John T. Van Stan, II
Ethan Gutmann
Jan Friesen
Editors

Precipitation Partitioning by Vegetation

A Global Synthesis

Illustrated by Tyasseta and Siloy

Springer

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Foreword

As a hydrologist, I would like to know what happens in the terrestrial branch of the water cycle. The processes that return precipitation to the atmosphere as water vapor or to the oceans as river or groundwater flow are many and complex. If we ever want to be able to understand the hydrological cycle and the impacts that humans have on it, if we ever want to be able to manage our water resources in a sustainable manner, we need to understand these processes. For most raindrops that fall over land, the first thing that happens is that they hit a plant. Unfortunately, or in the present context, interestingly, this simple observation quickly leads to a large set of questions about what happens next: Does the drop stay on the leaf to evaporate back once the rain stops or does it fall through the canopy? Are drops that fall through concentrated, inducing relatively fast preferential flow through the soil, or is the rain dispersed? If we cannot get these very first processes right, how can we ever hope to come to grips with the next steps? These hydrological processes are relatively simple compared to the potentially even more relevant chemical and biological processes that take place when precipitation works its way through a canopy. From the movement of nutrients, spores, and bacteria to the functioning of epiphytes and decomposition of leaf litter, the movement of water through canopies governs a wide array of processes.

For a long time, these processes were not broadly recognized as significant or important. Over the last decades, precipitation partitioning and associated biogeochemical processes have received more of the attention they deserve. This book brings together, for the first time, the results of this recent work and provides a broad overview of what has become known. Now that the relevance of precipitation partitioning is well established, this monograph quickly brings every scholar up to date.

Precipitation partitioning is a highly interdisciplinary subject. One can look at the processes from a botanical point of view and wonder what the different evolutionary functions are that let plants “develop” certain mechanisms. One can also look at the ecosystem as a whole or one can look at it from a hydrological or meteorological point of view. In order to get it right, all these points of view will have to be brought together, something this book really brings to the fore. Similarly, in different ecosystems and landscapes, different partitionings take place with different biogeochemical results. For this reason, the large geographical diversity represented in the book is especially relevant. From American grasslands and croplands to forests in Europe and savanna in Africa, we see large variations that are captured by the widespread empirical evidence in the different chapters.

This geographical and disciplinary diversity is also reflected in the experiences and expertise of the editors. The three people making up the editorial team sufficiently overlap in their interests to ensure a coherent picture of the state of the art. To provide at the same time a comprehensive overview, they bring together a broad set of skills from LIDAR and satellite remote sensing to field measurements and hydrological and meteorological modeling. Personally, I really appreciate the fact that all editors contributed to new methods for measuring the complex processes of precipitation partitioning. I remember well how one of the editors, Jan Friesen, traveled through Ghana with John Selker and me to directly measure tree stem compression caused by canopy rainfall interception. As an example of how involved any of the measurements in this book can get, I just want to mention that to ensure a constant temperature around the clock, we wrapped the trees in electric blankets. Running generators to keep trees warm at night in Africa sounds like a silly thing to do, but it also exemplifies the subtle difficulties that had to be overcome for all experiments underlying the new insights presented in this book.

It is clear that this book is not the last word on precipitation partitioning, as the last chapter clearly explains. The book ends with an overview of the many unknowns that persist. The simplest question, how much rainfall is intercepted and evaporates before it can reach the root zone, has been around at least since the end of the nineteenth century. This monograph shows that there has been great progress, but that the enormous diversity of plants, ecosystems, and landscapes ensures that much research remains to be done.

As a final word of introduction, I must mention the great graphical summaries of the different chapters. The researchers have worked closely with cartoonists to make the essence of the findings clear with pictures that inform scholars and laypersons alike. The cartoons are rich in detail, further emphasizing the complexity and interrelatedness of all processes taking place. At the same time, they bring lightness and humor, which are so often lacking in scientific tomes.

Image credit: © A. Bagus Tyasseta

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Preface

Water is fundamental to life on Earth, including its dissolved and suspended materials, associated energy, and pathways through the land surface and atmosphere. Therefore, understanding and managing water resources is also fundamental to the sociocultural and economic underpinnings of human civilization. Given this importance, it is astonishing that, for the very first interaction between precipitation and the land surface (most of which is vegetated), there has been no comprehensive and global synthesis and evaluation of extant research. Although observations of precipitation–vegetation interactions have been reported since Theophrastus, over two millennia ago, the editors and contributing authors are not aware of a single volume that has since exclusively focused on these processes. Since Theophrastus, research on how vegetation "partitions" precipitation has become geographically extensive, but studies placing precipitation partitioning processes into global context are rare. The few studies that have considered the macroscale role of precipitation–vegetation interactions find significant influences over global hydrological processes, climate, and terrestrial ecosystem functioning (e.g., Miralles et al. 2010; Murray 2014; Porada et al. 2018). As such, *Precipitation Partitioning by Vegetation: A Global Synthesis* is not only timely but also a long overdue synthesis and evaluation—something often considered necessary for the progression of any discipline (Moldwin et al. 2017). This volume synthesizes research on precipitation partitioning by vegetation to date and globally contextualizes this knowledge with an explicit discussion of relevance and impacts to the climate and terrestrial ecosystem functioning, as well as direct socioeconomic effects. Our intention is for this to be a comprehensive reference for researchers and students seeking to discover what has been done and to inspire future research on both long-standing and new questions. Indeed, how can we manage water resources if we do not have an accurate accounting of, or even consistent accounting methods for determining, "how much precipitation *actually* reaches the surface?"

Savannah, GA, USA — John T. Van Stan, II
Boulder, CO, USA — Ethan Gutmann
Leipzig, Germany — Jan Friesen

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About the Illustrators

Image credit: © A. Bagus Tyasseta

A. Bagus Jati Tyasseta (left), or Tyasseta (bagusseta1982@gmail.com), is an Indonesian artist working in the comic industry currently living in Jakarta with his family. He obtained a Master of Fine Arts in Sequential Art from Savannah College of Art and Design in Savannah, Georgia (USA) where he met Dr. Van Stan. He has published several comic titles in Indonesia and is currently working for an American comic publisher. His other artworks can be viewed in his artstation page: https://www.artstation.com/tyasseta.

Fredy Siloy (right), or Siloy (Siloyfredy@gmail.com), is a game developer at noon and color artist at night. He obtained a Bachelor of Fine Arts from Institut Teknologi Bandung in Bandung, West Java (Indonesia). He is currently developing a channel game for kids named *Tappy Taps* and casual game channel named *Ikan Asin Production.* Please check out more of his artworks: www.ikaanstudio.com.

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Image credit: © A. Bagus Tyasseta

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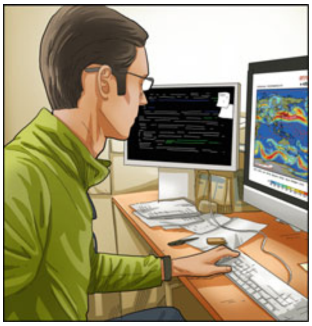

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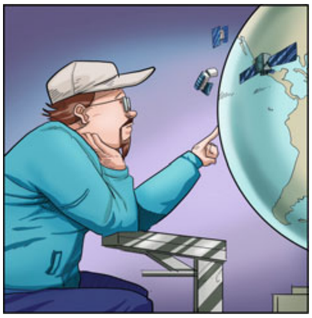
Ethan Gutmann, Ph.D. is a Hydrologist in the Research Applications Lab at the National Center for Atmospheric Research in Boulder, Colorado (USA). His background in hydrology, geology, and computer science found a happy marriage in remote sensing and hydrologic and atmospheric modeling. A passion for the outdoors has taken him to remote corners of the world, climbing mountains in Peru, Nepal, and Tanzania. He also enjoys scientific outreach, having dabbled in science blogging at Ars Technica and science videography with Earth Initiatives.



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Jan Friesen, Ph.D. is an Ecohydrologist at the Department of Catchment Hydrology, Helmholtz Centre for Environmental Research—UFZ, Leipzig (Germany). His research primarily focuses on forest ecohydrology, remote sensing, and sensor development where he applies and develops new monitoring solutions to bridge the gap between site studies and remote sensing. He has extensive experience in semiarid and data-scarce countries such as Ghana, Burkina Faso, Nigeria, and Oman and his work has a strong connection to water management issues.

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2018 So Far
Evaporation
The Last Century
1918 - 2017 CE
Early Observations
1850 - 1900 CE
Throughfall
stemflow
Enlightenment
1750 - 1800 CE
The Origins
500 - 50 BCE

Precipitation Partitioning, or to the Surface and Back Again: Historical Overview of the First Process in the Terrestrial Hydrologic Pathway

1

John T. Van Stan, II and Jan Friesen

Abstract

This chapter presents a history of the interdisciplinary field focused on improving our understanding of the first step in the terrestrial hydrologic cycle: precipitation partitioning by vegetation. We describe the origins of interest, rooted in observations from "The Father of Botany," Theophrastus (350 BCE) and synthesize the early formal hydrologic and biogeochemical research (~1800–1917) that provided the foundation for modern precipitation partitioning investigation. To examine the field's publication and citation trends over the past century (1918–2017), a meta-analysis of precipitation partitioning research sampled from the Thompson Reuter's Web of Science is presented and discussed. Finally, a summary of research published on this topic through September 2018 (when this chapter was written) is used to discuss broad future directions as well as to introduce the overall structure of this book.

Keywords

Throughfall • Stemflow • Rainfall • Snow • Ice • Fog • History

1.1 Introduction

Any rain, snow, rime, or condensate (fog, mist or dew) attempting passage through a vegetated landscape will inevitably interact with its plant surfaces. These precipitation-vegetation interactions are the focus of a field called, "precipitation partitioning by vegetation," that has roots deep into the origins of natural science itself. Since precipitation partitioning is typically the first process to alter the amount and patterning of meteoric water, it affects all subsequent terrestrial hydrological and related ecological processes (Savenije 2004, 2018). The nature of any below-canopy precipitation (or "net precipitation") flux's hydrologic and ecological influence can depend on how that water penetrated the vegetation canopy, e.g., as a drip from surfaces and through canopy gaps (called "throughfall") or as a flow down the stem (called "stemflow"). The partitioning process also returns a portion of precipitation back to the atmosphere (called "interception") in the canopy, the understory and litter layer (Gerrits and Savenije 2011), which is of large enough magnitude to influence regional and global water (Porada et al. 2018) and energy budgets (Davies-Barnard et al. 2014; Van der Ent et al. 2014). Excellent historical reviews exist for fields with which precipitation partitioning overlaps—forest hydrology and biogeochemistry (Andréassian 2004; McGuire and Likens 2011)—but none have summarized and discussed historical aspects of the precipitation partitioning field itself. Thus, this chapter examines the historical origins, developments and major advancements of research seeking to improve our understanding of the first process in the terrestrial hydrologic pathway through vegetated landscapes.

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We first describe the origins of interest regarding interactions between vegetation and precipitation and, then, discuss the early formal research studies that provided the foundation for modern precipitation partitioning investigation. A meta-analysis of studies published in this field over the past century (1918–2017) is presented and discussed. Finally, a summary of research published in the first nine months of 2018 is used to discuss broad future directions as well as to introduce the overall chapter structure of this book project.

1.2 Origins

Processes governing the capture, storage, evaporation, and redistribution of precipitation by plants were little discussed before the nineteenth century. However, as early as 350 years BCE, Greek naturalists began recording the effects of precipitation partitioning at the surface, and many of these observations fascinated scientists through the Age of Enlightenment and into modern times.

Beginning with the first-known scientific publication on plants, *Historia Plantarum* (350–287 BCE), the Greek naturalist and philosopher Theophrastus (371–287 BCE) described many of the ecological effects now attributed, in part or in whole, to precipitation partitioning. His first discussion of these effects touched on rainfall redistribution by throughfall, although this term and other modern hydrologic terms (e.g., stemflow and interception) were not yet explicitly used. Early in the third volume, Theophrastus reviews observations from Anaxagoras (510–428 BCE), Diogenes (412–323 BC), and Cleidemos (fifth–fourth century BCE) on the role that rainfall redistribution plays in the dispersal of seeds (section i, 3), concluding with his own observations that throughfall "brings down many of the seeds with it, and at the same time causes a sort of decomposition of the soil and of the water" (section i, 11) (Theophrastus 1483). Regarding stemflow, *Historia Plantarum* (volume IV, section iii, 4–5) reports observations related to the now well-recognized capability of trees (Hildebrandt and Eltahir 2006), shrubs (Whitford et al. 1997), herbs, like thyme (Belmonte Serrato and Romero Díaz 1998), and grasses (Roth-Nebelsick et al. 2012) to survive in arid environments through funnelling dew, fog, and scant amounts of rainfall to their root systems. Theophrastus hypothesized that plants situated "in the land where no rain falls" were sustained "by the dew" for he considered it to be "sufficient [water], considering the size of such plants and their natural character." The idea that precipitation intercepted by plant canopies was taken up by the plant was also discussed by Leonardo da Vinci, in his notebooks (1478–1518 CE), where he states that "the [rain] water which falls upon the shoot can run down to nourish the bud, by the drop being caught in the hollow [axil] at the insertion of the leaf." Water uptake by canopy surfaces has now become a widely-observed phenomenon (see Chap. 10). It was also reported that fig trees can "become diseased if there is heavy rain; for then the parts toward the root [where stemflow infiltrates] and the root itself [where stemflow can preferentially flow: Johnson and Lehmann (2006)] become, as it were, sodden" (volume IV, section xiv, 6).

Even the interception, storage and evaporation, of rain and snow is briefly addressed in Theophrastus' observations of silver fir (*Abies alba*) trees. He describes this species' foliage as being "so dense that neither snow nor rain penetrates it" (volume III, section ix, 6–7). The effects of rainwater entrained on, and flowing across, plant surfaces were also described during his studies of infestation and pollination. Infestation of olive trees was described as being "prevented from appearing under the skin [of the fruit] if there is rain after the rising of Arcturus [the northern springtime star]" (volume IV, section xiv, 9). We now understand that within-canopy transport of rainwater can affect the spread of pathogens (Garbelotto et al. 2003), see also Chap. 14 of this volume. Theophrastus notes the importance of avoiding rainfall during artificial pollination of fig trees (volume II, section viii, 1–3), as rainwater entrained on the canopy surfaces can wash away pollen, as observed by Lee et al. (1996), and may reduce available pollen for insect pollinators.

Theophrastus' observations impressed Pliny the Elder (23–79 CE), who called him "the most trustworthy of the Greek writers" (Parejko 2003). Thus, it is no surprise that Pliny was the next naturalist to observe and report the effects of precipitation partitioning by vegetation. In Pliny's *Naturalis Historia* (77–79 CE) he not only describes rainfall interception and throughfall, but even qualitatively compares the droplet size distributions of throughfall between tree species! "The drops of water that fall from the pine, the *Quercus*, and the holm-oak are extremely heavy, but from the cypress fall none" (volume XVII, chapter xviii) (c.f., Hall and Calder 1993). In the same chapter, Pliny confirms Theophrastus' observations that substantial interception is likely due to "foliage being densely packed." Then, he describes an effect of precipitation partitioning that was not quantitatively observed until the twentieth century: the canopy's ability to "smooth" rainfall intensity (Keim and Skaugset 2004; Trimble and Weitzman 1954), "the alder [canopy] is very dense … it serves as an effectual protection against heavy rains." Pliny also sparked scientific and public interest about the chemical composition of throughfall and stemflow through his observation of allelopathy, or the chemical inhibition of the establishment and growth of competing plants, in the shadows cast by certain trees, especially *Juglans* (walnut) species: "The shadow of the walnut tree is poison to all plants within its compass" (volume XVII, chapter xviii). Modern work has not only identified that allelopathic compounds are leached from walnut leaves during rainfall (Jose and Gillespie 1998) but that this process occurs in the canopies of other species, like *Fagus sylvatica* (European beech) (Bischoff et al. 2015). Pliny advocated for future natural scientific inquiry on processes within the "shadows of trees," concluding that "in the case of every variety of plant, the shade is found to act either as a kind of nurse or a harsh step-mother." During the 1350s, the Moroccan Islamic scholar, Ibn Baṭṭūṭah, gave perhaps the harshest account of rain-plant interactions during his travels through southern Tibet, stating that there were "poisonous grasses growing, such that when the rains fall upon it, and run in torrents to the neighboring rivers, no one dares of consequence drink of the water during the time of their rising: and should anyone do so, he dies immediately." (Ibn Baṭṭūṭah 1356). Despite this shocking account and Pliny's prior urging for greater study of the processes at play in the black box enshrouded by the canopy's shadow, no known attempts to measure, estimate or monitor the storage, evaporation, and redistribution of precipitation by plants occurred for centuries.

1.3 The First Observations and Development of Conceptual Foundations

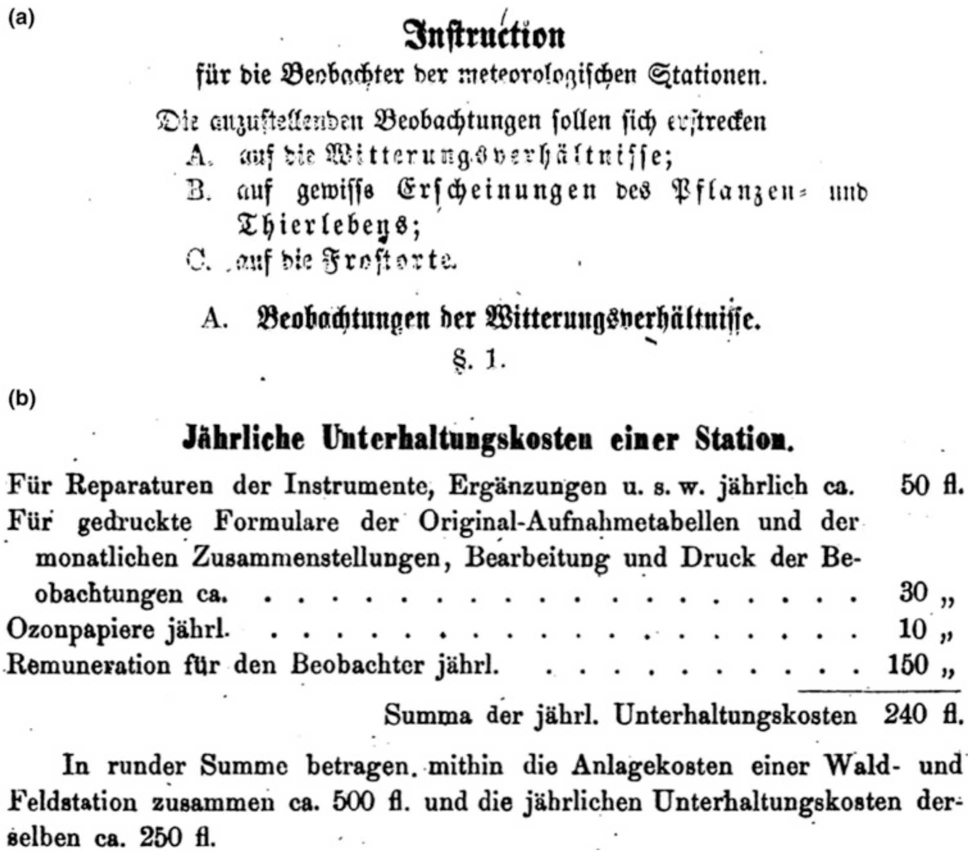
1.3.1 Foundational Hydrologic Observations

European adventurers during the eighteenth century reported on the links between precipitation and vegetation (von Humboldt and Bonpland 1807) and cases where indigenous peoples used precipitation-vegetation interactions to their benefit (De Galindo and Glas 1764). Both von Humboldt and Captain George Glas witnessed, in particular, the people of the Canary Islands using fog capture by vegetation canopies to significant supplement their water resource needs (De Galindo and Glass 1764; Kunkel 2012). The account of Captain Glas is particularly detailed and has been used to introduce the relevance of fog interception in early research (Kerfoot 1968):

> In one of the Canary Islands grows a tree which furnishes water to the inhabitants and beasts of the whole place … its leaves constantly distill such a quantity of water as is sufficient to furnish drink to every creature in [El] Hierro, nature having provided this remedy for the drought of the island. … On the north side of the trunk are two tanks or cisterns. One of these contains water for the drinking of the inhabitants, and the other that which they use for their cattle, washing and such like purposes. Every morning, near this part of the island, a cloud of mist arises from the sea, which the south and easterly winds force against the fore-mentioned steep cliff so that the cloud … advances slowly … and then rests upon the thick leaves and wide-spreading branches of the tree from whence it distills in drops.

No quantitative observations of precipitation partitioning were made by these eighteenth-century European adventurers. Interest in precipitation partitioning within the scientific community fully awakened in the mid-nineteenth century when Dove (1855), after analyzing rainfall observations in the temperate zone, posed the question of how changes in forest cover may influence rainfall patterns. Thus motivated, Krutzsch (1855) reviewed Swiss and French deforestation work to develop a conceptual description of forest canopy interception processes and their potential influence on rainfall intensity, soil organic matter content, infiltration and erosion. Although he describes forest canopy interception, no direct observations are reported or cited in 1855. Nearly a decade later, Krutzsch (1863, 1864) reports the first-known direct observations of canopy precipitation partitioning after updating his monitoring network to observe below-canopy precipitation (throughfall) in Tharandt, Saxony, Germany. To our knowledge this was the first national, at that time associated to the Kingdom of Saxony, monitoring network dedicated to forest-meteorological observations. These throughfall observations were used to estimate canopy saturation point for the first time: 0.2 mm (Krutzsch 1864). A direct relationship between relative throughfall and storm size across storms was also first reported, with relative throughfall being 9–57% of storms ranging 1.1–14.8 mm in magnitude. Although multiple insights were gained by Krutzsch's (1864) throughfall observations, more questions (and, as a result, more interest) arose in the scientific community. Broader measurements of canopy precipitation partitioning, including stemflow, were begun in 1868 in Bavaria, Germany by Ebermayer (Ebermayer 1873; Bühler 1918) after visiting Krutzsch's meteorological monitoring stations in Tharandt (Hölzl 2010). Similar to Krutzsch's monitoring network, Ebermayer also set up a series of national (Kingdom of Bavaria) long-term observatories. Similar field campaigns, although on more local scales (e.g., experimental forests, botanic gardens, or single trees), for precipitation partitioning were begun by researchers throughout mainland Europe, e.g., France [Mathieu in 1866 per Clavé (1875)], Switzerland [Frankhauser in 1869 per Maurice and Frécaut (1962)], and the Czech Republic (Johnen and Breitenlohner 1879).

Interestingly, both Krutzsch and Ebermayer published details regarding instrumentation as well as costs per station for their observatories. For example, Fig. 1.1 shows the annual maintenance and observer costs as well as the overall installation costs for the Bavarian observatory. For the Saxon observatory installed in 1862–1863, the investment costs were estimated to 87 Thaler and 4 Neugroschen (Saxon currency around 1862) whereas the annual cost for observation amounted to 30 Thaler



(a)

Inſtruction
für die Beobachter der meteorologiſchen Stationen.

Die anzuſtellenden Beobachtungen ſollen ſich erſtrecken
A. auf die Witterungsverhältniſſe;
B. auf gewiſſe Erſcheinungen des Pflanzen- und Thierlebens;
C. auf die Froſtorte.

A. Beobachtungen der Witterungsverhältniſſe.
§. 1.

(b)

Jährliche Unterhaltungskosten einer Station.

Für Reparaturen der Instrumente, Ergänzungen u. s. w. jährlich ca.	50 fl.
Für gedruckte Formulare der Original-Aufnahmetabellen und der monatlichen Zusammenstellungen, Bearbeitung und Druck der Beobachtungen ca.	30 „
Ozonpapiere jährl.	10 „
Remuneration für den Beobachter jährl.	150 „
Summa der jährl. Unterhaltungskosten	240 fl.

In runder Summe betragen mithin die Anlagekosten einer Wald- und Feldstation zusammen ca. 500 fl. und die jährlichen Unterhaltungskosten derselben ca. 250 fl.

Fig. 1.1 Costs for the **a** Saxon forest-meteorological observatory (Krutzsch 1863) and **b** annual maintenance and observer costs per station for the Bavarian observatory network (Ebermayer 1873)

(Krutzsch 1863). This equates to approximately $160 (nineteenth century, i.e., unadjusted for inflation). Observers that worked at any study site location experiencing sub-zero temperatures were paid an extra 20 Thalers, amounting to 50 Thaler per station. For the Bavarian observatory, installed in 1866, Ebermayer estimated an investment cost of 500 guilders (Bavarian currency at the time) and annual maintenance and observer costs of 250 guilders per station (Ebermayer 1873).

Throughfall observations began without spatial replication, comparing measurements of one open field gauge and one below-canopy gauge (Ebermayer 1873). Despite this limitation, Ebermayer (1873): (1) reported that annual relative throughfall varied significantly across forest types (68–75% of rainfall) and across four seasonal leaf states; (2) estimated the first snow interception amount (38% of snowfall); and (3) provided detailed instrumentation information. The first discussion of throughfall spatial variability was based on observations from Groß Karlowitz (now Velké Karlovice, Czech Republic) by Johnen and Breitenlohner (1879)—although the number of gauges deployed was not specified. This study also first reported the effect of event duration on interception capacity (i.e., short, low intensity rainfall produces greater interception and the opposite conditions increase throughfall). Aware of the need to account for interstorm and spatial throughfall variability but limited by costs and logistics, Bühler (1892) distributed gauges under different degrees of canopy cover and differently aged trees in two Swiss forests (including snow, but not stemflow) and recorded discrete storm size and intensity. Under this sampling design, Bühler (1892) first found the asymptotic relationship between relative interception and storm size, where relative interception is highest for small storms (<5 mm), decreasing until large storms (>10 mm) and remaining more-or-less stable. Hoppe (1896) conducted what is considered to be the first high-resolution throughfall study where 20 gauges were distributed along two crossing lines at a distance of 2 m in Brunneck and Farnleite, Austria (Fig. 1.2a). Impressively, this first high-resolution throughfall study also included meticulous photogrammetric analyses of canopy closure and density (Fig. 1.2b). These past results inspired Ebermayer's comprehensive manuscript (synthesizing data from Bavaria, Prussia, France and Switzerland) and clearly influenced his discussion as he noted that his throughfall results should be treated as "minimal crown influence" (i.e., lower boundary conditions) rather than an average (Ebermayer 1897).

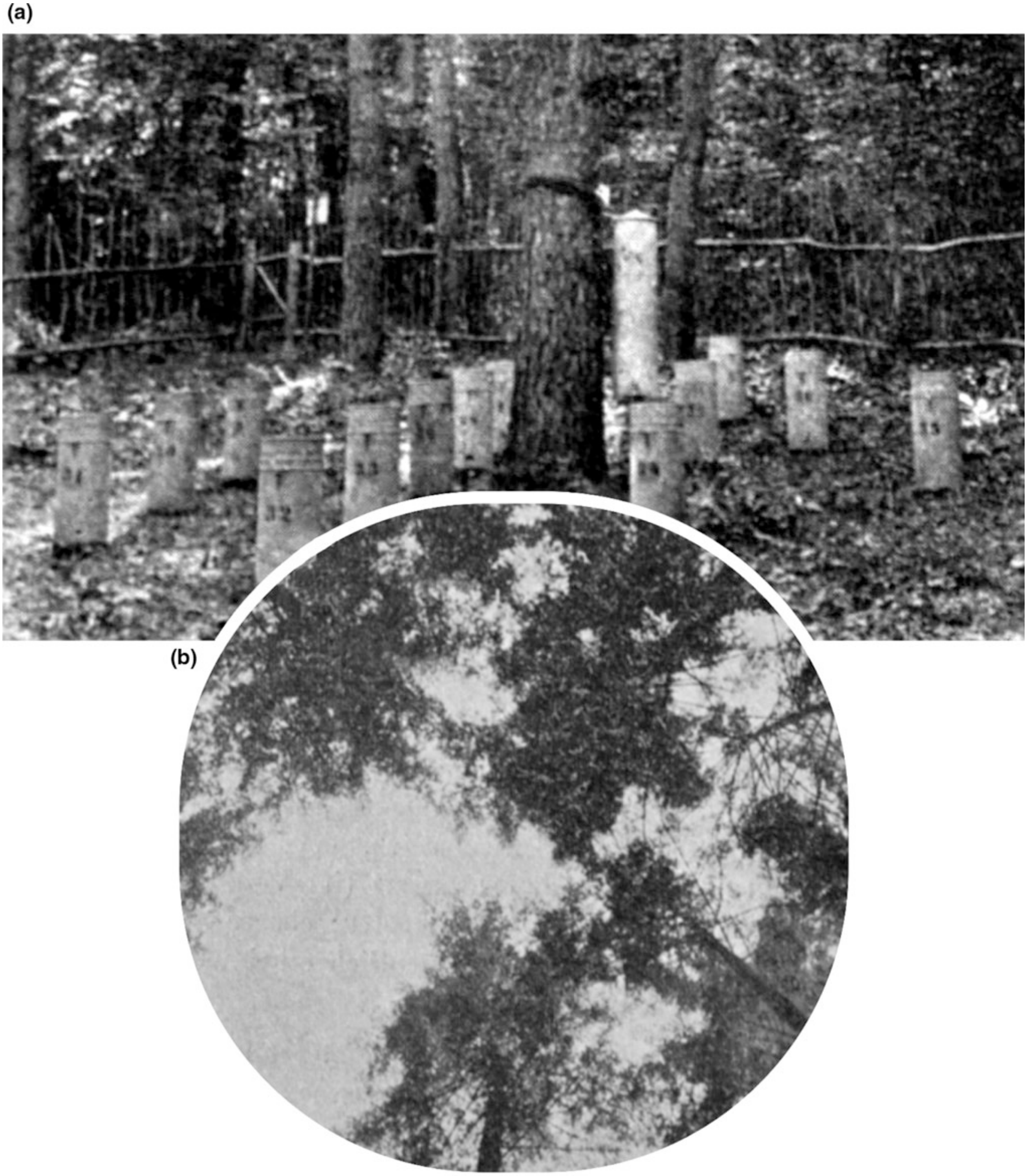


Fig. 1.2 Photographs taken by Hoppe (1896) showing **a** the first high-resolution throughfall monitoring campaign and **b** canopy closure above an example throughfall gauge. A detail worth noting is the presence of stemflow monitoring (see the collar connected to trunk in the photograph center)

Stemflow was, reportedly, not measured until 1868 at Ebermayer's Johannes-Kreuz site; however, based on later publications it seems these stemflow observations were never published (Bühler 1892; Ebermayer 1873; Ney 1894). The first published stemflow observations were by Riegler (1881) alongside a conceptual discussion of the stemflow process.

Stemflow was measured from four isolated trees, each a different species with unique canopy structuring: *Fagus sylvatica*, *Quercus robur*, *Acer platanoides*, and *Abies excelsa* (Riegler 1881). His discussion was more robust than his sampling campaign, synthesizing the scant stemflow data available at that time to support hypotheses about stemflow's relationship with branch angle and bark roughness (Riegler 1881). He cites an interesting personal communication with Professor Kerner (likely Anton Josef Kerner at the University of Vienna from 1878 to 1895) about experiments that involved pouring small grist grains onto branches and leaves to visualize water flow (i.e., stemflow) patterns (Riegler 1881). We could not find the results of these experiments. Riegler (1881) also collected throughfall and open rainfall, ultimately concluding that previous work (i.e., Ebermayer 1873) required correction for stemflow and recommending future work include stemflow in the canopy water balance. Ney (1893, 1894) was the first to comprehensively measure and estimate stand-scale stemflow and may actually have been the first stemflow observer, as Ebermayer (1873) mentioned that Ney made the stemflow observations at Johannes-Kreuz from 1868 to 1871 (that, as mentioned earlier, were not published). Ney (1893) included stemflow measurements across forest types, leaf states and precipitation types—namely rain, snow and even dew. Surprisingly, his analysis extends even further, into the influence of stand age, interspecific traits, canopy density (Ney 1893). His proceeding publication summarized previous stemflow observations and emphasized stemflow's importance to net precipitation calculations (Ney 1894). Although rarely cited, the results of Ney (1893, 1894) confirm many of the late twentieth century and early twenty-first century ecohydrology literature (Friesen and Van Stan 2019).

By the end of the nineteenth century, scientists had achieved a profound understanding of most processes underlying the hydrological aspects of precipitation partitioning, how to measure these processes, and how to estimate those that were not directly measurable at that time (like canopy water storage). Enough observations and discussions had been published by the early twentieth century that Zon (1912) and Bühler (1918) were able to develop comprehensive reviews of precipitation partitioning studies with reference to both rain and snow. These reviews highlighted throughfall and stemflow measurements and the indirect estimate of interception, leaving the interception components, water storage and evaporation, understudied. Horton (1919) then closed this gap by presenting direct estimates of rainwater storage capacity for different leaf structures, discussing how to disentangle storage and evaporation components of interception, and placing these interception components into context alongside net precipitation measurements and wind conditions. Horton's (1919) seminal paper, being cited copiously since and continuing to be cited today, thus completed the conceptual foundation upon which modern precipitation partitioning work began to build.

1.3.2 Foundational Biogeochemical Observations

Quantitative observations of the exchange (leaching or uptake), transformation, and wash-off of deposited nutrients during precipitation partitioning began in croplands. These agricultural roots stem from nutrient content analyses becoming key to studies on the efficacy of fertilizer application methods during the mid-to-late 1800s (Johnson 1869). Indeed, conservation of fertilizer was of significant socioeconomic and cultural importance to both farmers and nations before development of the Haber-Bosch method for synthesizing ammonia (Erisman et al. 2008). Despite conjecture on nutrient exchange between leaves and precipitation by Stephen Hales (1727), where his observations of submerged leaves (Fig. 1.3) prompted the hypothesis that "nourishment … is conveyed into vegetable thro' the leaves, which plentifully imbibe the dew and rain, which contain salt, sulphur, etc.," research on biogeochemical aspects of precipitation partitioning did not mature until the mid-twentieth century. In fact, chemical leaching between precipitation and plant surfaces was not generally accepted by the publishing biogeochemical community until its experimental confirmation via isotopically labeled nutrients in the 1950s (Long et al. 1956; Silberstein and Wittwer 1951). Of course, the loss of internal solutes from damaged or dead plant materials into water has been known since the dawn of human civilization (q.e.d., popular plant-based beverages, like beer, tea, or coffee). The delay in recognizing and quantifying nutrient exchanges between precipitation and living plant surfaces appears to be, in large part, due to an extensive and sometimes contentious debate that began in the 1870s—as summarized by Le Clerc and Breazeale (1908). The debate seems to have been rooted in the Earl of Dundonald's (1795) hypothesis that solutes within plants are protected by their "outward surface," preventing "their being acted upon by rain or moisture." This hypothesis was oddly foundational to his overarching theory of natural science, stating that "the insolubility, to a certain degree, of this system [plant surfaces], adopted by nature, is undoubtedly preferred … for it is evident that if putrefaction or oxygenation had possessed the power of rendering all the vegetable matter, by a speedy process, soluble in water … the rains would have washed down such extracts and soluble matters, as fast as formed, into the rivers and springs, contaminating the waters and rendering them unfit for the existence of fishes, or for the use of terrestrial animals" (Dundonald 1795). Dundonald (1795) goes on to describe the "pernicious consequences" that would result should plant surfaces chemically

Fig. 1.3 An illustration of a branch submersion experiment performed by Hales (1727). Observations of the leaves during long-term submersion inspired Hales to hypothesize about the possibility of nutrient exchange between precipitation and leaf surfaces (image from Hales 1727)

interact with precipitation, including "the sea, in the process of time, would thereby receive all the [dissolved] vegetable produce of the dry land and the Earth would ultimately become barren." Thus, the world's first authoritative treatise on plant biogeochemistry argued that precipitation and internal plant solutes could not interact without catastrophic consequences.

Major leaps in chemical and agricultural science throughout the mid-1800s, due primarily to Germany's Agricultural Experimental Stations, debunked many of Dundonald's theories on plant biogeochemistry (Johnson 1869). However, the Earl's theory that chemical leaching between plants and precipitation was impossible, remained an ingrained belief of the scientific community. This theory even persisted despite experiments showing that in-tact leaves (albeit detached from the stem) could enrich purified water with soluble salts, in eight successive trials, and that the mass of salt dissolved into the water was similar to the mass lost in the leaves' ash-ingredients (de Saussure 1804). Nineteenth-century plant scientists ascribed de Saussure's (1804) observations of solute leaching to the leaves being damaged. In fact, only damaged plants were thought to lose solutes to precipitation (Guilbert et al. 1931; Ritthausen 1856). By the late 1800s, the most famous plant physiologist of the time, Dr. Samuel W. Johnson of Yale, still downplayed de Saussure's (1804) foliar leaching observations, stating "all experiments which indicate great loss [of solutes] in this way [i.e., interaction with precipitation], have been made on the cut plant, and their results may not hold good to the same extent for uninjured tissues of plants" (Johnson 1869). Still, observations were mounting that perplexed plant biogeochemists (who denied precipitation-related solute exchange), beginning with the first observations of crop nutrient contents at various growth stages (Norton 1847). Norton's (1847) perplexing observation was that certain nutrients in crops did not continually accumulate until ripening; rather, they maximized around the heading period then diminished until harvest (Le Clerc and Breazeale 1908). Many scientists asked, "where are these nutrients going?" and most believed they were being translocated back to the roots or soil, but they could not be found there (Le Clerc and Breazeale 1908).

Liebscher (1887) hypothesized that this loss of nutrients in healthy crops was due to portions of the plant withering and decaying; however, nutrient losses of this kind only accounted for a portion. After reviewing the nineteenth-century plant biogeochemical literature, Wehmer (1892) posited that "plant food" was removed from leaves by precipitation. Although he did not collect data himself, both the estimate of the potential nutrient loss from rain-related leaching and a conceptual process of leaching were provided (Wehmer 1892). Le Clerc and Breazeale (1908) state that Wehmer's (1892) review and hypothesis were opposed by his contemporaries to "so great an extent that it seems to have been relegated to the background.” Indeed, even Le Clerc and Breazeale (1908), who observed rainfall enrichment with salts after passing through various crop canopies, still concluded that only wash-off processes occur, “plants exude salts upon their surfaces, and the rain then washes these salts back to the soil,” and stopped short of indicating that solute leaching could occur between precipitation and plant surfaces. Another notable work on the enrichment of rainfall by plant exudates is the review by Arens (1934). Thus, the application of isotopically labeled nutrients to biogeochemical research was required to confirm uptake and leaching from plant leaves experimentally (Long et al. 1956; Silberstein and Wittwer 1951).

Le Clerc and Breazeale (1908) were not the first to observe and discuss the wash-off of plant exudates by precipitation—this, like leaching, was first observed by de Saussure (1804). During observations of cucumber leaves, he noticed exudations that formed crusts across the leaf surface (de Saussure 1804). He tested the exudate crust and found that, although it was not deliquescent, a portion was soluble in water and likely to be washed off by precipitation (de Saussure 1804). Johnson (1869) discusses these, and similar findings on other crops, and indicates that the wash-off of exudates during precipitation may represent “a considerable share of the variations in percentage and composition of the fixed ingredients of plants.” It was not realized that precipitation wash-off also includes “dry” deposited atmospheric materials, or that these materials had biogeochemical importance, until the mid-twentieth century (Ingham 1950; Meetham 1950). Shortly after Ingham’s and Meetham’s (1950) publications, scientists recognized dry deposition contributions to net precipitation chemistry (Eriksson 1952; Tamm 1951). Thus, it was in the 1950s that a robust conceptual foundation of precipitation partitioning biogeochemical aspects (that included elemental leaching, uptake, transformation and wash-off) was achieved. This decade also produced the first comparative observations of throughfall chemistry beneath various forest canopies, specifically pine, oak and birch (Tamm 1951). Tamm (1951) compared throughfall Ca, K, Na and P concentrations to open rainfall to highlight the significant enrichment of these nutrients in throughfall (by 4–70 times). The first annual throughfall nutrient yields were reported as 25–30 kg K, 11 kg Ca, 9 kg Na, and nearly 900 kg of carbohydrates ha^{-1} year^{-1} for an apple orchard (Dalbro 1955). In the same year, Will (1955) roughly estimated throughfall nutrient yields for select solutes, but did not publish the full study until a few years later (Will 1959). These nutrient yields surprised many plant biogeochemists and placed throughfall, particularly leaching by throughfall, into the standard research methodology for nutrient budgeting (Tukey 1966). However, biogeochemical aspects of stemflow were still unexamined. Stemflow properties (acidity and particulate content) were first reported by Pozdnyakov (1956), but stemflow nutrient concentrations and fluxes, including interspecific and seasonal variability, would not be reported until Voigt (1960). Then, the potential for stemflow nutrient fluxes to exert significant localized ecological effects was not recognized until Eaton et al. (1973) and Mahendrappa and Ogden (1973).

1.4 The Last Century: A Bibliometric Analysis from 1918 to 2017

Since the hydrological and biogeochemical foundations of precipitation partitioning research were laid, the new research topics raised and addressed over the last century in this field have been substantial and diverse. Rather than attempt a complete summary of key advancements in this field, which would likely require much more space than available for this chapter, we perform a meta-analysis of publication and citation trends from Thompson Reuter’s Web of Science (WoS). Certainly, WoS represents only a portion of the full corpus of literature on any subject, placing some limitations on our bibliometric analyses—see recent discussions on this topic (Harzing and Alakangas 2016; Mongeon and Paul-Hus 2016). The WoS sample of publications and citations on precipitation partitioning is assumed to provide sufficient coverage and stability of coverage (i.e., Harzing and Alakangas 2016); however, we acknowledge a bias in WoS toward English publications, which did not become the dominant language of science until after the Second World War (Gordin 2015). Besides missing some early works in other languages, we are unsure of the exact impact of over-sampling English publications on the bibliometric analyses. Another consideration regarding language: although key terms for precipitation interception processes—canopy/leaf and stem/trunk evaporation and water storage—were used by the research community prior to 1918, key terms for net precipitation fluxes—throughfall and stemflow—are not to be found in the WoS publication database until Ellison and Coaldrake (1954). Notwithstanding, use of WoS enables assessment of the disciplines (or “Research Areas” per WoS) where precipitation partitioning research has been published and cited.

Queries over the past century, excluding patents and limited to titles, abstracts and keywords, resulted in the following total number of publications for bibliometric analysis: 3666 for throughfall, 2405 for rainfall interception, 1494 for stemflow, 387 for snow interception and 136 for fog interception. Search results were manually reviewed to remove unrelated publications from the dataset. Of the 252 research areas categorized by WoS, rainfall interception and throughfall studies represented the greatest diversity across disciplines, being published in over 90 research areas. Despite stemflow research having the latest start, it has been published in 77 research areas. Snow and fog interception studies were represented in

63 and 50 research areas, respectively. The dominant research area for publication of all precipitation partitioning topics over the past century was "Environmental Sciences & Ecology," representing 80–90% of publications. For throughfall and stemflow, journals in the "Forestry" research area ranked second, having published at least 70% of research. A significant portion of studies on all interception topics were published in "Meteorology & Atmospheric Sciences" outlets. The dominance of forestry journals in throughfall and stemflow aligns with net precipitation fluxes having primarily been investigated for their role in forest water and nutrient budgets over the past century (Parker 1983; Van Stan and Gordon 2018; Will 1955). On the other hand, studies on vegetation water storage and evaporation of precipitation have primarily been motivated by an interest in moisture return to the atmosphere—explaining the dominance of meteorology and atmospheric science journals over the past century (Horton 1919; Lundberg and Halldin 2001; Rutter et al. 1971; van Dijk et al. 2015). Over one-quarter of snow interception papers were published in the mathematics research area, consisting of work with a modeling focus (Hellström 2000; Liston and Elder 2006; Pomeroy et al. 1998). Nearly one-third of fog interception publications are published in the biodiversity and conservation research area, likely because many fog-reliant ecosystems are biodiversity "hot spots" in need of conservation science (Bruijnzeel et al. 2011).

Precipitation partitioning research has been frequently cited by the broader scientific community between 1918 and 2017. The number of studies in WoS that cite precipitation partitioning literature over the past century was 10 times (stemflow) to 25 times (snow interception) the number of publications on the subject! These citations yielded 100-year H-indices (not including self-citations) ranging from 35 (fog) to 117 (throughfall). Research areas citing precipitation partitioning research over the past century were more diverse than the publication research areas, by 1.5–2 times. The number of research areas citing each topic was 106 (fog interception) to 140 (throughfall), but the environmental science and ecology arena dominated the citations for all topics.

In total, studies from all keyword searches in WoS represented author affiliations from 121 different countries in every world region. A pictograph of these results per country (for the top 25 countries) shows the dominance of European, North American, East Asian, and Oceanian countries in publication output over the past century (Fig. 1.4). However, in examining international publication trends, it is important to recognize that multiple socioeconomic, political, and physical geographic factors underly "why" scientists start investigating precipitation partitioning processes and interact to determine "how" these investigations are enabled and supported. We also reiterate that our bibliometric analysis under-represents native language scientific publication, which could increase the number of publications represented in Fig. 1.4. A few major world regions are strongly represented by a single country in the precipitation partitioning literature: Brazil (South America), India (South Asia), and Mexico (Central America) (Fig. 1.4). Although South African researchers were active from the early days of precipitation partitioning research in forests and grasslands (Beard 1955; Phillips 1926, 1928; Wicht 1941), their work in the field slowed through the century, resulting in their ranking 29th (n publications = 48)—tied with Chile. Of all Middle Eastern countries, Iran produced the most publications on this topic over the past century (31st, n publications = 36), which

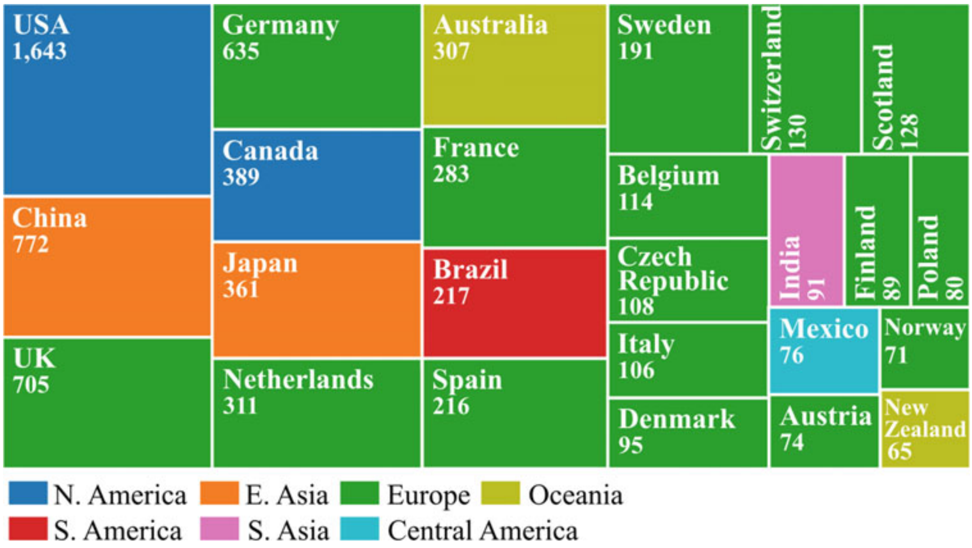


Fig. 1.4 Pictogram of the 25 countries that have published precipitation partitioning research according to the Web of Science database, where box size is weighted by number of publications and the color indicates each country's world region

appears to have been principally motivated by concerns about the degradation of the Caspian Oriental Beech Forests over the past decade (Ahmadi et al. 2009). For Southeastern Asia, Indonesia has produced the most publications on this topic per the WoS database (32nd, *n* studies = 31), generally rooted in the work of Calder et al. (1986). However, the first English publication on precipitation partitioning from Southeastern Asia appears to be an assessment of five Malaysian catchments (Low and Goh 1972). To date, no work in English on this subject has been reported for Central Asia or the Congo, areas with quite different vegetation, each equally meriting precipitation partitioning research in order to close regional data gaps and achieve a macroscale to global-scale understanding.

1.5 Current Relevance

Nine months into 2018 (at the time of writing this chapter), over 100 papers have already been published examining precipitation partitioning and its relationships with ecosystem functions, showing the growing relevance of the field. We focus this review of recent research on publications and presentations that have described new processes and estimates of states or fluxes. Thus, studies which report data on previously known processes, states or fluxes for new plant species, vegetation covers, etc., have been excluded from the following discussion. There is also not enough room in this chapter to fully describe the processes underlying each of these highlights; as such, the intention is that the reader will refer to the cited publication or presentation for greater detail. Not all results indicate that precipitation partitioning significantly influence the studied ecosystem properties; for example, no influence was found for throughfall on root biomass (Qi et al. 2018), contradicting long-cited semi-quantitative work regarding throughfall patterns and root patterns (Ford and Deans 1978). The oft-cited work on stemflow's role in generating "fertile islands" around plant roots in arid environments (Whitford et al. 1997) has also been challenged by meticulous manipulation experiments that found the stemflow influence alone was inadequate to engender fertile islands (Li et al. 2017). Some natural and plantation forest systems' may even be resilient to changes in precipitation partitioning (Orság et al. 2018), and their canopy ecohydrological processes, themselves, may be resilient to climate changes (Gimeno et al. 2018). Identifying the degree to which ecosystem elements, processes and the entire ecosystems, themselves, are resilient or sensitive to interception, throughfall and stemflow is a complex and critical pursuit.

Regarding rainfall interception research, global estimates of rainfall storage and evaporation from vegetation have been revised to include nonvascular vegetation (lichens and bryophytes), increasing global vegetation water storage capacity, from 0.4 to 2.7 mm, and evaporation by 61% (Porada et al. 2018). Savenije (2018) commented on the Porada et al. (2018) interception estimates, stating they "suggest that water balance computations need to be revisited." Indeed, much work thus far in 2018 has examined rainwater storage and evaporation controls in vegetation. One highlight in this research vein includes work by Klamerus-Iwan and Witek (2018) that quantifies and characterizes the effects of leaf pollutant uptake and infection on leaf water storage capacity. Significant work has been done on intercepted water taken up by leaves and redistributed within plants—and a new review article summarizes these foliar water uptake pathways, the biophysical conditions underlying them, and provides quantitative assessment of this process within plant water budgets (Berry et al. 2019). There is also a growing awareness of the importance of storm events and precipitation routing within the canopy to plant–microbe interactions, especially regarding the "disease triangle" between hosts, pathogenic microbes and their environment (Aung et al. 2018).

For throughfall, significant work continues to focus on the effects of its reduction on multiple ecosystem functions, like net ecosystem productivity, soil moisture dynamics or soil gas emissions (e.g., Bracho et al. 2018; O'Connell et al. 2018; Samuelson et al. 2018). Understanding of throughfall kinetic energy and soil erosion in forests was recently revised to recognize the importance of understory vegetation influences (Lacombe et al. 2018). New insights into fine-scale spatial variability in throughfall amount and intensities have also been gained, revealing the importance of patterns in storage "refilling" due to within-storm evaporation (Keim and Link 2018). Fine-scale temporal variability in throughfall generation processes is on the horizon, as near real-time observations systems are being tested in the field that yield water stable isotope measurements every few minutes (Herbstritt et al. 2018). In geomorphology, recent findings indicate throughfall measurements may be important for fallout radionuclide-based methods used to determine stream suspended sediment source and age (Karwan et al. 2018). Soil aggregate stability and associated organic carbon stocks appear to rely, in part, on throughfall (Zhang et al. 2018). For stemflow, an "alternative water transport system" for plants was recently identified and described that relies on stemflow (Biddick et al. 2018). Stemflow from forests' fog water harvesting may play an important role in water resources along the arid Omani coast, having been estimated to increase precipitation available for recharge by 20% (Friesen et al. 2018). Debate has recently arisen regarding stemflow research, where scientists are asking what metrics (stemflow percentage, yield, input, or funneling ratio) under which circumstances should researchers report for stemflow (Carlyle-Moses et al. 2018). This question was, in part, motivated by a recent global analysis of stemflow in forests that indicates stemflow may exert significant ecological influences on near-stem soil biogeochemical processes via resource limitation (Van Stan and Gordon 2018).

There have also been many new insights from studies investigating all precipitation partitions. Recent work indicates that dissolved organic matter in throughfall and stemflow (called "tree-DOM") can be significantly concentrated compared to other terrestrial hydrologic fluxes (Van Stan and Stubbins 2018), that tree-DOM is structurally diverse (Stubbins et al. 2017), and that it may provide a highly biolabile C subsidy to soil microbes (Howard et al. 2018). In the tropics, a comprehensive evaluation of DOM optical and isotopic properties indicated that tree-DOM may reach stream networks, where it may be rapidly metabolized (Osburn et al. 2018). Regarding agricultural science, recent work has elucidated throughfall's and stemflow's role in pesticide transport (Glinski et al. 2018), and it was found that precipitation partitioning should be considered when managing crop canopies for rainfed agriculture (Hakimi et al. 2018; Niether et al. 2018).

Finally, significant progress has been made at the intersection of microbiology and precipitation partitioning. The first report of bacterial cells transported from the canopy to the soils during storms found that this flux can equal quadrillions of cells ha^{-1} year^{-1} (Bittar et al. 2018). Analysis of the bacterial community structure via high-throughput sequencing, found for the first time that throughfall and stemflow fluxes can carry taxa known to engage in soil and litter biogeochemical processes, and that their community composition may be principally controlled by atmospheric deposition and storm synoptic patterns (Teachey et al. 2018). These bacterial hitchhikers share their hydrologic highway with a large quantity of metazoans: 1.2 million rotifers; 216,000 nematodes (many being bacterial feeders!); 160,000 tardigrades; 73,000 mites; and 25,000 collembolans year^{-1} tree^{-1} (Ptatscheck et al. 2018). Considering the abundance of fungal spores (Gönczöl and Révay 2004), archaea (Watanabe et al. 2016), particulates (Bischoff et al. 2015), and so on, the latest findings show that throughfall and stemflow may best be analogized as ephemeral, but congested, hydrologic highways between the plant canopy and any receiving surface or subsurface ecosystem. Future research will, undoubtedly, shed fascinating insights into whether these compounds and creatures survive their interactions with precipitation partitioning, where they end up, what they do there, and how much it matters at various ecosystem scales.

1.6 Conclusions: The Structure of This Volume

We began this chapter and, thereby, this book, by familiarizing our readers with the Peripatetic origins and foundational observations of precipitation–vegetation interactions. It was the impacts of precipitation partitioning at the surface, in the "shadows" cast by plant canopies, that caught the eyes of the "Father of Botany" (Theophrastus) and Pliny the Elder over 2000 years ago. Contrary, however, to the chronological order of discovery in this field, this book will address the impacts of precipitation partitioning only after a thorough description of the underlying processes behind the "shadow," or, put more scientifically, within the black box: water storage on vegetation (Chap. 2) and evaporation (Chap. 3). We follow the remaining precipitation that drains from the canopy to the surface as throughfall and stemflow (Chap. 4) and, then, examine the dissolved and particulate composition of these net precipitation fluxes (Chap. 5) as well as their spatiotemporal patterns at the surface (Chap. 6). To contextualize, for the first time, all precipitation partitioning processes into the global hydrologic cycle and climate system, Chap. 7 describes common parametrizations and applies land surface models to estimate the impacts of precipitation on regional and global hydrologic forecasts and land-atmosphere energy exchange. Precipitation interception, throughfall, and stemflow are also placed into context within vegetated ecosystem processes, starting with the C cycle (Chap. 8), and then vertically through the ecosystem itself: starting with the plants inhabiting plant canopies, epiphytes (Chap. 9), then examining the water and nutrient balance of plants rooted in soils (Chap. 10), impacts on litter biogeochemistry (Chap. 11) and soil physicochemistry (Chap. 12), then concluding with the relevance of precipitation partitioning to subsurface waters (Chap. 13). As precipitation partitioning interacts across all habitats of vegetated ecosystems, a discussion is provided regarding its interactions with microbiota in habitats throughout the plant microbiome (Chap. 14). Finally, the importance of precipitation partitioning to the human environment is highlighted via description of the economic valuation of its ecoservices (Chap. 15). To be as comprehensive a text as possible on its subject, the final chapter concludes with currently unanswered questions that the field considers to be key to the illumination of processes at the conceptually shadowed intersection of hydrologic, ecological, and climate theory. It is our hope that this book will add fuel to the fire that Theophrastus and Pliny ignited and make it brighter—bright enough to concentrate its beams toward the darker reaches of current theory while keeping conspicuous the lessons of past research.

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