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

John Van Stan[1], Scott Allen[2], Doug Aubrey[3], Z. Carter Berry[4], Matt Biddick[5], Miriam Coenders-Gerrits[6], Paolo Giordani[7], Sybil Gotsch[8], Ethan Gutmann[9], Yakov Kuzyakov[10], Donat Magyar[11], Valentina Mella[12], Kevin Mueller[1], Alexandra Ponette-Gonzalez[13], Philipp Porada[14], Carla Rosenfeld[15], Jack Simmons[16], Sridhar Kandikere R[17], Aron Stubbins[18], and Travis Swanson[16]

[1]Cleveland State University
[2]University of Nevada Reno
[3]Savannah River Ecology Laboratory
[4]Chapman University System
[5]Technische Universität München
[6]Delft University of Technology
[7]University of Genoa
[8]University of Kentucky
[9]National Center for Atmospheric Research
[10]Georg-August-Universitat Gottingen
[11]National Center for Public Health
[12]The University of Sydney
[13]University of North Texas
[14]Universitat Hamburg
[15]Carnegie Museum of Natural History
[16]Georgia Southern University
[17]Mangalore University
[18]Northeastern University

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Abstract

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


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J.T. Van Stan[1], S.T. Allen[2], D.P. Aubrey[3], Z.C. Berry[4], M. Biddick[5], A.M.J. Coenders-Gerrits[6], P. Giordani[7], S.G. Gotsch[8], E.D. Gutmann[9], Y. Kuzyakov[10,11], D. Magyar[12], V.S.A. Mella[13], K.E. Mueller[1], A.G. Ponette-González[14], P. Porada[15], C.E. Rosenfeld[16], J. Simmons[17], K.R. Sridhar[18], A. Stubbins[19], T. Swanson[20]

[1] Biological, Geological and Environmental Sciences, Cleveland State University, OH, USA
[2] Natural Resources & Environmental Science, University of Nevada-Reno, NV, USA
[3] Savannah River Ecology Lab & Warnell School of Forestry, University of Georgia, GA, USA
[4] Biology, Wake Forest University, NC, USA
[5] Terrestrial Ecology Research Group, Technical University of Munich, Freising, German
[6] Water Management, Delft University of Technology, The Netherlands
[7] Dipartimento di Farmacia, University of Genoa, Italy
[8] Forestry and Natural Resources, University of Kentucky, KY, USA
[9] Research Applications Laboratory, National Center for Atmospheric Research, CO, USA
[10] Soil Science of Temperate Systems, Agricultural Soil Science, Georg-August-Universität, Göttingen, Germany
[11] Peoples Friendship University of Russia (RUDN University), 117198 Moscow, Russia
[12] National Public Health Center, Budapest, Hungary
[13] Sydney School of Veterinary Science, The University of Sydney, NSW, Australia
[14] Geography and the Environment, University of North Texas, TX, USA
[15] Biology, Universität Hamburg, Hamburg, Germany
[16] Minerals and Earth Sciences, Carnegie Museum of Natural History, PA, USA
[17] Philosophy and Religious Studies, Georgia Southern University, GA, USA
[18] Biosciences, Mangalore University, India
[19] Marine & Environmental Science, Civil & Environmental Engineering, and Chemistry & Chemical Biology, Northeastern University, MA, USA
[20] Geology and Geography, Georgia Southern University, Savannah, GA, USA

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

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

Introduction

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

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

Water science faces criticism regarding its alleged conceptual and theoretical stagnation (Nature Sustainability, 2021) due to a "techno optimism that tries to solve all problems despite not asking fundamental questions" (Scarrow 2021). We argue that this issue is not unique to water science; that modern natural scientists often approach their study systems 'beneath an umbrella,' and that this 'umbrella perspective' has occluded phenomena that occur just before, during, and after storms. Consistent with this thesis, philosopher Martin Heidegger argued that "Modern technology *is not applied to* natural science, far more [often] is modern natural science *the application of the 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.

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

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

Biogeochemistry and microbial ecology

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

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

The belated study of many aqueous hotpots and hot moments is surprising because they are visible to the human eye (Schumacher 1864; Bundt *et al.* 2001), albeit potentially missed by soil moisture sensors or lysimeters (*sensu*, "a century of denial" of preferential flow paths; Beven (2018)). These often-overlooked fluxes are impactful. Nutrient rich waters entering dry soils induce bursts of decomposition and mineralization that produce CO_2 and inorganic N (Jarvis *et al.* 2007). However, measurements, and thus knowledge, of soil-atmosphere gas-exchanges are often discontinuous and biased toward 'dry' conditions (Scott *et al.* 1999; Ford *et al.* 2012). Although automated infrastructure for monitoring gas efflux exists, it is expensive, logistically challenging, and spatially limited (missing hotspots) (Fassbinder *et al.* 2013).

Microbial activities associated with transient, storm-related niches are observable by scientists who persist through the rain (Burgin *et al.* 2011). Oil-like sheen and rust-colored particles on some puddles can appear in forests (Figure 1f), reflecting iron-oxidizing bacteria in microsites of elevated or altered nutrient cycles. Such fluctuations between ferrous (Fe(II)) and ferric (Fe(III)) oxidation states also yield insights into interconnected cycles of other elements and molecules, including S, N, P, biominerals, other metal(loid)s (Li *et al.* 2012), organic C (Hall & Silver 2013; Matus *et al.* 2019), lignin (Merino *et al.* 2021a, b), and CH_4 (e.g., Dubinsky *et al.* 2010). Other visually observable cues of storm-related microbial activity can relate to elemental S (white/pale yellow deposits: Figure 1g) or green chloroplasts of photosynthesizing cyanobacteria and algae (Figure 1h).

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

Vegetation functions

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

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

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

Animal behavior

Our umbrella perspective may conceal or misinterpret important animal behaviors and animal-environment interactions. For example, koalas were often described as not needing to drink, because they were rarely observed doing so. Opportunistic observations during storms revealed koalas drink stemflow (Mella *et al.* 2020; Figure 1n). As koalas spend most of their time in trees, and storms make it hard to look upward, the natural drinking behavior of koalas was overlooked because scientists designed dry and comfortable observation methods. Improved understanding of koalas' physiological need for free water has consequences for their conservation and habitat management. Maned-sloths (*Bradypus torquatus*) share a similar story (de Albuquerque *et al.* 2021).

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

Earth and planetary surface processes

Forests' redistribution of stormwaters may influence sediment routing through watersheds, imparting 'biosignatures' to underlying soils and sediments that are useful for reconstructing the distribution of forests through deep time. Thus, scientist experiences in stormy forests today support efforts to understand Earth's geologic history and modern interactions within and between terrestrial and aquatic systems. For example, by the time storm events mobilize sediment along hillslopes and stream channels, hydrologic information is already modified by the watershed effects that include forests' interception, capture, and routing of water to/through soils. Integrated over that forest's lifetime, which may be thousands-to-millions of years, precipitation partitioning by vegetation is one of innumerable sedimentary processes that must be considered when reconstructing important components of Earth history from the sedimentary record (e.g., paleoclimate, sea-level change, and tectonics) (Jerolmack & Paola 2010). When canopies discharge intercepted water through drip-points or stemflow, this can localize hydrologic, geomorphic, and sedimentary processes. Therefore, observations of canopy stormwater routing may inspire novel hypotheses regarding these waters' capability to produce biosignatures (*i.e.*, any morphological, chemical, or isotopic traces from an organism). Known forest biosignatures include precipitation of cements (possibly microbially aided) (Perry *et al.* 2007), or the opposite, the formation of dissolution features (Lipar *et al.* 2021). Finally, geomorphologists visiting landscapes during storms may open creative avenues for interpreting landscape features on other planets. Use of Earth-based analogs to explain geomorphological processes on other planetary bodies is a well-established method (Dypvik *et al.* 2021; Conway 2022). For example, comparison of sediment routing by storms through watersheds with forest canopies versus bare-Earth watersheds and its eventual deposition, remains an unexplored space which could yield reasonable criteria for identifying forest biosignatures on planetary bodies.

Let's close the umbrella!

Scientists seem increasingly content to stay dry and rely on remote sensors and samplers, models, and virtual experiments to understand natural systems. Consequently, we can miss important stormy phenomena, imaginative inspirations, and opportunities to build intuition—all of which are critical to scientific progress, especially as global change alters storm and ecosystem characteristics, creating conditions that are novel to more recently evolved species (like us humans). The combination of human experiences in the storm, our 'shower thoughts', with technological tools arguably produce the best odds for scientific advancement. Although we focused on forests, the shade of our sheltered, umbrella perspective likely darkens our understanding of all natural and human systems. Our call, therefore, is for all those who study natural and socio-ecological systems to 'enter the storm' (with caution, of course) to collect human observations that complement other methods. We also challenge funding agencies, many of which have tilted support toward remote sensing, to explicitly support 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	- Wind variability/turbulence[1] - Droplet impacts and scouring flows[2] - Vapor plumes[3] and trapped water vapor in understory[4] - Rates of canopy snow sublimation v. melt[5,6]
Pools	- Mineralization of organic matter[7] - Dissolution of nutrients along bedrock-soil interface[8] - Filling/overflow of canopy water impoundments (dendro-/phytotelmata)[9] - Contributions to organismal pools in litter and soil[10]
Fluxes of matter	- Water: Novel/preferential flow paths through canopy[11], over soils[12], through soils[13] - Particles: Topsoil erosion and transport[2]; Washout of captured aerosols[14] - Solutes: Canopy-to-soil nutrient returns[15], pollutant input[16], allelochemicals[17] - Gasses: CO_2 "Birch" effect[18], N_2O flush[19]; leaf gas-exchange[20]
Microorganisms	- Resuscitation of dormant microorganisms[21] - Cell lysis by osmotic pressure[22] - Dispersal of fungal spores[23], phyllosphere bacteria[24] - Microsites where microbes switch to alternative terminal electron acceptors[25,26]
Vegetation	- Dispersal and establishment of reproductive materials[27,28] - Washout of plant-generated materials, like pollen[29] and nectars[30] - Novel water transport and uptake systems[31] - "Nurse" effects aiding water infiltration/reducing evaporation[32]
Animals	- Larval development of mosquitos[33] and other animals in/around treeholes[34] - Animal consumption of free water[35,36] and excretions into water flows[37] - Behaviors that directly "engineer" water processes in ecosystems[38] - Trophic structure and interactions[39,40]
Signaling	- Flush pathogens/stress indicators from phyllosphere[41] - Flush of organismal or waste products from insect infestation[42] - Flush of byproducts from canopy and epiphyte life events[43] - 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).

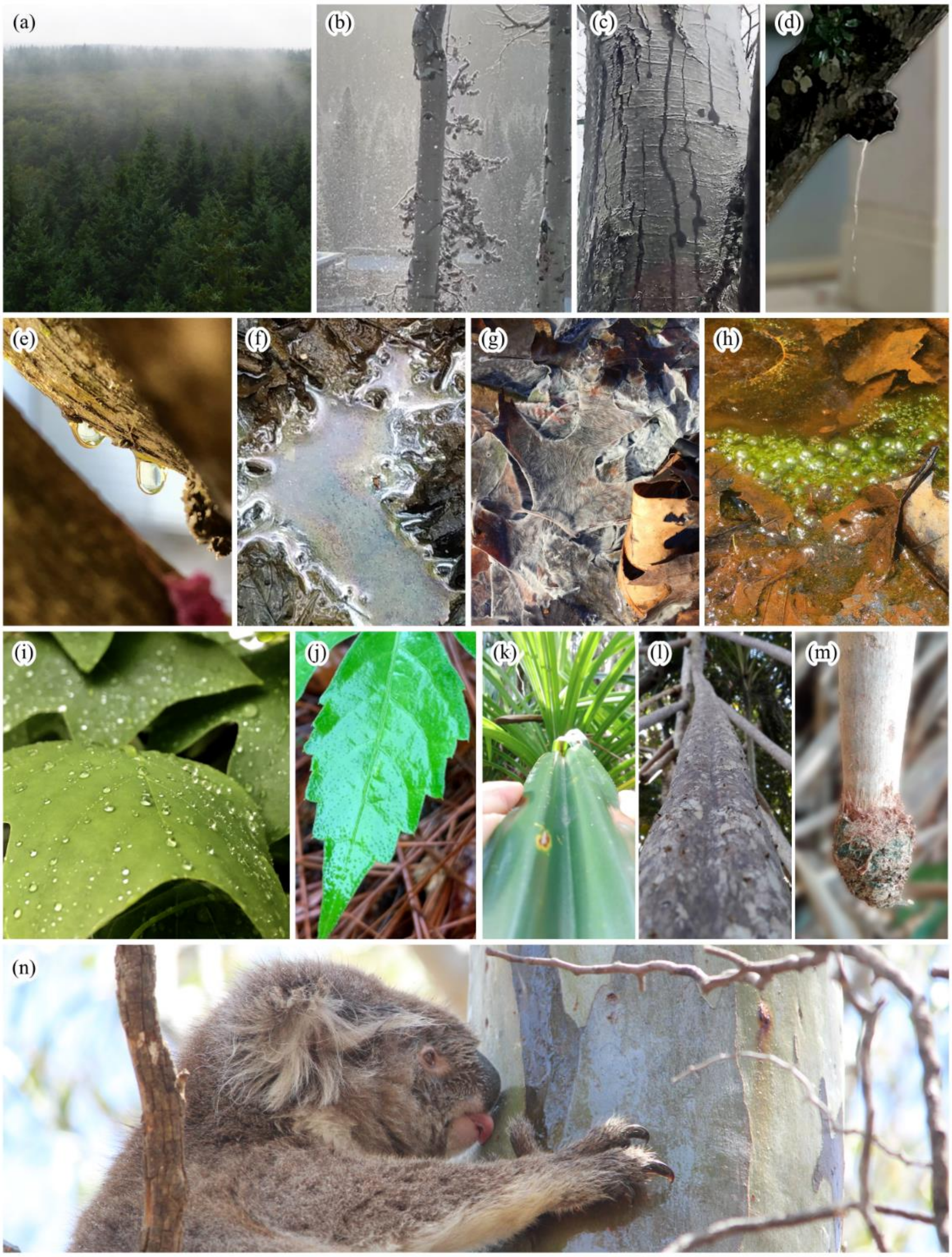

Figure 1: Photographs of example storm-related phenomena and indicators in forests observable to the human eye, but difficult for remote technological systems to record. Plumes of (a) condensed vapor above a canopy (A.M.J. Coenders-Gerrits) and wind-blown snow being redistributed (E.D. Gutmann). (c) 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).

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