

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% (median $P_T:P_{T,o}$ 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 (mixed 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 precipitation partitioning differed markedly from the site's overstory trees (*Pinus palustris*), and a discussion 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.

34 1. Introduction

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

53 Current theoretical and numerical modeling frameworks for canopy precipitation partitioning (see review by
54 Muzylo et al. (2009)), are almost exclusively based on observations beneath woody plants, like forests and shrublands
55 (Sadeghi et al., 2020). In forests, the past 150 years of research has primarily targeted dominant overstory trees
56 (Ebermayer, 1873; Van Stan and Gordon, 2018). However, herbaceous plants commonly dominate forest understories
57 and can be abundant beneath shrublands (Jiménez-Rodríguez et al., 2020; Lajtha and Schlesinger, 1986; Specht and
58 Moll, 1983). As a result, our current understanding of “net” precipitation (as measured beneath woody overstory
59 canopies) is not representative of the actual precipitation that reaches the surface (or litter layer: Gerrits and Savenije,
60 2011) beneath the understory. Herbaceous canopies are relevant to precipitation partitioning in more than the one-
61 third of the global land surface represented by forests; they also cover 27% and 11% of the global land surface in
62 grasslands and croplands, respectively (Alexandratos and Bruinsma, 2012; Suttie et al., 2005). It is unlikely that
63 current knowledge on precipitation partitioning based on woody vegetation is applicable to herbaceous vegetation,
64 since they differ in many hydrologically-relevant morphological features: smaller height, the lack of bark structure,
65 and presence of other stem features (like trichome hairs or desiccated leaves), etc. This raises unanswered and little-
66 researched, questions that must be addressed to include herbaceous plants in precipitation partitioning theory, e.g.:
67 How do these significant morphological differences affect canopy and stem water storage capacities? Do herbaceous
68 plants also favor throughfall generation, like woody plants, or do they more efficiently drain precipitation to their stem
69 bases (and, thereafter, their shallow roots)? In fact, several long-standing (and hitherto unanswered) calls for greater
70 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% of event
89 $P_{T,o}$ as P_S (Sadeghi et al., 2020). For our study on dogfennel, we hypothesized that, compared to past research on
90 woody plants, dogfennel stems and leaves (i) can store a hydrologically relevant amount of rainwater (i.e., within the
91 range of water storage capacities reported for woody plants: (Klamerus-Iwan et al., 2020), (ii) significantly reduce net
92 rainfall flux to the surface (i.e., $P_T + P_S \ll P_{T,o}$), and (iii) redistribute a substantial portion of $P_{T,o}$ to the surface via P_S
93 (i.e., P_S will often “funnel” more rainwater per storm to the soils surrounding stems than P_T , $P_{T,o}$ or P_g over the same
94 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 50.4 m² ha⁻¹ of basal area. Dogfennel, our study plant, was particularly dominant along the
107 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 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).

127 **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 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 cm² collection area each), three per
148 dogfennel clump (1,520.1 cm² 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 cm², 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., 2020).

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

166 **2.3. Water storage capacity estimation**

167 Maximum water storage capacity (S_u [mm]) was estimated for the dogfennel canopy and stem, both as volume [L] per
168 unit surface area [m²]. All field leaf and stem samples were collected during an inter-storm dry period (>24 h after
169 any rainfall). For the canopy, 50 leaves representing the median size of the site dogfennel plants were sampled (broken-
170 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
171 broken end of their leaf-stems were sealed with silicon to prevent water exchange from an area that was not previously
172 exposed in its natural state. Sampling for the stems was similar; however, since dogfennel heights reach (and can
173 exceed) 2 m, the stems were cut into 5 cm sections. Just as with the leaves, 50 representative samples of these stem
174 sections were weighed in the lab, then sealed with silicon on both ends. Next, all leaf samples and stem sections were
175 submerged in water for three days until achieving maximum saturation (per Van Stan et al., 2015), whereupon the
176 maximum saturation mass [g] was recorded. For comparison with the field-dry mass, all samples were oven-dried
177 until their mass no longer changed (mass recorded every 3 h), whereupon the oven-dried mass [g] was recorded. No

178 leaf or stem samples were oven dried longer than 15 h. The gravity convection oven (Isotemp, Fisher Scientific) was
 179 set to 40 °C (confirmed with a standard thermometer). The maximum volume of all samples' water storage capacity
 180 is the difference between saturation and oven-dried mass. The oven-dried leaves and stems did not visually appear to
 181 be damaged (aside from the sampling cuts, obviously) and care was taken to ensure the plant samples were not
 182 damaged. It is likely that internal (not externally intercepted) water was exchanged during this process; however, this
 183 is not entirely problematic as plant surfaces are known to permit interaction between externally intercepted water and
 184 internal water (Berry et al., 2019). Moreover, we explicitly acknowledge that these methods produce the “maximum”
 185 possible water storage capacity (hence, our objective to estimate maximum water storage capacity), as multiple
 186 intrinsic and extrinsic factors of plant surfaces could reduce the available water storage capacity in situ (Klamerus-
 187 Iwan et al., 2020).

188 Specific water storage capacity [mm] for the leaves and stems was determined by dividing the lab-derived
 189 maximum volume [mL] by the samples' surface area [cm²]. For leaves, after sampling, levelled photos of each sample
 190 were taken on a grid system (every block representing 2.5 cm x 2.5 cm for scale), then the leaf images were vectorized
 191 and processed for 2-D projected surface area using the “Measure Path” extension in Inkscape (v. 0.92, Inkscape.org).
 192 An example vectorized image of leaf area is provided in the supplemental materials (Figure S4). Error in this vector-
 193 based leaf surface area estimate was estimated by repeating the process five times for each leaf. Stem surface area for
 194 all samples was estimated from their radii and height. Specific water storage capacity estimates for the stem (0.436
 195 mm) and leaves (0.195 mm) were then scaled to S_u [mm as L m⁻²] using stem and leaf surface area estimates per plant
 196 (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
 197 divided by 1000. Plant stem and leaf surface area estimates were determined from 5 representative plants that were
 198 cut from the site and separated into leaves and stems, then the sum of leaf and stem areas (determined as mentioned
 199 earlier in the paragraph) were divided by 5. Total leaf surface area compares well to values reported from ~1 m tall
 200 dogfennel plants, 212 cm² plant⁻¹ (Carlisle et al., 1980), considering our plants were much taller (~2 m).

201 2.4. Data analysis

202 Descriptive statistics were compiled for all variables presented and regression analyses were performed to relate plant
 203 canopy and hydrologic variables. All statistical analyses were done using Statistica 12 (StatSoft, Tulsa, OK, USA).
 204 Throughfall volumes [L] from all gauges were summed and converted to yields [mm] by dividing by the total gauge
 205 area [m²]. Stemflow yield [mm] for an individual plant was determined by dividing its volume [L] by the projected
 206 canopy area [m²]. To compare stemflow production across plants, two metrics were computed per plant for each storm:
 207 normalized stemflow ($\bar{P}_{S,i}$ [-]) and the funneling ratio (F [-]). $\bar{P}_{S,i}$ was computed per Keim et al. (2005):

$$208 \quad (1) \bar{P}_{S,i} = \frac{(P_{S,i} - \bar{P}_S)}{s_S}$$

209 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
 210 in a single storm, and s_S is the standard deviation of stemflow for all plants in a single storm. F for individual plants
 211 in each storm were computed per (Herwitz, 1986):

$$212 \quad (2) F = \frac{P_{S,i}}{B_i P}$$

213 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
214 indicated in the results). There are an increasing number of F metrics (Carlyle-Moses et al., 2018; Levia and Germer,
215 2015); however, the selected method is the most common F metric applied to stemflow data to date. Moreover, in situ
216 observations of non-collared dogfennel plants during rainfall confirmed that dogfennel P_S rates did not produce visible
217 runoff areas.

218 3. Results

219 3.1. Storm and plant structural conditions

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

232 3.2. Partitioning into water storage, throughfall and stemflow

233 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
234 of $P_{T,o}$, respectively, beneath dogfennels at our site. Water storage capacity achieved by dogfennel leaves in the lab
235 was 0.90 ± 0.04 mm, while dogfennel stems stored a capacity of 0.43 ± 0.02 mm (Figure 3). This resulted in the total
236 S_U of dogfennel plants in the understory of this study site being approximately 1.3 mm. This S_U estimate agrees with
237 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
238 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
239 mean $P_{T,o}$ yield, 16.5 mm (from Table 1). A large portion of the rainwater captured on dogfennel canopies was able
240 to overcome stem water storage capacity and generate P_S . Dogfennel P_S data were highly skewed, producing a mean
241 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
242 events including occult precipitation, both maximum $P_S:P_{T,o}$ and $P_T:P_{T,o}$ exceeded 100%: $P_T:P_{T,o}$ during mixed storms
243 maximized at 192%; whereas, the maximum for $P_S:P_{T,o}$ was just over 900% (Table 2). Note that dew in the understory
244 was not measured by the above-canopy rainfall gauges and estimated $P_{T,o}$ was only increased by an assumed maximum
245 dew contribution equal to S_U (1.33 mm), thus dew accumulation allows P_T and P_S to exceed 100% of P_g and $P_{T,o}$

246 (Table 2). When compared to rainfall above the overstory (P_g), the medians are much smaller: $P_T:P_g$ being 45% and
247 58% for rain-only storms and mixed storms, respectively, and $P_S:P_g$ being 4.1% and 14.7%, respectively (Table 2).

248 Yield [mm] were estimated for dogfennel P_T and P_S across storms, and both event-level P_T and P_S yields
249 linearly correlated with estimated event-level $P_{T,o}$ (Figure 4a-b). Since, for P_T , the catchment area (canopy area above
250 the gauge) is equal to the input area (soil area below the gauge), P_T yield from the canopy and P_T supply to the surface
251 are equal and the term “yield” will be applied for both. Median P_T yield beneath dogfennel for the measured storms
252 was 4.4 mm with an interquartile range of 1.1 mm to 11.3 mm (Figure 4c). Maximum P_T yield approached 50 mm
253 during a large-magnitude rain storm (where $P_g = 101.3$ mm). Since the canopy area that generates stemflow is many
254 times greater than the surface area around plant stems that receive stemflow (see Table 1), P_S yield and F will differ.
255 F are typically used to represent P_S supply to soils, and is done so in the proceeding section. Yields of P_S from
256 dogfennel were as high as 24 mm, but the median was 0.4 mm and the interquartile range was narrow, 0.1-1.3 mm
257 (Figure 4c).

258 3.3. Stemflow and throughfall variability

259 Coefficients of variability (CV) and quartile variability (CQV) were computed for both P_S and P_T , relative to P_g and
260 $P_{T,o}$ (Table 2), and storm-normalized temporal stability plots were generated for P_S yield only (Figure 5). Storm-
261 normalized temporal stability plots were not generated for P_T yields because the experimental design accounts for its
262 spatial variability through deployment of large gauge areas (compared to dogfennel canopy area); which permit
263 estimates of variability across a few large-area gauges (Table 2), but limits the observable variability. CV and CQV
264 for relative P_T ranged from 22-90% and were generally lower for rain-only storms, <40%, than for mixed storms,
265 >60% (Table 2). Variability in relative P_S across study plants, ranging from 77-257%, was always greater than
266 observed for relative P_T for the monitored storms (Table 2). Due to the greater skew in the relative P_S data compared
267 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
268 for rain and the mixed storms; however, the CV for $P_S:P_g$ was greater for rain-only storms compared to mixed storms.

269 Temporal stability of normalized stemflow, $\bar{P}_{S,i}$ (Figure 5) indicates that there were only a few plants that
270 captured most of the $P_{T,o}$ drained as stemflow (three plants' mean $\bar{P}_{S,i} \gg 1$). Thus, most of the studied dogfennel
271 plants captured similar amounts of $P_{T,o}$ as stemflow—having $\bar{P}_{S,i}$ between -1 and 1 ($y = 0$ represents the central
272 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
273 around their stem bases (Figure 5). Mean F across all plants was 87, and for the 27 plants whose mean $\bar{P}_{S,i}$ fell between
274 -1 and 1, median F ranged 18-200 (Figure 5). However, for the three plants with the highest $\bar{P}_{S,i}$, their mean F values
275 were 287, 476 and 484 (Figure 5). These voluminous stemflow-generating plants, alone, account for one-third of total
276 P_S volume (8,734 mL / 27,870 mL). To evaluate possible canopy structural influences over P_S variability, various
277 directly-measured structural metrics were compared: radii of canopies and stems and the vertical variability in leaf
278 angle (see supplemental Figure S5). No clear visible or statistical correlations or correspondences were found between
279 these structural variables and $\bar{P}_{S,i}$ across plants (Figure S5). In fact, variability in the measured canopy structural
280 variables was low (Table 1) compared to the variability observed for dogfennel P_S and $\bar{P}_{S,i}$ (Figure 5).

281 4. Discussion

282 4.1. Overstory throughfall partitioning by dogfennel

283 Partitioning of overstory throughfall by this example dominant understory and pasture forb resulted in hydrologically
284 relevant losses of rainwater to the surface at our site (Table 2). As maximum water storage capacity is a major driver
285 of rainfall interception (Klaassen et al., 1998), the magnitude of dogfennel's overstory throughfall interception may
286 be attributed to its canopy being able to store a sizeable magnitude of rainwater per unit area, 1.33 mm (Figure 3). A
287 synthesis of water storage capacities for the leaves of herbaceous plants has been done (alongside other plant types)
288 (Breuer et al., 2003), but less research has estimated the stem component (or a reported a total including the stem
289 component) of water storage capacity for short vegetation (Bradley et al., 2003; Wang et al., 2016; Wohlfahrt et al.,
290 2006; Yu et al., 2012). However, the stems of herbaceous plants, even thick smooth stems (>1 cm in diameter) can
291 store nearly 0.5 mm: e.g., *Taraxacum officinale* (dandelion) (Wohlfahrt et al., 2006). Even thin (<1 cm radius)
292 herbaceous stems with epidermal outgrowths, like hairs, can store large amounts of rainwater: e.g., 0.25 mm for
293 *Achillea millefolium* (yarrow) and 0.20 mm for *Trifolium pretense* (red clover) (Wohlfahrt et al., 2006). In the case of
294 dogfennel stem water storage capacity at our site, the 0.43 mm estimate is within this range and its magnitude is likely
295 a result of two principal factors: (1) dense stem coverage by desiccated leaves (photo in Figure 3); and (2) this species
296 can achieve large densities, up to 700,000 stems ha⁻¹ (Dias et al., 2018) – 56,770 stems ha⁻¹ at our study site. We note
297 that, to our knowledge, stem water storage capacities for herbaceous plants with spines, thorns, etc. have not been
298 evaluated.

299 Overstory throughfall was also redistributed into a highly spatially variable (Table 2), but temporally
300 persistent pattern (Figure 5) beneath dogfennel canopies (where CV or CQV was approximately 20-40% for P_T and
301 80-250% for P_S ; Table 2), despite all measured canopy structures—like branch angle, stem size, canopy size, etc—
302 being similar (Table 1). Since our sampling plan measured P_T over a large area of the dogfennel canopy (rather than
303 at numerous localized points), this discussion point will focus on the intraspecific P_S observations. The high spatial
304 variability and temporal persistence of P_S across plants despite canopy structural similarity, raises the question: What
305 caused the intraspecific P_S patterns observed in this study? A likely explanation may be that, in this case, access to
306 precipitation for stemflow production is related to overstory throughfall patterns. Overstory throughfall patterns are
307 well-known to be spatially variable, but temporally persistent across forest types (Van Stan et al., 2020). Specifically,
308 individual dogfennel plants that persistently generated greater P_S than other plants may have just received greater
309 overstory throughfall from persistent overstory drip points. If the overstory throughfall pattern is a major driver of
310 intraspecific variability in P_S in this study, then the funneling ratios computed from mean overstory throughfall would
311 be incorrect (in Figure 5). In this case, funneling ratios (computed from the localized overstory throughfall above each
312 plant) would be similar across the monitored dogfennels. Testing this hypothesized relationship between dogfennel
313 P_S patterns and overstory throughfall patterns was not possible in the field, since sampling overstory throughfall would
314 prevent P_S from being generated by the plant. Future work to test this hypothesis could, however, make use of rainfall
315 simulators.

316 The large diversion of rainwater and dew to their stem base may be partially responsible for dogfennel
317 survival during extended periods of drought (or improved invasion efficacy during droughts: Loveless, 1959;

318 Forthman, 1973), and may also explain why this species tends to be one of the most problematic in improved grazing
319 systems located in Florida (Sellers et al., 2009). Rainfall patterns in central and south Florida may also intersect with
320 dogfennel's canopy water balance to "tip the scales" in its favor. Specifically, rainfall in our study region is often
321 limited from January through May, with the bulk of rainfall occurring from June through October, and the water
322 storage capacity of burgeoning dogfennel plants during early spring may enhance chances of individual plant survival
323 (resulting in large infestations as referenced previously).

324 **4.2. Overstory (woody) and understory (herbaceous) canopies may partition rainfall differently**

325 The dominant understory plant at our study site, dogfennel, intercepted similar amounts of overstory throughfall,
326 interquartile range 11-59% storm⁻¹ (Table 2), as compared to the gross rainfall interception by their overstory pine
327 canopy, interquartile range 19-60% storm⁻¹ (Van Stan et al., 2017b). Similar rainwater interception between dogfennel
328 and the pine overstory may be due to dogfennel's maximum water storage capacity comparing favorably to that of
329 overstory tree species, 0.07-4.30 mm (Klamerus-Iwan et al., 2020). Even the maximum stem water storage capacity
330 is of similar magnitude to values reported by past work on woody plants, 0.2-5.9 mm (Klamerus-Iwan et al., 2020),
331 albeit on the lower end of the range. Most current research on stem water storage has focused on intrinsic factors of
332 woody plant stems, like bark thickness, porosity, microrelief, or roughness (Ilek et al., 2017; Levia and Herwitz, 2005;
333 Levia and Wubben, 2006; Sioma et al., 2018; Van Stan et al., 2016; Van Stan and Levia, 2010); however, other stem
334 structures besides bark may be capable of storing substantial water: e.g., the desiccated leaves of our study plant.

335 There were differences in how gross rainfall was redistributed by the overstory canopy compared to how
336 overstory throughfall was redistributed by the dogfennel understory. Stemflow from the overstory, *P. palustris*, was
337 negligible at this site, 0.2% of gross rainfall (Yankine et al., 2017), but median dogfennel P_S was 7.6% of overstory
338 throughfall (with an interquartile range of 2.8-27.2%) (Table 2). Annual relative P_S (and P_T) estimates from trees and
339 herbaceous plants reported by previous work indicates that herbaceous plants are generally greater stemflow producers
340 than woody plants (Sadeghi et al., 2020). Although relative P_T beneath dogfennel was similar to observations of
341 relative overstory throughfall beneath *P. palustris* at this site (Mesta et al., 2017), throughfall has been found to be
342 generally lower beneath herbaceous plant canopies than for woody ones (Sadeghi et al., 2020). This seems reasonable,
343 because, if interception is similar between herbaceous plants and woody plants, then an increase in relative stemflow
344 would necessitate a decrease in relative throughfall. The results of this study support statements by several past studies
345 suggesting that plants in the understory and overstory interact differently with rainfall. Thus, we repeat the long-
346 standing calls for greater research on understory precipitation partitioning, particularly stemflow, research (Price et
347 al., 1997; Price and Watters, 1989; Verry and Timmons, 1977; Yarie, 1980).

348 **4.3. A brief discussion on dew-generated throughfall and stemflow**

349 For a few storms ($n = 5$), dew contributed significantly to P_T and P_S by the studied dogfennel plants. The median P_T
350 generated from dew beneath dogfennels at our site was 0.74 mm plant⁻¹ with an interquartile range of 0.47-0.99 mm
351 plant⁻¹, resulting in a total dew-related contribution to T of 17.1 mm over the study period. Volumes of stemflow under
352 dewfall totaled 558 mL for all study plants, with individuals supplementing the dew-related P_T with up to 61 mL plant⁻¹

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

371 **5. Conclusions**

372 *Eupatorium capillifolium* (Lam., dogfennel) in the understory of an urban forest fragment intercepted 20.4% of
373 overstory throughfall from *Pinus palustris* (Mill.). The remaining 71.0% and 7.9% of overstory throughfall reached
374 the surface beneath dogfennels as understory throughfall and stemflow, respectively. The partitioning of overstory
375 throughfall by this understory forb differs considerably from the rainfall partitioning of the woody overstory,
376 especially regarding stemflow (7.9% versus <0.2%). During a few storms that occurred in tandem with dewfall,
377 dogfennels were able to augment stemflow (and throughfall) production through capturing dew. These processes may
378 help explain how dogfennels survive extended droughts, and even show improved invasion efficacy during droughts,
379 making it one of the most problematic weeds in southeastern US grazing systems. Stemflow variability among
380 individual plants was very high (CV ~250%), but no dogfennel canopy structures measured in this study provided
381 statistically significant insights into this stemflow variability. Future work will assess to what extent overstory
382 throughfall variability drives understory stemflow variability for plants, like dogfennel, of similar intraspecific canopy
383 structure. However, in forests, overstory throughfall is not the final frontier for determining net rainfall, and
384 investigations on how it is intercepted and redistributed by herbaceous plants is needed to improve our understanding
385 of exactly how much (and in what pattern) rainfall reaches the surface. For other vegetated ecosystems where
386 herbaceous plants are the overstory (grasslands and croplands), precipitation partitioning research is also needed.

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390 **Code/Data availability**

391 Data is permanently archived at <https://digitalcommons.georgiasouthern.edu/> and freely available.

392 **Author contribution**

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

400 **Competing interests**

401 The authors have no competing interests.

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564 **Table 1:** Descriptive event statistics for rainfall (observed), overstory throughfall (estimated per Figure S2) and
 565 measured individual plant traits. When minimum overstory throughfall was zero, dew occurred – as verified by air
 566 temperatures equalling dew point temperatures.
 567

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

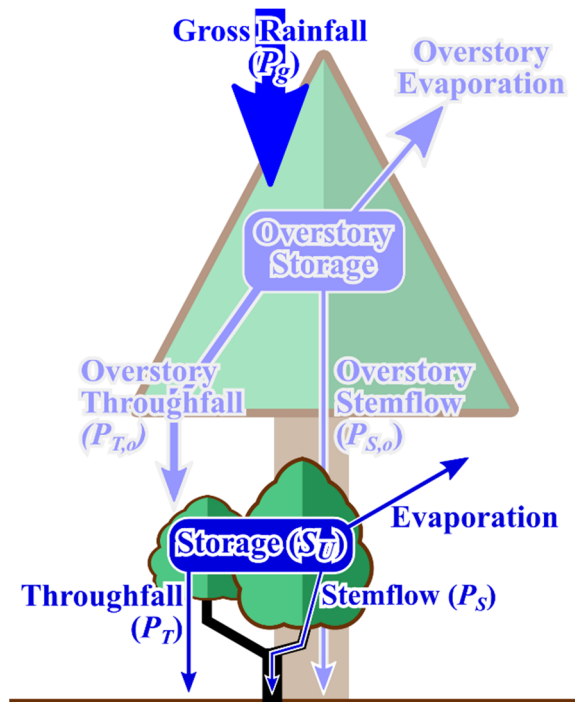
568

569 **Table 2:** Descriptive statistics of relative throughfall (P_T) and stemflow (P_S) yield from dogfennel plants expressed
570 as a proportion of gross rainfall (P_g) and estimated overstory throughfall ($P_{T,o}$). Coefficients of variation (CV) and
571 quartile variation (CQV) are also provided. For storms where dew occurred in the understory, dew was not measured
572 by above-canopy P_g gauges, but was included in the estimated $P_{T,o}$ estimate by assuming dew represented at least
573 additional 1.33 mm (i.e., S_u).
574

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

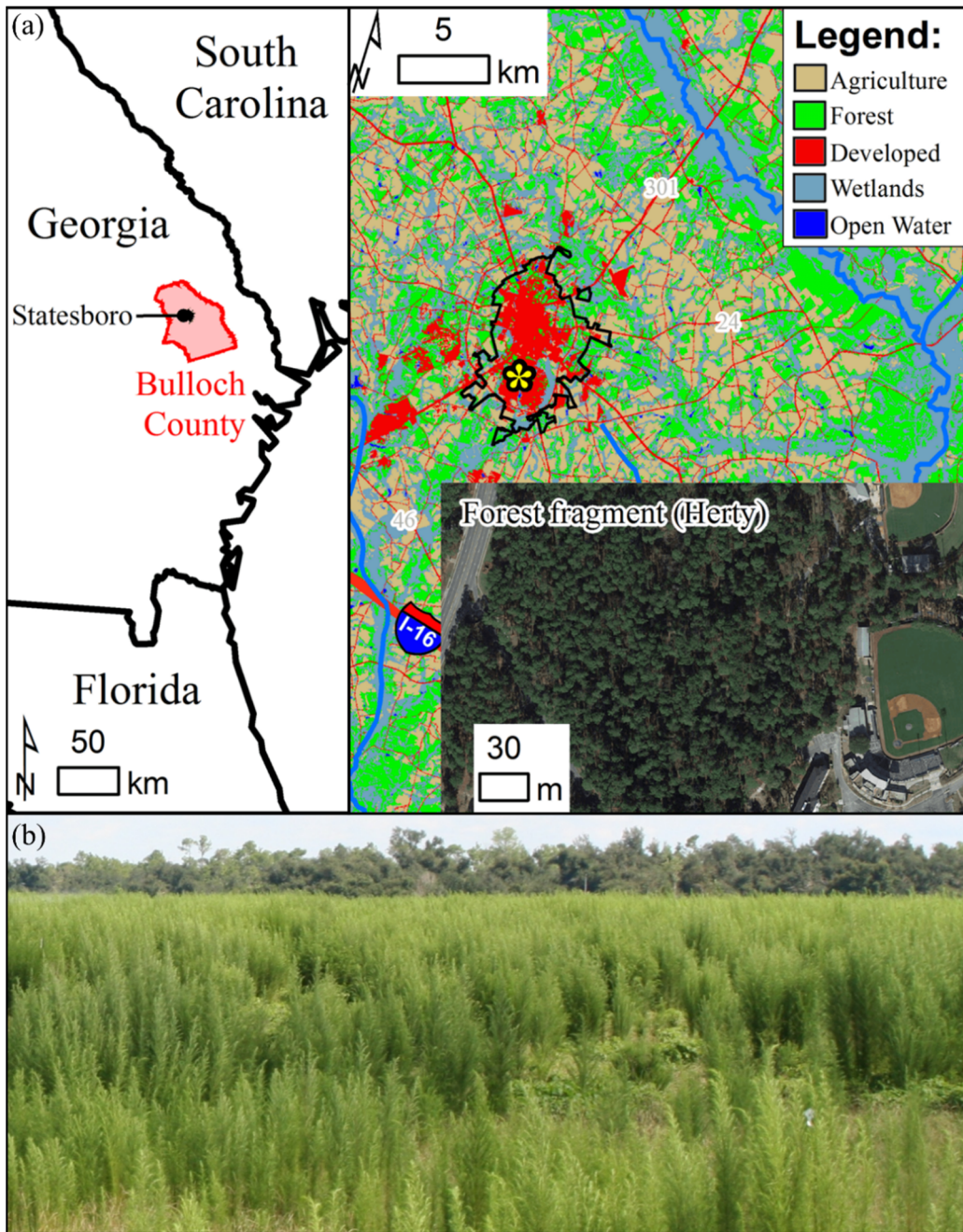
*Storms with occult precipitation.

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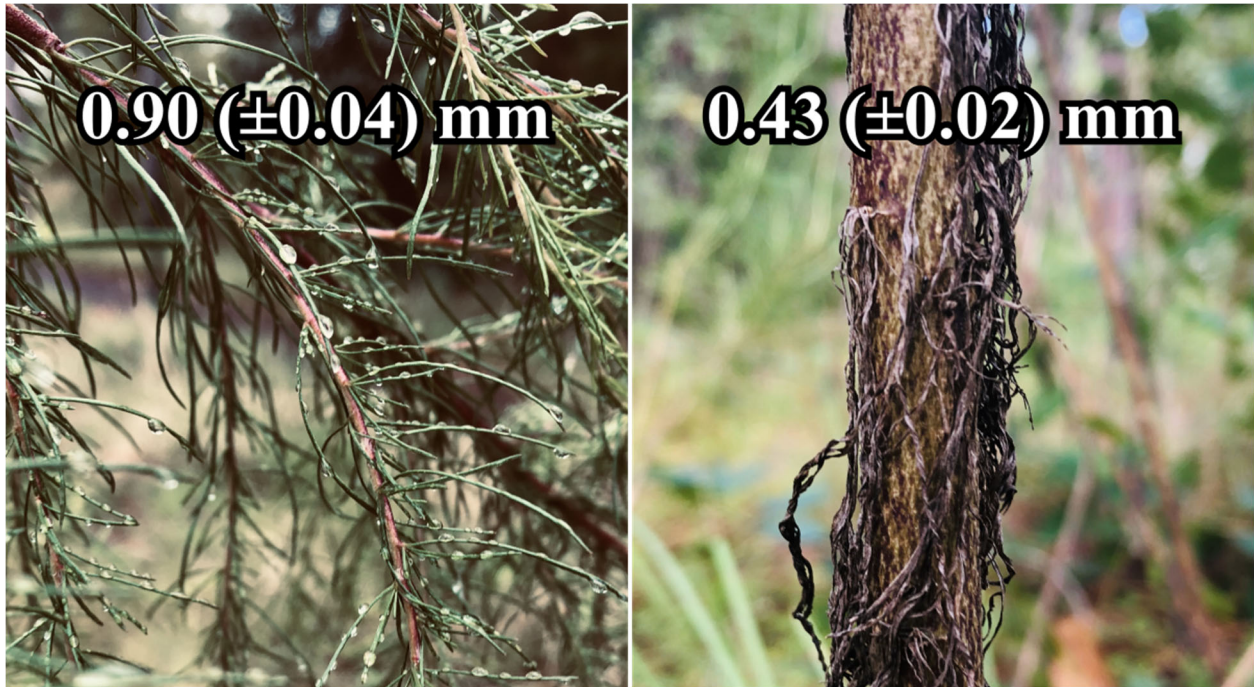


576

577 **Figure 1:** Partitioning of gross rainfall by the overstory (light blue) and by the understory (dark blue). Overstory
 578 throughfall ($P_{T,o}$), the input to the understory canopy, was estimated from past work at the site (see supplemental
 579 materials). The proceeding of maximum understory water storage capacity (S_U), throughfall (P_T), and stemflow (P_S)
 580 were measured in this study.

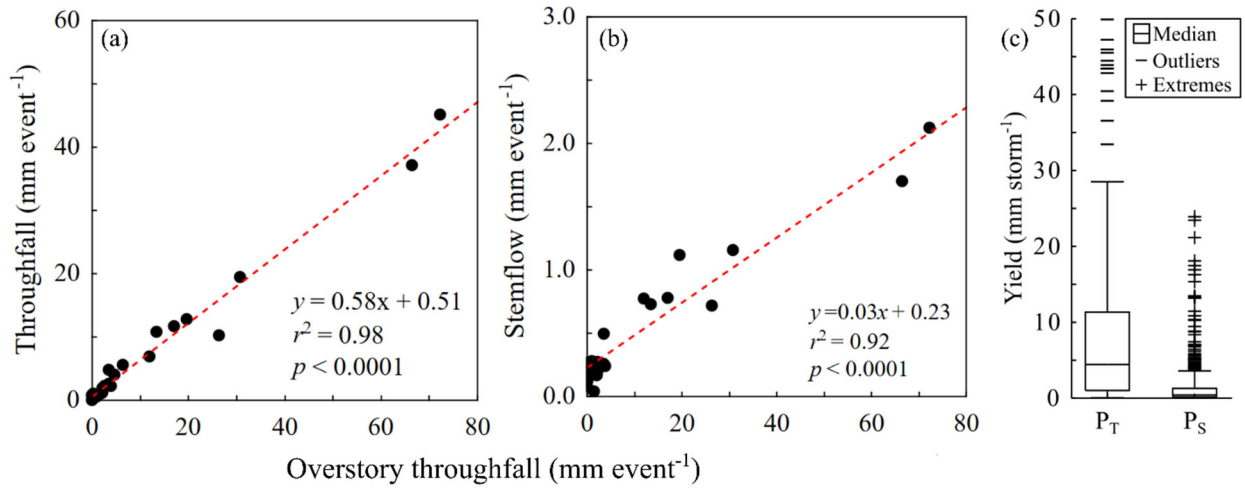


581
 582 **Figure 2:** (a) Location of the studied *Pinus palustris* (longleaf pine) forest fragment, Charles H. Herty Pines Nature
 583 Preserve, on the Statesboro, Georgia (USA) campus of Georgia Southern University, where *Eupatorium capillifolium*
 584 (dogfennel) is a dominant understory plant. (b) Dogfennel can dominate pastures as well, as shown by the photograph
 585 (credit: Brent A. Sellers). Map layer sources: State and county boundaries, and aerial imagery ©ESRI, TomTom North
 586 America, Inc. The land use layer was derived from the National Land Cover Database 2011 (full metadata and data
 587 access link: <https://gdg.sc.egov.usda.gov/Catalog/ProductDescription/NLCD.html>).

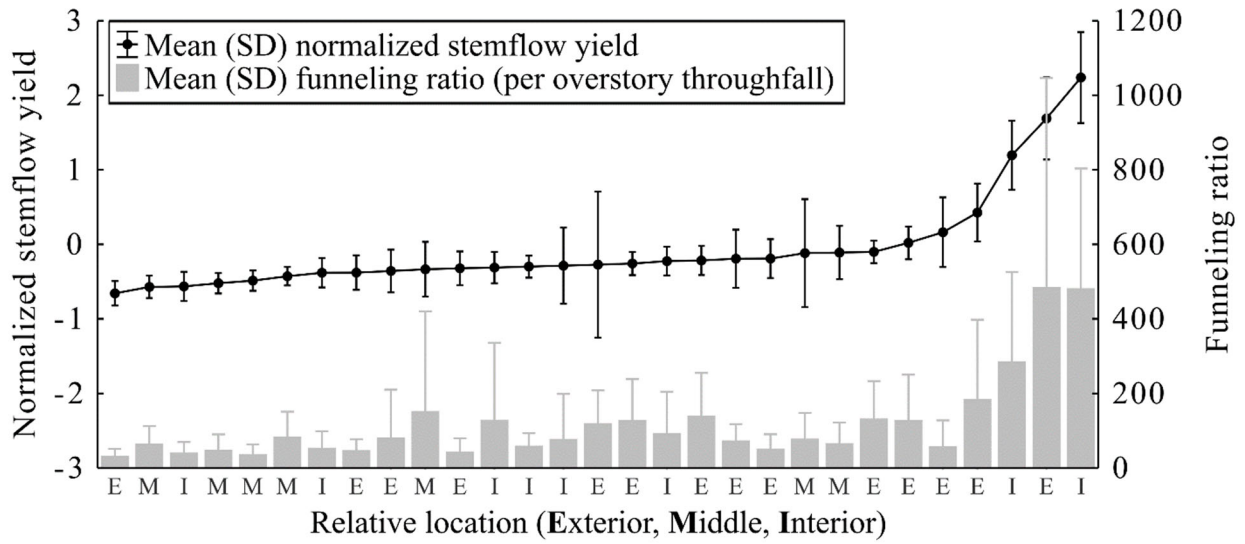


588

589 **Figure 3:** Water storage capacity (standard error) for the (left) canopy and (right) stem of *Eupatorium capillifolium*
590 (dogfennel) per lab-based submersion tests on samples collected from the Herty Pines understory.



591
 592 **Figure 4:** Scatter plots showing the response of *Eupatorium capillifolium* (dogfennel) (a) throughfall (P_T) and (b)
 593 stemflow (P_S) yields across all rainfall events (without occult precipitation). (c) Boxplot showing yields from
 594 individual P_T gauges and plants' P_S (Line and box: median and interquartile range; whiskers: non-outlier range; other
 595 symbols represent outliers and extreme values).



596

597 **Figure 5:** Mean and standard deviation (SD) of normalized stemflow yield plant⁻¹ and associated funnelling ratio per
 598 Herwitz (1986) in order of rank per mean normalized stemflow yield. Plant locations within clusters are indicated (E
 599 = external, M = middle, between the interior and exterior, and I = interior).