

# Ecosystem and community resistance to five years of drought and deluge in a sagebrush steppe

Andrew T. Tredennick<sup>1,\*</sup>, Andrew R. Kleinbesselink<sup>2</sup>, and Peter B. Adler<sup>1</sup>

<sup>1</sup>*Department of Wildland Resources and the Ecology Center, Utah State University, Logan, Utah*

<sup>2</sup>*Department of Ecology and Evolutionary Biology, University of California, Los Angeles, Los Angeles, California*

Last compile: June 22, 2017

## Abstract

Precipitation is predicted to become more variable in the western U.S., meaning years of above and below average precipitation will become more common. Such periods of drought and deluge could become major drivers of plant community dynamics and ecosystem functioning in water limited grasslands. Here we report the results of a five-year experiment where we used drought and irrigation treatments (50% decrease/increase) to see how a sagebrush steppe plant community in Idaho will respond to future climate changes. The ecosystem was surprisingly resistant to both drought and irrigation. Aboveground net primary productivity (ANPP) responded positively to ambient growing season precipitation, but the response did not vary across treatments. There was also no evidence that treatment effects grew over time. The similarity of ecosystem functioning was not due to compensatory shifts at the plant community level, where species composition among treatments was similar and remarkably stable over the five years. At least in the short-term, ecosystem functioning and community composition in this sagebrush steppe system is resistant to increases and decreases in growing season precipitation.

*Key words: aboveground net primary productivity, climate change, community dynamics, drought, ecosystem resistance, sagebrush steppe*

## 1 Introduction

2 As the rate of climate change accelerates, ecologists are being pressed to forecast its impacts  
3 on ecosystem functions and services. Making such forecasts faces two challenges. First, future  
4 conditions are likely to be outside the historical range of variability (Smith 2011), meaning we  
5 cannot simply look to the past to predict the future. Second, ecosystems will likely exhibit unique  
6 responses to climate change induced resource alterations (e.g., Byrne et al. 2017), meaning we

---

\*Corresponding author; e-mail: atredenn@gmail.com

cannot simply look across space to predict the future. These two challenges motivate the use of *in situ* experimental manipulations of resource availability (Avolio et al. 2015).

Manipulating potentially limiting resources offers a route to understanding how ecosystems will respond to resource levels that fall outside the historical range of variability (Knapp et al. 2017). Chronic alterations to resource availability should cause community composition to shift over time, the focal ecosystem is sensitive to the manipulated resource. Species' relative abundances are expected to re-order and, eventually, some species will be lost from the local community and new species will be gained (Smith et al. 2009, Avolio et al. 2015). On the heels of changes in community composition, subsequent changes in the level of ecosystem functioning may occur.

Smith et al. (2009) introduced the 'Hierarchical Response Framework' for understanding the interplay of community composition and ecosystem functioning in response to resource manipulations over time. In the near term, ecosystem functioning such as annual net primary productivity (ANPP) will reflect the physiological responses of individual species to the manipulated resource level. For example, ANPP may decline under simulated drought because the initial community consisted of drought-intolerant species (Hoover et al. 2014). Over longer time spans, ecosystem functioning may recover as new species colonize or initial species reorder in relative abundance. For example, ANPP may initially decline, but eventually rise back to pre-treatment levels once drought-tolerant species become more abundant and compensate for drought-intolerant species (Hoover et al. 2014). It is also possible that ecosystem functioning shifts to a new mean state, reflective of the suite of species in the new community (Knapp et al. 2012).

Much of the research on ecosystem and community responses to global climate change has focused on grassland systems, where soil water is typically a limiting resource. The sensitivity of ANPP to water availability in grasslands has been characterized spatially (across sites) and temporally (within sites). Across sites, there is a strong positive relationship between the amount of precipitation at a given site and mean ANPP (Sala et al. 1988, Huxman et al. 2004). Within sites, however, the response of ANPP to annual precipitation amount is much weaker (Huxman et al. 2004, Hsu et al. 2012). Furthermore, it is becoming clear that grassland ecosystem response to altered water availability is likely to be idiosyncratic, conforming to neither cross-site nor within-site ANPP-precipitation relationships (Wilcox et al. 2016). This is because within-site relationships do not account for species reordering under chronic resource alterations, while cross-site relationships may overestimate the ability of species compensation. Thus, discovering which ecosystems are most sensitive to chronic alterations of water availability, and the time scales at which ecosystem and community responses occur, is critical to avoid surprises in the face of climate change.

Here we report the results of a five-year precipitation manipulation experiment in a sagebrush steppe grassland. We imposed drought and irrigation treatments (50% decrease/increase) and

measured ecosystem (ANPP) and community (species composition) responses. We focus on how the drought and irrigation treatments affect the linear relationship between ANPP and growing season precipitation, and if community dynamics underly the ecosystem responses. In particular, we sought to answer the following questions:

1. Does drought or irrigation impact mean ANPP (i.e., different intercepts)?
2. Does drought or irrigation impact the effect of ambient precipitation on ANPP (i.e., different slopes)?
3. Is the resistance or sensitivity of ANPP to altered precipitation related to underlying community dynamics?

## Materials and Methods

### Study Area

We conducted our precipitation manipulation experiment at the United States Sheep Experimental Station (USSES) near Dubois, Idaho (44.2° N, 112.1° W), 1500 m above sea level. The vegetation is typical of high elevation sagebrush steppe. The plant community is dominated by the shrub *Artemisia tripartita* and three perennial bunchgrasses, *Pseudoroegneria spicata*, *Poa secunda*, and *Hesperostipa comata*. During the period of our experiment (2011 – 2015), average mean annual precipitation was 265 mm year<sup>-1</sup> and mean monthly temperature ranged from -5.2°C in January to 21.8°C in July.

### Precipitation Experiment

Between 1926 and 1932, range scientists at the USSES established 26 permanent 1 m<sup>2</sup> quadrats to track vegetation change over time. In 2007, we (well, one of us [P. Adler]) relocated 14 of the original quadrats, six of which were inside a large, permanent livestock enclosure. We use these six plots as control plots that have recieved no treatment, just ambient precipitation. In spring 2011, we (well, two of us [A. Kleinhesselink and P. Adler]) established 16 new 1 m<sup>2</sup> plots. We avoided areas on steep hill slopes, areas with greater than 20% cover of bare rock, and areas with greater than 10% cover of the shrubs *Purshia tridentata* and/or *Amelanchier utahensis*. We established the new plots in pairs and randomly assigned each plot in a pair to receive a “drought” or “irrigation” treatment.

Drought and irrigation treatments were designed to decrease and increase the amount of ambient precipitation by 50%, respectively. To achieve this, we used a system of rain-out shelters and automatic irrigation (Gherardi and Sala 2013). The rain-out shelters consisted of transparent acrylic shingles 1-1.5 m above the ground that covered an area of 2.5 × 2 m. The

shingles intercepted approximately 50% of incoming rainfall, which was channeled into 75 liter containers. Captured rainfall was then pumped out of the containers and sprayed on to the adjacent irrigation plot via two suspended sprinklers. Pumping was triggered by float switches once water levels reached about 20 liters. We disconnected the irrigation pumps each fall and reconnected them, often with difficulty, each spring. The rain-out shelters remained in place throughout the year.

To make sure the treatments were having the desired effects, we monitored soil moisture in four of the drought-irrigation pairs using Decagon Devices (Pulman, Washington) 5TM and EC-5 soil moisture sensors. We installed four sensors in each plot, two at 5 cm soil depth and two at 25 cm soil depth. We also installed four sensors in areas nearby the four selected plot pairs to measure ambient soil moisture at the same depths. Soil moisture measurements were automatically logged every four hours. We coupled this temporally intensive soil moisture sampling with spatially extensive readings taken at six points within all 16 plots and associated ambient measurement areas. These snapshot data were collected on 06/06/2012, 04/29/2015, 05/07/2015, 06/09/2015, and 05/10/2016 using a handheld EC-5 sensor.

## Data Collection

We estimated aboveground net primary productivity (ANPP) using a radiometer to relate ground reflectance to plant biomass (see Byrne et al. 2011 for a review). We recorded ground reflectance at four wavelengths, two associated with red reflectance (626 nm and 652 nm) and two associated with near-infrared reflectance (875 nm and 859 nm). At each plot in each year, we took four readings of ground reflectances at the above wavelengths. We also took readings in ten calibration plots adjacent to the experimental site, in which we harvested all aboveground biomass, dried it to a constant weight at 60°C, and weighed it to estimate ANPP.

For each plot and year, we averaged the four readings for each wavelength and then calculated NDVI using the MODIS and AVHRR algorithms. To convert NDVI to ANPP we regressed NDVI against the dry biomass weight from the ten calibration plots. We fit regressions to MODIS-based NDVI and AVHRR-based NDVI for each year and retained the regression with the better fit. Using the best regression equation for each year, we predicted ANPP (Appendix 1).

Species composition data came from two sources: yearly census maps for each plot made using a pantograph (Hill 1920) and yearly counts of annual species in each plot. The maps record the spatial location of all individuals in the plot and the basal cover of each individual with cover greater than 1 cm. Using those annual maps, we aggregated over individuals to calculate total basal cover for each species in each plot. We made a large plot-treatment-year by species matrix, where columns were filled with either basal cover or density, depending on the measurement made for the particular species. So we could analyze the different types of data together, we

ANDY:  
add para-  
graph  
on VWC  
model

PETER:  
check this  
section

standardized the values in each column. This puts all abundance values on the same scale, but comes with the limitation that all species are weighted equally. Nonetheless, this scaling approach allows a comprehensive view of community composition dynamics through time.

## Data Analysis

Our main goal was to test whether the relationship between ANPP and growing season precipitation (hereafter, precipitation) differed among the drought, control, and irrigation treatments. To achieve this goal, we fit a multi-level random intercept and random slope regression with  $\log(\text{ANPP})$  as the response variable and soil moisture (volumetric water content) as the sole predictor. We fit the model under a Bayesian framework, allowing us to test for treatment differences by comparing the posterior distributions of the treatment-level coefficients (e.g., Tredennick et al. 2013). Both  $\log(\text{ANPP})$  and soil moisture were standardized to have mean 0 and unit variance before fitting the model [i.e.,  $(x_i - \bar{x})/\sigma_x$ ].

Our multi-level model has three grouping levels for coefficients, representing the nested structure of the data: (i) overall coefficients, (ii) treatment coefficients, and (iii) plot coefficients. Each subsequent level is drawn from the distribution of coefficients at the previous level. Formally, our model is defined as follows:

$$\mu_{i(j(k(t)))} = \beta_{0,j(k)} + \beta_{1,j(k)}x_i + \gamma_t, \quad (1)$$

$$y_{i(j(k(t)))} \sim \text{Normal}(\mu_{i(j(k(t)))}, \sigma_k^2), \quad (2)$$

where  $\mu_{i(j(k))}$  is the deterministic prediction from the regression model for observation  $i$  for plot  $j$  associated with treatment  $k$  in year  $t$ ,  $\beta_{0,j(k)}$  is the intercept for plot  $j$  associated with treatment  $k$ ,  $\beta_{1,j(k)}$  is the slope term for the effect of soil moisture for plot  $j$  associated with treatment  $k$ ,  $\gamma_t$  is the intercept offset for year  $t$ , and  $\sigma_k^2$  is the process variance for treatment  $k$ . Data include the standardized  $\log(\text{ANPP})$  observations  $(y_{i(j(k(t)))})$  and soil moisture ( $x_i$ ). Although we include observation subscript  $i$  on the  $x$ s, observations within a treatment-year all share the same soil moisture values.

The intercept and slope terms are modeled hierarchically to account for the non-independence of observations across years within plots and to allow us to test the hypothesis that our treatments alter the ANPP-soil moisture relationship. As noted above, plot-level coefficients are drawn from treatment-level coefficients, which are drawn from overall coefficients. We also include a covariance structure among the intercept and slope at each level. Formally, our hierarchical structure is as follows, where we drop the intercept (0) and slope (1) subscripts and instead refer to a vector of coefficients,  $\beta$ :

$$\beta_{j(k)} \sim \text{MVN}(\beta_k, \Sigma(k)), \quad (3)$$

$$\beta_k \sim \text{MVN}(\beta, \Sigma), \quad (4)$$

$$\beta \sim \text{Normal}(0, 1), \quad (5)$$

where  $\beta_{j(k)}$  is the vector of regression coefficients (intercept and slope) for plot  $j$  associated with treatment  $k$ ,  $\beta_k$  is the vector of coefficients for each treatment, and  $\beta$  is the vector of overall coefficients. The plot- and treatment-level coefficients are drawn from multivariate normal distributions with covariance matrix  $\Sigma$ . For the plot-level coefficients, each treatment has its own variance-covariance matrix (i.e.,  $\Sigma(k)$ ). The overall coefficients are drawn from a normal prior with mean 0 and standard deviation 1. The random year effects ( $\gamma$ ) are drawn from a normal prior with mean 0 and standard deviation  $\sigma_{\text{year}}$ , which was drawn from a weibull distribution. A full description of model is in Appendix 2.

We fit the model using a Bayesian approach, obtaining posterior estimates of all unknowns via the No-U-Turn Hamiltonian Monte Carlo sampler in Stan (Stan Development Team 2016a). We used the R package ‘rstan’ (Stan Development Team 2016b) to link R (R Core Team 2016) to Stan. We obtained samples from the posterior distribution for all model parameters from four parallel MCMC chains run for 10,000 iterations, saving every 10<sup>th</sup> sample. Traceplots of all parameters were visually inspected to ensure well-mixed chains and convergence. We also made sure all scale reduction factors ( $\hat{R}$ ) were less than 1.1.

To see if community composition differed among treatments through time, we used non-dimensional multivariate scaling (NMDS) based on Bray-Curtis distances. For each year of the experiment, we first calculated Bray-Curtis distances among all plots, and then extracted those distances for use in the NMDS. Because we standardized species’ abundances, some values were negative, which is not allowed for calculating Bray-Curtis distances. We simply added ‘2’ to each abundance value to ensure all values were greater than zero. We plotted the first two axes of NMDS scores to see if community composition overlapped, or not, among treatments in each year. We used the ‘metaMDS()’ function in the R package ‘vegan’ (Oksanen 2016) to calculate Bray-Curtis distances and then to run the NMDS analysis. Lastly, we examined rank clocks of species’ abundances through time to assess the stability of community composition over the course of the experiment (Collins et al. 2008). Rank clocks were made using ‘ggplot2’ (Wickham 2009) and R code from the ‘codyn’ package (Hallett et al. 2016).

All R code and data necessary to reproduce our analysis has been archived on Figshare ([link here after acceptance](#)) and released on GitHub ([https://github.com/atredennick/usses\\_water/releases/v0.1](https://github.com/atredennick/usses_water/releases/v0.1)). We also include annotated Stan code in our model description in Appendix 2.

## Results

Three of our five treatment years fell in years of below average rainfall (Fig. 1A). Thus, those three years represent a lower magnitude of absolute change in precipitation experienced by the treatments. Averaged across treatments, ANPP varied from a minimum of  $74.5 \text{ g m}^{-2}$  in 2014 to a maximum of  $237.1 \text{ g m}^{-2}$  in 2016 (Fig. 1C). ANPP was slightly higher in irrigation plots and slightly lower in drought plots (Fig. 1C), corresponding to estimated soil volumetric water content (VWC) differences among treatments (Fig. 1B). Such differences in soil VWC indicate our treatment infrastructure was successful.

Cumulative growing season soil moisture had a positive effect on ANPP (mean of  $\beta_1 = 0.43$ ; 80% BCI = -0.05, 0.88; 95% BCI = -0.36, 1.15) (Fig. 1D). Average ANPP was similar among treatments (similar intercepts, Fig. 2A), as was the effect of precipitation (similar slopes, Fig. 2B). In an average precipitation year (i.e.,  $x = 0$  in Eq. 1), the probability that ANPP in a control plot is greater than ANPP in a drought plot was 0.71, and the probability that ANPP in a control plot is lower than in an irrigation plot was 0.41. In other words, the posterior distributions of  $\beta_0(\text{control}) - \beta_0(\text{drought})$  and  $\beta_0(\text{control}) - \beta_0(\text{irrigation})$  broadly overlapped zero. There was also no evidence that the treatment effects became more important over time because there was no directional trend in the yearly treatment effects estimated from the ANPP-Treatment model (Fig. 3).

Community composition was similar among treatments. In no year did community composition among treatments not overlap, and they were equally dispersed in all years (Fig. 4). Likewise, community composition was remarkably stable over time, with no evidence of divergence among treatments (Fig. 4). Species' abundances and ranks showed little deviation over the five-year experiment, regardless of treatment (Fig. 5).

## Discussion

Ecosystem response to chronic resource alteration is expected to follow a temporal trend. Initially, ecosystem response will be modest and reflect the physiological responses of constituent species. Over longer time periods, species reordering will cause greater responses as species better able to take advantage of, or cope with, new resource levels become more abundant. This temporal trend is formalized by the 'Hierarchical Response Framework' (HRF, Smith et al. 2009), and has been empirically supported (Knapp et al. 2012, Wilcox et al. 2016). A lingering question is not whether the HRF is a reasonable model of ecosystem dynamics, but rather how the time scales of ecosystem response and community change differ among ecosystems. Indeed, previous work has shown that community compositional shifts can be both rapid, on the order of years (Hoover et al. 2014), and slow, on order of decades (Knapp et al. 2012, Wilcox et al. 2016). To add to

205 this growing body of knowledge, we performed a precipitation manipulation experiment in a  
206 sagebrush steppe ecosystem.

207 Surprisingly, ANPP was not sensitive to either drought or irrigation treatments, whether in  
208 the context of growing season precipitation (Fig. 2) or in the context of year since the experiment  
209 began (Fig. 3). This is surprising because grasslands generally, and sagebrush steppe specifically,  
210 are considered water-limited systems. Thus, our expectation was that ANPP would be tightly  
211 linked to soil water availability. ANPP was slightly lower in drought plots and slightly higher in  
212 irrigation plots, but these differences were not statistically important.

213 In the absence of community composition data, an obvious hypothesis to explain the lack  
214 of ANPP response is that species reordered rapidly. In so doing, newly abundant species could  
215 compensate for the loss of ecosystem functioning of previously abundant species. We did not find  
216 this to be the case, as specie composition was remarkably stable over the course of the experiment  
217 (Fig. 3).

218 In combination, the lack of ecosystem and community response to drought or irrigation  
219 shows that this sagebrush steppe ecosystem is resistant to chronic alterations in water availability.  
220 There are three possible explanations for the resistance we found. First, it could be that our  
221 experiment simply was not long enough to induce responses. This may be true for community  
222 responses, which can take decades (Wilcox et al. 2016), but the response of grassland ANPP to  
223 water manipulations is typically immediate (e.g., Hoover et al. 2014).

224 Second, it could be that our manipulations were not large enough to induce a response. That  
225 is, maybe a 50% decrease/increase in any given year is not abnormal give our sites historical range  
226 of variability (Knapp et al. 2017). We cannot definitively rule out this possibility, but we have  
227 reason to believe our manipulations *should* have been large enough. Using the methods described  
228 by Lemoine et al. (2016), we calculated the percent reduction and increase of mean growing season  
229 precipitation necessary to reach the 1% and 99% extremes of the historical precipitation regime  
230 at our site. The 1% quantile of precipitation at our site is 110 mm, a 47% reduction from the  
231 mean, and the 99% quantile is 414 mm, a 77% increase from mean growing season precipitation  
232 (Appendix 3). Thus, our drought treatment represented extreme precipitation amounts, especially  
233 in years where ambient precipitation was below average (Fig. 1A). The irrigation treatment may  
234 have been too small, however.

235 Third, the ecosystem and community resistance to drought and deluge we observed could  
236 be a real phenomenon in this system.



## Acknowledgments

We gratefully acknowledge the support of the Utah Agricultural Experiment Station (journal paper xxxx). We thank the many summer research technicians who collected the data reported in this paper and the US Experimental Sheep Station for facilitating work on their property. We also thank Susan Durham for clarifying our thinking on the statistical analyses and Kevin Wilcox for helpful discussions on analyzing community composition data.

## Funding

NSF DBI-1400370 to Andrew Tredennick.

NSF Graduate Research Fellowship to Andrew Kleinhesselink.

NSF DEB-1353078 and DEB-1054040 to Peter Adler.

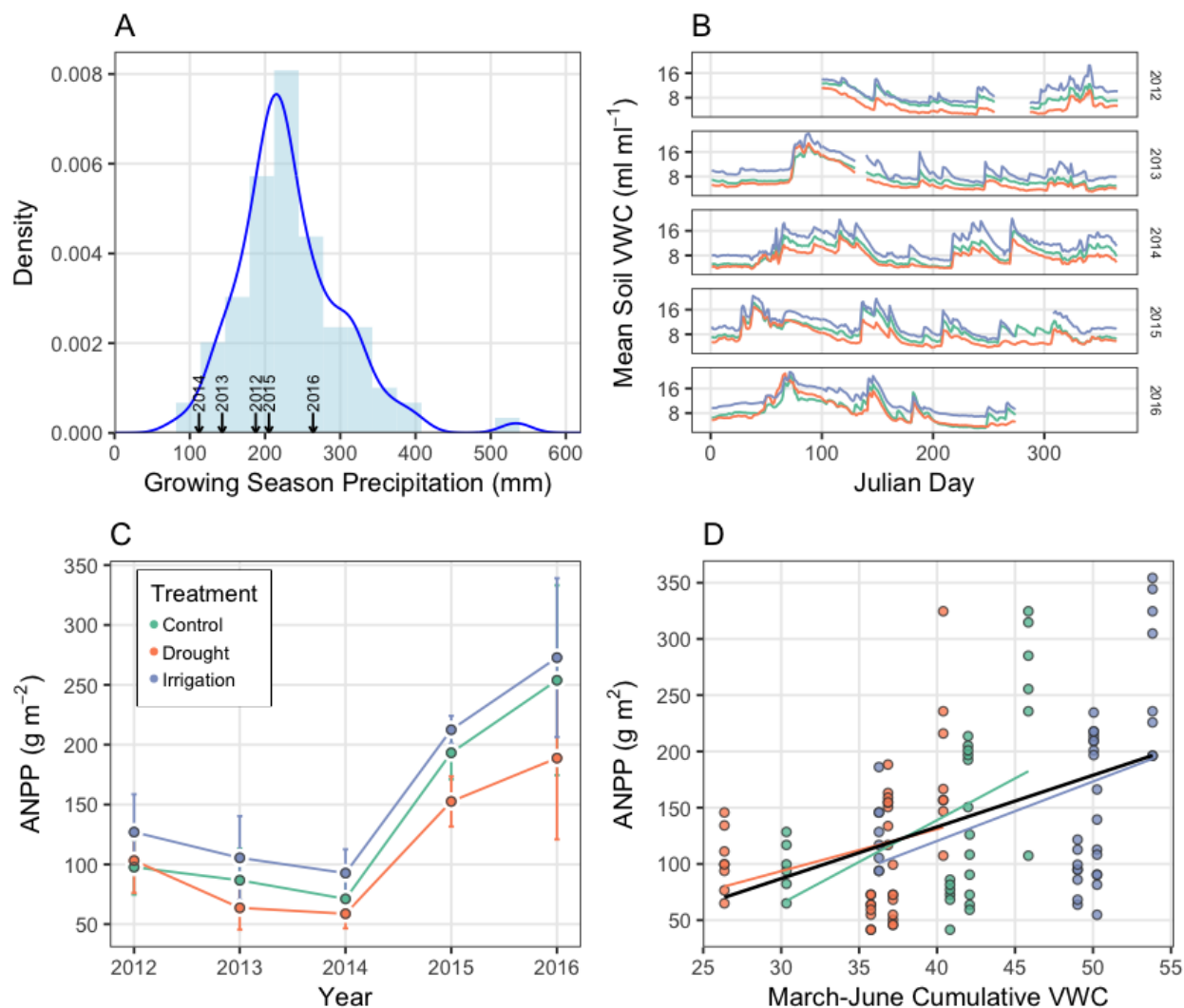


Figure 1: (A) Probability density of historical precipitation from 1926-2016, with the years of the experiment shown with arrows on the \*x\*-axis. (B) Observed soil volumetric water content (VWC) over the course of the experiment. (C) Mean (points) ANPP and its standard deviation (error bars) for each year of the experiment. (D) Scatterplot of ANPP versus growing season precipitation. Colored regression lines are independently-fit linear models for each treatment with no random effects structure; dark black regression line is a linear regression through all the point with no random effects structure. Our analysis seeks to find if the data supports a model with different intercepts and/or slopes for each treatment, while also accounting for nonindependence of samples within plots across years. Color mapping for panels B-D is shown in the legend for panel C.

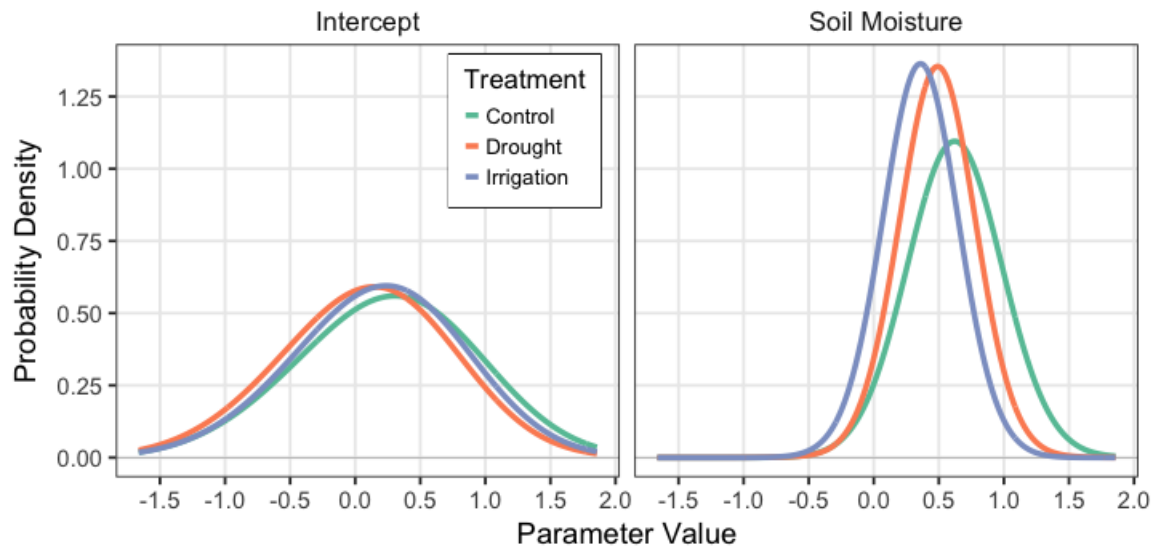


Figure 2: Posterior distributions of treatment-level parameters ('Intercept' and the effect of 'Soil Moisture'). Kernel bandwidths of posterior densities were adjusted by a factor of 5 for visual clarity.

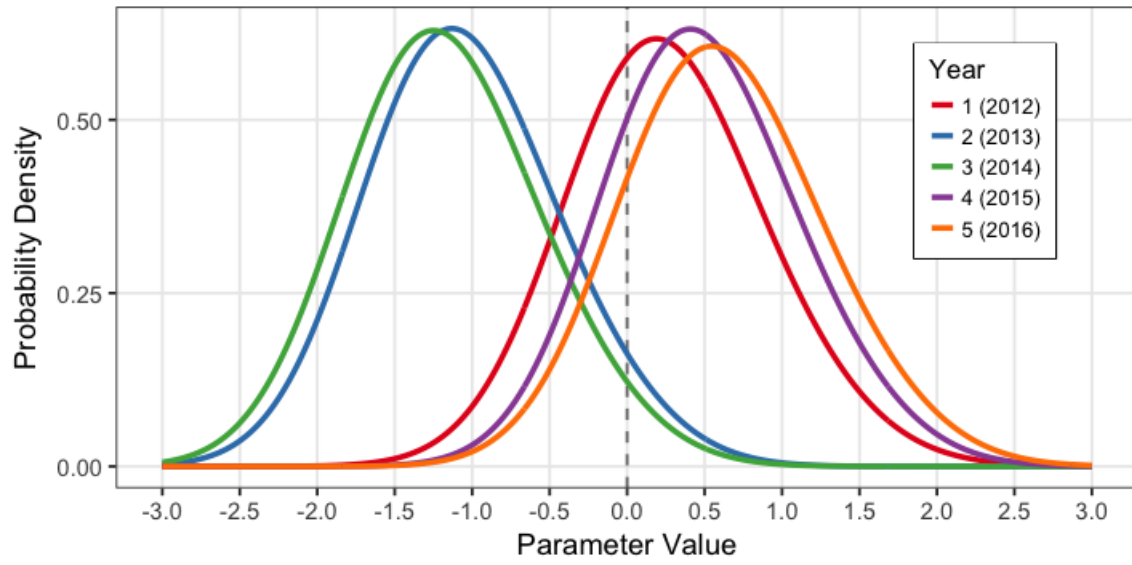


Figure 3: Posterior distributions of random year effects (intercept offsets).

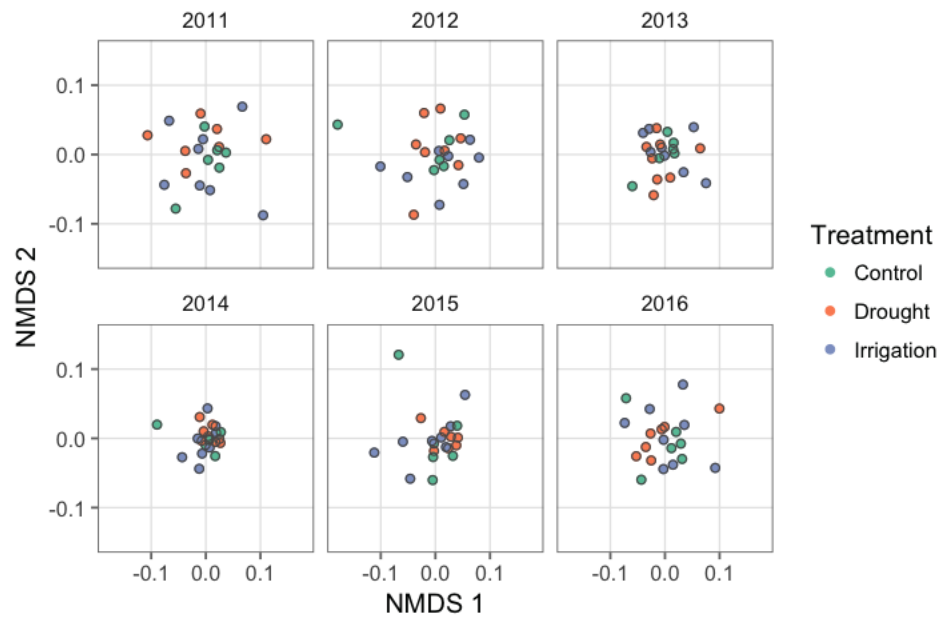
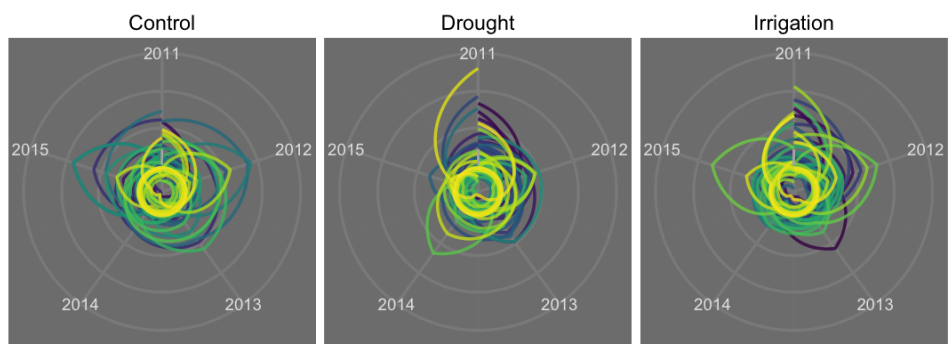
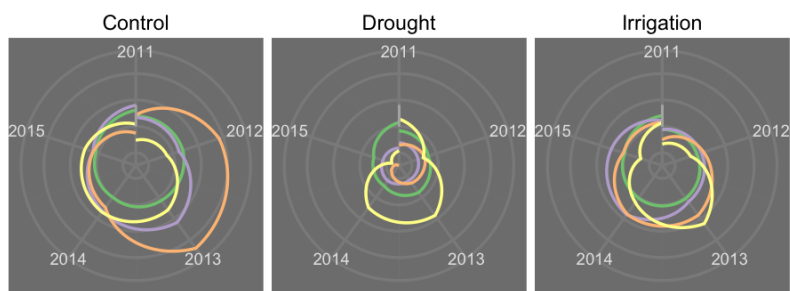


Figure 4: Nonmetric multidimensional scaling scores representing plant communities in each plot, colored by treatment.

A. All species



B. Dominant species



Species ■ *Artemisia tripartita* ■ *Hesperostipa comata* ■ *Poa secunda* ■ *Pseudoroegneria spicata*

Figure 5: Rank clocks of average species' scaled abundance by treatment. (A) All species. (B) Dominant species.

## References

- Avolio, M. L., K. J. L. Pierre, G. R. Houseman, S. E. Koerner, E. Grman, F. Isbell, D. S. Johnson, and K. R. Wilcox. 2015. A framework for quantifying the magnitude and variability of community responses to global change drivers. *Ecosphere* 6:1–14.
- Byrne, K. M., P. B. Adler, and W. K. Lauenroth. 2017. Contrasting effects of precipitation manipulations in two Great Plains plant communities. *Journal of Vegetation Science* 28:238–249.
- Byrne, K. M., W. K. Lauenroth, P. B. Adler, and C. M. Byrne. 2011. Estimating Aboveground Net Primary Production in Grasslands: A Comparison of Nondestructive Methods. *Rangeland Ecology & Management* 64:498–505.
- Collins, S. L., K. N. Suding, E. E. Cleland, M. Batty, S. C. Pennings, K. L. Gross, J. B. Grace, L. Gough, J. E. Fargione, and C. M. Clark. 2008. Rank clocks and plant community dynamics. *Ecology* 89:3534–3541.
- Gherardi, L. A., and O. E. Sala. 2013. Automated rainfall manipulation system: a reliable and inexpensive tool for ecologists. *Ecosphere* 4:1–10.
- Hallett, L. M., S. K. Jones, A. A. M. MacDonald, M. B. Jones, D. F. B. Flynn, J. Ripplinger, P. Slaughter, C. Gries, and S. L. Collins. 2016. codyn: An r package of community dynamics metrics. *Methods in Ecology and Evolution* 7:1146–1151.
- Hill, R. R. 1920. Charting Quadrats with a Pantograph. *Ecology* 1:270–273.
- Hoover, D. L., A. K. Knapp, and M. D. Smith. 2014. Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology* 95:2646–2656.
- Hsu, J. S., J. Powell, and P. B. Adler. 2012. Sensitivity of mean annual primary production to precipitation. *Global Change Biology* 18:2246–2255.
- Huxman, T. E., M. D. Smith, P. A. Fay, A. K. Knapp, M. R. Shaw, M. E. Loik, S. D. Smith, D. T. Tissue, J. C. Zak, J. F. Weltzin, W. T. Pockman, O. E. Sala, B. M. Haddad, J. Harte, G. W. Koch, S. Schwinning, E. E. Small, and D. G. Williams. 2004. Convergence across biomes to a common rain-use efficiency. *Nature* 429:651–654.
- Knapp, A. K., M. L. Avolio, C. Beier, C. J. W. Carroll, S. L. Collins, J. S. Dukes, L. H. Fraser, R. J. Griffin-Nolan, D. L. Hoover, A. Jentsch, M. E. Loik, R. P. Phillips, A. K. Post, O. E. Sala, I. J. Slette, L. Yahdjian, and M. D. Smith. 2017. Pushing precipitation to the extremes in distributed experiments: recommendations for simulating wet and dry years. *Global Change Biology* 23:1774–1782.
- Knapp, A. K., J. M. Briggs, and M. D. Smith. 2012. Community stability does not preclude ecosystem sensitivity to chronic resource alteration. *Functional Ecology* 26:1231–1233.
- Lemoine, N. P., J. Sheffield, J. S. Dukes, A. K. Knapp, and M. D. Smith. 2016. Terrestrial Precipitation Analysis (TPA): A resource for characterizing long-term precipitation regimes and extremes. *Methods in Ecology and Evolution* 7:1396–1401.
- Oksanen, J. 2016. *Vegan: ecological diversity*.
- R Core Team. 2016. *R: A Language and Environment for Statistical Computing*. Vienna, Austria.
- Sala, O. E., W. J. Parton, L. A. Joyce, and W. K. Lauenroth. 1988. Primary production of the central

286 grassland region of the United States.

287 Smith, M. 2011. An ecological perspective on extreme climatic events: A synthetic definition and  
 288 framework to guide future research. *Journal of Ecology* 99:656–663.

289 Smith, M. D., A. K. Knapp, and S. L. Collins. 2009. A framework for assessing ecosystem dynamics  
 290 in response to chronic resource alterations induced by global change. *Ecology* 90:3279–3289.

291 Stan Development Team. 2016a. Stan: A C++ Library for Probability and Sampling, Version 2.14.1.

292 Stan Development Team. 2016b. Rstan: the R interface to Stan, Version 2.14.1.

293 Tredennick, A. T., L. P. Bentley, and N. P. Hanan. 2013. Allometric convergence in savanna trees  
 294 and implications for the use of plant scaling models in variable ecosystems. *PLoS One* 8:e58241.

295 Wickham, H. 2009. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, NY.

296 Wilcox, K. R., J. M. Blair, M. D. Smith, and A. K. Knapp. 2016. Does ecosystem sensitivity to  
 297 precipitation at the site-level conform to regional-scale predictions? *Ecology* 97:561–568.