

Shower Thoughts: Why Scientists Should Spend More Time in the Rain

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43 **Abstract.** Rainwater is a vital resource and dynamic driver of terrestrial ecosystems. Yet, processes
44 controlling precipitation inputs and interactions during storms are often poorly seen, and poorly
45 sensed when direct observations are substituted with technological ones. We discuss how human
46 observations complement technological ones, and the benefits of scientists spending more time in the
47 storm. Human observation can reveal ephemeral storm-related phenomena such as biogeochemical
48 ‘hot moments’, organismal responses, and sedimentary processes which can then be explored in
49 greater resolution using sensors and virtual experimentation. Storm-related phenomena trigger
50 lasting, oversized impacts on hydrologic and biogeochemical processes, organismal traits/functions,
51 and ecosystem services. We provide examples of phenomena in forests, across disciplines and scales,
52 to inspire mindful, holistic observation of ecosystems during storms. We conclude that technological
53 observations alone are insufficient to trace the process complexity and unpredictability of fleeting
54 biogeochemical or ecological events without the “shower thoughts” produced by scientists’ human
55 sensory and cognitive systems during storms.

56 **Key words.** Extreme event biogeochemistry, Field and laboratory studies, Sampling bias, Climate
57 change, Precipitation, Condensation, Ecosystem functioning.

58 **Introduction**

59 When caught in the rain, we have all run for cover—often to a nearby tree. Stepping over
60 ephemeral puddles and streams, marveling at how quickly the soil changes from supportive and
61 predictable to untrustworthy: slippery, soft, and spongy. Waiting out the storm, we may move to avoid
62 the increasingly drippy areas overhead, eventually leaning on the trunk to rest. Then, as the canopy
63 saturates, water flows down the bark in rivulets, soaking our backs. Perhaps we escape at first chance,
64 forgoing further observation. Yet, as natural scientists, these experiences can reveal ephemeral
65 phenomena prompting curiosity and novel insight.

66 Human observation during storms has profoundly affected our understanding of ecosystems,
67 from the earliest recorded botanical observations (Theophrastus’ *Historia Plantarum*) and indigenous
68 practices. The Bimbache community of El Hierro (Canary Islands) observed water running down tree
69 bark during fog events and captured it for drinking, washing, and agriculture (Galindo & Glass 1764).
70 If more contemporary hydrologists had watched the raking of fog by trees, forest managers may not
71 have logged the Bull Run watershed (Portland, OR, USA), which reduced local precipitation by 30%
72 (Harr, 1982). What stormy phenomena remain unknown, or are overlooked or misunderstood,
73 because of our absence in ecosystems during foggy, rainy, or snowy periods? Could our dry and
74 technological biases limit the progress of natural science (Chu & Evans 2021) by constraining the
75 ‘what if...’ and ‘I wonder how...’ musings that often inspire research?

76 Water science faces criticism regarding its alleged conceptual and theoretical stagnation
77 (Nature Sustainability, 2021) due to a “techno optimism that tries to solve all problems despite not
78 asking fundamental questions” (Scarrow 2021). We argue that this issue is not unique to water
79 science; that modern natural scientists often approach their study systems ‘beneath an umbrella,’ and
80 that this ‘umbrella perspective’ has occluded phenomena that occur just before, during, and after
81 storms. Consistent with this thesis, philosopher Martin Heidegger argued that “Modern technology *is*
82 *not applied to* natural science, far more [often] is modern natural science *the application of the*
83 *essence of technology*” (Heidegger 1977). Thus, although remote sensing and virtual experimentation

with models are useful, their utility is limited because they cannot measure or test the phenomena or hypotheses that we have not yet observed or imagined. Mitigating these blindspots through mindful observations throughout storms may yield various benefits, including improved leveraging of technological sensing, sampling, and models. Real-time observation of storm-related phenomena could shine light on the black boxes inherent to beneath-umbrella perspectives. Indeed, many scientific breakthroughs were not products of technological advancement itself, but were enabled by using new technology as an extension of the human observation system (*e.g.*, Lavoisier’s early hydro-geological research (Meldrum 1933; Rappaport 1967)) and imagination (*e.g.*, eddy covariance systems permit verification of theoretical estimates of momentum, heat, and gas exchanges from ecosystems (Foken *et al.* 2012)).

Humans are sophisticated sensor systems with high-frequency sound, sight, and smell detection, integrated with distributed temperature and pressure sensing across our bodies, *etc.* However, we have many limitations (*e.g.*, being relativistic, uncalibrated, state-dependent, having low recording capacity and biased memory). Technology counters these limitations but is most effective when complemented by human input. Human experience in the storm builds our intuition—motivating the expansion of technology’s observational capabilities. Finally, the ‘shower thoughts’ of scientists integrate technological observations, model hypotheses, and field realities into general theory for further testing. We present examples across disciplines, focused on forests (Table 1, Figure 1), as evidence of the need for natural scientists to emerge from beneath the umbrella and get wet.

103

What’s beyond our “umbrella” science? Examples from forests

Ecohydrology

Our umbrella perspective has resulted in ecosystem scientists knowing little about the filling and emptying of water within forest components as it drains through the overstory, understory, litter, and soil, or evaporates to the atmosphere (Coenders-Gerrits *et al.* 2020). Reviews on rain-canopy and snow-canopy interactions show that many land surface models have severely limited observational

110 bases for storage estimates (Lundquist *et al.* 2021), substantial variability in process representation
111 (Gutmann 2020), or are missing spatiotemporally concentrated fluxes between ‘reservoirs’, like the
112 water which drains down plant stems, stemflow (Murray *et al.* 2013). Depending on the interactions
113 between storm and canopy conditions, surfaces may be saturated in minutes, but this water could
114 evaporate over the following hours (or days for snow). Land surface models, however, often compute
115 canopy water and energy balances with a fixed time step that may be inconsistent with evaporation’s
116 actual timing. This can result in models predicting the canopy is dry when, in reality, it is wet (Llorens
117 *et al.* 2014; Binks *et al.* 2021).

118 Solving such issues with technology is challenging. Sensors measuring humidity and water
119 vapor flux over canopies may see less precisely during, or be blinded by, precipitation (Allen *et al.*
120 2020; Coenders-Gerrits *et al.* 2020). Even when technology is properly monitoring areas of interest,
121 moisture contributions from low-lying fog events (Izett *et al.* 2019), vapor trapped beneath the canopy
122 (Schilperoort *et al.* 2020), or condensate plumes (Figure 1a) may sneak into (or out of) the system,
123 undetected by remote sensors. Catching these phenomena with human eyes could inform canopy
124 water budgets and amelioration of leaf water deficits (Berry *et al.* 2019; Weathers *et al.* 2020). In
125 cold regions/seasons, technological monitoring may miss snow redistributed from canopies to the
126 surface via wind (Figure 1b) or meltwater drainage driven by a tree’s low bark albedo or internal heat
127 (Figure 1c), affecting snow water storage at scales relevant to forest and water management
128 (Dickerson-Lange *et al.* 2021; Levia & Underwood 2004). These issues result in land surface models
129 using a wide variety of formulae and parameters for storm-vegetation interactions, indicating that we
130 have a poor understanding of how to model these processes at large scales (Gutmann 2020). Thus,
131 direct observations from scientists regarding when and where unique ecohydrological conditions
132 emerge could result in a synergy between human observation and technological advancement.

133 ***Biogeochemistry and microbial ecology***

134 Storms can rapidly soak ecosystems, accelerating the flushing, recharge, and transport of
135 solids and solutes, reactivating interactions with microorganisms (McClain *et al.* 2003), acting as
136 ‘stirrers’ to force reactions outside of equilibrium or steady states. As climates change, stirring is
137 changing too as storm frequencies or intensities increase in some regions (Pendergrass 2018; Tan *et*
138 *al.* 2019), and decrease in others (Pokhrel *et al.* 2021). Both cases will have biogeochemical
139 implications (Gutiérrez del Arroyo & Silver 2018; Deng *et al.* 2021). Predicting where and when
140 hotspots and hot moments will arise in relation to storm events is, however, not straightforward.

141 Forests provide clues for human observers to infer where storm-related biogeochemical hot
142 moments may arise. Forest canopies redistribute stormwater, creating localized ‘drip points’, under
143 which throughfall inputs can be >10 times greater than open rain (Zimmermann *et al.* 2009) (Figure
144 1d). If branches efficiently capture and drain stormwaters to the stem, rainwater inputs to near-stem
145 soils can be >100 times greater (Herwitz 1986). Canopy-draining stormwaters flush substantial, but
146 highly variable across space and time, quantities of inorganic nutrients (Ponette-González *et al.* 2020)
147 and dissolved organic matter (tree-DOM). Tree-DOM visibly colors these waters (Stubbins *et al.*
148 2020) (Figure 1e), carries more carbon (C) to forest floors than is exported via streams or stored
149 within the ecosystem, and may be critical to forests’ net C storage and export (Ryan *et al.* 2021).
150 Canopy stormwaters also carry biota, including newly-discovered fungal species (Magyar *et al.*
151 2021).

152 The belated study of many aqueous hotspots and hot moments is surprising because they are
153 visible to the human eye (Schumacher 1864; Bundt *et al.* 2001), albeit potentially missed by soil
154 moisture sensors or lysimeters (*sensu*, “a century of denial” of preferential flow paths; Beven (2018)).
155 These often-overlooked fluxes are impactful. Nutrient rich waters entering dry soils induce bursts of
156 decomposition and mineralization that produce CO₂ and inorganic N (Jarvis *et al.* 2007). However,
157 measurements, and thus knowledge, of soil-atmosphere gas-exchanges are often discontinuous and
158 biased toward ‘dry’ conditions (Scott *et al.* 1999; Ford *et al.* 2012). Although automated infrastructure

159 for monitoring gas efflux exists, it is expensive, logistically challenging, and spatially limited
160 (missing hotspots) (Fassbinder *et al.* 2013).

161 Microbial activities associated with transient, storm-related niches are observable by scientists
162 who persist through the rain (Burgin *et al.* 2011). Oil-like sheen and rust-colored particles on some
163 puddles can appear in forests (Figure 1f), reflecting iron-oxidizing bacteria in microsites of elevated
164 or altered nutrient cycles. Such fluctuations between ferrous (Fe(II)) and ferric (Fe(III)) oxidation
165 states also yield insights into interconnected cycles of other elements and molecules, including S, N,
166 P, biominerals, other metal(loid)s (Li *et al.* 2012), organic C (Hall & Silver 2013; Matus *et al.* 2019),
167 lignin (Merino *et al.* 2021a, b), and CH₄ (e.g., Dubinsky *et al.* 2010). Other visually observable cues
168 of storm-related microbial activity can relate to elemental S (white/pale yellow deposits: Figure 1g)
169 or green chloroplasts of photosynthesizing cyanobacteria and algae (Figure 1h).

170 Smells can also cue humans into ephemeral microbial activities. Hydrogen sulfide gas from
171 sulfate-reducing microbes smells like rotten eggs (Keiluweit *et al.* 2016). Although sulfate reduction
172 and sulfide gas formation are anaerobic processes, well-drained and -aerated soils can develop anoxic
173 microsites (Keiluweit *et al.* 2018) and host sulfate reducing microbes ‘who’ await favorable
174 conditions (Peters & Conrad 1996). The smell of ‘fresh rain’ is also microbially generated, mainly
175 from terpenoids produced by *Streptomyces* bacteria and filamentous fungi (Yamada *et al.* 2015).
176 Following their noses, scientists have been led to interesting discoveries. Becher *et al.* (2020) showed
177 these terpenoids attract springtails to aid in long-distance spore dispersal.

178

179 ***Vegetation functions***

180 Leaves, bark, and epiphytes are often wet. Their wetness can be estimated using sensors
181 (Klemm *et al.* 2002) and energy balance models (Asdak *et al.* 1998), but these approaches may not
182 reveal the incredible variation among leaf surfaces (Figure 1i-j). This variability in wetness has wide-
183 reaching impacts, for example, by: reducing or enhancing C uptake (Aparecido *et al.* 2017; Hanba *et*
184 *al.* 2004; Misson *et al.* 2005); altering pathways of precipitation to the ground (Van Stan *et al.* 2011;

185 Van Stan & Allen 2020); providing opportunities for leaf or stem water uptake and ‘rehydration’
186 (Mayr *et al.* 2014; Mason Earles *et al.* 2016; Berry *et al.* 2019, 2021); capturing substantial moisture
187 in barks and deadwood (Floriancic *et al.* 2022). Rain not only wets leaves, but also renders light more
188 diffuse, which can boost photosynthesis (Berry & Goldsmith 2020).

189 Wandering a rain-soaked forest reveals the multitude of ways plants take advantage of storm-
190 induced flow pathways. Rainy visits to Lord Howe Island (Australia) led Biddick *et al.* (2018) to
191 discover ‘roots’ *aboveground* that harvest water from preferential flow paths through the plant’s own
192 gutter-like leaves and branch channels (Figure 1k-m). Mosses, lichens, and other nonvascular
193 epiphytes adapted to anhydrobiosis are dependent on canopy storm-related hydration-dehydration
194 cycles, like stemflow or storage and evaporation of water within bark (Porada & Giordani 2021).
195 Because different nonvascular epiphytes depend on different sources of water (Gauslaa 2014),
196 observation of the type, intensity and dynamics of precipitation becomes crucial to understanding
197 their ecophysiology and effect on ecosystem function. Stormwaters often exceed the water storage
198 capacity of epiphytic vegetation, leading to overflow (Mendieta-Leiva *et al.* 2020) and nutrient
199 leaching from the canopy (Coxson 1991; Van Stan & Pypker 2015). Following these stormwater and
200 nutrient pulses, dry landscapes transform in ways that may unveil avenues toward the discovery of
201 new life and processes.

202

203 ***Animal behavior***

204 Our umbrella perspective may conceal or misinterpret important animal behaviors and animal-
205 environment interactions. For example, koalas were often described as not needing to drink, because
206 they were rarely observed doing so. Opportunistic observations during storms revealed koalas drink
207 stemflow (Mella *et al.* 2020; Figure 1n). As koalas spend most of their time in trees, and storms make
208 it hard to look upward, the natural drinking behavior of koalas was overlooked because scientists
209 designed dry and comfortable observation methods. Improved understanding of koalas’ physiological

210 need for free water has consequences for their conservation and habitat management. Maned-sloths
211 (*Bradypus torquatus*) share a similar story (de Albuquerque *et al.* 2021).

212 Insect behaviors have also been observed to change during storms. Maschwitz & Moog (2000)
213 reported an ant colony prevented their bamboo nest from flooding by communally drinking
214 stormwaters, then urinating in an area that would drain away from the nest. Rapid changes in humidity
215 and air pressure can influence insect behavior (Wellington 1946), yet these effects have primarily
216 been studied during the dry periods between storms (Enjin 2017). Approaching storms can increase
217 foraging time for a honeybee species, *Apis mellifera* (He *et al.* 2016), and reduce mating activities in
218 three taxonomically-unrelated insect species (Pellegrino *et al.* 2013). Immediately after storms, insect
219 foraging behavior increases because higher humidity reduces desiccation risk and stormwaters can
220 uncover resources (Gordon *et al.* 2013). Thus, our future presence in the storm could help uncover
221 novel insights regarding how animals shelter, feed, and hydrate.

222

223 ***Earth and planetary surface processes***

224 Forests' redistribution of stormwaters may influence sediment routing through watersheds,
225 imparting 'biosignatures' to underlying soils and sediments that are useful for reconstructing the
226 distribution of forests through deep time. Thus, scientist experiences in stormy forests today support
227 efforts to understand Earth's geologic history and modern interactions within and between terrestrial
228 and aquatic systems. For example, by the time storm events mobilize sediment along hillslopes and
229 stream channels, hydrologic information is already modified by the watershed effects that include
230 forests' interception, capture, and routing of water to/through soils. Integrated over that forest's
231 lifetime, which may be thousands-to-millions of years, precipitation partitioning by vegetation is one
232 of innumerable sedimentary processes that must be considered when reconstructing important
233 components of Earth history from the sedimentary record (e.g., paleoclimate, sea-level change, and
234 tectonics) (Jerolmack & Paola 2010). When canopies discharge intercepted water through drip-points
235 or stemflow, this can localize hydrologic, geomorphic, and sedimentary processes. Therefore,

236 observations of canopy stormwater routing may inspire novel hypotheses regarding these waters’
237 capability to produce biosignatures (*i.e.*, any morphological, chemical, or isotopic traces from an
238 organism). Known forest biosignatures include precipitation of cements (possibly microbially aided)
239 (Perry *et al.* 2007), or the opposite, the formation of dissolution features (Lipar *et al.* 2021). Finally,
240 geomorphologists visiting landscapes during storms may open creative avenues for interpreting
241 landscape features on other planets. Use of Earth-based analogs to explain geomorphological
242 processes on other planetary bodies is a well-established method (Dypvik *et al.* 2021; Conway 2022).
243 For example, comparison of sediment routing by storms through watersheds with forest canopies
244 versus bare-Earth watersheds and its eventual deposition, remains an unexplored space which could
245 yield reasonable criteria for identifying forest biosignatures on planetary bodies.

246

247 **Let’s close the umbrella!**

248 Scientists seem increasingly content to stay dry and rely on remote sensors and samplers,
249 models, and virtual experiments to understand natural systems. Consequently, we can miss important
250 stormy phenomena, imaginative inspirations, and opportunities to build intuition—all of which are
251 critical to scientific progress, especially as global change alters storm and ecosystem characteristics,
252 creating conditions that are novel to more recently evolved species (like us humans). The combination
253 of human experiences in the storm, our ‘shower thoughts’, with technological tools arguably produce
254 the best odds for scientific advancement. Although we focused on forests, the shade of our sheltered,
255 umbrella perspective likely darkens our understanding of all natural and human systems. Our call,
256 therefore, is for all those who study natural and socio-ecological systems to ‘enter the storm’ (with
257 caution, of course) to collect human observations that complement other methods. We also challenge
258 funding agencies, many of which have tilted support toward remote sensing, to explicitly support
259 activities that place researchers ‘in the storm.’

Table 1: Response of various forest ecosystem components to storms, focusing mainly on the responses that are difficult to observe with technological equipment.

Response of:	Examples
Energy	<ul style="list-style-type: none"> - Wind variability/turbulence¹ - Droplet impacts and scouring flows² - Vapor plumes³ and trapped water vapor in understory⁴ - Rates of canopy snow sublimation v. melt^{5,6}
Pools	<ul style="list-style-type: none"> - Mineralization of organic matter⁷ - Dissolution of nutrients along bedrock-soil interface⁸ - Filling/overflow of canopy water impoundments (dendro-/phytotelmata)⁹ - Contributions to organismal pools in litter and soil¹⁰
Fluxes of matter	<ul style="list-style-type: none"> - Water: Novel/preferential flow paths through canopy¹¹, over soils¹², through soils¹³ - Particles: Topsoil erosion and transport²; Washout of captured aerosols¹⁴ - Solutes: Canopy-to-soil nutrient returns¹⁵, pollutant input¹⁶, allelochemicals¹⁷ - Gasses: CO₂ “Birch” effect¹⁸, N₂O flush¹⁹; leaf gas-exchange²⁰
Microorganisms	<ul style="list-style-type: none"> - Resuscitation of dormant microorganisms²¹ - Cell lysis by osmotic pressure²² - Dispersal of fungal spores²³, phyllosphere bacteria²⁴ - Microsites where microbes switch to alternative terminal electron acceptors^{25,26}
Vegetation	<ul style="list-style-type: none"> - Dispersal and establishment of reproductive materials^{27,28} - Washout of plant-generated materials, like pollen²⁹ and nectars³⁰ - Novel water transport and uptake systems³¹ - “Nurse” effects aiding water infiltration/reducing evaporation³²
Animals	<ul style="list-style-type: none"> - Larval development of mosquitos³³ and other animals in/around treeholes³⁴ - Animal consumption of free water^{35,36} and excretions into water flows³⁷ - Behaviors that directly “engineer” water processes in ecosystems³⁸ - Trophic structure and interactions^{39,40}
Signaling	<ul style="list-style-type: none"> - Flush pathogens/stress indicators from phyllosphere⁴¹ - Flush of organismal or waste products from insect infestation⁴² - Flush of byproducts from canopy and epiphyte life events⁴³ - Geomorphological alteration (over multiple events)⁴⁴

[1] Ruchith & Ernest Raj (2020), [2] Dunkerley (2020), [3] Jiménez-Rodríguez *et al.* (2021), [4] Jiménez-Rodríguez *et al.* (2020), [5] Lundquist *et al.* (2021), [6] Levia & Underwood (2004), [7] Qualls (2020), [8] Backnäs *et al.* (2012), [9] Mendieta-Leiva *et al.* (2020), [10] Ptatscheck *et al.* (2018), [11] Weathers *et al.* (2020), [12] Herwitz (1986), [13] Friesen (2020), [14] Ponette-González *et al.* (2022), [15] Parker (1983), [16] Klučiarová *et al.* (2008), [17] Molina *et al.* (1991), [18] Unger *et al.* (2010), [19] Enanga *et al.* (2016), [20] Berry *et al.* (2019), [21] Placella *et al.* (2012), [22] Bottner *et al.* (1998), [23] Magyar *et al.* (2021), [24] Teachey *et al.* (2018), [25] Burgin *et al.* (2011), [26] Keiluweit *et al.* (2016), [27] Reski (2018), [28] Barthlott *et al.* (2014), [29] Verstraeten *et al.* (2019), [30] Campbell *et al.* (2013), [31] Biddick *et al.* (2018), [32] Vicente *et al.* (2022), [33] Fish & Carpenter (1982), [34] Kirsch *et al.* (2021), [35] Mella *et al.* (2020), [36] de Albuquerque *et al.* (2021), [37] Beard *et al.* (2002), [38] Maschwitz & Moog (2000), [39] Romero *et al.* (2020), [40] Skagen *et al.* (2012), [41] Van Stan *et al.* (2020), [42] Arango *et al.* (2019), [43] Guidone *et al.* (2021), [44] Lipar *et al.* (2021).

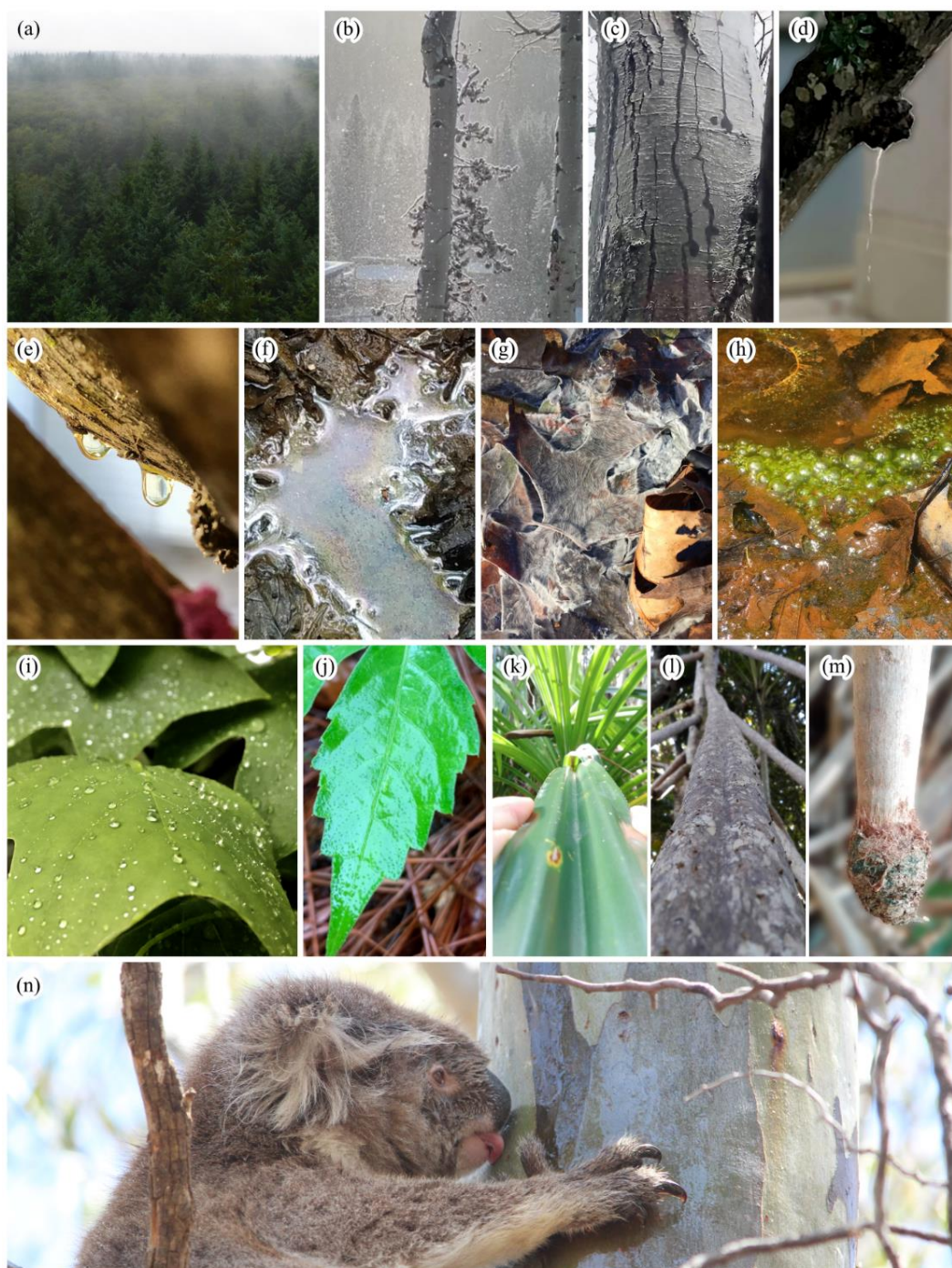


Figure 1: Photographs of example storm-related phenomena and indicators in forests observable to the human eye, but difficult for remote technological systems to record. Plumes of (a) condensed vapor above a canopy (A.M.J. Coenders-Gerrits) and wind-blown snow being redistributed (E.D. Gutmann). (c) Chemically-enriched meltwaters can be seen draining down this trunk beneath the ice layer (image from video: <https://imgur.com/hgemi5E>). (d) Drip point where rainfall is concentrated by the up-gradient canopy area (J.T. Van Stan). (e) Throughfall droplets gleaming amber, indicating light-absorbing dissolved organic matter (J.T. Van Stan). (f) Oil-like sheen produced by Fe-oxidizing bacteria (K.E. Mueller). (g) Streamers of elemental S-containing bacteria (*Thiothrix* sp.) in a small sulfide-rich spring (J. Cosmidis). (h) Green chloroplasts of photosynthesizing cyanobacteria and algae (C.E. Rosenfeld). Leaf surface wetting patterns may range from (i) minimal coverage by small droplets (J.T. Van Stan) to (j) full coverage by a thin film (Z.C. Berry). *Pandanus forsteri*'s (k) trough-like leaves and (l) branches that direct rainfall to (m) aerial root tips (M. Biddick). (n) Koala drinks stemflow (V.S.A. Mella, Koala Clancy Foundation).

References.

- Allen, S.T., Aubrey, D.P., Bader, M.Y., Coenders-Gerrits, M., Friesen, J., Gutmann, E.D., *et al.* (2020). Key Questions on the Evaporation and Transport of Intercepted Precipitation. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 269–280.
- Aparecido, L.M.T., Miller, G.R., Cahill, A.T. & Moore, G.W. (2017). Leaf surface traits and water storage retention affect photosynthetic responses to leaf surface wetness among wet tropical forest and semiarid savanna plants. *Tree Physiol*, 37, 1285–1300.
- Arango, C., Ponette-González, A., Neziri, I. & Bailey, J. (2019). Western spruce budworm effects on throughfall N, P, and C fluxes and soil nutrient status in the Pacific Northwest. *Can J For Res*, 49, 1207–1218.
- Asdak, C., Jarvis, P.G. & Gardingen, P.V. (1998). Evaporation of intercepted precipitation based on an energy balance in unlogged and logged forest areas of central Kalimantan, Indonesia. *Agric For Meteorol*, 92, 173–180.
- Backnäs, S., Laine-Kaulio, H. & Kløve, B. (2012). Phosphorus forms and related soil chemistry in preferential flowpaths and the soil matrix of a forested podzolic till soil profile. *Geoderma*, 189–190, 50–64.
- Barthlott, W., Große-Veldmann, B. & Korotkova, N. (2014). Orchid seed diversity: A scanning electron microscopy survey. Turland NJ, Rodewald M, eds. Berlin: Botanic Garden and Botanical Museum Berlin-Englera.
- Beard, K.H., Vogt, K.A. & Kulmatiski, A. (2002). Top-down effects of a terrestrial frog on forest nutrient dynamics. *Oecologia*, 133, 583–593.
- Becher, P.G., Verschut, V., Bibb, M.J., Bush, M.J., Molnár, B.P., Barane, E., *et al.* (2020). Developmentally regulated volatiles geosmin and 2-methylisoborneol attract a soil arthropod to *Streptomyces* bacteria promoting spore dispersal. *Nat Microbiol*, 5, 821–829.
- Berry, Z.C., Ávila-Lovera, E., de Guzman, M.E., O’Keefe, K. & Emery, N.C. (2021). Beneath the Bark: Assessing Woody Stem Water and Carbon Fluxes and Its Prevalence Across Climates and the Woody Plant Phylogeny. *Front For Glob Change*, 4, 675299.
- Berry, Z.C., Emery, N.C., Gotsch, S.G. & Goldsmith, G.R. (2019). Foliar water uptake: processes, pathways, and integration into plant water budgets. *Plant Cell Environ*, 42, 410–423.
- Berry, Z.C. & Goldsmith, G.R. (2020). Diffuse light and wetting differentially affect tropical tree leaf photosynthesis. *New Phytol*, 225, 143–153.
- Beven, K. (2018). A Century of Denial: Preferential and Nonequilibrium Water Flow in Soils, 1864–1984. *Vadose Zone J*, 17.
- Biddick, M., Hutton, I. & Burns, K.C. (2018). An alternative water transport system in land plants. *Proceedings of the Royal Society B: Biological Sciences*, 285, 20180995.
- Binks, O., Finnigan, J., Coughlin, I., Disney, M., Calders, K., Burt, A., *et al.* (2021). Canopy wetness in the Eastern Amazon. *Agric For Meteorol*, 297, 108250.
- Bottner, P., Austrui, F., Cortez, J., Billès, G. & Coûteaux, M.M. (1998). Decomposition of ¹⁴C- and ¹⁵N-labelled plant material, under controlled conditions, in coniferous forest soils from a north–south climatic sequence in western Europe. *Soil Biol Biochem*, 30, 597–610.
- Bundt, M., Widmer, F., Pesaro, M., Zeyer, J. & Blaser, P. (2001). Preferential flow paths: biological ‘hot spots’ in soils. *Soil Biol Biochem*, 33, 729–738.
- Burgin, A.J., Yang, W.H., Hamilton, S.K. & Silver, W.L. (2011). Beyond carbon and nitrogen: how the microbial energy economy couples elemental cycles in diverse ecosystems. *Front Ecol Environ*, 9, 44–52.
- Campbell, J., Bengtson, P., Fredeen, A.L., Coxson, D.S. & Prescott, C.E. (2013). Does exogenous carbon extend the realized niche of canopy lichens? Evidence from sub-boreal forests in British Columbia. *Ecology*, 94, 1186–1195.
- Chu, J.S.G. & Evans, J.A. (2021). Slowed canonical progress in large fields of science. *Proceedings of the National Academy of Sciences*, 118.
- Coenders-Gerrits, A.M.J., Schilperoort, B. & Jiménez-Rodríguez, C. (2020). Evaporative Processes on Vegetation: An Inside Look. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 35–48.
- Conway, S.J. (2022). Planetary geomorphology. *Geological Society, London, Memoirs*, M58-2021–33.

- Coxson, D.S. (1991). Nutrient release from epiphytic bryophytes in tropical montane rain forest (Guadeloupe). *Can J Bot*, 69, 2122–2129.
- de Albuquerque, N.M., Ruiz-Esparza, J., da Rocha, P.A., Beltrão-Mendes, R. & Ferrari, S.F. (2021). Spontaneous ingestion of water by a free-ranging maned sloth, *Bradypus torquatus*, in the Ibura National Forest, northeastern Brazil. *Behaviour*, 158, 177–193.
- Deng, L., Peng, C., Kim, D.-G., Li, J., Liu, Y., Hai, X., *et al.* (2021). Drought effects on soil carbon and nitrogen dynamics in global natural ecosystems. *Earth Sci Rev*, 214, 103501.
- Dickerson-Lange, S.E., Vano, J.A., Gersonde, R. & Lundquist, J.D. (2021). Ranking Forest Effects on Snow Storage: A Decision Tool for Forest Management. *Water Resour Res*, 57.
- Dubinsky, E.A., Silver, W.L. & Firestone, M.K. (2010). Tropical forest soil microbial communities couple iron and carbon biogeochemistry. *Ecology*, 91, 2604–2612.
- Dunkerley, D. (2020). A review of the effects of throughfall and stemflow on soil properties and soil erosion. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 183–214.
- Dypvik, H., Hellevang, H., Krzesińska, A., Sætre, C., Viennet, J.-C., Bultel, B., *et al.* (2021). The Planetary Terrestrial Analogues Library (PTAL) – An exclusive lithological selection of possible martian earth analogues. *Planet Space Sci*, 208, 105339.
- Enanga, E.M., Creed, I.F., Casson, N.J. & Beall, F.D. (2016). Summer storms trigger soil N₂O efflux episodes in forested catchments. *J Geophys Res Biogeosci*, 121, 95–108.
- Enjin, A. (2017). Humidity sensing in insects — from ecology to neural processing. *Curr Opin Insect Sci*, 24, 1–6.
- Fassbinder, J.J., Schultz, N.M., Baker, J.M. & Griffis, T.J. (2013). Automated, Low-Power Chamber System for Measuring Nitrous Oxide Emissions. *J Environ Qual*, 42, 606–614.
- Fish, D. & Carpenter, S.R. (1982). Leaf Litter and Larval Mosquito Dynamics in Tree-Hole Ecosystems. *Ecology*, 63, 283–288.
- Floriansic, M.G., Allen, S.T., Meier, R., Truniger, L., Kirchner, J.W. & Molnar, P. (2022). Potential for significant precipitation cycling by forest-floor litter and deadwood. *Ecohydrology*.
- Foken, T., Aubinet, M. & Leuning, R. (2012). The Eddy Covariance Method. In: *Eddy Covariance*. Springer Netherlands, Dordrecht, pp. 1–19.
- Ford, C.R., McGee, J., Scandellari, F., Hobbie, E.A. & Mitchell, R.J. (2012). Long- and short-term precipitation effects on soil CO₂ efflux and total belowground carbon allocation. *Agric For Meteorol*, 156, 54–64.
- Friesen, J. (2020). Flow Pathways of Throughfall and Stemflow Through the Subsurface. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 215–228.
- Galindo, J.D.A. de & Glass, G. (1764). *The History of the Discovery and Conquest of the Canary Islands*. A. Pope & J. Swift.
- Gauslaa, Y. (2014). Rain, dew, and humid air as drivers of morphology, function and spatial distribution in epiphytic lichens. *The Lichenologist*, 46, 1–16.
- Gordon, D.M., Dektar, K.N. & Pinter-Wollman, N. (2013). Harvester Ant Colony Variation in Foraging Activity and Response to Humidity. *PLoS One*, 8, e63363.
- Guidone, M., Gordon, D.A. & van Stan, J.T. (2021). Living particulate fluxes in throughfall and stemflow during a pollen event. *Biogeochemistry*, 153, 323–330.
- Gutiérrez del Arroyo, O. & Silver, W.L. (2018). Disentangling the long-term effects of disturbance on soil biogeochemistry in a wet tropical forest ecosystem. *Glob Chang Biol*, 24, 1673–1684.
- Gutmann, E.D. (2020). Global Modeling of Precipitation Partitioning by Vegetation and Their Applications. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 105–120.
- Hall, S.J. & Silver, W.L. (2013). Iron oxidation stimulates organic matter decomposition in humid tropical forest soils. *Glob Chang Biol*, 19, 2804–2813.
- Ham, R.D. (1982). Fog drip in the bull run municipal watershed, oregon. *J Am Water Resour Assoc*, 18, 785–789.
- Hanba, Y.T., Moriya, A. & Kimura, K. (2004). Effect of leaf surface wetness and wettability on photosynthesis in bean and pea. *Plant Cell Environ*, 27, 413–421.
- He, X.-J., Tian, L.-Q., Wu, X.-B. & Zeng, Z.-J. (2016). RFID monitoring indicates honeybees work harder before a rainy day. *Insect Sci*, 23, 157–159.
- Heidegger, M. (1977). The question concerning technology. In: *The question concerning technology: and other essays*. (ed. Lovitt, W. trans.). Garland Publishing, New York.

- Herwitz, S.R. (1986). Infiltration-excess caused by stemflow in a cyclone-prone tropical rainforest. *Earth Surf Process Landf*, 11, 401–412.
- Herwitz, S.R. & Slye, R.E. (1995). Three-dimensional modeling of canopy tree interception of wind-driven rainfall. *J Hydrol*, 168, 205–226.
- Izett, J.G., Schilperoort, B., Coenders-Gerrits, M., Baas, P., Bosveld, F.C. & van de Wiel, B.J.H. (2019). Missed Fog? On the Potential of Obtaining Observations at Increased Resolution During Shallow Fog Events. *Boundary Layer Meteorol*, 173, 289–309.
- Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., *et al.* (2007). Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the “Birch effect.” *Tree Physiol*, 27, 929–940.
- Jerolmack, D.J. & Paola, C. (2010). Shredding of environmental signals by sediment transport. *Geophys Res Lett*, 37, L19401.
- Jiménez-Rodríguez, C.D., Coenders-Gerrits, M., Schilperoort, B., González-Angarita, A. del P. & Savenije, H. (2021). Vapor plumes in a tropical wet forest: spotting the invisible evaporation. *Hydrol Earth Syst Sci*, 25, 619–635.
- Jiménez-Rodríguez, C.D., Coenders-Gerrits, M., Wenninger, J., Gonzalez-Angarita, A. & Savenije, H. (2020). Contribution of understory evaporation in a tropical wet forest during the dry season. *Hydrol Earth Syst Sci*, 24, 2179–2206.
- Keiluweit, M., Gee, K., Denney, A. & Fendorf, S. (2018). Anoxic microsites in upland soils dominantly controlled by clay content. *Soil Biol Biochem*, 118, 42–50.
- Keiluweit, M., Nico, P.S., Kleber, M. & Fendorf, S. (2016). Are oxygen limitations under recognized regulators of organic carbon turnover in upland soils? *Biogeochemistry*, 127, 157–171.
- Kirsch, J.-J., Sermon, J., Jonker, M., Asbeck, T., Gossner, M.M., Petermann, J.S., *et al.* (2021). The use of water-filled tree holes by vertebrates in temperate forests. *Wildlife Biol*, 2021.
- Klemm, O., Milford, C., Sutton, M.A., Spindler, G. & van Putten, E. (2002). A climatology of leaf surface wetness. *Theor Appl Climatol*, 71, 107–117.
- Klučiarová, D., Márton, P., Pichler, V., Márton, E. & Túnyi, I. (2008). Pollution Detection by Magnetic Susceptibility Measurements Aided by the Stemflow Effect. *Water Air Soil Pollut*, 189, 213–223.
- Levia, D.F. & Underwood, S.J. (2004). Snowmelt induced stemflow in northern hardwood forests: a theoretical explanation on the causation of a neglected hydrological process. *Adv Water Resour*, 27, 121–128.
- Li, Y., Yu, S., Strong, J. & Wang, H. (2012). Are the biogeochemical cycles of carbon, nitrogen, sulfur, and phosphorus driven by the “FeIII–FeII redox wheel” in dynamic redox environments? *J Soils Sediments*, 12, 683–693.
- Lipar, M., Szymczak, P., White, S.Q. & Webb, J.A. (2021). Solution pipes and focused vertical water flow: Geomorphology and modelling. *Earth Sci Rev*, 218, 103635.
- Llorens, P., Domingo, F., Garcia-Estringana, P., Muzylo, A., & Gallart, F. (2014). Canopy wetness patterns in a Mediterranean deciduous stand. *J Hydrol*, 512, 254–262.
- Lundquist, J.D., Dickerson-Lange, S., Gutmann, E., Jonas, T., Lumbrazo, C. & Reynolds, D. (2021). Snow interception modelling: Isolated observations have led to many land surface models lacking appropriate temperature sensitivities. *Hydrol Process*, 35.
- Magyar, D., Van Stan, J.T. & Sridhar, K.R. (2021). Hypothesis and theory: Fungal spores in stemflow and potential bark sources. *Front For Glob Change*, 4, 19.
- Maschwitz, U. & Moog, J. (2000). Communal peeing: a new mode of flood control in ants. *Naturwissenschaften*, 87, 563–565.
- Mason Earles, J., Sperling, O., Silva, L.C.R., McElrone, A.J., Brodersen, C.R., North, M.P., *et al.* (2016). Bark water uptake promotes localized hydraulic recovery in coastal redwood crown. *Plant Cell Environ*, 39, 320–328.
- Matus, F., Stock, S., Eschenbach, W., Dyckmans, J., Merino, C., Nájera, F., *et al.* (2019). Ferrous Wheel Hypothesis: Abiotic nitrate incorporation into dissolved organic matter. *Geochim Cosmochim Acta*, 245, 514–524.
- Mayr, S., Schmid, P., Laur, J., Rosner, S., Charra-Vaskou, K., Dämon, B., *et al.* (2014). Uptake of Water via Branches Helps Timberline Conifers Refill Embolized Xylem in Late Winter. *Plant Physiol*, 164, 1731–1740.

450 McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., *et al.* (2003).
 451 Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems.
 452 *Ecosystems*, 6, 301–312.

453 Meldrum, A.N. (1933). Lavoisier’s Early Work in Science 1763–1771. *Isis*, 19, 330–363.

454 Mella, V.S.A., Orr, C., Hall, L., Velasco, S. & Madani, G. (2020). An insight into natural koala drinking
 455 behaviour. *Ethology*, 126, 858–863.

456 Mendieta-Leiva, G., Porada, P. & Bader, M.Y. (2020). Interactions of Epiphytes with Precipitation
 457 Partitioning. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp.
 458 133–146.

459 Merino, C., Kuzyakov, Y., Godoy, K., Jofré, I., Nájera, F. & Matus, F. (2021a). Iron-reducing bacteria
 460 decompose lignin by electron transfer from soil organic matter. *Science of The Total Environment*, 761,
 461 143194.

462 Merino, C., Matus, F., Kuzyakov, Y., Dyckmans, J., Stock, S. & Dippold, M.A. (2021b). Contribution of the
 463 Fenton reaction and ligninolytic enzymes to soil organic matter mineralisation under anoxic conditions.
 464 *Science of The Total Environment*, 760, 143397.

465 Misson, L., Lunden, M., McKay, M. & Goldstein, A.H. (2005). Atmospheric aerosol light scattering and
 466 surface wetness influence the diurnal pattern of net ecosystem exchange in a semi-arid ponderosa pine
 467 plantation. *Agric For Meteorol*, 129, 69–83.

468 Molina, A., Reigosa, M.J. & Carballeira, A. (1991). Release of allelochemical agents from litter, throughfall,
 469 and topsoil in plantations of *Eucalyptus globulus* Labill in Spain. *J Chem Ecol*, 17, 147–160.

470 Murray, S.J., Watson, I.M. & Prentice, I.C. (2013). The use of dynamic global vegetation models for
 471 simulating hydrology & the potential integration of satellite observations. *Prog Phys Geogr*, 37, 63–97.

472 Parker, G.G. (1983). Throughfall and Stemflow in the Forest Nutrient Cycle. pp. 57–133.

473 Pellegrino, A.C., Peñaflor, M.F.G.V., Nardi, C., Bezner-Kerr, W., Guglielmo, C.G., Bento, J.M.S., *et al.*
 474 (2013). Weather Forecasting by Insects: Modified Sexual Behaviour in Response to Atmospheric Pressure
 475 Changes. *PLoS One*, 8, e75004.

476 Pendergrass, A.G. (2018). What precipitation is extreme? *Science* (1979), 360, 1072–1073.

477 Perry, R.S., Mcloughlin, N., Lynne, B.Y., Sephton, M.A., Oliver, J.D., Perry, C.C., *et al.* (2007). Defining
 478 biominerals and organominerals: Direct and indirect indicators of life. *Sediment Geol*, 201, 157–179.

479 Peters, V. & Conrad, R. (1996). Sequential reduction processes and initiation of CH₄ production upon
 480 flooding of oxic upland soils. *Soil Biol Biochem*, 28, 371–382.

481 Placella, S.A., Brodie, E.L. & Firestone, M.K. (2012). Rainfall-induced carbon dioxide pulses result from
 482 sequential resuscitation of phylogenetically clustered microbial groups. *Proceedings of the National*
 483 *Academy of Sciences*, 109, 10931–10936.

484 Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Gädeke, A., *et al.* (2021). Global terrestrial
 485 water storage and drought severity under climate change. *Nat Clim Chang*, 11, 226–233.

486 Ponette-González, A.G., Chen, D., Elderbrock, E., Rindy, J.E., Barrett, T.E., Luce, B.W., *et al.* (2022). Urban
 487 edge trees: Urban form and meteorology drive elemental carbon deposition to canopies and soils. *Environ*
 488 *Pollut*, 314, 120197.

489 Ponette-González, A.G., Van Stan, J.T. & Magyar, D. (2020). Things seen and unseen in throughfall and
 490 stemflow. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 71–
 491 88.

492 Porada, P. & Giordani, P. (2021). Bark Water Storage Plays Key Role for Growth of Mediterranean
 493 Epiphytic Lichens. *Front For Glob Change* 4, 668682.

494 Ptatscheck, C., Milne, P.C. & Traunsperger, W. (2018). Is stemflow a vector for the transport of small
 495 metazoans from tree surfaces down to soil? *BMC Ecol*, 18, 43.

496 Qualls, R.G. (2020). Role of precipitation partitioning in litter biogeochemistry. In: *Precipitation*
 497 *Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 163–182.

498 Rappaport, R. (1967). Lavoisier’s geologic activities, 1763–1792.

499 Reski, R. (2018). Quantitative moss cell biology. *Curr Opin Plant Biol*, 46, 39–47.

500 Romero, G.Q., Marino, N.A.C., MacDonald, A.A.M., Céréghino, R., Trzcinski, M.K., Mercado, D.A., *et al.*
 501 (2020). Extreme rainfall events alter the trophic structure in bromeliad tanks across the Neotropics. *Nat*
 502 *Commun*, 11, 3215.

- Ruchith, R.D. & Ernest Raj, P. (2020). Time–height variation of winds and turbulence during typical tropical pre-monsoon thunderstorm events observed from high-resolution Doppler wind lidar measurements. *Natural Hazards*, 103, 1355–1365.
- Ryan, K.A., Adler, T., Chalmers, A., Perdrial, J., Shanley, J.B. & Stubbins, A. (2021). Event Scale Relationships of DOC and TDN Fluxes in Throughfall and Stemflow Diverge From Stream Exports in a Forested Catchment. *J Geophys Res Biogeosci*, 126.
- Scarrow, R. (2021). Step back from scientific hubris. *Nat Sustain*, 4, 1015–1016.
- Schilperoort, B., Coenders-Gerrits, M., Jiménez Rodríguez, C., van der Tol, C., van de Wiel, B. & Savenije, H. (2020). Decoupling of a Douglas fir canopy: a look into the subcanopy with continuous vertical temperature profiles. *Biogeosciences*, 17, 6423–6439.
- Schumacher, W. (1864). *Die Physik des Bodens*. Wiegandt and Hempel, Berlin.
- Scott, A., Crichton, I. & Ball, B.C. (1999). Long-Term Monitoring of Soil Gas Fluxes with Closed Chambers Using Automated and Manual Systems. *J Environ Qual*, 28, 1637–1643.
- Skagen, S.K. & Adams, A.A.Y. (2012). Weather effects on avian breeding performance and implications of climate change. *Ecological Applications*, 22, 1131–1145.
- Stubbins, A., Guillemette, F. & Van Stan, J.T. (2020). Throughfall and Stemflow: The Crowning Headwaters of the Aquatic Carbon Cycle. In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 121–132.
- Tan, X., Gan, T.Y., Chen, S., Horton, D.E., Chen, X., Liu, B., *et al.* (2019). Trends in Persistent Seasonal-Scale Atmospheric Circulation Patterns Responsible for Seasonal Precipitation Totals and Occurrences of Precipitation Extremes over Canada. *J Clim*, 32, 7105–7126.
- Teachey, M.E., Pound, P.T., Ottesen, E.A. & Van Stan, J.T. (2018). Bacterial community composition of throughfall and stemflow. *Front For Glob Change*, 1, 7.
- Too much and not enough. (2021). *Nat Sustain*, 4, 659–659.
- Unger, S., Máguas, C., Pereira, J.S., David, T.S. & Werner, C. (2010). The influence of precipitation pulses on soil respiration – Assessing the “Birch effect” by stable carbon isotopes. *Soil Biol Biochem*, 42, 1800–1810.
- Van Stan, J.T. & Allen, S.T. (2020). What we know about stemflow’s infiltration area. *Front For Glob Change*, 3, 61.
- Van Stan, J.T., Morris, C.E., Aung, K., Kuzyakov, Y., Magyar, D., Rebollar, E.A., *et al.* (2020). Precipitation Partitioning - Hydrologic Highways between Microbial Communities of the Plant Microbiome? In: *Precipitation Partitioning by Vegetation*. Springer International Publishing, Cham, pp. 229–252.
- Van Stan, J.T., Ponette-González, A.G., Swanson, T. & Weathers, K.C. (2021). Throughfall and stemflow are major hydrologic highways for particulate traffic through tree canopies. *Front Ecol Environ*, 19, 404–410.
- Van Stan, J.T. & Pypker, T.G. (2015). A review and evaluation of forest canopy epiphyte roles in the partitioning and chemical alteration of precipitation. *Sci Total Environ*, 536, 813–824.
- Van Stan, J.T., Siegert, C.M., Levia, D.F. & Scheick, C.E. (2011). Effects of wind-driven rainfall on stemflow generation between codominant tree species with differing crown characteristics. *Agric For Meteorol*, 151, 1277–1286.
- Verstraeten, A., Gottardini, E., Bruffaerts, N., de Vos, B., Vanguelova, E., Cristofolini, F., *et al.* (2019). The role of pollen in forest throughfall biochemistry. In: *XXV IUFRO World Congress: Forest Research and Cooperation for Sustainable*. Pesquisa Florestal Brasileira, Curitiba, Brazil, p. 201.
- Vicente, E., Moreno-de las Heras, M., Merino-Martín, L., Nicolau, J.M. & Espigares, T. (2022). Assessing the effects of nurse shrubs, sink patches and plant water-use strategies for the establishment of late-successional tree seedlings in Mediterranean reclaimed mining hillslopes. *Ecol Eng*, 176, 106538.
- Weathers, K.C., Ponette-González, A.G. & Dawson, T.E. (2020). Medium, Vector, and Connector: Fog and the Maintenance of Ecosystems. *Ecosystems*, 23, 217–229.
- Wellington, W.G. (1946). The effects of variations in atmospheric pressure upon insects. *Can J Res*, 24, 51–70.
- Yamada, Y., Kuzuyama, T., Komatsu, M., Shin-ya, K., Omura, S., Cane, D.E., *et al.* (2015). Terpene synthases are widely distributed in bacteria. *Proceedings of the National Academy of Sciences*, 112, 857–862.
- Zimmermann, A., Zimmermann, B. & Elsenbeer, H. (2009). Rainfall redistribution in a tropical forest: Spatial and temporal patterns. *Water Resour Res*, 45, W11413.