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OPINION

Pushing precipitation to the extremes in distributed experiments: recommendations for simulating wet and dry years

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Abstract

Intensification of the global hydrological cycle, ranging from larger individual precipitation events to more extreme multiyear droughts, has the potential to cause widespread alterations in ecosystem structure and function. With evidence that the incidence of extreme precipitation years (defined statistically from historical precipitation records) is increasing, there is a clear need to identify ecosystems that are most vulnerable to these changes and understand why some ecosystems are more sensitive to extremes than others. To date, opportunistic studies of naturally occurring extreme precipitation years, combined with results from a relatively small number of experiments, have provided limited mechanistic understanding of differences in ecosystem sensitivity, suggesting that new approaches are needed. Coordinated distributed experiments (CDEs) arrayed across multiple ecosystem types and focused on water can enhance our understanding of differential ecosystem sensitivity to precipitation extremes, but there are many design challenges to overcome (e.g., cost, comparability, standardization). Here, we evaluate contemporary experimental approaches for manipulating precipitation under field conditions to inform the design of 'Drought-Net', a relatively low-cost CDE that simulates extreme precipitation years. A common method for imposing both dry and wet years is to alter each ambient precipitation event. We endorse this approach for imposing extreme precipitation years because it simultaneously alters other precipitation characteristics (i.e., event size) consistent with natural precipitation patterns. However, we do not advocate applying identical treatment levels at all sites – a common approach to standardization in CDEs. This is because precipitation variability varies >fivefold globally resulting in a wide range of ecosystem-specific thresholds for defining extreme precipitation years. For CDEs focused on precipitation extremes, treatments should be based on each site's past climatic characteristics. This approach, though not often used by ecologists, allows ecological responses to be directly compared across disparate ecosystems and climates, facilitating process-level understanding of ecosystem sensitivity to precipitation extremes.

Keywords: climate extremes, drought, field experiments, precipitation regimes, wet years

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Introduction

Global climate models forecast a future with more frequent large precipitation events, extended dry periods, and an increase in extreme wet *and* dry years (Seneviratne *et al*., 2012; Fischer *et al*., 2013; IPCC, 2013; Singh *et al*., 2013). Indeed, recent trends in precipitation have been consistent with this expected intensification of the global hydrological cycle (Frich *et al*., 2002; Trenberth *et al*., 2003; Groisman *et al*., 2005; Huntington, 2006; Marvel & Bonfils, 2013; Donat *et al*., 2016). Extreme precipitation years have been linked to local-scale increases in exotic species (Concilio *et al*., 2015), regional-scale mortality in forests (Breshears *et al*., 2005), and carbon cycle anomalies with global implications (Reichstein *et al*., 2013; Zscheischler *et al*., 2014a, b; Ahlström *et al*., 2015; Ruppert *et al*., 2015; Haverd *et al*., 2016). However, because extreme precipitation periods are by definition statistically rare (i.e., as those years exceeding 1st to 10th percentile thresholds based on historical records; Easterling *et al*., 2000; Jentsch, 2006; Jentsch *et al*., 2007; Smith, 2011a; Knapp *et al*., 2015), our understanding of the mechanisms underlying ecological responses and feedbacks to climate extremes is quite limited (Smith, 2011b; Reichstein *et al*., 2013; Kayler *et al*., 2015). Furthermore, because natural climate extremes tend to be especially well studied when substantial ecological consequences are evident, our perception of ecosystem responses to climate extremes may be biased toward extreme ecological responses (Smith, 2011b). Indeed, results from a limited number of field experiments that simulate climate extremes suggest that ecosystem sensitivity can vary substantially, with some types of climate extremes causing relatively minor ecological responses and some ecosystems surprisingly unresponsive to short-term and even multiyear periods of climate extremes (De Boeck *et al*., 2011; Jentsch *et al*., 2011; Smith, 2011b; Collins *et al*., 2012; Hoover *et al*., 2014; Tielbörger *et al*., 2014). While experiments are critical for identifying mechanisms underlying ecological responses (Smith, 2011a; Beier *et al*., 2012; Reichstein *et al*., 2013), most climate extremes experiments (and most global change experiments in general, Knapp *et al*., 2012) are conducted with unique approaches and methods, making it a challenge to determine whether apparent differences in sensitivity to climate extremes are due to different methodologies or from differences in key ecosystem attributes (Smith, 2011b). This has prompted multiple calls for ecologists to move beyond conducting unique, local-scale studies and initiate multisite (and multibiome), coordinated experiments that impose comparable treatments and measure common response variables across all sites (Beier *et al*., 2004, 2012; Smith *et al*., 2009; Luo *et al*., 2011; Smith, 2011b; Knapp *et al*., 2012; Vicca *et al*., 2012; Fraser *et al*., 2013, 2015). Such networked experiments (*sensu* the Nutrient Network; Borer *et al*., 2014) have the potential to be especially important for understanding the mechanisms underlying differential ecosystem sensitivity to climate extremes given how infrequently these climatic periods occur naturally (Smith, 2011a; Knapp *et al*., 2015).

Designing coordinated distributed experiments (CDEs) focused on climate can be challenging from a logistical as well as a scientific perspective. Logistically, it can be a significant challenge to keep costs of climate manipulation infrastructure low, maintenance minimal, and sampling expectations reasonable (Marion *et al*., 1997; Fraser *et al*., 2013). Nonetheless, such attributes are keys for (i) including experimental sites that are remote and difficult to access and (ii) enabling broad participation and collaboration among scientists in both developed and developing countries (Fraser *et al*., 2013; Borer *et al*., 2014). The latter is particularly important for increasing the geographic coverage of CDEs beyond North America and Europe and reducing biases associated with experiments largely restricted to certain biomes (Beier *et al*., 2012; Fraser *et al*., 2013).

From a scientific point of view, designing a network of experiments focused on assessing ecosystem sensitivity to extreme wet or dry years across a range of ecosystem types (e.g., deserts, grasslands, shrublands, forests) poses additional and unique challenges, particularly with imposing treatments that represent extreme years for all sites. In the analyses below, we focus on the dual challenge of determining and implementing treatments to simulate extreme precipitation years in CDEs that can (i) be imposed with a relatively simple and low-cost approach, and (ii) facilitate comparisons of responses across diverse ecosystems to identify mechanisms underlying differential sensitivity. Such analyses are timely given that Drought-Net (http://www.drought-net.org/), a CDE, focused on extreme drought is in its initial stage of implementation. We begin by reviewing how ecologists currently manipulate precipitation under field conditions and assess the merits of these approaches for imposing extreme wet and dry years in distributed experiments. We then consider an approach that best meets the attributes of successful CDEs (Fraser *et al*., 2013) and evaluate how well such an approach captures key precipitation attributes, besides amount, of historically extreme wet and dry years (Knapp *et al*., 2015).

Contemporary approaches for manipulating precipitation in field experiments

We conducted a literature review (Web of Science, Thomson Reuters, Manhattan, NY, USA) of peer-reviewed studies that reported results from experiments that either increased and/or reduced precipitation amount under field conditions (agricultural systems excluded). We restricted our analysis to papers published from 2006 to 2015 to provide a contemporary view of the most common approaches used by ecologists. From the 596 papers returned from a keyword search combining 'precipitation', 'drought', 'experiment', and 'ecosystem', we excluded model simulation studies, reviews, meta-analyses, and experiments that manipulated precipitation pattern but not amount. In the remaining 257 papers, we first categorized experiments according to how precipitation was manipulated (manipulation type: *passive* = no energy input required to manipulate precipitation amount beyond the initial deployment of infrastructure vs. *active* = energy required to alter precipitation amount during the experimental period). We then focused on the rationale investigators used for selecting precipitation treatments by categorizing experiments into three broad treatment goals. These goals were as follows: (i) to alter precipitation by an *absolute* amount (e.g., + or −200 mm), (ii) to impose a *relative* change in precipitation (e.g., + or −40% of ambient precipitation), or (iii) to *match* treatments to a target level of precipitation based on historical records or a future expected scenario (see Fig. 1 legend for more details). Finally, we determined the type of ecosystem manipulated for each experiment and grouped these based on a modified Whittaker biome classification system (Whittaker, 1975).

We found that the approaches currently used by ecologists to alter precipitation under field conditions differ considerably between experiments that simulate periods of increased vs. decreased precipitation. For example, ~88% of experiments that increased precipitation used an active approach whereas ~72% of those that reduced precipitation did so passively (Fig. 1). While techniques for increasing precipitation inputs were quite variable among experiments, most experiments imposing passive reductions in precipitation used some form of the rainfall shelters originally designed by Yahdjian & Sala (2002) or a throughfall displacement (TDE) approach (e.g., Wullschleger & Hanson, 2006). With these shelters and the TDE approach, each rainfall event is reduced by a constant proportion.

Differences between precipitation addition vs. reduction experiments also were noted when considering treatment goals (absolute, relative, or matched to a target level). Treatments designed to simulate periods with increased precipitation most commonly (~64%) added a fixed or absolute amount of precipitation above ambient or the long-term mean, whereas experiments that decreased precipitation most often (~94%) imposed treatments based on proportional or relative

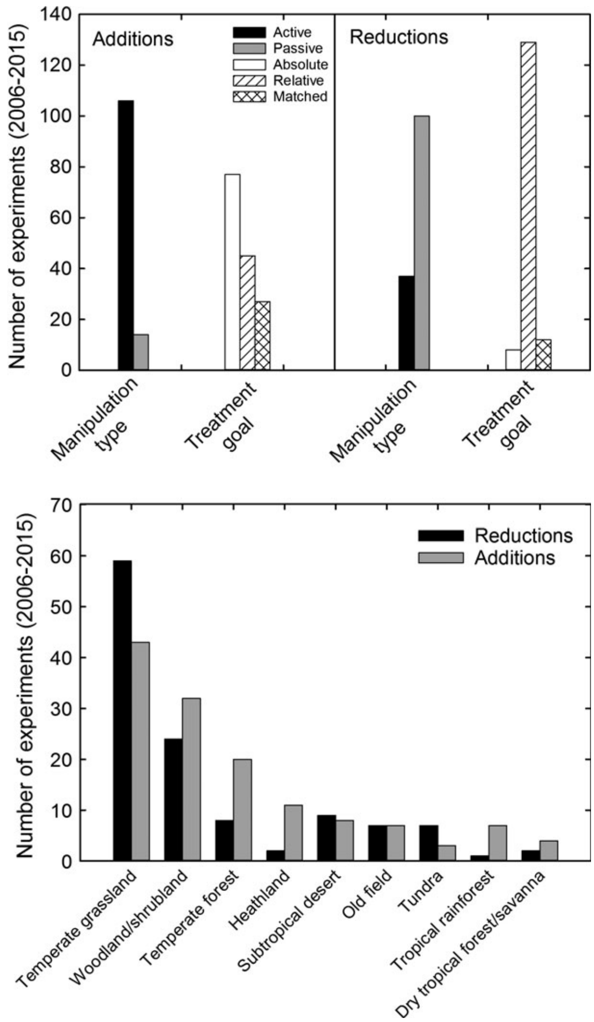

Fig. 1 Summary of how and where ecologists have conducted precipitation manipulation experiments based on a Web of Science search of papers published during 2006–2015. Precipitation addition and reduction experiments were assessed separately. Top: experiments categorized based on the type of manipulation (*passive* = no energy input required to manipulate precipitation amount or *active* = energy required to alter precipitation amount during the experimental period) and the goal of the treatment (to alter precipitation by an *absolute* amount, a *relative* or proportional amount, or to *match* the precipitation treatment to an IPCC scenario or statistical target). Bottom: precipitation reduction and addition experiments summarized according to the types of ecosystems in which they have been conducted. Ecosystem types with less than three experiments are not included. A Boolean search using the key words 'precipitation', 'drought', 'experiment', and 'ecosystem' was used to identify the 257 experiments summarized. Note that when a paper reported results from a study that both increased and decreased precipitation, these were counted as two experiments since often the approach used to implement these treatments differed. Moreover, some long-term experiments were included more than once when papers were published based on different periods of data collection.

reductions in ambient precipitation amounts (Fig. 1). Treatments designed to match a particular past or future scenario (e.g., IPCC 2013) or a statistical target for precipitation change were relatively uncommon regardless of whether precipitation was increased (22%) or decreased (8%). Combined, this diversity in approaches for how precipitation is altered and the varied rationale for determining treatment levels highlights the challenge of synthesizing results from these experiments (Jentsch *et al.*, 2007; Fraser *et al.*, 2013).

There was also substantial variation among biomes in the type of precipitation experiments conducted (Fig. 1, see also Beier *et al.*, 2012). As expected, short-statured (temperate grassland) biomes were home to the greatest number of precipitation manipulation experiments over the last 10 years, with far fewer experiments conducted in forests. There was also a clear pattern of biomes dominated by woody species hosting many more precipitation addition than reduction experiments, with the opposite true in grassland and tundra biomes (Fig. 1). Whether these patterns are driven by logistical challenges (it is difficult and expensive to reduce precipitation inputs from forests, Wullschleger & Hanson, 2006) or ecological relevance (droughts are widely considered a key driver of grassland dynamics, Sala *et al.*, 2012) is difficult to determine. Regardless, the unequal coverage of biomes with respect to precipitation experiments underscores the need for designing CDEs that can be deployed in multiple ecosystem types, particularly in geographic regions underrepresented by past experiments (Beier *et al.*, 2012).

Simulating extreme precipitation years in distributed experiments

Identifying mechanisms underlying differential ecosystem sensitivity to extreme wet or dry years requires careful consideration of treatment levels and how they are selected. Past CDEs have used standardized or fixed treatments across all sites based on the argument that 'the power of a distributed experiment lies in identical replication of treatments' (Borer *et al.*, 2014). We do not recommend this approach for a CDE focused on assessing ecosystem sensitivity to extreme precipitation years. This is because an extreme year is defined statistically and is contingent on historical precipitation variability (Jentsch, 2006). However, interannual variability in annual precipitation varies substantially (fivefold) over the globe (Knapp & Smith, 2001; Davidowitz, 2002), and as a result, the statistical thresholds for defining an extreme wet or dry year also differ dramatically among sites. For example, Knapp *et al.* (2015) analyzed >1600 long-term (100-year) precipitation records from sites distributed globally and reported that the deviation from mean annual precipitation (MAP) necessary to achieve a statistically extreme dry year varied on average between −30% and −70%, with xeric regions requiring greater deviations than mesic regions. Greater variation was observed when determining the increase in precipitation required to achieve a statistically extreme wet year (ranging from +40% for sites with high MAP to +150% for arid sites, Fig. 2). Even among sites with similar MAP, substantial variation in the precipitation anomalies necessary to achieve extreme precipitation years was evident (Knapp *et al.*, 2015). For example, in more arid regions (MAP <500 mm) some sites required only a 25% reduction from MAP to achieve a statistically extreme dry year whereas a 75% reduction was necessary in other sites, reflecting a wide range in historic precipitation variability among sites, even in arid biomes (Davidowitz, 2002). Thus, a CDE that reduced precipitation by a fixed or standardized amount for all sites (for example −40%) would be inappropriate for comparing ecosystem responses and inferring sensitivity to extreme drought because this treatment would be statistically extreme for some sites but not others (Fig. 2).

To insure that all sites in a CDE are experiencing extreme precipitation increases or decreases to a comparable degree, we recommend that treatment levels are matched to historical levels of precipitation variability for each site. This philosophy of selecting treatments to match site-based criteria has been employed infrequently for precipitation manipulation experiments (Fig. 1). However, among other multisite global change experiments, matching treatments to a target, such as specific IPCC scenarios, is more common. For example, treatments in most FACE sites targeted ~ 550 μmol mol^{-1} CO_2 (Leakey *et al.*, 2009) and the International Tundra Experiment warmed plots by ~2 °C across a large number of high latitude sites to match IPCC projections (Arft *et al.*, 1999). In these cases, future increases in CO_2 and temperature were not expected to vary substantially among sites, thus imposing identical treatments matched to a common target was justified. Adopting a site-specific approach for imposing extreme precipitation treatments is a significant departure from contemporary experimental designs of CDEs and for previous precipitation experiments (Fig. 1). But such a departure is necessary to ensure that comparably extreme levels of precipitation are imposed at all sites (Fig. 2). Fortunately, web tools are available to quantify site-specific statistically extreme precipitation levels based on historical records or interpolated data for terrestrial

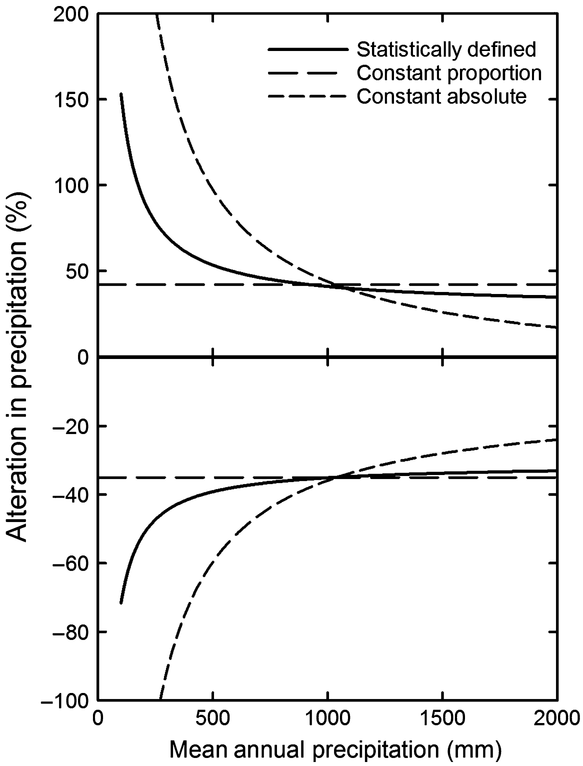

Fig. 2 Comparison of three approaches for determining precipitation treatment levels in an experiment distributed across sites that vary in mean annual precipitation (MAP). The solid line depicts how much precipitation must be increased or decreased (on average across sites) to achieve a statistically defined extreme precipitation year based on historical precipitation records (for this example extreme is ≤10th or ≥90th percentile; Knapp *et al*., 2015). Note that to achieve an extreme wet (top) or dry (bottom) year, the mean deviation from average precipitation increases as mean annual precipitation (MAP) decreases. This is because, in general, interannual variability in precipitation increases in more arid regions, and thus, the thresholds required to achieve statistical extremity also increase. The dashed lines show how treatments based on altering precipitation amount by either a constant absolute or proportional amount compares to that necessary to achieve a statistically extreme wet or dry year. Curves depicting the impact of these types of treatments are based on determining the value for each that achieved a statistically extreme wet or dry year at 1000-mm MAP and maintaining these treatment levels constant across the MAP gradient. Note that standardizing treatments across all sites, either as an absolute or proportional amount of precipitation added or removed, results in treatments that are not comparably extreme among sites. This is particularly true in more arid regions where identical treatment levels based on proportional or absolute changes substantially under- or overshoot actual extreme levels, respectively.

sites across the globe (Lemoine *et al*., 2016); thus, treatment levels needed to impose comparable levels of precipitation extremity can be easily determined for most terrestrial ecosystems included in a CDE.

Imposing extreme precipitation amounts

As noted earlier, to maximize participation and geographic coverage of a CDE focused on ecosystem responses to extreme precipitation years, logistically simple and relatively low-cost experimental infrastructure is needed. While our literature review revealed a great diversity of techniques for altering precipitation inputs under field conditions, the most commonly used approach was originally designed by Yahdjian & Sala (2002) to passively reduce precipitation inputs into modestly sized plots (Fig. 1). This low-cost, low maintenance shelter infrastructure consists of a roof with strips of transparent plastic evenly spaced to intercept a proportion of each precipitation event. The amount of precipitation removed by the roof is thus determined by the density of strips and the proportional area they cover. Detailed analyses indicate that the roof suspended over treatment plots only minimally affects key environmental variables such as temperature and light (Yahdjian & Sala, 2002). This passive approach, though frequently modified for site-specific applications, is widely used in many types of ecosystems and has even been scaled up and deployed below the tree canopy in forests to displace throughfall (Wullschleger & Hanson, 2006; Nepstad *et al*., 2007; da Costa *et al*., 2010; Pangle *et al*., 2015). Recently, Gherardi & Sala (2013) expanded the capabilities of this infrastructure by coupling precipitation reduction treatments with addition treatments as part of an automated rainfall manipulation system (ARMS). With this system, precipitation intercepted from one plot is transferred to an adjacent plot with a solar-powered pump, permitting extreme wet and dry treatments to be imposed concurrently. Although originally designed for symmetrical treatments (i.e., −50%, +50%), unequal addition and removal treatments (i.e., −50%, +30%) can also be achieved by either applying only a portion of the intercepted precipitation to the addition plot or using a larger roof to capture additional precipitation to transfer. Importantly, the ARMS was designed to be relatively low cost (depending on the ecosystem type) with minimal electrical demands met by solar cells (Gherardi & Sala, 2013); hence, the general design fits the cost criterion of Fraser *et al*. (2013) for designing a successful CDE.

Can experiments simulate other important attributes of extreme precipitation years?

Extreme wet and dry years differ from each other by more than just precipitation amount (Knapp *et al*., 2015). For example, dry years are usually warmer and have higher radiation inputs than average years (De Boeck *et al.*, 2011; Beier *et al.*, 2012). In addition, in most major terrestrial ecosystems, extreme wet years can be distinguished by the presence of several large (statistically extreme) daily precipitation events; these are lacking in extreme dry years (Knapp *et al.*, 2015). Wet years also have larger average event sizes and more precipitation events than dry years. In contrast, extreme dry years primarily differ from average precipitation years by an increase in the number of dry days between precipitation events (Knapp *et al.*, 2015). While the precipitation manipulation infrastructure described above (Yahdjian & Sala, 2002; Gherardii & Sala, 2103) was not designed to influence temperature, it is important to ensure that this approach realistically alters other key precipitation attributes besides amount. This is particularly true given the growing number of studies indicating that event size, number, seasonality, and the length of dry periods can all significantly influence ecosystem function independent of amount (Knapp *et al.*, 2002, 2008; Heisler-White *et al.*, 2009; Thomey *et al.*, 2011; Beier *et al.*, 2012; Raz-Yaseef *et al.*, 2012; Walter *et al.*, 2012; Coe & Sparks, 2014; Grant *et al.*, 2014; Zeppel *et al.*, 2014; Wilcox *et al.*, 2015).

We evaluated how realistically precipitation patterns are altered by the ARMS infrastructure (Gherardi & Sala, 2013) by simulating changes in five important precipitation attributes when precipitation is increased or decreased to extreme levels with this approach. These attributes were as follows: the number of extreme (99th percentile) precipitation events, the average event size, the number of precipitation events, the number of extreme (95th percentile) periods of consecutive dry days (a dry day was defined as one with <0.3 mm of recorded precipitation), and the average length of dry periods. For three locations representing very different climates and ecosystem types (desert grassland in New Mexico, USA, mesic grassland in Kansas, USA, and temperate forest in Massachusetts, USA), we calculated a probability distribution based on 100-year historical precipitation records and categorized years as average (45th–55th percentile), extreme wet (>90th percentile), and extreme dry (<10th percentile; see Knapp *et al.*, 2015 for additional details). For each of these three types of years, we calculated each of the five precipitation attributes above from daily precipitation records at the sites. We then simulated treatments imposed by ARMS by manipulating daily precipitation regimes for each average year by (i) removing a proportion of each precipitation event to simulate a statistically extreme dry year and (ii) increasing each daily event by the proportion necessary to achieve a statistically extreme wet year. Precipitation attribute data (the five attributes considered collectively) for average, extreme wet, and dry years as well as simulated extreme wet and dry years were visualized with metaMDS (Fig. 3), and differences between simulated rainfall patterns and actual rainfall patterns were assessed using the VEGAN package in R (Oksanen *et al.*, 2014). To test for differences among centroid means, we ran PERMANOVA using the adonis function.

Results from this simulation (Fig. 3) indicate that the simulated extreme dry years were indistinguishable from actual extreme dry years in the forest ($P = 0.155$) and grassland sites ($P = 0.103$) and differed only slightly at the desert site ($P = 0.039$). Simulated extreme wet years differed more in multivariate space from actual extreme wet years (only in the forest site were they not significantly different, $P = 0.088$), but in all cases, these five precipitation attributes collectively were more similar to extreme wet than average years. This matching of attributes between simulated vs. actual extreme wet or dry years occurred because the ARMS approach altered most (but not all) precipitation attributes in ways that are similar to patterns observed during actual extreme precipitation years. For example, the ARMS approach increased the number of large (extreme) precipitation events and event size (but not event number) for simulated extreme wet years. In contrast, the ARMS eliminated extreme large events while decreasing event size and increasing the length of dry periods between events for simulated extreme dry years. The latter occurred because very small daily events were reduced below the 0.3 mm threshold (see Knapp *et al.*, 2015), and thus, these effectively became dry days. Overall, our analyses suggest that the ARMS approach is effective at simulating extreme dry and wet years across a broad range of ecosystem types. Although more labor- and energy-intensive experimental approaches would provide complete control over the timing and size of each precipitation event, more effectively capturing all attributes of actual extreme years, such approaches would not meet the low-cost, low maintenance criteria for successful CDEs (Fraser *et al.*, 2013).

Conclusions

The potential for increases in climatic extremes to alter ecosystem structure and function is well recognized, with impacts that may exceed gradual changes in means (Smith, 2011a). Extreme wet and dry years are defined statistically based on historical precipitation records, and this historical perspective is particularly important given that extreme climatic periods can drive strong directional selection over evolutionary time scales, determining the traits found in plant

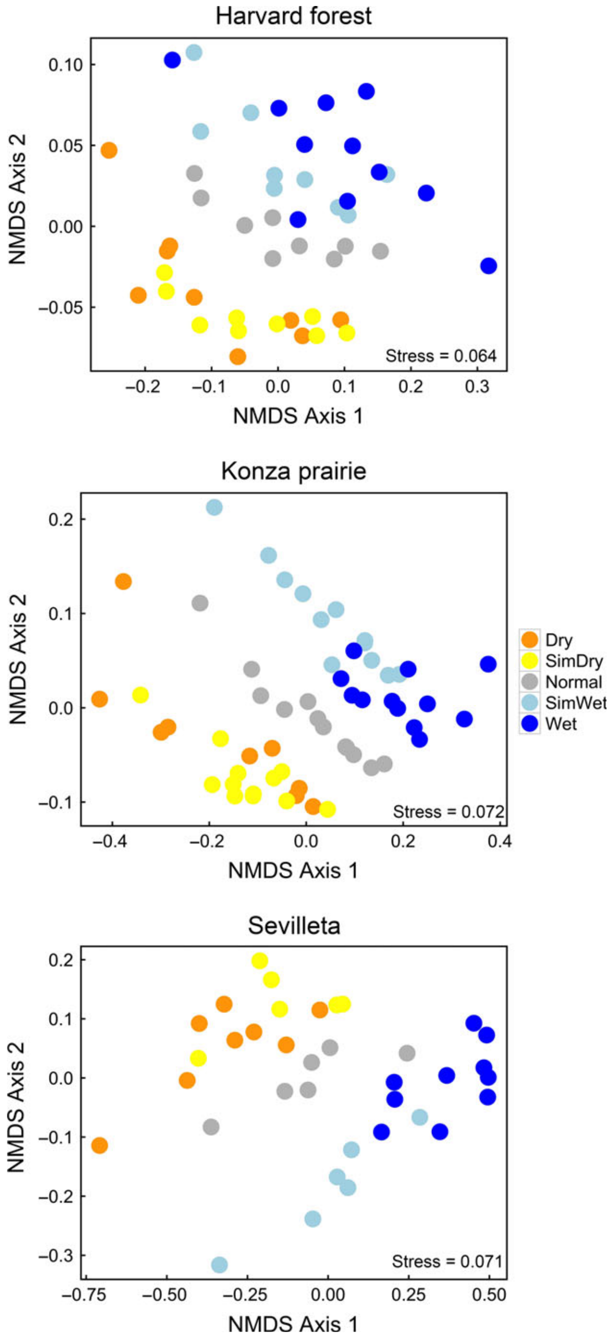

Fig. 3 Multidimensional scaling analysis of the impact of simulating extreme dry and wet years using ARMS (Gherardi & Sala, 2013) on five precipitation regime attributes: average precipitation event size, the number of precipitation events, the average length of dry periods between events (a dry day = <0.3 mm of precipitation), the number of extremely large (99th percentile) precipitation events, and the number of extremely long (95th percentile) periods of consecutive dry days (see Knapp *et al.*, 2015 for more detail). Simulations were performed in three ecosystem types selected to span a wide range of mean annual precipitation levels in the United States (NE Deciduous forest in Massachusetts, central mesic grassland in Kansas, and SW desert grassland in New Mexico). Dry years were simulated by removing a fixed proportion of each precipitation event by the amount necessary to reduce precipitation in normal years to a statistically extreme level. Extreme wet years were simulated by increasing by a constant proportion each precipitation event from normal years. Precipitation attributes from actual extreme dry, wet, and normal years are shown as well. PERMANOVA indicated that there were overall significant differences among groups ($P < 0.001$) for all sites.

communities and influencing ecosystem function (Gutschick & BassiriRad, 2003). But there is tremendous variability globally in where and how often extreme responses in ecosystem function occur (Xiao *et al.*, 2016). Consequently, there is a clear need for coordinated distributed experiments (CDEs) focused on (i) identifying which types of ecosystems are most vulnerable to climate extremes and (ii) understanding why some ecosystems are more sensitive to extremes than others.

Based on our analysis above, we offer two recommendations for the design of extreme precipitation CDEs. First, contrary to most multisite experiments we recommend that treatment levels vary among sites, reflecting differences in historical precipitation variability. Thus, to impose comparably extreme precipitation treatments at all sites in a CDE, ecosystems with higher historical precipitation variability will require alterations in precipitation that exceed those in ecosystems that have experienced less precipitation variability. Experimental designs that include ecosystem-specific treatments matched to a target (e.g., a 1-in-100-year precipitation amount) are not commonly used by ecologists. But this approach is critical for climatic extremes experiments to assess differential sensitivity across multiple ecosystems. Second, given recent recognition of the important role of other precipitation attributes (e.g., event size, event number, event seasonality, and the duration of dry periods between events) for ecosystem functioning, it is imperative that CDEs simulate extreme precipitation years in ways that alter these variables in a manner consistent with patterns observed in naturally occurring wet and dry years. Fortunately, relatively low-cost experimental infrastructure capable of altering precipitation amount *and* pattern in realistic ways already exists (Yahdjian & Sala, 2002; Gherardi & Sala, 2013). If other approaches for manipulating precipitation amount are used, we recommend that concurrent changes in key precipitation attributes are also assessed (see Fig. 3) to ensure that 'hidden treatments' are not influencing ecological responses. We hope our analyses and recommendations facilitate the design of a new generation of CDEs (such as Drought-Net) focused on manipulating extremes in precipitation. Such experiments will enable ecologists to better understand how and why ecosystems differ in their sensitivity to extremes in precipitation as well as help identify underlying mechanisms. The latter are urgently needed given forecasts for intensification of precipitation regimes globally.

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References

Ahlström A, Raupach MR, Schurgers G *et al.* (2015) The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink. *Science*, **348**, 895–899.

Arft AM, Walker MD, Gurevitch J *et al.* (1999) Responses of tundra plants to experimental warming: meta-analysis of the international tundra experiment. *Ecological Monographs*, **69**, 491–511.

Beier C, Emmett B, Gundersen P *et al.* (2004) Novel approaches to study climate change effects on terrestrial ecosystems in the field - drought and passive night time warming. *Ecosystems*, **7**, 583–597.

Beier C, Beierkuhnlein C, Wohlgemuth T *et al.* (2012) Precipitation manipulation experiments—challenges and recommendations for the future. *Ecology Letters*, **15**, 899–911.

Borer ET, Harpole WS, Adler PB, Lind EM, Orrock JL, Seabloom EW, Smith MD (2014) Finding generality in ecology: a model for globally distributed experiments. *Methods in Ecology and Evolution*, **5**, 65–73.

Breshears DD, Cobb NS, Rich PM *et al.* (2005) Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, **102**, 15144–15148.

Coe KK, Sparks JP (2014) Physiology-based prognostic modeling of the influence of changes in precipitation on a keystone dryland plant species. *Oecologia*, **176**, 933–942.

Collins SL, Koerner SE, Plaut JA *et al.* (2012) Stability of tallgrass prairie during a 19-year increase in growing season precipitation. *Functional Ecology*, **26**, 1450–1459.

Concilio AL, Prevéy JS, Omasta P, O'Connor J, Nippert JB, Seastedt TR (2015) Response of a mixed grass prairie to an extreme precipitation event. *Ecosphere*, **6**, 1–12.

da Costa ACL, Galbraith D, Almeida S *et al.* (2010) Effect of 7 year of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist*, **187**, 579–591.

Davidowitz G (2002) Does precipitation variability increase from mesic to xeric biomes? *Global Ecology and Biogeography*, **11**, 143–154.

De Boeck HJ, Dreesen FE, Janssens IA, Nijs I (2011) Whole-system responses of experimental plant communities to climate extremes imposed in different seasons. *New Phytologist*, **189**, 806–817.

Donat MG, Lowry AL, Alexander LV, O'Gorman PA, Maher N (2016) More extreme precipitation in the world's dry and wet regions. *Nature Climate Change*, **6**, 508–513.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. *Science*, **289**, 2068–2074.

Fischer EM, Beyerle U, Knutti R (2013) Robust spatially aggregated projections of climate extremes. *Nature Climate Change*, **3**, 1033–1038.

Fraser LH, Henry HA, Carlyle CN *et al.* (2013) Coordinated distributed experiments: an emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment*, **11**, 147–155.

Fraser LH, Pither J, Jentsch A *et al.* (2015) Worldwide evidence supporting the unimodal relationship between productivity and plant species richness. *Science*, **349**, 302–305.

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein Tank AMG, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, **19**, 193–212.

Gherardi LA, Sala OE (2013) Automated rainfall manipulation system: a reliable and inexpensive tool for ecologists. *Ecosphere*, **4**, 1–10.

Grant K, Kreyling J, Dienstbach LF, Beierkuhnlein C, Jentsch A (2014) Water stress due to increased intra-annual precipitation variability reduced forage yield but raised forage quality of a temperate grassland. *Agriculture, Ecosystems and the Environment*, **186**, 11–22.

Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, Razuvaev VN (2005) Trends in intense precipitation in the climate record. *Journal of Climate*, **18**, 1326–1350.

Gutschick VP, BassiriRad H (2003) Extreme events as shaping physiology, ecology, and evolution of plants: toward a unified definition and evaluation of their consequences. *New Phytologist*, **160**, 21–42.

Haverd V, Smith B, Trudinger C (2016) Dryland vegetation response to wet episode, not inherent shift in sensitivity to rainfall, behind Australia's role in 2011 global carbon sink anomaly. *Global Change Biology*, **22**, 2315–2316.

Heisler-White JL, Blair JM, Kelly EF, Harmoney K, Knapp AK (2009) Contingent productivity responses to more extreme rainfall regimes across a grassland biome. *Global Change Biology*, **15**, 2894–2904.

Hoover DL, Knapp AK, Smith MD (2014) Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology*, **95**, 2646–2656.

Huntington TG (2006) Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology*, **319**, 83–95.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qing D, Plattner G-K *et al.*), 1535 pp. Cambridge University Press, Cambridge, UK.

Jentsch A (2006) Extreme climatic events in ecological research. *Frontiers in Ecology and the Environment*, **4**, 235–236.

Jentsch A, Kreyling J, Beierkuhnlein C (2007) A new generation of climate-change experiments: events, not trends. *Frontiers in Ecology and the Environment*, **5**, 365–374.

Jentsch A, Kreyling J, Elmer M *et al.* (2011) Climate extremes initiate ecosystem-regulating functions while maintaining productivity. *Journal of Ecology*, **99**, 689–702.

Kayler ZE, De Boeck HJ, Fatichi S *et al.* (2015) Experiments to confront the environmental extremes of climate change. *Frontiers in Ecology and the Environment*, **13**, 219–225.

Knapp AK, Smith MD (2001) Variation among biomes in temporal dynamics of aboveground primary production. *Science*, **291**, 481–484.

Knapp AK, Fay PA, Blair JM *et al.* (2002) Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. *Science*, **298**, 2202–2205.

Knapp AK, Beier C, Briske DD *et al.* (2008) Consequences of more extreme precipitation regimes for terrestrial ecosystems. *BioScience*, **58**, 811–821.

Knapp AK, Smith MD, Hobbie SE *et al.* (2012) Past, present and future roles of long-term experiments in the LTER Network. *BioScience*, **62**, 377–389.

Knapp AK, Hoover DL, Wilcox KR *et al.* (2015) Characterizing differences in precipitation regimes of extreme wet and dry years: implications for climate change experiments. *Global Change Biology*, **21**, 2624–2633.

Leakey AD, Ainsworth EA, Bernacchi CJ, Rogers A, Long SP, Ort DR (2009) Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany*, **60**, 2859–2876.

Lemoine NP, Sheffield J, Dukes JS, Knapp AK, Smith MD (2016) Terrestrial Precipitation Analysis (TPA): a resource for characterizing long-term precipitation regimes and extremes. *Methods in Ecology and Evolution*, **7**, doi:10.1111/2041-210X.12582.

Luo Y, Melillo J, Niu S *et al.* (2011) Coordinated approaches to quantify long-term ecosystem dynamics in response to global change. *Global Change Biology*, **17**, 843–854.

Marion GM, Henry GHR, Freckman DW *et al.* (1997) Open-top designs for manipulating field temperature in high-latitude ecosystems. *Global Change Biology*, **3**, 20–32.

Marvel K, Bonfils C (2013) Identifying external influences on global precipitation. *Proceedings of the National Academy of Sciences*, **110**, 19301–19306.

Nepstad DC, Tohver IM, Ray D, Moutinho P, Cardinot G (2007) Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology*, **88**, 2259–2269.

Oksanen J, Blanchet FG, Kindt R *et al.* (2014) Package vegan: Community ecology package. Available at: http://CRAN.R-project.org/package=vegan (accessed 15 April 2016).

Pangle RE, Limousin J-M, Plaut JA *et al.* (2015) Prolonged experimental drought reduces plant hydraulic conductance and transpiration and increases mortality in a piñon-juniper woodland. *Ecology and Evolution*, **8**, 1618–1638.

Raz-Yaseef N, Yakir D, Schiller G, Cohen S (2012) Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns. *Agricultural and Forest Meteorology*, **157**, 77–85.

Reichstein M, Bahn M, Ciais P *et al.* (2013) Climate extremes and the carbon cycle. *Nature*, **500**, 287–295.

Ruppert JC, Harmoney K, Henkin Z, Snyman HA, Sternberg M, Willms W, Linstädter A (2015) Quantifying drylands' drought resistance and recovery: the importance of drought intensity, dominant life history and grazing regime. *Global Change Biology*, **21**, 1258–1270.

Sala OE, Gherardi LA, Reichmann L, Jobbagy E, Peters D (2012) Legacies of precipitation fluctuations on primary production: theory and data synthesis. *Philosophical Transactions of the Royal Society of London B*, **367**, 3135–3144.

Seneviratne SI, Nicholls N, Easterling D *et al.* (2012) Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC SREX Report)* (eds Field CB, Barros V, Stocker TF *et al.*), pp. 109–230. Cambridge University Press, Cambridge, UK.

Singh D, Tsiang M, Rajaratnam B, Diffenbaugh NS (2013) Precipitation extremes over the continental United States in a transient, high-resolution, ensemble climate model experiment. *Journal of Geophysical Research: Atmospheres*, **118**, 7063–7086.

Smith MD (2011a) The ecological role of climate extremes: current understanding and future prospects. *Journal of Ecology*, **99**, 651–655.

Smith MD (2011b) An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *Journal of Ecology*, **99**, 656–663.

Smith MD, Knapp AK, Collins SL (2009) A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology*, **90**, 3279–3289.

Thomey ML, Collins SL, Vargas R, Johnson JE, Brown RF, Natvig DO, Friggens MT (2011) Effect of precipitation variability on net primary production and soil respiration in a Chihuahuan Desert grassland. *Global Change Biology*, **17**, 1505–1515.

Tielbörger K, Bilton MC, Metz J *et al.* (2014) Middle-Eastern plant communities tolerate 9 years of drought in a multi-site climate manipulation experiment. *Nature Communications*, **5**, 5102. doi:10.1038/ncomms6102.

Trenberth KE, Dai A, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. *Bulletin of the American Meteorological Society*, **84**, 1205–1217.

Vicca S, Gilgen AK, Camino Serrano M *et al.* (2012) Urgent need for a common metric to make precipitation manipulation experiments comparable. *New Phytologist*, **195**, 518–522.

Walter J, Grant K, Beierkuhnlein C, Kreyling J, Weber M, Jentsch A (2012) Increased rainfall variability reduces biomass and forage quality of temperate grassland largely independent of mowing frequency. *Agriculture, Ecosystems and the Environment*, **148**, 1–10.

Whittaker RH (1975) *Communities and Ecosystems*. MacMillan Publishing Company Inc, New York.

Wilcox KR, Von Fisher J, Muscha J, Petersen M, Knapp AK (2015) Contrasting above- and belowground sensitivity of three Great Plains grasslands to altered rainfall regimes. *Global Change Biology*, **21**, 335–344.

Wullschleger SD, Hanson PJ (2006) Sensitivity of canopy transpiration to altered precipitation in an upland oak forest: evidence from a long-term field manipulation study. *Global Change Biology*, **12**, 97–109.

Xiao J, Liu S, Stoy PC (2016) Preface: Impacts of extreme climate events and disturbances on carbon dynamics. *Biogeosciences*, **13**, 3665–3675.

Yahdjian L, Sala OE (2002) A rainout shelter design for intercepting different amounts of rainfall. *Oecologia*, **133**, 95–101.

Zeppel MJB, Wilks JV, Lewis JD (2014) Impacts of extreme precipitation and seasonal changes in precipitation on plants. *Biogeosciences*, **11**, 3083–3093.

Zscheischler J, Michalak AM, Schwalm C *et al.* (2014a) Impact of large-scale climate extremes on biospheric carbon fluxes: an intercomparison based on MsTMIP data. *Global Biogeochemical Cycles*, **28**, 585–600.

Zscheischler J, Reichstein M, Harmeling S, Rammig A, Tomelleri E, Mahecha MD (2014b) Extreme events in gross primary production: a characterization across continents. *Biogeosciences*, **11**, 2909–2924.