the stem base. Leaf angle at the stem was

125 determined for two leaves at each height using the iProtactor App for iPhone (2013, Phoenix Solutions) which logs

126 an angle after the levelling of the iPhone camera (see Figure S1 for example).

2.2. Hydrometeorological monitoring

128 Rainfall amount, duration and intensity for discrete rain events were automatically logged every 5 min by a weather

129 station installed above the canopy (on the rooftop of nearby Brannen Hall at ~40 m height), which is located 100 m

130 from Herty Pines. Rainfall observations were recorded by three tipping bucket gauges (TE-525MM, Texas

131 Electronics, Dallas, TX, USA) interfaced with a CR1000 datalogger (Campbell Scientific, Logan, Utah, USA). This

132 weather station logged a suite of other meteorological variables; however, since these data do not represent the

133 meteorological conditions experienced by the understory, they are not reported or examined here. As observing $P_{T,o}$

134 directly would prevent direct observation of P_T and P_S beneath dogfennel plants, $P_{T,o}$ was estimated from previous

135 field measurements at the site (Figure S2). We assume that the past observed rainfall relationship with $P_{T,o}$ at the site

136 was similar during our study period. Although we are unable to assess whether and to what degree there is a difference

137 between these observation periods, the canopy is mature and there has been no known/noticeable disturbance or

138 change in canopy structure since the previous observation period. A discrete event was defined as any atmospheric

139 moisture (rainfall or dew) that resulted in a measurable quantity of throughfall and stemflow (more than a few mL)

140 that occurred after a minimum interstorm dry period of 8 h. Few events consisted of early morning dew contributions

141 (visually observed during sampling and ~~as~~ verified by air temperatures equalling dew point temperatures), and these

142 occurred after low-magnitude nighttime rainfall. When dew was present in the understory, there was no response from
143 above-canopy rain gauges; thus, a post-hoc estimate of occult dew contribution to $P_{T,o}$ was made by assuming the dew
144 contribution was equal to the understory canopy water storage capacity (1.33 mm – methods described later). An
145 important limitation to this dew estimate is that it represents the maximum possible dew contribution. Rain events
146 without dewfall required at least ~4 mm of rainfall for generation of P_T or P_S from the monitored dogfennel canopies.

147 Throughfall gauges consisted of 9 randomly placed funnels (506.7 cm^2 collection area each), three per
148 dogfennel clump (1,520.1 cm^2 total collection area per clump), connected to HDPE bottles that were manually
149 measured with graduated cylinders immediately after a storm ended (within 4 h). The total canopy area of dogfennel
150 plants at this site rarely exceed 2,000 cm^2, resulting that the total throughfall gauge area per clump generally
151 represented >75% of canopy area; which is a comparatively much larger gauge-to-canopy area than most past
152 throughfall studies on forest canopies (Van Stan et al., 20~~1~~209).

153 Standard stemflow measurement methods developed for woody plants (use of flexible tubing wrapped around
154 a woody stem: Sadeghi et al., 2020~~19~~) are not suitable for dogfennel; moreover, no standard stemflow collection
155 devices exist for herbaceous plants. Thus, stemflow collars were constructed from aluminum foil, 15-mm inner-
156 diameter flexible polyethylene tubing, electrical tape, and silicon (see Figure S3). Aluminum foil was folded over
157 itself several times to strengthen the collar (typically ~160 mm length of foil was folded to ~40 mm) and connected
158 to plastic tubing with stainless steel staples. The aluminum collar was then folded around the lower stem of the dog
159 fennel and secured with electrical tape. To seal the aluminum foil, staple connections, and the interstices between the
160 foil, tubing and stem, silicon was thinned with hydrotreated light (95-100%) naphtha (VM&P Naphtha, Klean-Strip,
161 Memphis TN USA), allowing for it to completely fill the aluminum cone up to the tube opening and make a water-
162 tight seal. While naphtha-thinned silicon was poured into collars, the tube opening was covered. An additional benefit
163 of naphtha-thinned silicon was that, due to the evaporation of naphtha, the silicon shrinks, thereby, pulling the collar
164 taut and stiffening/strengthening the stemflow collection device and extending the lifespan of the collar. Stemflow
165 was measured with a graduated pipette (with 1 mL graduations) from 500 mL plastic bottles connected to the tubing
166 base.

167 **2.3. Water storage capacity estimation**

168 Maximum water storage capacity (S_u [mm]) was estimated for the dogfennel canopy and stem, both as volume [L] per
169 unit surface area [m^2]. All field leaf and stem samples were collected during an inter-storm dry period (>24 h after
170 any rainfall). For the canopy, 50 leaves representing the median size of the site dogfennel plants were sampled (broken-
171 off at the base of the leaf), taken back to the lab, their "field-dry" mass [g] determined on a bench scale, and then the
172 broken end of their leaf-stems were sealed with silicon to prevent water exchange from an area that was not previously
173 exposed in its natural state. Sampling for the stems was similar; however, since dogfennel heights reach (and can
174 exceed) 2 m, the stems were cut into 5 cm sections. Just as with the leaves, 50 representative samples of these stem
175 sections were weighed in the lab, then sealed with silicon on both ends. Next, all leaf samples and stem sections were
176 submerged in water for three days until achieving maximum saturation (per Van Stan et al., 2015), whereupon the
177 maximum saturation mass [g] was recorded. For comparison with the field-dry mass, all samples were oven-dried

178   until their mass no longer changed (mass recorded every 3 h), whereupon the oven-dried mass [g] was recorded. No

179   leaf or stem samples were oven dried longer than 15 h. The gravity convection oven (Isotemp, Fisher Scientific) was

180   set to 40 °C (confirmed with a standard thermometer). The maximum volume of all samples' water storage capacity

181   is the difference between saturation and oven-dried mass. The oven-dried leaves and stems did not visually appear to

182   be damaged (aside from the sampling cuts, obviously) and care was taken to ensure the plant samples were not

183   damaged. It is likely that internal (not externally intercepted) water was exchanged during this process; however, this

184   is not entirely problematic as plant surfaces are known to permit interaction between externally intercepted water and

185   internal water (Berry et al., 2019). Moreover, we explicitly acknowledgenote that these methods produce the

186   "maximum" possible water storage capacity (hence, our objective to estimate maximum water storage capacity), as

187   multiple intrinsic and extrinsic factors of plant surfaces could reduce the available water storage capacity in situ

188   (Klamerus-Iwan et al., 20<u>20</u>19).

189   Specific water storage capacity [mm] for the leaves and stems was determined by dividing the lab-derived

190   maximum volume [mL] by the samples' surface area [cm^2] and corrected per cover fraction. For leaves, after sampling,

191   levelled photos of each sample were taken on a grid system (every block representing 2.5 cm x 2.5 cm for scale), then

192   the leaf images were vectorized and processed for 2-D projected surface area using the "Measure Path" extension in

193   Inkscape (v. 0.92, Inkscape.org). An example vectorized image of leaf area is provided in the supplemental materials

194   (Figure S4). Error in this vector-based leaf surface area estimate was estimated by repeating the process five times for

195   each leaf. Stem surface area for all samples was estimated from their radii and height. Specific water storage capacity

196   estimates for the stem (0.436 mm) and canopyleaves (0.195 mm) were then scaled to S_u [mm as L m^{-2}] using stem and

197   leaf surface area estimates per plant (171.9 cm^2 plant^{-1} and 807.5 cm^2 plant^{-1}, respectively), and multiplied by the site

198   plant density (5.68 plants m^{-2})site leaf area and stem area indices and divided by 1000. Plant stem and leaf surface

199   area estimates were determined from 5 representative plants that were cut from the site and separated into leaves and

200   stems, then the sum of leaf and stem areas (determined as mentioned earlier in the paragraph) were divided by 5. Total

201   leaf surface area compares well to values reported from ~1 m tall dogfennel plants, 212 cm^2 plant^{-1} (Carlisle et al.,

202   1980), considering our plants were much taller (~2 m).

2.4. Data analysis

204   Descriptive statistics were compiled for all variables presented and regression analyses were performed to relate plant

205   canopy and hydrologic variables. All statistical analyses were done using Statistica 12 (StatSoft, Tulsa, OK, USA).

206   Throughfall volumes [L] from all gauges were summed and converted to yields [mm] by dividing by the total gauge

207   area [m^2]. Stemflow yield [mm] for an individual plant was determined by dividing its volume [L] by the projected

208   canopy area [m^2]. To compare stemflow production across plants, two metrics were computed per plant for each storm:

209   normalized stemflow ($\bar{P}_{S,i}$ [-]) and the funneling ratio (F [-]). $\bar{P}_{S,i}$ was computed per Keim et al. (2005):

210   (1) $\bar{P}_{S,i} = \dfrac{(P_{S,i} - \bar{P}_S)}{s_S}$

where $P_{S,i}$ is stemflow volume [mL] from each individual plant in a single storm, $\bar{P}_S$ is the mean stemflow for all plants in a single storm, and s_S is the standard deviation of stemflow for all plants in a single storm. F for individual plants in each storm were computed per (Herwitz, 1986):

$$(2) \quad F = \frac{P_{S,i}}{B_i P}$$

where B_i is the basal area [cm^2] at the base of an individual plant and P will be either P_g or $P_{T,o}$ (this will be explicitly indicated in the results). There are an increasing number of F metrics (Carlyle-Moses et al., 2018; Levia and Germer, 2015); however, the selected method is the most common F metric applied to stemflow data to date. Moreover, in situ observations of non-collared dogfennel plants during rainfall confirmed that dogfennel P_S rates did not produce visible runoff areas.

3. Results

3.1. Storm and plant structural conditions

Discrete rain events, as measured above the forest canopy, ranged in magnitude from 0.1 mm (during dewfall) to 101.3 mm (Table 1). The distribution of storm magnitudes was skewed, such that the mean, 16.5 mm, was many times greater than the median, 6.6 mm (Table 1). Estimated overstory throughfall ($P_{T,o}$) ranged from 0 (again, during dewfall) to 72.2 mm, with a median of 3.5 mm (Table 1). Thirty of the plants in the selected dogfennel clusters - those being monitored for stemflow - had an average canopy radius of 18.3 cm ($\pm$4.5 cm standard deviation), which was nearly identical to the median canopy radius (Table 1). The stem radii of all measured dogfennel plants ranged from 0.1 - 0.7 cm, with a mean radius of 0.6 cm (Table 1). The resulting ratio of canopy:stem radii was also normally distributed, with a mean and median of ~36 (dimensionless), but ranging from 24 to 50 (Table 1). For all plants, the mean leaf angle decreased from 54° to 32° from vertical with increasing canopy height; i.e., the higher in the dogfennel canopy, the closer the leaf angle approaches vertical (Table 1). This trend appears consistent across each individual study plant regardless of which clump the plants' resided, as the standard deviation across all elevations are low, 1.8-3.1° from vertical, and do not overlap (Table 1).

3.2. Partitioning into water storage, throughfall and stemflow

The sum of data from all storms throughout the study period resulted in P_T, P_S and I of 71%, 8%, and 21% as a portion of $P_{T,o}$, respectively, beneath dogfennels at our site. Water storage capacity achieved by dogfennel leaves in the lab was 0.90 $\pm$ 0.04 mm, while dogfennel stems stored a capacity of 0.43 $\pm$ 0.02 mm (Figure 3). This resulted in the total S_U of dogfennel plants in the understory of this study site being approximately 1.3 mm. This S_U estimate agrees with the reductions of $P_{T,o}$ observed below dogfennels: for example, mean P_T:$P_{T,o}$ was 76.6% for rain-only storms (Table 2), or a mean yield of P_T = 12.9 mm which exceeds a 1.3 mm reduction (due to S_U and evaporation) in the estimated mean $P_{T,o}$ yield, 16.5 mm (from Table 1). A large portion of the rainwater captured on dogfennel canopies was able to overcome stem water storage capacity and generate P_S. Dogfennel P_S data were highly skewed, producing a mean relative P_S (P_S:$P_{T,o}$) of 36.8%, but a median of 7.6% within a narrow interquartile range, 2.8%-27.2% (Table 2). For

244 ~~mixed storms (rain + dew)~~events including occult precipitation, both maximum P_S:$P_{T,o}$ and P_T:$P_{T,o}$ exceeded 100%:

245 P_T:$P_{T,o}$ during mixed storms maximized at 192%; whereas, the maximum for P_S:$P_{T,o}$ was just over 900% (Table 2).

246 Note that dew in the understory was not measured by the above-canopy rainfall gauges and estimated $P_{T,o}$ was only

247 increased by an assumed maximum dew contribution equal to S_U (1.33 mm), thus dew accumulation allows P_T and P_S

248 to exceed 100% of P_g and $P_{T,o}$ (Table 2). When compared to rainfall above the overstory (P_g), the medians are much

249 smaller: P_T:P_g being 45% and 58% for rain-only storms and mixed storms, respectively, and P_S:P_g being 4.1% and

250 14.7%, respectively (Table 2).

251 Yield [mm ~~per catchment area~~] were estimated for dogfennel P_T and P_S across storms, and both event-level

252 P_T and P_S yields linearly correlated with estimated event-level $P_{T,o}$ (Figure 4a-b). Since, for P_T, the catchment area

253 (canopy area above the gauge) is equal to the input area (soil area below the gauge), P_T yield from the canopy and P_T

254 supply to the surface are equal and the term "yield" will be applied for both. Median P_T yield beneath dogfennel for

255 the measured storms was 4.4 mm with an interquartile range of 1.1 mm to 11.3 mm (Figure 4c). Maximum P_T yield

256 approached 50 mm during a large-magnitude rain storm (where P_g = 101.3 mm). Since the canopy area that generates

257 stemflow is many times greater than the surface area around plant stems that receive stemflow (see Table 1), P_S yield

258 and F will differ. F are typically used to represent P_S supply to soils, and is done so in the proceeding section. Yields

259 of P_S from dogfennel were as high as 24 mm, but the median was 0.4 mm and the interquartile range was narrow, 0.1-

260 1.3 mm (Figure 4c).

261 **3.3. Stemflow and throughfall variability**

262 Coefficients of variability (CV) and quartile variability (CQV) were computed for both P_S and P_T, relative to P_g and

263 $P_{T,o}$ (Table 2), and storm-normalized temporal stability plots were generated for P_S yield only (Figure 5). Storm-

264 normalized temporal stability plots were not generated for P_T yields because the experimental design accounts for its

265 spatial variability through deployment of large gauge areas (compared to dogfennel canopy area); which permit

266 estimates of variability across a few large-area gauges (Table 2), but limits the observable variability. CV and CQV

267 for relative P_T ranged from 22-90% and were generally lower for rain-only storms, <40%, than for mixed storms,

268 >60% (Table 2). Variability in relative P_S across study plants, ranging from 77-257%, was always greater than

269 observed for relative P_T for the monitored storms (Table 2). Due to the greater skew in the relative P_S data compared

270 to relative P_T, CV was many times greater than CQV for relative P_S (Table 2). CV and CQV for P_S:$P_{T,o}$ was similar

271 for rain and the mixed storms; however, the CV for P_S:P_g was greater for rain-only storms compared to mixed storms.

272 Temporal stability of normalized stemflow, $\bar{P}_{S,i}$ (Figure 5a) indicates that there were only a few plants that

273 captured most of the $P_{T,o}$ drained as stemflow (three plants' mean $\bar{P}_{S,i}$ >> 1). Thus, most of the studied dogfennel

274 plants captured similar amounts of $P_{T,o}$ as stemflow—having $\bar{P}_{S,i}$ between -1 and 1 (y = 0 represents the central

275 tendency of $\bar{P}_{S,i}$ data). Funneling ratios (F based on $P_{T,o}$) show that all plants concentrated P_S yields to the surface

276 around their stem bases (Figure 5a). Mean F across all plants was 87, and for the 27 plants whose mean $\bar{P}_{S,i}$ fell

277 between -1 and 1, median F ranged 18-200 (Figure 5a). However, for the three plants with the highest $\bar{P}_{S,i}$, their mean

278 F values were 287, 476 and 484 (Figure 5a). These voluminous stemflow-generating plants, alone, account for one-

279 third of total P_S volume (8,734 mL / 27,870 mL). To evaluate possible canopy structural influences over P_S variability,

280   various directly-measured structural metrics were compared: radii of canopies and stems ~~(Figure 5b)~~ and the vertical

281   variability in leaf angle (<u>see supplemental </u>Figure <u>S</u>5~~c~~). No clear visible or statistical correlations or correspondences

282   were found between these structural variables and $\bar{P}_{S,i}$ across plants (Figure <u>S</u>5). In fact, variability in the measured

283   canopy structural variables was low (Table 1~~; Figure 5b-c~~) compared to the variability observed for dogfennel P_S and

284   $\bar{P}_{S,i}$ (Figure 5~~a~~).

4. Discussion

4.1. Overstory throughfall partitioning by dogfennel

287   Partitioning of overstory throughfall by this example dominant understory and pasture forb resulted in hydrologically

288   relevant losses of rainwater to the surface at our site (Table 2). As <u>maximum </u>water storage capacity is a major driver

289   of rainfall interception (Klaassen et al., 1998), the magnitude of dogfennel's overstory throughfall interception may

290   be attributed to its canopy being able to store a sizeable magnitude of rainwater per unit area, 1.33 mm (Figure 3). A

291   synthesis of water storage capacities for the leaves of herbaceous plants has been done (alongside other plant types)

292   (Breuer et al., 2003), but less research has estimated the stem component (or a reported a total including the stem

293   component) of water storage capacity for short vegetation (Bradley et al., 2003; Wang et al., 2016; Wohlfahrt et al.,

294   2006; Yu et al., 2012). However, the stems of herbaceous plants, even thick smooth stems (>1 cm in diameter) can

295   store nearly 0.5 mm: e.g., *Taraxacum officinale* (dandelion) (Wohlfahrt et al., 2006). Even thin (<1 cm radius)

296   herbaceous stems with epidermal outgrowths, like hairs, can store large amounts of rainwater: e.g., 0.25 mm for

297   *Achillea millefolium* (yarrow) and 0.20 mm for *Trifolium pretense* (red clover) (Wohlfahrt et al., 2006). In the case of

298   dogfennel stem water storage capacity at our site, the 0.43 mm estimate is within this range and its magnitude is likely

299   a result of two principal factors: (1) dense stem coverage by desiccated leaves (photo in Figure 3); and (2) this species

300   can achieve large densities, up to 700,000 stems ha^{-1} (Dias et al., 2018)<u> – 56,770 stems ha^{-1} at our study site</u>. We note

301   that, to our knowledge, stem water storage capacities for herbaceous plants with spines, thorns, etc. have not been

302   evaluated.

303   Overstory throughfall was also redistributed into a highly spatially variable (Table 2), but temporally

304   persistent pattern (Figure 5~~a~~) beneath dogfennel canopies (where CV or CQV was approximately 20-40% for P_T and

305   80-250% for P_S: Table 2), despite all measured canopy structures—like branch angle, stem size, canopy size, etc—

306   being similar (Table 1~~; Figure 5b-c~~). Since our sampling plan measured P_T over a large area of the dogfennel canopy

307   (rather than at numerous localized points), this discussion point will focus on the intraspecific P_S observations. The

308   high spatial variability and temporal persistence of P_S across plants despite canopy structural similarity, raises the

309   question: What caused the intraspecific P_S patterns observed in this study? A likely explanation may be that, in this

310   case, access to precipitation for stemflow production is related to overstory throughfall patterns. Overstory throughfall

311   patterns are well-known to be spatially variable, but temporally persistent across forest types (Van Stan et al., 20<u>20</u>~~19~~).

312   <u>Specifically</u>~~For example~~, individual dogfennel plants that persistently generated greater P_S than other plants may have

313   just received greater overstory throughfall from persistent overstory drip points. If the overstory throughfall pattern is

314   a major driver of intraspecific variability in P_S in this study, then the funneling ratios computed from mean overstory

315　throughfall would be incorrect (in Figure 5a). In this case, funneling ratios (computed from the localized overstory

316　throughfall above each plant) would be similar across all the monitored dogfennels. Testing this hypothesized

317　relationship between dogfennel P_S patterns and overstory throughfall patterns was not possible in the field, since

318　sampling overstory throughfall would prevent P_S from being generated by the plant. Future work to test this hypothesis

319　could, however, make use of rainfall simulators.

320　　　　The large diversion of rainwater and dew to their stem base may be partially responsible for dogfennel

321　survival during extended periods of drought (or improved invasion efficacy during droughts: Loveless, 1959;

322　Forthman, 1973), and may also explain why this species tends to be one of the most problematic in improved grazing

323　systems located in Florida (Sellers et al., 2009). Rainfall patterns in central and south Florida may also intersect with

324　dogfennel's canopy water balance to "tip the scales" in its favor. Specifically, rainfall in our studythat region is often

325　limited from January through May, with the bulk of rainfall occurring from June through October, and the water

326　storage capacity of burgeoning dogfennel plants during early spring may enhance chances of individual plant survival

327　(resulting in large infestations as referenced previously).

4.2. Overstory (woody) and understory (herbaceous) canopies may partition rainfall differently

329　The dominant understory plant at our study site, dogfennel, intercepted similar amounts of overstory throughfall,

330　interquartile range 11-59% storm^{-1} (Table 2), as compared to the gross rainfall interception by their overstory pine

331　canopy, interquartile range 19-60% storm^{-1} (Van Stan et al., 2017b). Similar rainwater interception between dogfennel

332　and the pine overstory may be due to dogfennel's maximum water storage capacity comparing favorably to that of

333　overstory tree species, 0.07-4.30 mm (Klamerus-Iwan et al., 20202019). Even the maximum stem water storage capacity

334　is of similar magnitude to values reported by past work on woody plants, 0.2-5.9 mm (Klamerus-Iwan et al., 20202019),

335　albeit on the lower end of the range. Most current research on stem water storage has focused on intrinsic factors of

336　woody plant stems, like bark thickness, porosity, microrelief, or roughness (Ilek et al., 2017; Levia and Herwitz, 2005;

337　Levia and Wubbena, 2006; Sioma et al., 2018; Van Stan et al., 2016; Van Stan and Levia, 2010); however, other stem

338　structures besides bark may be capable of storing substantial water: e.g., the desiccated leaves of our study plant.

339　　　　There were differences in how gross rainfall was redistributed by the overstory canopy compared to how

340　overstory throughfall was redistributed by the dogfennel understory. Stemflow from the overstory, *P. palustris*, was

341　negligible at this site, 0.2% of gross rainfall (Yankine et al., 2017), but median dogfennel P_S was 7.6% of overstory

342　throughfall (with an interquartile range of 2.8-27.2%) (Table 2). Annual relative P_S (and P_T) estimates from trees and

343　herbaceous plants reported by previous work (Figure 6a-b), showsindicates that herbaceous plants are generally

344　greater stemflow producers than woody plants (Sadeghi et al., 200220)(Figure 6b). Although relative P_T beneath

345　dogfennel was similar to observations of relative overstory throughfall beneath *P. palustris* at this site (Mesta et al.,

346　2017), throughfall has been found to be generally lower beneath herbaceous plant canopies than for woody ones

347　(Sadeghi et al., 2020)(Figure 6a). This seems reasonable, because, if interception is similar between herbaceous plants

348　and woody plants, then an increase in relative stemflow would necessitate a decrease in relative throughfall. The

349　results of this study and the synthesis presented in Figure 6 confirmssupport statements by several past studies

350　suggesting that plants in the understory and overstory interact differently with rainfall. Thus, we repeat the long-

351 standing calls for greater research on understory precipitation partitioning, particularly stemflow, research (Price et
352 al., 1997; Price and Watters, 1989; Verry and Timmons, 1977; Yarie, 1980).

4.3. A brief discussion on dew-generated throughfall and stemflow

354 For a few storms (n = 5), dew contributed significantly to P_T and P_S by the studied dogfennel plants. The median P_T
355 generated from dew beneath dogfennels at our site was 0.74 mm plant^{-1} with an interquartile range of 0.47-0.99 mm
356 plant^{-1}, resulting in a total dew-related contribution to T of 17.1 mm over the study period. Volumes of stemflow under
357 dewfall totaled 558 mL for all study plants, with individuals supplementing the dew-related P_T with up to 61 mL plant^{-}
358 ^{1} (yielding an additional ~0.6 mm). Dew contributions to net precipitation below plant canopies have rarely been
359 studied. The earliest quantity for dew drainage was 0.08 mm from a single event on a single tree in Johanniskreuz,
360 Germany (Ney, 1893). Since then, to our knowledge, only one other study has examined dew-related drainage from
361 plants, focusing on stemflow from the herbaceous *Ambrosia artemisiifolia* (common ragweed) (Shure and Lewis,
362 1973). They estimated that the drainage of dew via P_S resulted in an additional input of 1.1 L month^{-1} during the
363 growing season, and hypothesized that this process may "play a vital role in governing the density, diversity, and
364 distribution of plant species within field ecosystems" (Shure and Lewis, 1973). Dew drainage from plant canopies and
365 down stems may, in addition to being a valuable water source, influence plant-soil interactions by transporting leached
366 or dry deposited materials to the soils—something also discussed by (Shure and Lewis, (1973). Globally, dew
367 contributes a small percentage to the annual precipitation (Baier, 1966), however, in semiarid and arid (Baier, 1966;
368 Hao et al., 2012), as well as summer-dry climates (Tuller and Chilton, 1973), dew can form a significant water input.
369 It is reasonable to suppose, then, that in such ecologic settings as these any factor which doubles the frequency of
370 plant-moisture availability, even though the amounts be small, must materially affect the plant growing condition.
371 Therefore, further research is needed to assess dew (and mixed storms) drainage in arid and semiarid climates, with
372 days on which dew occurs being ≥70% per year (Hao et al., 2012). The global importance of occult precipitation and
373 resulting wet canopy conditions has recently been reviewed and described as a critical future research direction for
374 plant sciences (Dawson and Goldsmith, 2018). Given these scant but ecologically relevant findings, further research
375 on the influence of condensation events on plant-soil interactions via throughfall and stemflow may be merited.

5. Conclusions

377 *Eupatorium capillifolium* (Lam., dogfennel) in the understory of an urban forest fragment intercepted 20.4% of
378 overstory throughfall from *Pinus palustris* (Mill.). The remaining 712.0% and 7.69% of overstory throughfall reached
379 the surface beneath dogfennels as understory throughfall and stemflow, respectively. The partitioning of overstory
380 throughfall by this understory forb differs considerably from the rainfall partitioning of the woody overstory,
381 especially regarding stemflow (7.96% versus <0.2%). During a few storms that occurred in tandem with dewfall,
382 dogfennels were able to augment stemflow (and throughfall) production through capturing dew. These processes may
383 help explain how dogfennels survive extended droughts, and even show improved invasion efficacy during droughts,
384 making it one of the most problematic weeds in southeastern US grazing systems. Stemflow variability among
385 individual plants was very high (CV ~250%), but no dogfennel canopy structures measured in this study provided

386 statistically significant insights into this stemflow variability. Future work will assess to what extent overstory
387 throughfall variability drives understory stemflow variability for plants, like dogfennel, of similar intraspecific canopy
388 structure. However, in forests, overstory throughfall is not the final frontier for determining net rainfall, and
389 investigations on how it is intercepted and redistributed by herbaceous plants is needed to improve our understanding
390 of exactly how much (and in what pattern) rainfall reaches the surface. For other vegetated ecosystems where
391 herbaceous plants are the overstory (grasslands and croplands), precipitation partitioning research is also needed.

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Code/Data availability

396 Data is permanently archived at https://digitalcommons.georgiasouthern.edu/ and freely available.

Author contribution

398 DARG conceived and designed the study in consultation with JTVS and AMJCG. DARG designed field collection
399 devices in consultation with JTVS and AMJCG, then deployed devices, collected data, performed the data analysis,
400 and drafted the initial manuscript with input from all authors. BAS contributed expertise regarding relevant range-
401 and pastureland topics, assisting with data analysis/interpretation. SMMS performed a literature synthesis for
402 discussions comparing herbaceous and woody plants' rainfall partitioning and used this synthesis to assist in
403 manuscript writing. JTVS was the principal undergraduate research supervisor for DARG. All authors contributed to
404 manuscript revisions.

Competing interests

406 The authors have no competing interests.

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15

571 **Table 1:** Descriptive event statistics for rainfall (observed), overstory throughfall (estimated per Figure S2) and
572 measured individual plant traits. When minimum overstory throughfall was zero, dew occurred – as verified by air
573 temperatures equalling dew point temperatures.
574

| Parameter (units)	Mean	Median	±SD	Min.	Max.
Rainfall (mm)	16.5	6.6	25.8	0.1	101.3
Overstory throughfall (mm)	11.0	3.5	18.7	0.0	72.2
Canopy radius (cm)	18.3	18.4	4.5	12.2	26.2
Stem radius (cm)	0.5	0.6	0.1	0.3	0.7
Canopy:stem radii	36.3	36.1	7.4	24.1	50.0
Leaf angle at the stem (degrees from vertical)					
1.00 m height	54.0	54.0	2.0	50.5	59.0
1.25 m height	45.9	46.5	3.1	40.5	50.5
1.50 m height	39.6	39.5	1.8	36.0	43.0
1.75 m height	34.0	34.5	2.3	30.0	39.0
2.00 m height	31.9	32.0	2.8	25.0	36.5

575

576 **Table 2:** Descriptive statistics of relative throughfall (P_T) and stemflow (P_S) yield from dogfennel plants expressed
577 as a proportion of gross rainfall (P_g) and estimated overstory throughfall ($P_{T,o}$). Coefficients of variation (CV) and
578 quartile variation (CQV) are also provided. For storms where dew occurred in the understory, dew was not measured
579 by above-canopy P_g gauges, but was included in the estimated $P_{T,o}$ estimate by assuming dew represented at least
580 additional 1.33 mm (i.e., S_u).
581

| Parameter	Mean (SD)	Median	Q1	Q3	Max	CV	CQV
Rain storms							
P_T:P_g (%)	43.6 (15.2)	44.9	34.3	52.4	101.7	34.9	20.9
P_S:P_g (%)	18.8 (47.3)	4.1	1.7	13.8	434.3	251.6	78.1
P_T:$P_{T,o}$ (%)	76.6 (29.3)	72.0	58.5	91.1	190.6	38.3	21.8
P_S:$P_{T,o}$ (%)	36.8 (93.5)	7.6	2.8	27.2	900.3	254.1	81.3
Mixed storms*							
P_T:P_g (%)	70.3 (43.7)	58.0	39.5	102.9	149.4	62.2	44.5
P_S:P_g (%)	32.7 (45.2)	14.7	5.2	39.7	198.0	138.2	76.8
P_T:$P_{T,o}$ (%)	72.0 (30.2)	69.1	53.2	86.9	191.6	41.9	24.1
P_S:$P_{T,o}$ (%)	33.4 (86.2)	8.1	3.0	24.3	900.3	257.4	78.0

*Storms with ~~light rain + dew~~occult precipitation.

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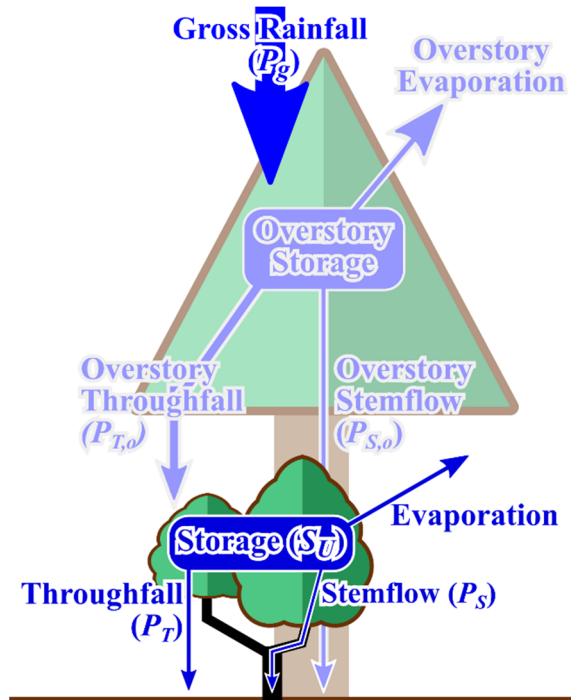
Figure 1: Partitioning of gross rainfall by the overstory (light blue) and by the understory (dark blue). Overstory throughfall ($P_{T,o}$), the input to the understory canopy, was estimated from past work at the site (see supplemental materials). The proceeding of maximum understory water storage capacity (S_U), throughfall (P_T), and stemflow (P_S) were measured in this study.
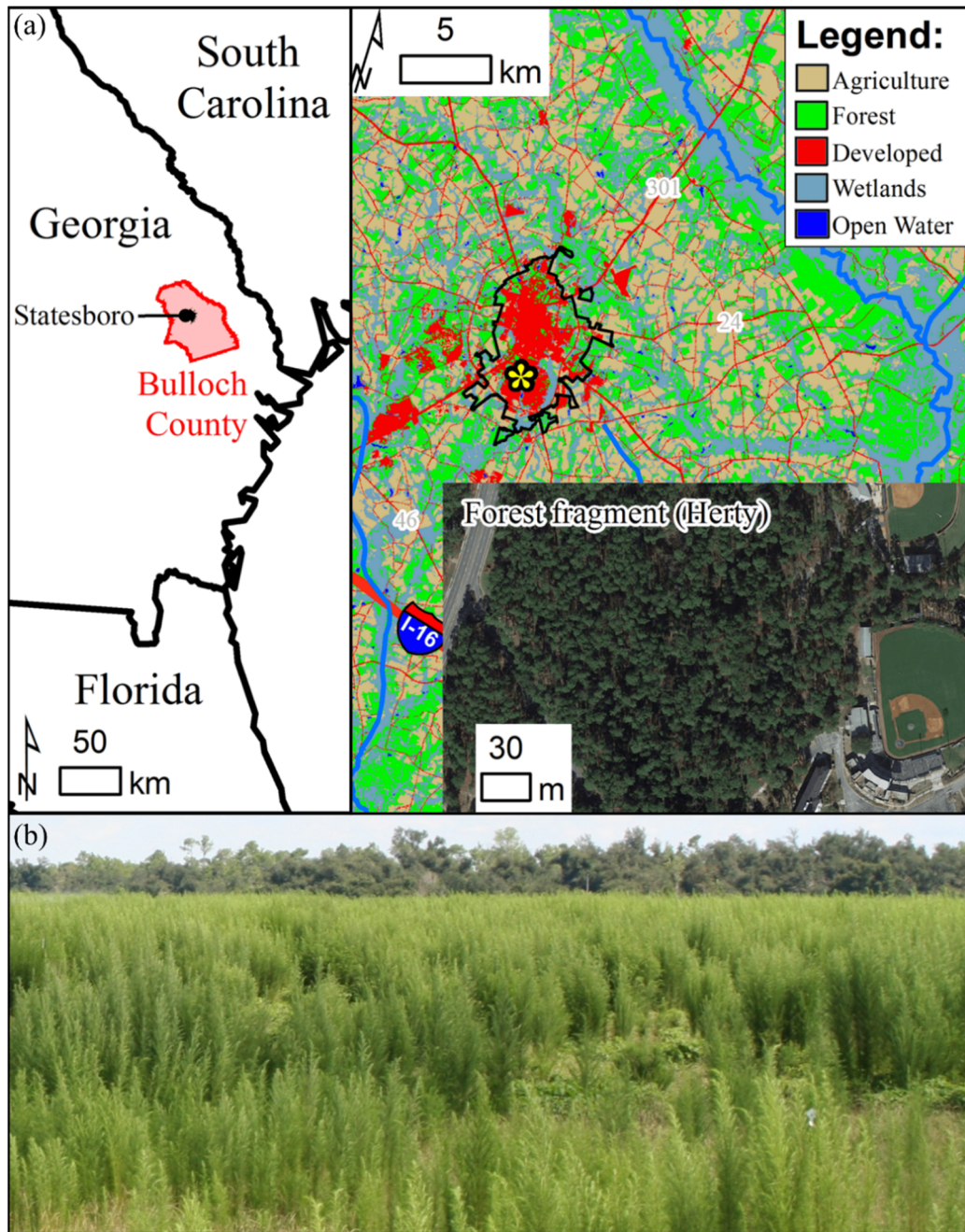
**Figure 2:** (a) Location of the studied *Pinus palustris* (longleaf pine) forest fragment, Charles H. Herty Pines Nature Preserve, on the Statesboro, Georgia (USA) campus of Georgia Southern University, where *Eupatorium capillifolium* (dogfennel) is a dominant understory plant. (b) Dogfennel can dominate pastures as well, as shown by the photograph (credit: Brent A. Sellers). Map layer sources: State and county boundaries, and aerial imagery ©ESRI, TomTom North America, Inc. The land use layer was derived from the National Land Cover Database 2011 (full metadata and data access link: https://gdg.sc.egov.usda.gov/Catalog/ProductDescription/NLCD.html).

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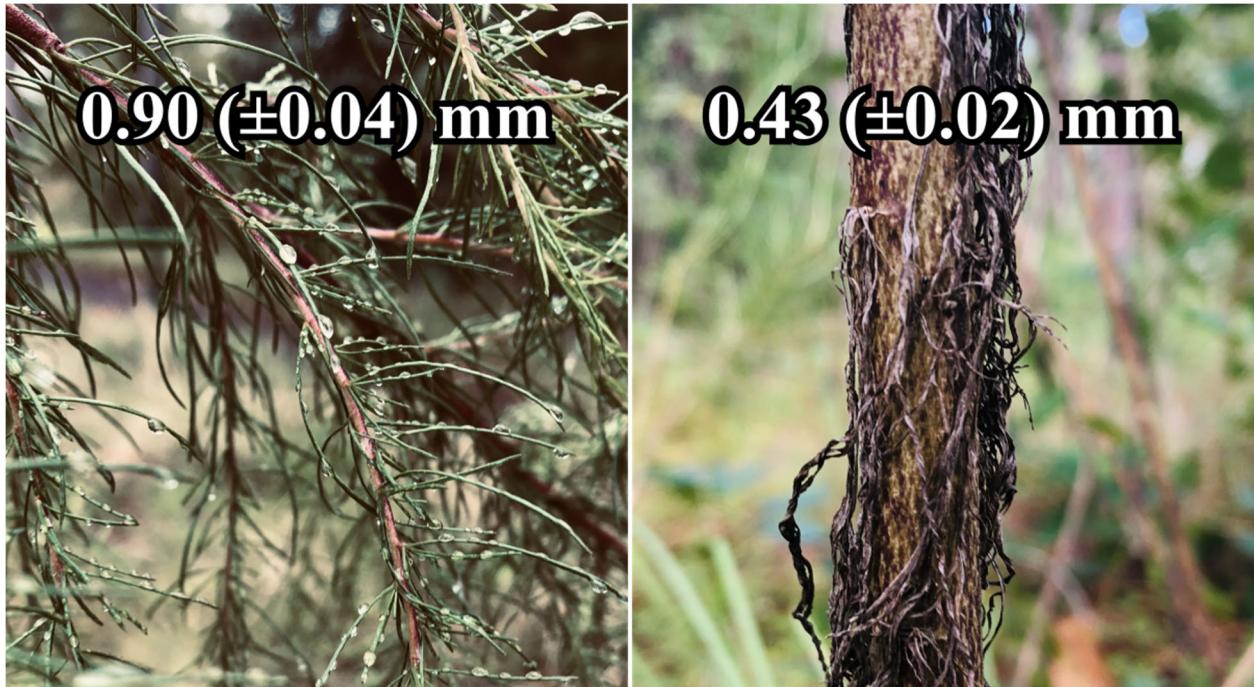
Figure 3: Water storage capacity (standard error) for the (left) canopy and (right) stem of *Eupatorium capillifolium* (dogfennel) per lab-based submersion tests on samples collected from the Herty Pines understory.
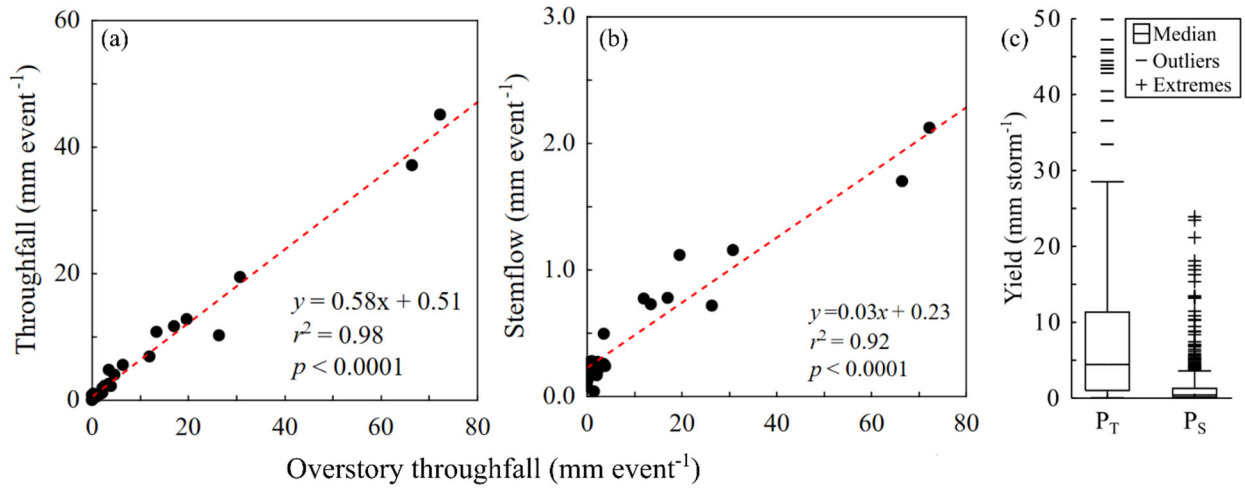
Figure 4: Scatter plots showing the responseBoxplot of *Eupatorium capillifolium* (dogfennel) (a) throughfall (P_T) and (b) stemflow (P_S) yields across all rainfall events (without occult precipitation). (c) Boxplot showing yields from individual P_T gauges and plants' P_S. (Line and box: median and interquartile range; whiskers: non-outlier range; other symbols represent outliers and extreme values).

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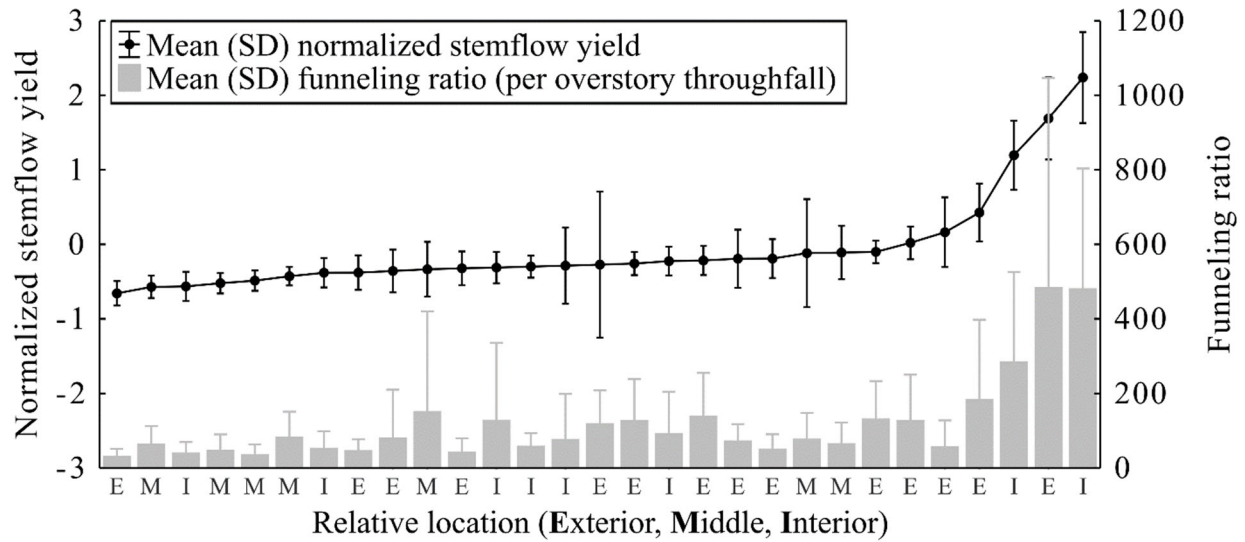
Figure 5: ~~No dogfennel (*Eupatorium capillifolium*) plant structural metrics correlate ($r^2 < 0.1$ for all regression lines)~~ ~~with normalized stemflow yields or funnelling ratio. (a)~~ Mean and standard deviation (SD) of normalized stemflow yield ~~per~~ plant[-1] and associated funneling ratio per ~~(~~Herwitz~~,~~ (1986) in order of rank per mean normalized stemflow yield. ~~Plant~~ ~~compared to their~~ location~~s~~ within clusters are indicated (E = external, M = middle, between the interior and exterior, and I = interior)~~.~~

Reviewer 1: "Gordon et al. present observations of understory rainfall interception in the southeastern US. Dogfennel, the understory plant they study, is a tall and dense forb that the authors show can have a major effect on rainfall partitioning. The topic is of great interest to HESS readers, as rainfall interception is an important component of the water cycle that is nevertheless relatively poorly studied and represented in models. The authors make a compelling case that this is particularly so for low-stature and understory vegetation, such as the dogfennel communities they study."

Response: We thank Reviewer 1 for their appreciation of the manuscripts' strengths and insightful comments regarding the study weaknesses. We have addressed these comments as described below and believe our revised manuscript has been greatly improved.

"The overstory throughfall fluxes, which act as the normalization factor in the most important event-level rainfall partitioning estimates and are thus essential to the authors' conclusions, are interpolated rather than measured. The authors acknowledge this potentially major source of uncertainty only briefly when discussing the spatial variability (l280, Fig. 5). I feel that this issue needs to be addressed head on, as I have several concerns. First, it further introduces spatial variability. However, the spatial variability of understory throughfall (and overstory throughfall) is not analysed, despite the redundancy in the measurements. Second, there could well be an association between overstory throughfall and relevant dogfennel parameters such as their density. Such an association would need to be addressed if the authors want to draw robust ecosystem level conclusions. Third, there may be a temporal bias here as well, but it is difficult to say because the study periods in which overstory and understory throughfall measurements were conducted are neither stated nor compared. Fourth, while the interpolation of spatially averaged overstory throughfall (supplement) provides a decent fit overall, the linear association is clearly insufficient for small rain events. For zero rainfall, it predicts negative throughfall. The authors, however, analyse small events in great detail. It is not clear to me how these issues impinge on their estimates of understory throughfall for small events."

Response: The reviewer is correct that we estimated the stand-level overstory throughfall flux using recent data measured at the site. Unfortunately, it is not possible to directly measure overstory throughfall AND measure understory partitioning simultaneously. This is because the direct measurement (via tipping buckets or bottles, etc) of overstory throughfall would disturb or remove understory throughfall and stemflow. We respectfully disagree that we have "only addressed [this issue] in a cursory manner." In fact, we explicitly state in lines 133-138 (and in the supplement) how and why we estimated overstory throughfall, and discussed how this constrains our ability to broadly interpret understory throughfall and stemflow patterns.

The reviewer raises two issues regarding the overstory throughfall estimation methods: (i) the linear association between rainfall and overstory throughfall "predicts negative throughfall" in small events; and (ii) there "may be a temporal bias" as the data for estimating overstory throughfall were collected prior to the start of this study. Regarding point (i), the reviewer is absolutely correct. However, overstory throughfall estimates for our small storms were not negative; so, after returning to the analysis spreadsheet, we realized that the wrong method was reported. Overstory throughfall (TF_o) was estimated from the association between TF_o (as a % of rainfall) and storm size (R) using the so-called "Aston" curve: TF_o[%] = a * (1 - EXP (-b * R[mm])). This does not return negative TF_o for small storms. We apologize for this error and have updated the supplemental figure to reflect the correct

method. Regarding point (ii), we do not believe that there is any significant temporal bias. The canopy is mature and there has been no known/noticeable disturbance or change in canopy structure. As a result, although one can never be entirely certain, we assume that the association between overstory throughfall and storm size has not changed. This is now explicitly stated in the methods in lines 135-138.

"the uncertainties that arise from the ad-hoc estimation of dewfall are not addressed or quantified."

Response: The dew estimation was, in fact, done post-hoc: after dew was observed during sampling. Still, we have edited the manuscript in lines 140-145 to explicitly state the conditions surrounding our post-hoc dew estimate, including: (1) the assumption underlying the dew estimates (equating it with canopy water storage capacity), (2) the implications of this assumption (that dew estimates are maximums), and (3) confirmation of dew occurrence using quantitative meteorological measurements (beyond the binary/qualitative present or absent, to the eye, during sampling).

"Apart from the issues raised above, the statistical analyses of rainfall partitioning are insufficient. The authors do not report the overall partitioning over the entire study period (e.g. stemflow vs total rainfall or overstory throughfall) and the associated uncertainties. The analyses at the event level that are shown are insufficient for three reasons. First, the overall partitioning is not reported. The individual ratios (e.g. stemflow divided by rainfall) in Tab. 1 cannot be averaged to obtain the overall ratio. The authors, however, do just that in the conclusions (they even report the median rather than the average) when they write: 'Eupatorium capillifolium (Lam., dogfennel) in the understory of an urban forest fragment intercepted 20.4% of verstory throughfall from Pinus palustris (Mill.).. I would expect both errors (aggregating ratios, median instead of mean) to overemphasize small events, and thus to overestimate throughfall/rainfall. The event-level fluxes need to be summed, see e.g. doi:10.1029/2000WR900074, doi:10.1016/S0022-1694(01)00393-6, doi:10.1088/1748-9326/ab1049, for how to estimate overall partitioning and its uncertainties (due to spatial variability, stems that were not instrumented, observation errors, etc.). Second, only summary statistics such as the median are shown (Tab. 1). A scatter plot would allow the reader to draw additional inferences, such as in what way stemflow increases disproportionately for larger events. Third, it is not clear how the data were spatially aggregated. Three clumps were instrumented, and I assume they were averaged over, but how?

Response: We appreciate the reviewer's comments on the statistical analyses and, firstly, we agree that the overall median is not the standard statistic reported for annual precipitation partitioning fractions – it is the sum. Therefore, we now include the total precipitation partitioning fractions from scaled summations across the study. Secondly, the reviewer requested a scatter plot of event summed data with respect to storm size. This has been added to the manuscript (panels a-b in the revised Figure 4). Thirdly, regarding spatial considerations, no spatial analyses (beyond comparison of CV and normalized stemflow values) were done. Even these spatial analyses are rarely done (see recent review: doi: 10.1007/978-3-030-29702-2_6).

"I could not follow the rationale behind the interception capacity measurements. How long were they dried in the oven? Did the leaf itself (not the intercepted water) lose weight during that period? Why not compare it to the weight before wetting? The other issue, which is that the submersion in the lab is very different from the wetting due to rainfall in the field, would remain. This needs to be spelled out clearly, cf. doi:10.1016/S0022-1694(01)00393-6.

Response: We agree with the reviewer that the water storage capacity estimation methods require clarification. The details requested by the reviewer (and some additional information) is now provided in Lines 178-188. We also agree that we should clarify differences between this method and how leaves/stems wet in nature. This has been added to the manuscript.

"The throughfall funnels are not described in detail, and there is not a single picture. The authors argue that they provide more robust estimates because they are larger than most rain gauges that are commonly used for such purposes, but at approximately 25x25 cm, this difference does not strike me as particularly noteworthy. Given the relatively large density of dogfennel plants, however, it is not clear to what extent the plants and hence the throughfall were disturbed by the installation of the funnels.

Response: Dimensions of funnels are described, and we now provided a photograph of a deployed throughfall gage in the supplemental materials. To clarify: we did not state that these funnels were bigger than most funnels – rather, we noted that funnel size was larger per unit canopy area for the studied plant, dogfennel, compared to trees.

"I would not be able to reproduce the scaling of the rainfall interception capacity measurements from the leaf to the plot scale. The authors mention in l176 that they use estimates of leaf area, but these estimates are never introduced. Equations would also help, as would a consistent terminology (surface area seemingly refers to very different things in the same paragraph)."

Response: We agree and have provided greater detail on the scaling methods for water storage capacity in lines 195-202, stating "Specific water storage capacity estimates for the stem (0.436 mm) and leaves (0.195 mm) were then scaled to Su [mm as L m-2] using stem and leaf surface area estimates per plant (171.9 cm2 plant-1 and 807.5 cm2 plant-1, respectively), and multiplied by the site plant density (5.68 plants m-2) and divided by 1000. Plant stem and leaf surface area estimates were determined from 5 representative plants that were cut from the site and separated into leaves and stems, then the sum of leaf and stem areas (determined as mentioned earlier in the paragraph) were divided by 5."

"It is not clear how dogfennel density (e.g. at what scale) was determined and whether the numbers given in Section 2.1 refer to the clumps the authors study or to other areas."

Response: We agree. Details for estimating stem density are now provided in lines 115-117, stating "Dogfennel density was estimated in ten 10x10 m plots by counting the stems clump-1 for 3 randomly-selected clumps in each plot. For each plot, the mean stems clump-1 were multiplied by the number of clumps plot-1. Finally, all stems plot-1 were summed and scaled to 1 ha."

"The three clumps the authors study are not described in detail. How do they differ? What do they look like? Does that have an impact on the rainfall partitioning?"

Response: The plants from each clump are described in detail in Table 1. From the details in Table 1, the plants were all very similar.

"The regression analysis shown in Fig. 5 (of doubtful value because it relies on the unrealistic assumption on overstory throughfall) is not described. According to the figures, it looks like the authors regressed the ranks rather than the actual observations, which would need justification. So would the fact that the authors apparently did not consider the joint influences of explanatory variables."

Response: We have removed the bottom panels of Fig. 5 and now provide scatterplots in the supplement (new Figure S5) that shows no statistically significant correlations for the variables (or no significant differences for the categorical variable) presented in the old Figure 5. No multivariate statistical methods were applied to assess multivariate influences over stemflow variability as all bivariate results were very highly un-significant (r2 ~ 0 and p > 0.9).

"Figure 6 compares rainfall partitioning of herbaceous plants and trees, but I suppose the climatic conditions differ between the two and thus constitute a major confounding factor. These concerns are, however, not addressed."

Response: We have removed Figure 6 from the manuscript for two reasons (1) there is already a synthesis work published that we can cite and (2) we believe that this synthesis figure merits greater consideration in a different, broader paper.

Reviewer 2.

"In my view, the submitted study is highly interesting and convincing, carefully conducted, and well presented. It is well suited for the journal and should be of high interest for the readers. For further clarification, I suggest to add more details on the conducted lab investigations: how long were the plant samples dried in the oven?, and more details on the mass balances (how the final values of storage capacity were obtained) would be helpful."

Response: We thank Reviewer 2 for their appreciation of the manuscript and their suggested revisions. We have addressed these comments by providing greater details on the lab investigations and related data analyses in lines 115-117, 135-138, 140-145, and 178-202; as well as by providing additional figures to the manuscript (Figure 4a-b) and the supplemental materials (Figures S2, S3b, and S5).