Guidelines and considerations for designing field experiments simulating precipitation extremes in forest ecosystems

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Abstract

1. Precipitation regimes are changing in response to climate change, yet understanding of how forest ecosystems respond to extreme droughts and pluvials remains incomplete. As future precipitation extremes will likely fall outside the range of historical variability, precipitation manipulation experiments (PMEs) are critical to advancing knowledge about potential ecosystem responses. However, few PMEs have been conducted in forests compared to short-statured ecosystems, and forest PMEs have unique design requirements and constraints. Moreover, past forest PMEs have lacked coordination, limiting cross-site comparisons. Here, we review and synthesize approaches, challenges, and opportunities for conducting PMEs in forests, with the goal of guiding design decisions, while maximizing the potential for coordination.

2. We reviewed 63 forest PMEs at 70 sites world-wide. Workshops, meetings, and communications with experimentalists were used to generate and build consensus around approaches for addressing the key challenges and enhancing coordination.

3. Past forest PMEs employed a variety of study designs related to treatment level, replication, plot and infrastructure characteristics, and measurement approaches.

Important considerations for establishing new forest PMEs include: selecting appropriate treatment levels to reach ecological thresholds; balancing cost, logistical complexity, and effectiveness in infrastructure design; and preventing unintended water subsidies. Response variables in forest PMEs were organized into three broad tiers reflecting increasing complexity and resource intensiveness, with the first tier representing a recommended core set of common measurements.

4. Differences in site conditions combined with unique research questions of experimentalists necessitate careful adaptation of guidelines for forest PMEs to balance local objectives with coordination among experiments. We advocate adoption of a common framework for coordinating forest PME design to enhance cross-site comparability and advance fundamental knowledge about the response and sensitivity of diverse forest ecosystems to precipitation extremes.

1 | INTRODUCTION

The amount, timing, and distribution of precipitation are changing world-wide (IPCC, 2013). Precipitation extremes are increasingly falling outside the range of variability in which ecological communities have evolved, potentially leading to novel interactions between organisms and their environment (Williams, Jackson, & Kutzbach, 2007). Consequently, ecosystem responses to past climate variability may not provide sufficient basis for predicting responses to future extremes (Mora et al., 2013; Nippert et al., 2010).

Field-based precipitation manipulation experiments (PMEs) that control water inputs to push ecosystems beyond conditions under which they have developed are valuable for investigating responses to changing precipitation regimes (Beier et al., 2012; Kayler et al., 2015). While PMEs do not simulate all facets of climate change (e.g., humidity, cloudiness, and temperature; Novick et al., 2016; Williams et al., 2013), they can simulate potential future precipitation regimes. Moreover, PMEs permit measurements of ecosystem response to a discrete and quantifiable treatment, with both replication and greater control over confounding factors than with observational studies (Niu, Luo, Dietze, Keenan, & Shi, 2014). Here, we highlight the ability of well-designed PMEs to provide valuable insights about the magnitude and underlying mechanisms of ecological responses (Altwegg, Visser, Bailey, & Erni, 2017) and end-points for model parameterization and validation (Luo et al., 2011; McDowell, Ryan, Zeppel, & Tissue, 2013).

Most PMEs have been conducted in low-statured ecosystems, particularly grasslands, while those in tall-statured ecosystems (e.g., savannas, woodlands, and forests; hereafter "forests") are comparatively rare and geographically limited (e.g., concentrated in the US and Europe and in moisture-limited ecosystems; Figures 1 and 2). Of a total of 157 PMEs reviewed by E. Lebrija-Trejos et al. (unpublished data), 12% were in forests, while 79% were in grasslands and shrublands. Moreover, the response of forest ecosystems to periods of extreme high rainfall has rarely been considered, despite projected increases in both drought frequency and total rainfall in humid regions globally (Dai, 2013; IPCC, 2013).

Researchers conducting PMEs in forests face logistical and financial challenges because of the large vertical and horizontal reach and heterogeneity of the vegetation (Pangle et al., 2012), which limit the usefulness of small, relatively simple rain-out shelters designed for short-statured ecosystems (Yahdjian & Sala, 2002). However, forests have a disproportionate role in global carbon and water cycles (de Jong, Schaepman, Furrer, de Bruin, & Verburg, 2013). Knowledge of how other ecosystems respond to changing precipitation regimes may not translate directly to forests, due to fundamentally different drivers of NPP and other processes (Estiarte et al., 2016; Huxman et al., 2004; Wright, Williams, Starr, McGee, & Mitchell, 2013). Moreover, the long-lived nature of trees has direct impacts on resistance, recovery, and resilience to extremes across climatic gradients (Gazol, Camarero, Anderegg, & Vicente-Serrano, 2017), and trees have evolved different adaptations for resource acquisition and survival (e.g., deep roots, substantial interannual carbohydrate storage) than more water-limited grasses and shrubs (Baldocchi, Xu, & Kiang, 2004). Consequently, research questions often differ, with grassland PMEs typically emphasizing changes in community dynamics and functional trait composition at relatively fast turnover times, while forest PMEs often place greater focus on relationships between physiological mechanisms and response thresholds at larger spatial and temporal scales (Felton & Smith, 2017).

Past forest PMEs have employed a variety of treatment levels, response metrics, measurement techniques, and sampling
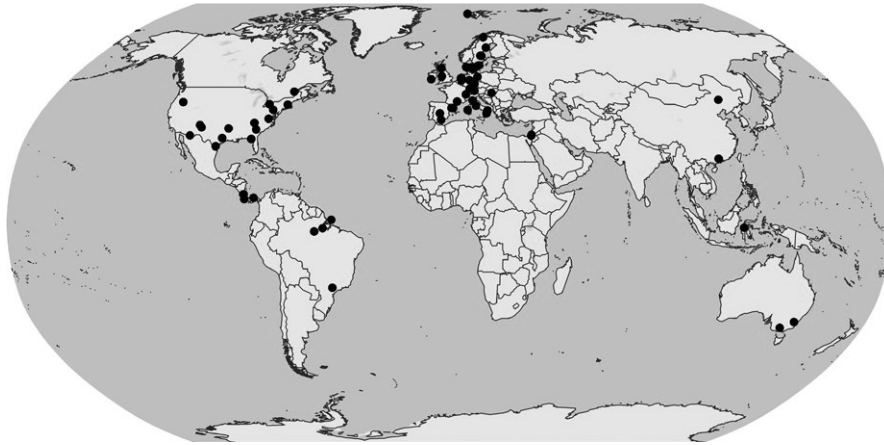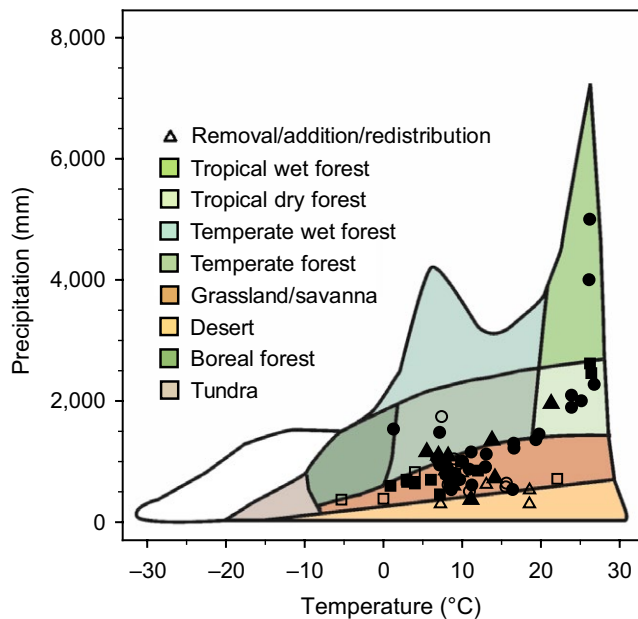
FIGURE 2 Mean annual temperature, precipitation, and biome of forest precipitation manipulation experiment sites based on Whittaker (1975), modified by Craine (2013). Solid symbols are forests, open symbols are shrublands

designs, and this lack of coordination has limited our ability to compare across sites and draw robust conclusions over large scales (Table 2). A coordinated, cost-efficient approach would facilitate implementation of PMEs across diverse forest types and advance fundamental understanding about forest responses to precipitation change (Vicca et al., 2012). To guide decisions on forest PME design, we sought to synthesize the advantages and disadvantages associated with different options, balancing coordination and cost-efficiency with adaptability. We consider four key components of forest PME design: (a) defining the treatment, (b) infrastructure, (c) plot design, and (d) response variables and measurement techniques. For each, we discuss key design considerations and identify trade-offs among approaches, and integrate these into a decision framework to maximize opportunities for coordination and synthesis (Table 1). While previous

reviews have emphasized the importance of PMEs and called for coordinated approaches (Beier et al., 2012; Fraser et al., 2013; Wu, Dijkstra, Koch, Peñuelas, & Hungate, 2011), none have addressed the unique challenges of designing experiments for forests. While we focus our analysis on precipitation extremes, we acknowledge the importance of also designing PMEs to address other complex aspects of precipitation change, such as seasonality or the intensity and/or number of events, and that the concepts and recommendations presented here may not apply to all PMEs.

2 | DETERMINING PME TREATMENTS

2.1 | Defining precipitation extremes

A fundamental goal of PMEs is to simulate changing precipitation regimes; therefore, clear criteria for characterizing such regimes are needed. Given sufficient climate data, meteorological precipitation extremes can be quantified statistically as the tails of the historical distribution (Smith, 2011). For example, identifying the 1% and 99% quantiles of a long annual precipitation record provides a simple metric to characterize once-in-a-century events that are expected to increase in frequency (Fischer, Sedláček, Hawkins, & Knutti, 2014). The importance of characterizing extremes based on site-specific climate data is highlighted by the marked differences in precipitation distributions across climates, with wet and dry extremes in humid regions varying by 30%–40% from average years, while in arid regions, these deviations increase to >60% and >150% for dry and wet years respectively (Knapp et al., 2015).

An alternative is to design PME treatments based on ecological precipitation extremes that account for site and ecosystem differences by identifying the change needed to trigger an extreme plant community response (Smith, 2011). This approach emphasizes underlying mechanisms controlling individual plant and ecosystem responses, and is less concerned with simulating actual historical or future extremes. Additionally, this approach accounts site-specific edaphic, topographic, and climatic characteristics (Gerten et al., 2008; Zeppel, Wilks, & Lewis, 2014).

TABLE 1 Framework for guiding decisions on forest precipitation manipulation experiment (PME) design

Study design component	Decision category	Options	Recommendation
Defining the PME treatment	Amount removal/addition	Long-term onsite precipitation data available	Calculate the site-specific 1% and 99% quantiles
		Long-term site data not available	Estimate quantiles (e.g., using web-based tool; Lemoine et al., 2016)
	Temporal distribution	Simulate meteorologically defined precipitation extremes based on historical record	Passive approach (recommended for most PMEs, unless not suitable for site-specific objectives)
		Simulate subannual changes in precipitation that differ from historical patterns	Active approach
	Snow manipulation	Snow provides substantial inputs to growing season plant water availability	Include snow manipulation in the PME treatment
		Small contribution of snow to growing season, rooting zone soil moisture	Snow manipulation unnecessary
Infrastructure	PME removal	Durability and resistance is of high priority; budget not a major constraint	Metal is ideal, otherwise use other locally available materials (wood, bamboo, plastic)
		Relatively low tree density; high winter snowfall; site easily accessible for repairs; minimal concern about striping effects	Fixed trough system installed with appropriate spacing and height; gutters to divert water off plot; measure actual amount
		Relatively high tree density; winter snowfall largely absent; remote location makes repairs difficult; concern about striping effects (requires rotating infrastructure)	Flat panel frames installed with appropriate spacing and height; gutters to divert water off plot; measure actual amount
	PME addition	Possible to collect rainfall or throughfall above the treatment plots	Passive gravity flow
		Collection of rainfall or throughfall above the treatment plots not possible	Irrigation with sprinklers or manual watering
Study design	Plot location	Consider the effects of topography on possible water subsidies into plots	Ideally on near-flat ground or along hydrologically isolated upper edge of ridge/hilltop
	Plot size	Consider the size needed to account for horizontal reach of tree roots and species diversity	Plot diameter at least twice the height of canopy trees, plus a buffer area
	Plot replication	Replication versus pseudoreplication	A minimum of three replicate plots recommended per treatment
		Gradient analysis—regression approach (with multiple treatment levels)	Recommended as a means to increase statistical robustness
	Trenching	Low concern about negative impacts on roots and rhizosphere	Trenching depth depends on rooting depth, soil depth, soil permeability, and slope
		High concern about negative impacts on roots and rhizosphere	Avoid trenching; compensate by using larger plot size and/or buffer area, together with strategic plot placement to minimize water subsidies
	Infrastructure control	Closed canopy structure	Infrastructure impacts likely negligible
		Open canopy structure	Infrastructure control may be important
Response variables	Recommended core variables (see Supporting Information Table S3 for details)	Site and microclimate characterization	Soil physical and chemical properties, vegetation, topography, soil moisture, precipitation, air temperature, relative humidity
		Individual plant responses	Stem diameter increment, height, leaf area, canopy phenology, dieback, mortality
		Ecosystem responses	Above-ground biomass, litterfall, root production, decomposition

2.2 | Determining the precipitation treatment amount

Previous approaches to defining PME treatment magnitude (the amount added or removed) have generally avoided creating conditions extreme enough to induce significant plant dieback or mortality. For example, in our literature review of 67 forest PMEs (Supporting Information Tables S1 and S2), most had treatments substantially less severe than the historically determined 1% and 99% quantiles (Figure 3). Consequently, it has been difficult to detect soil moisture thresholds required to cause an extreme ecological response. Additional, more extreme experiments are needed to explore the mechanisms of sensitivity and thresholds (Estiarte et al., 2016; Meir, Wood, et al., 2015).

When historical records are used to determine the target precipitation extremes, site-specific data provide the best metric, although data interpolated from nearby stations are a reasonable alternative, particularly if they offer longer records (Lemoine, Sheffield, Dukes, Knapp, & Smith, 2016). Designing PME treatments based on ecological precipitation extremes is more difficult than simply adding or removing precipitation in a fixed ratio. Biological responses are accurately found by carefully controlling soil moisture levels until specific biological thresholds are reached (e.g., Elliott, Miniat, Pederson, & Laseter, 2015; Meir, Wood, et al., 2015; Mitchell, O'Grady, Hayes, & Pinkard, 2014). While ecological thresholds can be detected by imposing different PME treatment levels, this approach is often cost-prohibitive at scale, and rare in practice (but see Luo, Jiang, Niu, & Zhou, 2017). Alternatively, a sufficiently extreme treatment
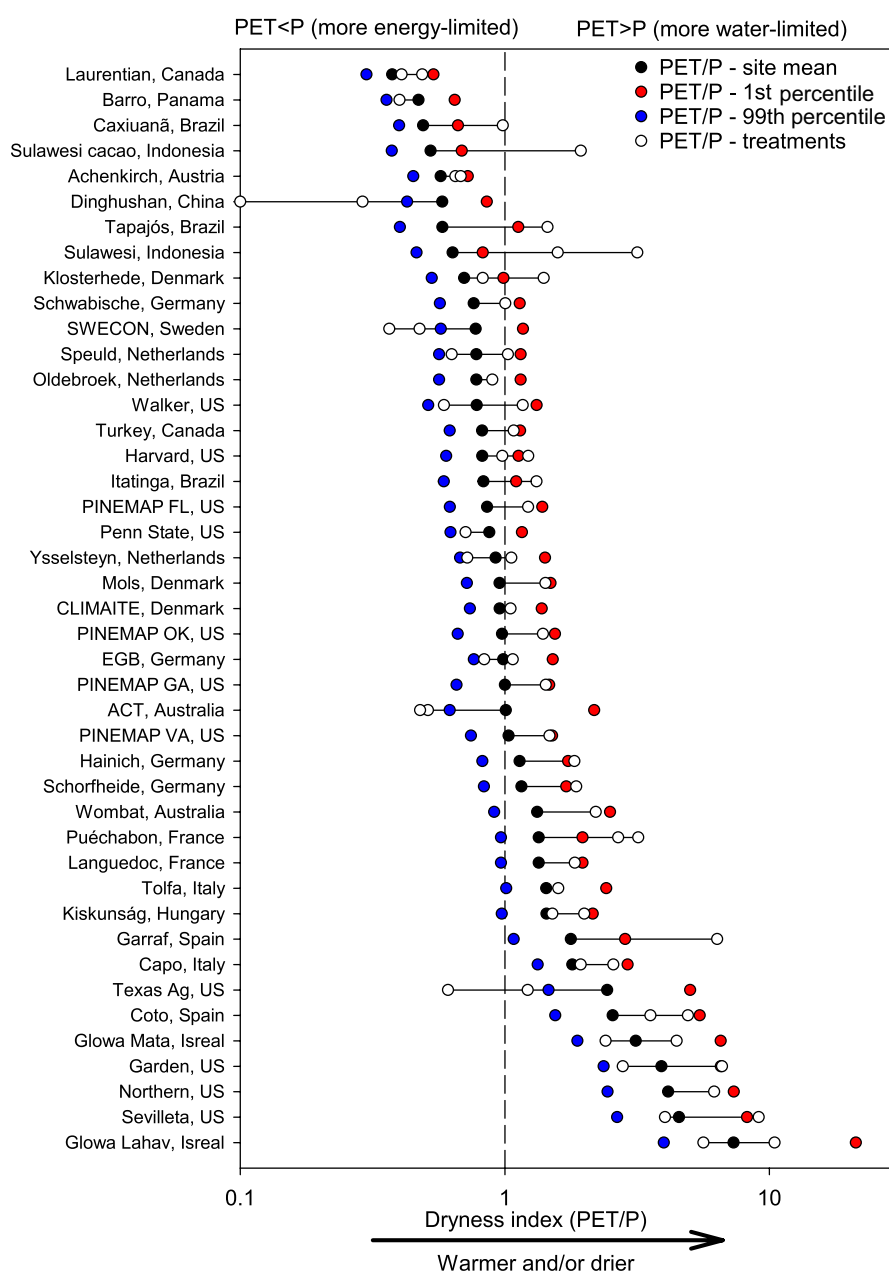

FIGURE 3 Forest precipitation manipulation experiments expressed on a dryness index following Budyko (1974), where PET is mean potential evapotranspiration and P is mean precipitation (note the logarithmic scale). Black circles indicate ambient values; open circles indicate experimental precipitation removals (shifted to the right) or additions (left). Red and blue circles indicate the first and 99th percentile of precipitation respectively. Methods are further described in Supporting Information Table S1; additional information on these studies is included in Supporting Information Table S2 (Asbjornsen et al. 2018)

continued over multiple years can be used to identify soil moisture thresholds that elicit nonlinear ecological responses (i.e., reduced NPP, mortality; Estiarte et al., 2016; Mitchell et al., 2016). Given that soil moisture is often a more direct driver of plant response than precipitation alone, this latter approach may be most consistent with many PME objectives.

High variability in ambient precipitation can create challenges to PME design, as the treatment year may overlap with abnormally high (or low) precipitation years, thereby weakening (or strengthening) the treatment (Hoover, Duniway, & Belnap, 2015). Where there are already trends in mean precipitation, this problem can be magnified. The most feasible approach to addressing this issue is to include at least three treatment years, although some ecosystems may require longer durations (Meir, Mencuccini, & Dewar, 2015). Ideally, a post-treatment study period should also be included to assess resilience and recovery, which may vary substantially among ecosystems and species (Gazol et al., 2017).

2.3 | Accounting for the temporal distribution of precipitation

Once the treatment magnitude has been determined, a passive approach is often used (80% of forest PMEs reviewed) in which each precipitation event is reduced or increased by a constant ratio. Knapp et al. (2017) found that passive removal closely approximates the attributes of both extreme dry and wet years across a broad range of ecosystem types. Thus, if the primary interest is to understand ecosystem responses to precipitation extremes, passive PMEs provide an efficient approach. Designing PMEs to simulate subannual extreme events or changes in precipitation distribution (Robinson et al., 2013) requires more complicated active approaches, such as removing all precipitation during certain seasons, deploying panels before large precipitation events, or irrigating during specified periods (Gherardi & Sala, 2013; Knapp, Harper, Danner, & Lett, 2002).

2.4 | Accounting for snow

A major challenge in forest PME design is manipulating winter precipitation in areas receiving persistent snow. In many high-latitude or high-altitude regions, annual precipitation has increased over the last century, but without a clear trend in winter precipitation (Ren, Arkin, Smith, & Shen, 2013). However, climate change projections include winter precipitation increases of up to 30% by 2100 and both historical records and models show increasing winter precipitation variability (Giorgi & Bi, 2005; Hayhoe et al., 2008). Climatic warming also reduces snowpack depth and duration (Kumar, Wang, & Link, 2012) and increases the incidence of rain relative to snow (Feng & Hu, 2007).

Although some grassland ecosystems also receive appreciable amounts of snow, their short stature significantly reduces the logistical complexity of snow manipulation (Sanders-DeMott & Templer, 2017). Snow fences commonly used for grassland PMEs (e.g., Wipf

& Rixen, 2010) are not well suited for forests because of their small area of influence and because trees reduce wind speeds, limiting the effectiveness of this approach. Snow removal in forests is commonly achieved by manual shovelling or by leaving the PME infrastructure in place over the winter (Blankinship & Hart, 2012). Manual shovelling typically requires PME infrastructure with removable panels or troughs to facilitate access. Efficiencies of snow interception by PME structures may be lower than for rainwater, with greater losses due to wind and gravity. Wider troughs have a greater snow-holding capacity, but can fail under snow loads if not properly designed. As with rain, this approach may produce a patchy distribution of snow, increasing heterogeneity in soil moisture and freezing.

Changing winter precipitation has a large direct impact on ecological processes where precipitation occurs mostly in winter and snowmelt significantly influences growing season soil moisture. Conversely, where soils are saturated during the spring thaw even in a dry year, reducing snow may not affect growing season water availability, so manipulating snow may not be a priority. Notwithstanding, the loss of winter snowpack increases soil freezing (Henry, 2007), damaging tree roots and reducing uptake of water and nutrients (Campbell, Socci, & Templer, 2014). Consequently, a fundamental consideration is the impact of snow manipulation on both water availability and soil temperature (Sanders-DeMott & Templer, 2017). Effects on soil temperature can be minimized by removing a portion of snowpack shortly before thawing. Where simulating soil freeze–thaw dynamics in a lower snow climate is a goal, snow should be removed consistently throughout the winter.

3 | INFRASTRUCTURE FOR ESTABLISHING PMES IN FOREST ECOSYSTEMS

The infrastructure used to establish forest PMEs has ranged from relatively simple passive throughfall exclusion gutter networks or gravity-fed rainfall addition, to more complex active designs, including automated panels and irrigation systems (Misson et al., 2011; Pangle et al., 2012; Pretzsch et al., 2014; Figure 4). The greatest limitation to forest PMEs has been their relatively high cost; this section focuses on providing guidelines for cost-efficient and broadly applicable passive approaches. Of the forest PMEs we reviewed, 49% were removals, 23% were additions, 20% were both, and the remaining 7% were redistributions (Table 2).

3.1 | Construction design and materials: precipitation removal PMEs

Two main types of infrastructure have been used to passively remove throughfall in forest ecosystems. The fixed trough system consists of flexible polyethylene sheeting secured to a frame (e.g., Pangle et al., 2012). Where a trough line intersects a tree, the tree can be fitted with a collar bonded to the trough with rolled clamping strips and caulking tape. Alternatively, pipe can be run from one trough to another around stems. Flat panel frames consist of rigid

plastic panels supported by frames (Nepstad, 2002). Advantages include the ability to place individual panels to avoid trees, and easy removal for cleaning, litter redistribution or repair. Panels can be moved periodically to reduce the effects of "striping"—the creation of wet and dry microsites beneath and between panels or troughs.

Many studies using passive throughfall exclusion structures require a system of gutters to divert the intercepted water away from the plot (Pangle et al., 2012). Flow meters can be attached to the gutters to quantify the actual throughfall removed, which may differ from the areal ground coverage due to factors such as wind, stemflow, and spillage. However, flow meters will slightly underestimate the water removed due to water remaining on (and evaporating from) the troughs, especially in small events. Ideally, throughfall should also be measured in control plots to obtain baseline values (Levia & Frost, 2006).

Determining the appropriate height and spacing of forest PME infrastructure involves several trade-offs. Troughs or panels need to be high enough (approximately 1.5 m) to allow for understorey growth, air movement, and access, yet construction costs and difficulty of maintenance and cleaning increase with height. Typically, troughs are located beneath the canopy, which can be challenging in low-statured woodlands and shrublands (Figure 4). Fixed troughs also require provisions for access, such as removing sections or spacing them far enough apart to walk between. Flat panels tend to be spaced on a grid, and their modular nature allows for the structure to be readily moved.

3.2 | Design of precipitation addition PMEs

Several approaches have been used for rainfall addition forest PMEs. Passive gravity flow systems divert captured throughfall into a lower elevation irrigation plot (e.g., Hanson & Wullschleger, 2003). Active irrigation allows the quantity and timing of water to be automatically controlled based on meteorological variables or soil moisture content (e.g., Linder, Benson, Myers, & Raison, 1987) and is most effective using a network of sprinklers placed 0.5–1.5 m above-ground level (Figure 4), or above the trees if to more accurately simulate rainfall (e.g., Pangle et al., 2012). Manual watering may be an option for small PMEs (Richter et al., 2012).

Experimental irrigation has been implemented most extensively in forest plantations, where water supplementation is often an important management tool (e.g., Jokela, Dougherty, & Martin, 2004).

FIGURE 4 Various structural designs used to divert throughfall: (a) Fixed troughs used by the PINEMAP project (Ward et al., 2015). (b) Underside of framing braces at the Hubbard Brook LTER. (c) Fixed trough system used at Thompson Farm in Durham, NH. (d) Polycarbonate troughs and metal framing at the Sevilleta LETR (Pangle et al., 2012). (e) Flat panel system at Caxiuanã National Forest (Nepstad, 2002); arrows show the flow path from panels to a plastic-lined trough. (f) Polyethylene sheet panels at Lore Lindu National Park, Indonesia (van Straaten, Veldkamp & Corre, 2011). (g) Automated retractable roof at the KROOF project, Kranzberg Forest, Germany (Pretzsch & Schütze, 2016; Pretzsch et al., 2014). Photo credits: (a) Geoffrey Lokuta, (b, c) Cameron McIntire, (d) Aimee Classen, (e) Daniel Metcalfe, (f) Oliver van Straaten, (g) Leonhard Steinacker

More recently, water addition PMEs have been conducted to assess climate change impacts in water-limited woodlands or dry forests (Plaut et al., 2013; Ruehr, Martin, & Law, 2012). In contrast, despite predictions that wetter sites will likely experience more extreme wet spells (IPCC, 2013), the response of mesic forests to precipitation additions has been poorly investigated, with previous studies utilizing relatively small plots (e.g., Gao, Zhao, Shen, Rao, & Hu, 2017; McCulley, Boutton, & Archer, 2007; Yavitt, Wright, & Wieder, 2004; but see Hanson, Todd, & Amthor, 2001). A unique study assessed the century-scale response of trees growing along irrigation channels, and reported lower growth increases when compared with a short-term 3-year irrigation period (Dobbertin et al., 2010; Feichtinger, Eilmann, Buchmann, & Rigling, 2015). Clearly, conducting more water addition forest PMEs represents a critical research need.

4 | STUDY DESIGN FOR FOREST PMES

4.1 | Location, size, and replication of the PME plots

Ideally, plots should be as similar as possible and on nearly flat ground or along the shoulder of a small ridge or hilltop to minimize lateral flow into the plot. Relatively large plot size (ideally ≥30 m^2) and low replication is an inherent trade-off faced by most forest PMEs. Although a common rule of thumb is to size plots at least twice the height of canopy trees, plot dimensions should be based on site-specific knowledge of lateral root distribution, preferably erring larger in the face of uncertainty and including a buffer to avoid edge effects (Pangle et al., 2012). In more diverse ecosystems, larger plots may be needed to include target tree species. Across the forest PMEs we reviewed, a minority reported including a buffer zone, and the median plot size was under 100 m^2 (Table 2). Few studies included plots >1,000 m^2, and only two (both tropical) studies employed 10,000 m^2 plots.

TABLE 2 Percent of reviewed forest precipitation manipulation experiments (see Supporting Information Table S2) that include specific design elements and fall within each plot area size range, excluding three studies with insufficient information (67 out of 70 reviewed studies; Asbjornsen et al. 2018)

	% Studies
Design	
Replication (*n* ≥ 2)	81
Infrastructure control	10
Buffer	41
Trenching	25
Plot size	
≤10 m^2	21
<10–100 m^2	31
<100–1,000 m^2	31
<1,000 m^2	18

Ideally, experiments should include replicate plots for each treatment, although pseudoreplication (treating measurements from within a single plot as replicates) is a common compromise. Only 55% of forest PMEs with plots >1,000 m^2 were replicated, whereas 88% of PMEs with plots <1,000 m^2 were replicated. When using a pseudoreplicated design, thorough plot characterization and collection of pretreatment data are crucial (Carpenter, 1989). Alternatively, including a range of PME treatment intensities and a regression approach provides greater statistical power for characterizing response surfaces, detecting threshold dynamics (Beier et al., 2012; McDowell et al., 2016; Plaut et al., 2013), and capturing these responses in models (Kayler et al., 2015).

4.2 | Trenching to minimize water subsidies

Three types of water subsidies can compromise the intended treatment: (a) lateral subsurface or overland flow, (b) extension of roots beyond the plot, and (c) root access to deep soil water or groundwater. The first two sources can be mitigated by trenching around the plot, as in 31% of published forest PMEs (Table 2). The depth of the trench required (typically >1 m) depends on rooting depth, soil depth, soil permeability, and slope. Trenches can be established on all sides, or just upslope, and plastic lining installed to impede lateral water flow and root growth. If a treatment plot is trenched, the control plot must be as well to account for any trenching artefact. A major disadvantage of trenching is damage to roots and the rhizosphere, but these effects diminish with time (Pretzsch & Schütze, 2016). Where access by roots to deep water sources is in question, verification by monitoring groundwater levels or using stable isotope ratios of xylem and soil water is important (Dawson et al., 2002; Hanson et al., 2001).

4.3 | Infrastructure control

The PME infrastructure may have unintended effects on the forest floor environment due to shading, reduced air movement, and the introduction of small-scale heterogeneity in soil moisture. The direct physical effects of irrigation infrastructure are likely quite minor relative to throughfall removal. Ideally, PMEs would include an infrastructure control for each treatment (a similar structure that does not affect precipitation; Figure 4). However, the additional cost may not be justified, particularly if light and air movement are already limited and gutters are highly transparent (Hanson, Todd, Edwards, & Huston, 1995; Pangle et al., 2012). Few forest PMEs included an infrastructure control (Table 2).

5 | SELECTING RESPONSE VARIABLES AND MEASUREMENT TECHNIQUES

While the particular research questions, logistics, and budget will influence decisions on response variables and measurement techniques, we provide a generalized framework for guiding this

process, categorized into three tiers (Supporting Information Table S3). Tier I represents a set of recommended core measurements selected to balance cost and effort with ability to enable meaningful cross-site comparisons and syntheses among forest PMEs (e.g., Vicca et al., 2012). Tier II and III measurements require increasing expense and expertise, and can be adapted to specific research goals.

5.1 | Site and microclimate characterization

Pretreatment characterization of site and microclimate conditions provides an important baseline for comparing responses and accounting for plot variability. Key Tier I site parameters include measurements of precipitation, air temperature, relative humidity, and soil moisture. Soil moisture is ideally measured continuously with sensors or potentiometers at multiple depths, or with frequent point measurements. Additional Tier II and III measurements include soil physical and chemical properties, soil hydraulic properties, and water content and potential.

5.2 | Measurements of plant physiological and growth responses

The temporal and spatial scales of forest response to extreme events requires that PME measurements integrate across multiple scales. Leaf-scale physiological and whole-plant growth responses can provide sensitive indicators of future ecosystem change that may not be detectable for many years. Establishing linkages across scales requires careful selection of response variables, summarized below.

5.2.1 | Leaf-level responses

Plant physiological responses include variables that respond quickly to environmental conditions, such as leaf water content, and predawn and mid-day water potential (to evaluate the degree of stress experienced by the plant hydraulic system). Considering the link between plant water and carbon relations, measurements of stomatal conductance, photosynthesis, and short-term growth (e.g., shoot extension) can be early indicators of physiological responses to water limitation (Flexas & Medrano, 2002; Hommel et al., 2014; Ripullone et al., 2009). While some of these measurements require specialized equipment and expertise (Tier II or III), plant functional traits (Tier I) are relatively simple to characterize and provide valuable insights about plant response to moisture stress (Stahl et al., 2013).

5.2.2 | Whole tree-level responses

Measuring sap flow has the advantage of directly quantifying water fluxes at the tree scale and providing continuous data on integrated plant responses to the treatment (Limousin et al., 2009). The cumulative influence of treatment on growth is typically assessed using repeated measurements of stem diameter (Tier I; de

Swaef, De Schepper, Vandegehuchte, & Steppe, 2015). Automated dendrometer bands can provide information at a high temporal resolution, allowing the separation of true growth from changing water storage (Brinkmann, Eugster, Zweifel, Buchmann, & Kahmen, 2016). Stem increment data (Tier I) can be scaled to derive cumulative biomass change via allometric equations over longer time periods. Combining tree-ring measurements with stable carbon and oxygen isotopes of wood can provide more specific information on the underlying physiological mechanisms driving growth trends (Brienen, Hietz, Wanek, & Gloor, 2013; Voltas, Chambel, Prada, & Ferrio, 2008). Quantifying nonstructural carbohydrates in twigs, stems, and roots can elucidate plant-level patterns of C allocation to current versus future growth and maintenance (Dickman, McDowell, Sevanto, Pangle, & Pockman, 2015; Körner, 2003). The impact of drought on plant hydraulics can be determined through measurements of the percentage loss of conductance, typically on excised roots and branches (Cochard, Cruiziat, & Tyree, 1992). Measures of leaf senescence, leaf area, crown dieback, root/shoot ratios, defence, and stress compounds, and mortality are often employed to assess how precipitation change impacts plant heath and survival (e.g., Gaylord et al., 2013). While measurements of whole-tree growth and dieback are considered Tier I, other Tier II and III measurements can be added to address specific study objectives (Supporting Information Table S3). Together, integrated assessments of plant carbon relations, hydraulic function, and organ or whole-plant injury can be used to infer drought resistance and resilience (McDowell et al., 2011; van der Molen et al., 2011).

5.3 | Ecosystem scale structure and processes

Linking the physiological and growth responses discussed above to ecosystem scale changes is critical to establishing long-term consequences of precipitation extremes in forest ecosystems. This requires integrating multiple factors over longer (seasonal or annual) time-scales, including ecosystem productivity, soil biogeochemical pools and fluxes, water balance, and plant community response.

5.3.1 | Ecosystem productivity

Assessing PME effects on above-ground productivity requires collecting stem increment and standing biomass data (discussed above). Other important Tier I data include litter production, reproductive allocation, and canopy phenology (using litter baskets). For below-ground responses, approaches range from assessing fine root production with root-ingrowth cores to provide a standard index (Tier I), to more sophisticated measures of fine root productivity using sequential coring or minirhizotrons (Milchunas, 2009; Vogt, Vogt, & Bloomfield, 1998). The high variability typical with root measurements can be assessed pretreatment and used to optimize replication via power analysis (Steidl & Thomas, 2001). To account for striping beneath troughs or panels, it is important to stratify sampling across these positions. Other components of below-ground

allocation (e.g., mycorrhizal fungi and carbon exudation to free-living rhizosphere microbes) require targeted (Tier II and III) sampling approaches (Mohan et al., 2014).

5.3.2 | Biogeochemical cycling

Changes in soil moisture can impact nutrient pools and fluxes (Cregger, McDowell, Pangle, Pockman, & Classen, 2014). Because forest ecosystems are typically nutrient limited (Elser et al., 2007), this is an indirect way for PMEs to affect forest productivity (Gessler, Schaub, & McDowell, 2017). As these measurements generally require lab facilities, most are considered Tier II or III (Supporting Information Table S3). Potential parameters include inorganic nutrient pools, total organic C and N, soil respiration, N mineralization, and decomposition rates (Klein, 2014; Schlesinger et al., 2016). Inorganic nutrients can be monitored using ion-exchange resin deployed up to several times annually (Fisk, Ratliff, Goswami, & Yanai, 2014; Robertson et al., 1999). Soil respiration can be measured in permanently installed collars using a portable CO_2 analyser. Total organic C and N stocks should be measured pretreatment across the soil profile and again every 3–5 years (Conant, Smith, & Paustian, 2003). Decomposition rates can be assessed using litter bags deployed at the beginning of the study, or annually throughout the study, using either native litter or standardized substrates (e.g., tea bags, wood dowels; Keuskamp, Dingemans, Lehtinen, Sarneel, & Hefting, 2013). Possible leaching of nutrients below the rooting zone in precipitation addition experiments could be quantified using lysimeters (Watmough, Koseva, & Landre, 2013).

5.3.3 | Water balance

Precipitation extremes likely alter surface evaporation, transpiration, soil water content, and hydrologic flows, which in turn, will affect hydrologic budgets across broad spatial scales (Asbjornsen et al., 2011; Caldwell et al., 2016; Wullschleger & Hanson, 2006). While the size of most PMEs limits their scalability, plot-level assessments of water balance are feasible by measuring its key components (Tier II; Supporting Information Table S3): transpiration (E_t), canopy interception (E_i), soil evaporation (E_s), precipitation (P), and deriving water yield (Q) as: $Q = P – E_t – E_i – E_s$. E_t is typically measured via whole-tree sapflux (Steppe, De Pauw, Doody, & Teskey, 2010) scaled using species-specific sapwood area estimates (Hernandez-Santana, Hernandez-Hernandez, Vadeboncoeur, & Asbjornsen, 2015). Canopy interception can be estimated from throughfall and precipitation (Holwerda, Scatena, & Bruijnzeel, 2006). In closed canopy forests, E_s is typically small, but in more open forests, E_s should be measured or modelled (Bruijnzeel, 2000).

5.3.4 | Plant community response

Increasing frequency of precipitation extremes can change the plant community on longer time-scales due to differential effects on seedling establishment and survival, and dieback and mortality of canopy trees. Assessing plant understorey mortality, regeneration dynamics, and species composition (all considered Tier I measurements) may provide a sensitive indicator of future plant demographic change (Anderegg, Anderegg, & Berry, 2013; Martinez-Vilalta & Lloret, 2016; Rother, Veblen, & Furman, 2015). However, care must be taken to avoid confounding effects of the infrastructure (e.g., striping, shading) and disturbance during data collection activities. Plant community changes can have cascading effects on other biotic interactions (e.g., herbivory, pests and pathogens, invasive species, insect dispersers or pollinators), as well feedbacks to faunal communities (Caldeira et al., 2015; Redmond, Cobb, Clifford, & Barger, 2015).

6 | LIMITATIONS OF FOREST PMES AND AVAILABLE TOOLS FOR ADDRESSING THEM

A major limitation of PMEs is that precipitation extremes co-occur with other global changes (e.g., increasing CO_2, atmospheric deposition, temperature, humidity) in complex ways (Trenberth et al., 2014), which are logistically impossible or financially prohibitive to address with PMEs. Moreover, interactions among multiple factors may cause response levels to decline over time (Leuzinger et al., 2011), while stress history "memory" may confer plant communities exposed to previous droughts with improved drought resistance (Backhaus et al., 2014). Another challenge shared by PMEs is their limited ability to capture processes that occur on larger spatial or temporal scales, especially since treatments often run only a few years, and the difficulties in extrapolating plot-level data to landscape and watershed scales. These issues are particularly challenging in forest PMEs due to the longevity of trees and the associated costs of implementing additional treatments. Superimposing forest PMEs on existing climate change experiments can help reduce the costs and effort for assessing interactions among multiple drivers, yet such opportunities are relatively rare. Conducting PME treatments over one or more decades offers the best opportunity to assess longer term climate change impacts. Additionally, emerging tools related to modelling and remote sensing can help address some of these limitations, provided that appropriate data are collected for their integration with PMEs.

6.1 | Modelling

With appropriate data for integration and testing, models can enhance what we learn from forest PMEs in several ways. First, models can be used to examine different global change factors alone and in combination to help resolve their individual and combined influences (McDowell et al., 2013; Ollinger, Goodale, Hayhoe, & Jenkins, 2008; Wright et al., 2013). Second, the limited duration of experiments makes it difficult to anticipate tipping points or longer term feedbacks involving nutrient cycles, community composition, or plant biogeography (Saura-Mas, Bonas, & Lloret, 2015). Here, too, models can add context by supporting virtual experiments across

broader spatial and temporal scales, and predicting response thresholds (Gustafson, De Bruijn, Miranda, & Sturtevant, 2016; Sitch et al., 2008). Finally, advances in land-surface modelling and data-model fusion have improved the degree to which plot-scale data on ecological processes and plant physiological mechanisms can be integrated with biophysical processes that regulate climate (Bonan & Doney, 2018; Dietze, LeBauer, & Kooper, 2013), hydrology (Christoffersen et al., 2014), and plant demographics (McMahon, Parker, & Miller, 2010). This opens up the potential for integrating short-term responses observed in PMEs with longer term regional- to global-scale feedbacks simulated by Earth system models.

6.2 | Canopy reflectance

Canopy-level remote sensing data provide a useful means of providing estimates of plant composition and canopy water status needed to spatially extend results and refine wider scale drought monitoring. Although the size of PME treatment plots precludes the use of most satellite-based data, rapid growth in the use of drones and lightweight multispectral and hyperspectral sensors offer promising alternatives. However, depending on sensor resolution, experimental infrastructure might complicate analysis except in closed canopy forests (or experiments with an infrastructure control plot). At the leaf level, the presence of water in foliage influences reflectance through the direct effects of water itself, primarily in the infrared region (e.g., at 1,450 and 1,950 nm), as well as a broad pattern of declining reflectance beginning at 1,400 nm (Kokaly, Asner, Ollinger, Martin, & Wessman, 2009). The consistency of these features has led to the development of simple water stress indices (Gao, 1996; Penuelas, Pinol, Ogaya, & Filella, 1997). Less understood are the indirect effects of water stress on leaf area, leaf angle, and pigments, which influence canopy spectral properties and are sensitive to changes in water status (Ollinger, 2011). With the improved understanding of plant responses that PMEs make possible, concurrent measurements of canopy reflectance can help resolve these relationships.

7 | CONCLUSION: TOWARDS A COORDINATED APPROACH FOR FOREST PMES

Advanced understanding of how future precipitation extremes will affect forests requires PMEs that push ecosystems beyond their physiological and ecological thresholds. Ideally, future PMEs would be distributed across diverse ecosystems and employ a common experimental design, response variables, and measurement techniques to facilitate cross-site analyses and identification of broad-scale patterns (http://wp.natsci.colostate.edu/droughtnet/).

We presented a framework to guide the design and implementation of forest PMEs that we hope will support cross-site synthesis (Table 1). We highlighted inherent trade-offs among different approaches, and emphasized the opportunity to significantly advance knowledge about response to precipitation extremes using cost-efficient experimental approaches. We organized common response variables used in forest PMEs into three tiers of complexity (Supporting Information Table S3), to assist researchers in identifying suitable metrics for each research context. Although most relevant for future forest PMEs, opportunities exist for applying this framework to existing experiments (e.g., by adopting the core variables) and to past forest PMEs (e.g., studies that included some core variables, and by normalizing the PME treatment based on the site-specific precipitation record as in Figure 3).

AUTHORS' CONTRIBUTIONS

H.A., M.D.S., and L.R. conceived the idea; J.C. led the data analysis; K.J. led the literature review; all authors participated in a 2015 workshop, contributed specific text, and edited drafts of the manuscript; H.A. led the writing along with J.C. and M.A.V.; C.M., P.H.T., and R.P.P. led specific sections.

DATA ACCESSIBILITY

Data associated with the literature review are available at https://doi.org/10.5061/dryad.f301j26.

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