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

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Supplemental Information

S1. Methods for the literature review of forest precipitation manipulation experiments.

Building off of the list of precipitation change experiments from Rustad (2008) an online literature search was conducted between January and May of 2015 on the ISI Web of Science and Google Scholar using search terms including combinations of "throughfall displacement", "throughfall exclusion", "precipitation manipulation experiment", "irrigation", "forest" and "shrubland". Additional studies were added that came to our attention before December 2016. Ecosystem type was classified based on site descriptions as "forest", "savanna" or "shrubland". In total we compiled 63 precipitation manipulation studies (additions, removals, or redistributions) at 70 sites (Table S1), including multi-treatment experiments (e.g., precipitation in combination with warming, etc.), occurring in forest ecosystems (including tall-statured shrublands, savannas, woodlands). For each study, we reviewed the precipitation manipulation project design and methods.

Of the 72 study sites, 69 were included in our methods analysis and reviewed for plot size, replication, buffer zone, trenching, infrastructure control and whether the treatment was "active" or "passive". Three studies were excluded, Hoglwald (Lamersdorf *et al.* 1998) Harderwijk, and Kootwijk (de Visser *et al.* 1994), because they did not report sufficient detail on the experimental design. Statistical analyses calculated from the remaining studies were based on self-reporting (e.g., if a study didn't include information on trenching or a buffer zone, it was assumed that these elements were not included in the experimental design). Plot size was reviewed for 68 of 69 studies, excluding one site (Leuk, Switzerland; (Richter *et al.* 2012)) which did not report plot dimensions.

We also evaluated the precipitation manipulation treatment for each study. Using information reported in the literature, the amount of precipitation excluded (or added) from treatment plots was calculated from changes in mean annual precipitation, changes from annual precipitation (i.e., change from control plots), reported percent exclusion (or addition), or from estimating the amount excluded (or added) from figures. A total of 55 study sites included enough information to estimate the amount of precipitation change. Long term precipitation and potential evapotranspiration (PET) time series from Climate Research Unit (CRU) TS3.22 high resolution gridded datasets (Harris *et al.* 2014) were downloaded for each site using the DroughtNet online precipitation tool: http://shiny-smith.biology.colostate.edu/DroughtNet/WebApps/Temporal_App/. From each time series, precipitation mean and percentiles (1^{st} and 99^{th}) were calculated and used to create the dryness index values (PET/P) for each site under control and treatment conditions. The final figure (Fig 2) includes data from 47 study sites. Additional sites were excluded due to 1) the CRU data was not available, 2) CRU data disagreed more than 30% from the reported mean annual precipitation for the site, or 3) the experiment was a temporal redistribution and did not alter dryness index at an annual time scale. At one site, Dinghushan, China (Chen *et al.* 2015), treatment dryness index value was set to the minimum value on our graph (0.1) as it was a full exclusion (no precipitation) experiment for at least an entire year.

Table S2. Treatment type, study names, locations, forest and manipulation types, and literature citations for the 70 precipitation manipulation experiments evaluated for this review.

Experiment Type	Site name	Study Location	Forest or Shrubland	Manipulation type	Publications
Additions	Barro Colorado Island	Panama, Panama	Forest	Addition	(Yavitt, Wright & Wieder 2004) (Wieder & Wright 1995)
	Cascade mountains	Oregon, United States	Forest	Addition	(Ruehr, Martin & Law 2012) (Ruehr *et al.* 2014)
	Hoglwald	Bavaria, Germany	Forest	Addition	(Lamersdorf *et al.* 1998)
	Pfynwald	Valais, Switzerland	Forest	Addition	(Brunner *et al.* 2009)
	Texas Agricultural Experiment Station La Copita Research Area	Texas, United States	Forest, Shrubland	Addition	(McCulley, Boutton & Archer 2007)
Removals	Ballyhooly Forest	Ireland, United Kingdom	Forest	Removal	(Ryan, O'Toole & Farrell 1998)
	Calabria	Calabria, Italy	Forest	Removal	(Cinnirella *et al.* 2002)
	Castellaneta	Taranto, Italy	Forest	Removal	(Borghetti *et al.* 1998)
	Caxiuanã National Forest	Pará, Brazil	Forest	Removal	(Fisher *et al.* 2007) (da Costa *et al.* 2010)
	Daintree Drought Experiment	Queensland, Australia	Forest	Removal	(Laurance 2015)
	Golfo Dulce Forest Reserve	Puntarenas, Costa Rica	Forest	Removal	(Cleveland *et al.* 2010)
	Hainich	Thuringia, Germany	Forest	Removal	(Felsmann *et al.* 2015) (Gimbel *et al.* 2015) (Baudis *et al.* 2014)
	Harvard Forest	Massachusetts, USA	Forest	Removal	(Borken *et al.* 2006)
	KROOF	Bavaria, Germany	Forest	Removal	(Pretzsch *et al.* 2014)
	La Selva Biological Station	Heredia, Costa Rica	Forest	Removal	(Waring & Hawkes 2014)
	Languedoc–Roussillon gradient	Occitanie, France	Forest	Removal	(Martin-StPaul *et al.* 2013) (Limousin *et al.* 2012)
	Laurentian Moutains	Quebec, Canada	Forest	Removal	(D'Orangeville *et al.* 2013)
	Prades Holm oak forest	Catalonia, Spain	Forest	Removal	(Barbeta, Ogaya & Peñuelas 2013) (Ogaya *et al.* 2011)

	Puéchabon Experimental Forest	Languedoc-Roussillon, France	Forest	Removal	(Misson *et al.* 2011)
	Schorfheide - Chorin	Brandenburg, Germany	Forest	Removal	(Felsmann *et al.* 2015) (Gimbel *et al.* 2015) (Baudis *et al.* 2014)
	Schwabische Alb	Baden-Württemberg, Germany	Forest	Removal	(Felsmann *et al.* 2015) (Gimbel *et al.* 2015) (Baudis *et al.* 2014)
	Sulawesi cacao plantation	Central Sulawesi, Indonesia	Forest	Removal	(van Straaten *et al.* 2010) (Schwendenmann *et al.* 2010)
	Sulawesi throughfall exclusion experiment	Central Sulawesi, Indonesia	Forest	Removal	(Moser *et al.* 2014) (van Straaten, Veldkamp & Corre 2011)
	Tapajós National Forest	Pará, Brazil	Forest	Removal	(Nepstad 2002) (Nepstad *et al.* 2007)
	Turkey Point Flux station	Ontario, Canada	Forest	Removal	(Mackay *et al.* 2012)
	Wombat State Forest	Victoria, Australia	Forest	Removal	(Hinko-Najera *et al.* 2015)
Multiple Treatments	Asa Experiment	Kronoberg, Sweden	Forest	addition, fertilization	(Bergh *et al.* 1999)
	Australian Capital Territory	Australian Capital Territory, Australia	Forest	addition, fertilization	(Linder *et al.* 1987)
	Flakaliden Experiment	Västerbotten, Sweden	Forest	addition, fertilization	(Bergh *et al.* 1999)
	Harderwijk	Gelderland, Netherlands	Forest	addition, fertilization	(de Visser *et al.* 1994)
	Kootwijk	Gelderland, Netherlands	Forest	addition, fertilization	(de Visser *et al.* 1994)
	Monte Rondinaio	Emilia-Romagna, Italy	Shrubland	addition, fertilization	(Brancaleoni *et al.* 2007)
	Mt. Taylor Ranger District	New Mexico, United States	Forest	addition, fertilization	(Gower, Vogt & Grier 1992)
	Ståsan	Dalarna, Sweden	Forest	addition, fertilization	(Axelsson & Axelsson 1986)

	SWECON	Gävleborg, Sweden	Forest	addition, fertilization	(Linder 1987)
	Penn State University	Pennsylvania, United States	Forest	addition, heating	(Rollinson, Kaye & Leites 2012)
	Svalbard	Svalbard, Norway	Shrubland	addition, heating, fertilization	(Wookey *et al.* 1995)
	Abisko Scientific Research Center	Norrbotten, Sweden	Shrubland	addition, heating, fertilization	(Press *et al.* 1998)
	Castanhal	Pará, Brazil	Forest	addition, litter removal	(Vasconcelos *et al.* 2008)
	Coulissenhieb II	Bavaria, Germany	Forest	Redistribution	(Gaul *et al.* 2008) (Muhr & Borken 2009)
	Texas WaRM Experiment	Texas, United States	Savana	redistribution, heating	(Volder, Tjoelker & Briske 2010)
	Dinghushan Biosphere Reserve	Gaungdong Province, China	Forest	removal, addition	Chen et al. (2015)(Chen *et al.* 2015)
	Fife	Scotland, United Kingdom	Forest	removal, addition	(Irvine *et al.* 1998)
	Glowa Jordan River Project	Lahav, Israel	Shrubland	removal, addition	(Sternberg *et al.* 2011)
	Glowa Jordan River Project	Mata, Israel	Shrubland	removal, addition	(Sternberg *et al.* 2011)
	Sevilleta LTER	New Mexico, United States	Forest	removal, addition	(Pangle *et al.* 2012) (Plaut *et al.* 2012) (Gaylord *et al.* 2013)
	Sierra Nevada National Park	Andalusia, Spain	Forest, Shrubland, grass	removal, addition	(Matías, Castro & Zamora 2011)
	Tolfa	Lazio, Italy	Forest	removal, addition	(Cotrufo *et al.* 2011)
	Walker Branch Watershed TDE	Tennessee, United States	Forest	removal, addition	(Hanson *et al.* 1998) (Wullschleger & Hanson 2006)
	Skogaby	Halland, Sweden	Forest	removal, addition	(Cienciala *et al.* 1994)
	Coto Nacional de	Castilla-La	Shrubland	removal,	(Parra *et al.* 2012)

	Quintos de Mora	Mancha, Spain		addition, burning	
	Solling	Hesse, Germany	Forest	removal, addition, chemical composition change	(Bredemeier *et al.* 1998)
	Klosterhede	Region of Southern Denmark, Denmark	Forest	removal, addition, fertilization	(Gundersen *et al.* 1998) (Beier *et al.* 1995)
	Leuk	Valais, Switzerland	Forest	removal, addition, heating	(Richter *et al.* 2012)
	Speuld	Gelderlan, Netherlands	Forest	removal, addition, nutrient removal	(Boxman *et al.* 1995)
	Ysselsteyn	Limburg, Netherlands	Forest	removal, addition, nutrient removal	(Boxman *et al.* 1995)
	Ecological-Botanical Garden, University of Bayreuth	Bavaria, Germany	Shrubland	removal, addition, redistribution	(Kreyling *et al.* 2008) (Jentsch *et al.* 2011)
	Garden Canyon, Fort Huachuca Military Reservation	Arizona, United States	Savana	removal, addition, redistribution	(Weltzin & McPherson 2000)
	Northern Great Basin Experimental Range	Oregon, Untied States	Shrubland	removal, addition, redistribution	(Bates *et al.* 2006) (Svejcar, Angell & Miller 1999)
	Itatinga Experimental Station	São Paulo, Brazil	Forest	removal, fertilization	(Christina *et al.* 2015) (Battie-Laclau *et al.* 2014)
	PINEMAP, FL	Florida, United States	Forest	removal, fertilization	(Will *et al.* 2015)
	PINEMAP, GA	Georgia, United States	Forest	removal, fertilization	(Will *et al.* 2015)
	PINEMAP, OK	Oklahoma, United States	Forest	removal, fertilization	(Will *et al.* 2015)
	PINEMAP, VA	Virginia, United States	Forest	removal, fertilization	(Will *et al.* 2015)
	Achenkirch	Tyrol, Austria	Forest	removal, heating	(Schindlbacher *et al.*

					2012)
	Capo Caccia	Sardinia, Italy	Shrubland	removal, heating	(De Dato *et al.* 2006)
	Clocaenog	Wales, United Kingdom	Shrubland	removal, heating	(Beier *et al.* 2004)
	Garraf	Catalonia, Spain	Shrubland	removal, heating	(Sardans, Peñuelas & Estiarte 2008)
	Kiskunság experimental site	Southern Great Plain, Hungary	Shrubland	removal, heating	(Lellei-Kovács *et al.* 2008)
	Mols	Central Denmark, Denmark	Shrubland	removal, heating	(Beier *et al.* 2004)
	Oldebroek	Gelderland, The Netherlands	Shrubland	removal, heating	(Beier *et al.* 2004)
	CLIMAITE	Capital Region of Denmark, Denmark	Shrubland	removal, heating, elevated CO_2	(Mikkelsen *et al.* 2008)

Table S3. Response metrics for detecting the effects of precipitation manipulation experiments (PMEs) on microclimate, soils, and vegetation. Each variable is assigned one of the following categories: Tier 1: recommended as part of core measurements to be collected for all forest PMEs to facilitate cross-site standardized analyses; Tier 2: measurements that provide additional supporting data to enhance interpretation of PME response with relatively low additional cost and technical complexity and expertise; Tier 3: measurements that allow for more in depth assessment of responses to PMEs, but typically require greater additional cost and technical complexity and expertise.

Parameter & response variable(s)	Method description	Tier 1	Tier 2	Tier 3	References
SITE AND MICROCLIMATE CHARACTERIZATION					
Air temperature	Temperature sensors	X			(Diamond *et al.* 2013; Bell *et al.* 2013, 2015, https://www.ncdc.noaa.gov/crn/publications.html),
Relative humidity	Relative humidity sensors	X			
Solar radiation	Photosynthetically active radiation sensors		X		
Precipitation	Tipping buckets or precipitation gauge	X			
Soil temperature (multiple depths)	Thermometer (point)	X			N/A
	Sensors (continuous)		X		N/A
Soil moisture	Volumetric water content (point measurements)	X			N/A
	Volumetric water content (sensors, continuous)		X		N/A
	Soil water tension (tensiometers)		X		(Cassel & Klute 1986)
	Plant available water (soil water retention curves)			X	(Brady & Weil 2008)
	Relative extractable water		X		(Granier, Loustau & Bréda 2000)
Soil nutrients	Exchangeable cations		X		(Robertson *et al.* 1999a)
	Resin-available N and P		X		(Fisk *et al.* 2014)

Total soil organic C	Volumetric (kg m^{-2} to a standard depth)		X		(Johnson *et al.* 2011; Rau *et al.* 2011)
LEAF LEVEL RESPONSES					
Gas exchange	Stomatal conductance (g_s) and photosynthesis (A)			X	(Long & Bernacchi 2003; Evans & Santiago 2014)
	Water use efficiency			X	(Anyia & Herzog 2004; Yan *et al.* 2011)Anyia and Herzog 2004, Chen et al. 2011
Water potential	$\Psi_{pre\text{-}dawn}$, $\Psi_{midday,}$ Ψ_{daily}		X		(Roman *et al.* 2015)
	Relative water content (Fresh Weight-Dry weight)/(Turgid weight-Dry weight)		X		(Smart & Bingham 1974)
	Water potential at 50% of the maximum stomatal conductance (P50)		X		(Klein 2014)
	$\Psi_{turgor\ loss\ point}$ (pressure-volume curves)			X	(Binks *et al.* 2016)
Photosynthetic capacity	CO_2 assimilation at the saturation light A_{sat}			X	(Kositsup *et al.* 2010)
	J_{max}, V_{cmax}, A_{sat}/R_{dark}			X	(Domingues *et al.* 2010; van de Weg *et al.* 2012)
Photosynthetic apparatus	Chlorophyll and other pigments			X	(Hiscox & Israelstam 1979; Lichtenthaler 1987)
	Fluorescence			X	(Corcuera & Notivol 2015; Sperlich *et al.* 2016)
	Photochemical Reflectance Index (PRI)			X	(Gamon, Peñuelas & Field 1992)
	Photorespiration			X	(Busch 2013)
Functional traits	Specific leaf area		X		(Pérez-Harguindeguy *et al.* 2013)
	Stomatal density & size		X		(Hultine & Marshall 2001)
WHOLE TREE LEVEL RESPONSES					
Stem hydraulic conductivity	$T/\Psi_{pd}\text{-}\Psi_{mid}$			X	(Sperry, Donnelly & Tyree 1988; Wheeler *et al.* 2013)

Hydraulic failure/xylem embolism	Hydraulic vulnerability curve			X	(Trifilò *et al.* 2015)
Aboveground tree growth / C allocation	Stem diameter increment (dendrometers)	X			(Keeland & Sharitz 1993; Deslauriers, Rossi & Anfodillo 2007)
	Tree height	X			(Larjavaara & Muller-Landau 2013)
	Leaf area index	X			(Liu, Jin & Zhou 2016)
	Wood density		X		(Williamson & Wiemann 2010)
	Dendrochronology (tree rings)			X	(Grissino-Mayer 2003; Speer 2010)
	Non-structural carbohydrates			X	(Quentin *et al.* 2015)
Belowground tree growth / C allocation	Standing root biomass		X		(Park *et al.* 2007)
	Shallow fine root production (e.g. to 20cm, at annual or sub-annual resolution)	X			(Tierney & Fahey 2007; Milchunas 2009)
	Allocation to mycorrhizal fungi			X	(Ekblad *et al.* 2013)
Canopy die-back / tree mortality	Visual observations	X			(Schomaker *et al.* 2007)
	Leaf area/leaf area index	X			(Liu *et al.* 2016)
Water use efficiency	Stable isotopes in tree rings ($\delta^{13}C$ and $\delta^{18}O$; c_i/c_a)			X	(McCarroll & Loader 2004; Gessler *et al.* 2014)
Hydraulic system	Wood anatomy		X		(Hacke *et al.* 2001; Scholz *et al.* 2013)
	Hydraulic conductivity and embolism (P50)		X		(Cochard *et al.* 2013)
	Leaf area:sapwood area ratio			X	(Vertessy *et al.* 1995)
Transpiration	Sap flow		X		(Granier 1985; Burgess *et al.* 2001; Steppe *et al.* 2010)
Source of water uptake (effective rooting depth)	Stable isotopes of water in soil and plant stem tissue ($\delta^{18}O$-δH)			X	(Dawson *et al.* 2002)
Canopy phenology	Bud break, shoot extension, flowering, senescence	X			(Denny *et al.* 2014; Elmendorf *et al.* 2016)
ECOSYSTEM SCALE RESPONSES					

Productivity / carbon balance	Annual aboveground biomass	X			(Kloeppel, Harmon & Fahey 2007)
	Litterfall	X			(Kloeppel, Harmon & Fahey 2007)
	Soil respiration		X		(Davidson *et al.* 2002)
	Herbivory, foliar pathogens		X		(Coley 1983)
	Stem respiration			X	(Hilman & Angert 2016)
Water balance	Transpiration		X		(Ewers *et al.* 2008; Hernandez-Santana *et al.* 2015)
	Throughfall		X		(Levia & Frost 2006)
	Stemflow		X		(Levia & Frost 2003)
	Runoff / infiltration		X		(Gerrits & Savenije 2011)
Biogeochemical cycling	Litterfall (nutrient fluxes)			X	(See *et al.* 2015)
	Decomposition (nutrient fluxes)		X		(Bärlocher 2007; Keuskamp *et al.* 2013)
	Soil N mineralization (In-situ N mineralization (monthly)		X		(Hart *et al.* 1994; Robertson *et al.* 1999b)
	Soil microbial dynamics - Biomass: chloroform fumigation, PLFA) - Community structure (High throughput sequencing)			X X	(Vance, Brookes & Jenkinson 1987; Baldrian *et al.* 2013) (Fierer *et al.* 2012; Morrison *et al.* 2016)
	Foliar nutrient uptake			X	(Fahey & Birk 1991)
	Foliar nutrient retranslocation / absorption			X	(Fahey & Birk 1991)
	Leaching / runoff losses			X	(Abdulkareem, Abdulkadir & Abdu 2015)
Demography	Tree mortality	X			(Doughty *et al.* 2015)
	Seedling recruitment		X		(Lloret, Penuelas & Ogaya 2004; Matías,

					Zamora & Castro 2012)
Soil microbial dynamics	Biomass (chloroform fumigation, PLFA)			X	(Vance, Brookes & Jenkinson 1987; Baldrian *et al.* 2013)
	Community structure (High throughput sequencing)			X	(Fierer *et al.* 2012; Morrison *et al.* 2016)

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