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Abstract:

As droughts become longer and more intense, impacts on terrestrial primary productivity are expected to increase progressively. Yet, some ecosystems appear to acclimate to drought, with constant or diminishing reductions in productivity as drought duration increases. We quantified the combined effects of drought duration and intensity on aboveground productivity in 74 grasslands and shrublands distributed globally. Ecosystem acclimation with multi-year drought was observed overall, except when droughts were extreme (i.e., 1-in-100-year or greater likelihood of occurrence) for consecutive years. Productivity losses after four years of extreme drought increased by ~160% compared to more moderate drought intensity. These results portend a foundational shift in ecosystem behavior if drought duration and intensity increase – from maintenance of reduced functioning over time to progressive and profound losses of productivity.

Main Text:

Drought, defined meteorologically as “a prolonged absence or marked deficiency of precipitation” (*sensu 1*), is a frequent and impactful disturbance in many terrestrial ecosystems globally. Although most droughts are short-term and moderate in intensity (*2*), the most damaging and costly droughts from the perspective of ecological, societal, and economic impacts are both prolonged – unfolding over multiple years – and extreme with respect to long-term variation in climate conditions (e.g., *3,4*). Although such drought events have historically occurred infrequently and in some places are absent from the recent historical record (*2,5*), there is evidence that longer-duration, intensified droughts are becoming more common (*6,7*) and will further increase in magnitude and frequency with global climate change (*5*,*8,9*). Yet, the impacts of multi-year, extreme droughts remain understudied, and past research is equivocal for how long-term droughts impact terrestrial ecosystems (*2*).

Theory predicts that as drought duration increases, the impacts of drought on ecosystem functioning (e.g., primary production) should accumulate or be magnified over time, resulting in more substantial losses in functioning – even for ecosystems that appear resistant to short-term drought (*2,10*). Several past studies report this expected cumulative pattern of response – a progressively more negative effect of drought on ecosystem functioning as duration increases (*11,12*). However, others find little evidence that increasing drought duration reduces functioning beyond that of a single-year drought (e.g., *13-15*). Indeed, some research suggests that ecosystem function can ‘acclimate’ or stabilize in response to multi-year drought (i.e., ecosystem acclimation; *16*), characterized by the impacts of drought remaining relatively constant or even diminishing over time (*11,16-19*). These variable responses to drought duration may result from differences in the magnitude (or intensity) of drought imposed. Indeed, drought duration and intensity are expected to interact in important ways (*2,10*). Droughts that are both prolonged and extreme are more likely to result in large impacts on ecosystem functioning (*10,20,21*). In contrast, short-term drought or prolonged moderate drought may result in lesser impacts on ecosystem functioning than extreme drought (*10,13,15*). Thus, to fully understand patterns of ecosystem response to drought duration we need to also assess its interaction with drought intensity.

Our goals for this study were to 1) determine if prolonged drought results in a pattern of ecosystem response consistent with ecosystem acclimation (constant or lessening over time) vs.

progressive losses (continuous decline over time), 2) quantify losses of ecosystem function attributable to each pattern, and 3) assess whether these patterns of loss change with the magnitude of drought imposed. We achieved these goals with results from the International Drought Experiment (IDE), a multi-year global-scale study of drought effects on aboveground net primary productivity (hereafter referred to as "productivity"), a key measure of ecosystem functioning and a major component of the terrestrial carbon cycle (*22*).

The International Drought Experiment

The IDE is a coordinated drought experiment established in grassland and shrubland ecosystems across the globe (Fig. 1A, table S1; *23*). These ecosystems cover ~40% of the Earth's land surface, provide crucial ecosystem services (e.g., food, forage, fiber, *24,25*), and their productivity is among the most responsive to precipitation variability (e.g., *26*). IDE sites were established on six continents and span broad precipitation, temperature, and environmental gradients (Fig. 1A, table S1; *27,28*). All IDE sites utilize a common experimental approach – passive rainfall manipulation shelters (*29*) that simulated year-round drought (365 days; *27*) for up to four years. This allows for drought-duration impacts to be assessed in a cost-effective manner, while still representing key characteristics of natural drought events (i.e., smaller and fewer rainfall events accompanied by longer periods between rainfall events, *29*). At the time of this analysis, there were 74 grassland and shrubland IDE sites that had imposed three (n = 21) or four (n = 53) years of drought (Fig. 1B).

In addition to drought duration, IDE was designed to capture another way in which drought events are changing: increased intensity (or magnitude). To accomplish this, we selected a statistically extreme target level of drought intensity tailored for each IDE site: a 1-in-100-year drought based on long-term annual precipitation amounts available from site-level historical records (Fig. 1B; *23*). By choosing this target level, our intent was to impose a scenario of extreme drought that is currently predicted to become more common with climate change in the near future, yet not so extreme as to be unrealistic (e.g., a 1-in-100-year drought will become more common well before a 1-in-1000-yr drought; *30*). Thus, the goal with IDE was to apply drought treatments that: 1) were historically and statistically rare for most if not all sites included in our study, but also 2) are forecast to become more common with climate change (*31*).

The IDE passive rainfall manipulation shelters rely on ambient precipitation to achieve drought (*29*). However, because ambient precipitation varied each year of the study, the target 1-

in-100-year drought treatment was realized only when ambient rainfall was less than or equal to mean annual precipitation (MAP) for a site (*23*). When this criterion was met, we categorized the drought treatment as "extreme" (following *27*). In contrast, when ambient annual rainfall was greater than MAP for a site, the target 1-in-100-year drought was not met, but drought was still imposed. For this scenario, we categorized the drought treatment as "moderate". The extreme and moderate categories of drought intensity align with those used in well-recognized drought classification systems, such as the US Drought Monitor (*23*). We also quantified the IDE drought treatments as a continuous variable using a common and comparable drought severity metric (*32*), calculated as the relative reduction in rainfall in the drought treatment from MAP (*23*). Average drought severity was significantly greater (~60%) for the extreme vs. moderate drought intensity categories (Fig. S1). An additional feature of the IDE design is that in any given year, approximately half of the sites experienced extreme, 1-in-100-year drought, and after multiple years, sites experienced different combinations of moderate and extreme drought years (Fig 1B). This allowed us to contrast unique sequences of moderate and extreme drought impacts over multiple years.

Variability in drought response over time

Previously, we showed that average productivity reductions were ~60% greater when a single-year drought was extreme vs. not extreme; however, variability among IDE sites in their response to short-term drought was surprisingly high, ranging from complete resistance (*i.e.,* no reduction in productivity) to large declines in productivity (*27*). Much of this variability in response was related to variation in drought severity, with productivity decreasing, as expected, with increasing drought severity (*27*). As drought duration was increased from one to four years in this study, we expected that variation in productivity responses among sites would decrease. However, average productivity responses to multiple (3 to 4) years of drought remained surprisingly variable, ranging from little response to as much as a 97% decline in productivity (Fig. 1B).

We examined a broad set of biotic and abiotic variables previously hypothesized to explain variation in drought response (*23*), including differences in plant species richness, abundance of key growth forms (*i.e*., graminoids), soil texture, MAP, mean annual temperature (MAT), mean aridity index (AI), interannual precipitation variability, precipitation seasonality, and previous and current year drought severity (table S2, Figs. S2-S5). We found that as drought extended over multiple years, previous year's drought severity (years 2 and 3), MAP (years 2-4), mean AI (year 3), interannual variation (year 4) and seasonality in precipitation (year 3), and plant species richness (years 1 and 4) were significant predictors of variation in drought response (Figs. S2-S5). Thus, as found in other studies (*27*,*33*), drier and less biodiverse sites, as well as those with more variable or more seasonal precipitation, experienced greater losses in productivity with drought. However, drought severity was the best and most consistent predictor of variation in drought response, as observed with single-year droughts (*27*).

Pattern of productivity loss with multi-year drought

Despite variation in drought response among sites, we expected that a pattern of progressive (or cumulative) losses of productivity would emerge at most sites as drought continued over multiple years. After a significant decline in productivity in the first year of drought (29%), when averaged across all sites and drought intensity categories, productivity losses did not continue to decrease over time (Fig 1C, table S3). Instead, ecosystem acclimation was generally observed. Notably, annual grasslands responded distinctly from perennial grasslands and shrublands, exhibiting a much larger initial response, but with the response lessening over time (table S3). Previous studies in annual-dominated systems have also found similar responses as well as strong drought resistance (*34,35*). Unfortunately, given the small number of annual-dominated IDE sites (n = 8) and their limited geographic coverage (seven of eight were in the southwestern United States and six experienced above-average precipitation in year 4), it is difficult to draw substantive conclusions about the nature of drought-duration effects based on these annual ecosystems. As such, we focused all subsequent analyses on the more widely represented perennial-dominated grassland and shrubland sites.

Interaction of drought duration and severity

The above analysis of drought-duration effects does not consider intensity (extreme vs. moderate) of the drought imposed. However, we expected that losses in productivity under extreme drought would be magnified over time, and most pronounced when drought intensity was consistently extreme over multiple years. We tested this prediction in four ways. First, we examined relationships between productivity responses and drought severity for each year of the drought using multi-model comparisons that also included previous year's drought severity to account for potential carry-over effects of the severity of drought from one year to the next (*23*). Consistent with simple linear regression analyses (table S2, Figs. S2-S5), current year's drought severity was the best predictor of variation in productivity response regardless of ecosystem type or previous year's drought severity (table S4, Fig. 2). However, this analysis does not consider whether drought intensity was extreme or not. Therefore, we tested if the slope of the relationship between productivity responses and drought severity would change depending on whether drought intensity was extreme vs. moderate. This analysis allowed us to consider the magnitude of the drought treatment as both a continuous (i.e., severity) and categorical variable when describing the productivity response to drought over time. We found that by year 3, the relationship between drought severity and productivity responses differed significantly between moderate *vs.* extreme droughts, with the difference in these relationships most pronounced in year 4 (Fig. 2, table S5). In other words, the slope of the relationship between drought severity and productivity loss became more negative over time when the intensity of the drought treatment was extreme, whereas the slope of the relationship for moderate intensity droughts did not change significantly over time. Third, we assessed the impact of extreme *vs.* moderate drought intensity in any given year during the 4-year period of precipitation reductions, regardless of previous year's drought severity. We found that a drought of extreme intensity in year 4 reduced productivity on average by 54% compared to an extreme drought in year 1, whereas the effects of moderate intensity droughts on productivity were independent of the year in which they occurred (Fig. 3A, table S6). Finally, we quantified productivity responses to the scenario in which consecutive 2-, 3- and 4-years of extreme drought intensity occurred (*i.e.,* drought was extreme in all prior years). For the subset of sites with such consecutive extreme drought years, the strongest duration effects were revealed (Fig. 3B, table S7), with an ~160% greater loss of productivity as duration increased from one to four years (29 vs. 77% reduction, respectively). Collectively, these results support predictions that droughts that are of extreme intensity cause greater impacts on ecosystem functioning than more moderate droughts of similar duration (*10*). Most importantly, however, we show that increasing drought duration concurrent with consistently extreme drought can result in progressive losses in ecosystem functioning that are more profound than previously reported (*11,12*).

Conclusions

Our results help to reconcile contrasting patterns of drought duration responses reported previously. IDE results show that after an initial loss of function in year one, ecosystems subjected to multiple years of moderate (or less severe) drought are likely to maintain this level of limited functioning (*i.e.,* exhibit ecosystem acclimation). In contrast, an increase in severity to historically extreme levels will result in a pattern of cumulative loss of function over time. There are several mechanisms that may result in patterns of ecosystem acclimation vs. cumulative effects of drought (*10,20,21*), including demographic and community shifts resulting from mortality or establishment failure (leading to loss in function), as well as plastic or adaptive responses to drought over time (leading to mitigation of loss over time). Although the IDE was not designed to rigorously test such mechanisms, available data from 49 sites on species gains and losses, as well as changes in species richness suggest that demographic and community shifts likely occurred (Fig. S6A, tables S8, S9), and over time greater species losses were significantly related to increased losses in productivity with drought (Fig. S6B, table S10). While additional research will be required to test mechanisms that may determine acclimation vs. cumulative responses to drought, such mechanistic understanding is crucial in a future where extreme droughts become the norm.

The lack of duration effect with moderate drought intensity is not entirely surprising given that many grassland and shrubland ecosystems occur in a broad range of semi-arid to arid climates, as did a majority of IDE sites (table S2). The ability of these water-limited systems to rapidly respond to short-term fluctuations in precipitation (*22,36,37*), but also maintain functioning for more extended dry periods is consistent with the long-term stability of these ecosystems (*38*). Indeed, it is also worth highlighting that a subset of sites was resistant to multiple years of drought regardless of severity. It may be that these ecosystems are less water-limited (table S2), and therefore less impacted by drought as has been observed for mesic grasslands (e.g., *14,16*). However, it should also be noted that drought experiments may underestimate drought effects (*39*), and although passive rainout shelters alter precipitation inputs and soil moisture in ways that accurately simulate changes in rainfall during natural droughts (*28*), they do not reproduce ancillary drought attributes such as higher temperatures and vapor pressure deficits that typically accompany drought events (*40-42*). While direct temperature effects are not particularly strong in grasslands (*43,44*), an increase in vapor pressure deficits during drought has the potential to reduce photosynthesis and productivity (*45,46*), and the lack of a temperature manipulation in this study could partially explain why some IDE sites were unresponsive to drought over time.

In summary, the discovery that the resistance to drought duration of grasslands and shrublands rapidly eroded with prolonged drought of extreme intensity portends an uncertain future for these ecosystems, threatening their long-term stability and the ecosystem goods and services they provide. Particularly alarming was the 160% (or 2.5-fold) greater reductions in productivity observed when extreme drought years occur consecutively. Extreme, consecutive drought years, including megadroughts (*8*), are expected to increase in the future with climate change (*8,31*). Although concerns about ecosystem stability in the face of ongoing increases in both drought magnitude and duration have been voiced for decades (*47,48*), our results provide experimental evidence in support of recent observations (*5*) that the functioning of these globally important ecosystems are at risk from longer and more intense droughts.

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Competing interests: The authors declare that they have no competing interests to report.

Data and materials availability: All code and derived data are publicly available on Dryad (*49*).

Supplementary Materials

Materials and Methods

Supplemental References and Notes

Figs. S1 to S6

Tables S1 to S10

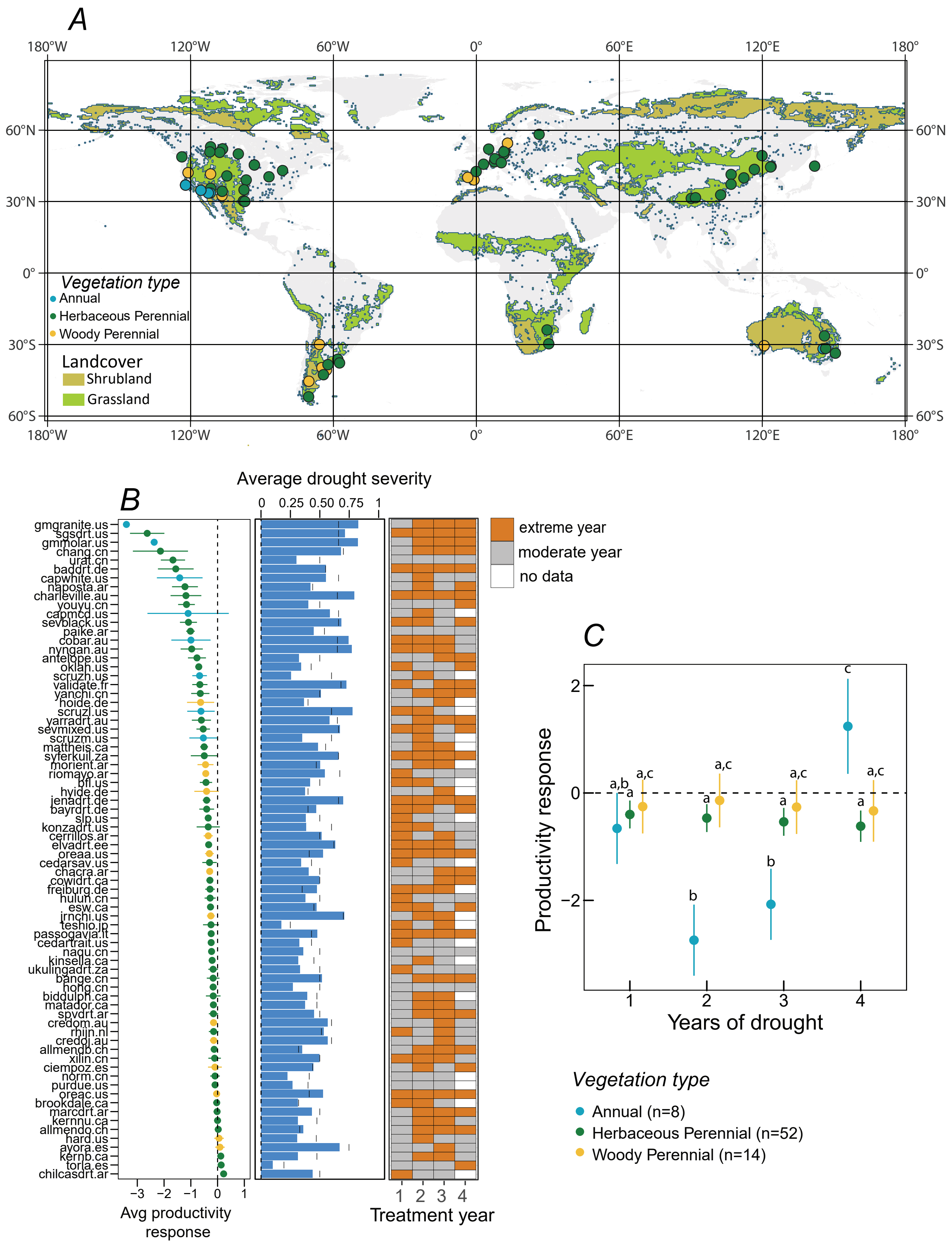
Figure captions

Fig. 1. Overview of the International Drought Experiment: geographic locations, drought treatments, and effects on aboveground productivity. (A) Locations of the 74 International Drought Experiment (IDE) sites included in this study and their distribution across six continents. Background shading denotes Moderated Resolution Imaging Spectroradiometer (MODIS)-derived landcover types (*50*) and the colors of the points denote the vegetation type of each site: annual, herbaceous perennial, or woody perennial (*23*). **(B)** Left panel shows the IDE sites ordered by the average productivity response to drought over the three to four-year duration of the experiment. Error bars denote the standard error for each site. The middle panel displays the average drought severity (defined as [mean annual precipitation (MAP) - precipitation received by drought treatment plots]/MAP; *23*) experienced over the duration of the experiment (blue bars). The expected average drought severity for the target 1-in-100-year drought treatment is indicated by the vertical black line. Overall, 53% of sites experienced an average precipitation reduction equivalent to the level expected with the target 1-in-100-year extreme drought treatment over the duration of the experiment. The right panel depicts the temporal sequence of extreme (orange) vs. moderate (grey) drought years imposed at each site (see Main text for details). Note that 21 sites imposed only three years of drought treatment, and therefore the designation for the fourth year of treatment is left empty (white). **(C)** Average productivity response to drought (moderate and extreme combined) over time for three vegetation types. Productivity response was calculated as the natural log of the ratio of productivity during drought to long-term mean productivity (*23*). For example, a productivity response of -1 equates to a change in productivity due to drought of about 63% of the long-term mean. Error bars depict 95% confidence interval and letters denote statistical differences among groups based on a linear mixed effect model and post-hoc comparison (table S3).

Fig. 2. Relationships between ecosystem productivity response to drought and drought severity across all sites (black line), and moderate (grey dots) vs. extreme (orange dots) drought intensities, for each of the four years of the experiment. Productivity response was calculated as the natural log of the ratio of productivity during drought to long-term mean productivity (*23*). Drought severity was calculated as: [mean annual precipitation (MAP) - precipitation received by drought treatment plots]/MAP (*23*). The regression across all sites was significant for all years (table S4). P-values for moderate and extreme regressions are shown in the bottom left corner of each panel (table S5): M = moderate regression, E = extreme regression, and MxE = the interaction between moderate and extreme regressions (i.e. whether the slopes differ from each other).

Fig. 3. Effects of drought duration (one to four years) on productivity responses for moderate *vs.* extreme drought intensities. (A) Despite an initial loss of productivity in in the first year, drought duration had no effect on productivity responses when drought was moderate (gray line), irrespective of whether drought was of extreme or moderate intensity in previous years. In contrast, drought duration increased productivity losses when drought was extreme (orange line), irrespective of whether previous years were extreme or moderate. Thus, an extreme drought in year four reduced productivity more than an extreme drought in year one. P-values for moderate and extreme regressions are shown in the bottom left corner of each panel (table S5): M = moderate regression, E = extreme regression, and MxE = the interaction between moderate and extreme regressions (i.e. whether the slopes differ from each other). **(B)** Drought

duration had much greater cumulative impacts on productivity if years were consecutively extreme. The slope of the relationship between time and productivity response for consecutive extreme drought was 2-fold greater than in A. Productivity responses to consecutive moderate droughts could not be assessed due to an insufficient number of sites experiencing three (n = 7) and four (n = 3; see Figure 1B) consecutive years of moderate drought. In both panels, productivity response was calculated as the natural log of the ratio of productivity during drought to long-term mean productivity (*23*), error bars depict standard error, and shading represents the 95% confidence interval of the regression. Summary statistics for the linear mixed effects model are shown in the bottom left corner: slope and p-value of the regression (tables S6 & S7).


A
180°W
120°W
60°W
0°
60°E
120°E
180°
60°N
30°N
0°
30°S
60°S
Vegetation type
Annual
Herbaceous Perennial
Woody Perennial
Landcover
Shrubland
Grassland
B
Average drought severity
0
0.25
0.50
0.75
1
gmgranite.us
sgsdrt.us
gmmolar.us
chang.cn
urat.cn
baddrt.de
capwhite.us
naposta.ar
charleville.au
youyu.cn
capmcd.us
sevblack.us
paike.ar
cobar.au
nyngan.au
antelope.us
oklah.us
scruzh.us
validate.fr
yanchi.cn
hoide.de
scruzl.us
yarradrt.au
sevmixed.us
scruzm.us
mattheis.ca
syferkuil.za
morient.ar
riomayo.ar
bfl.us
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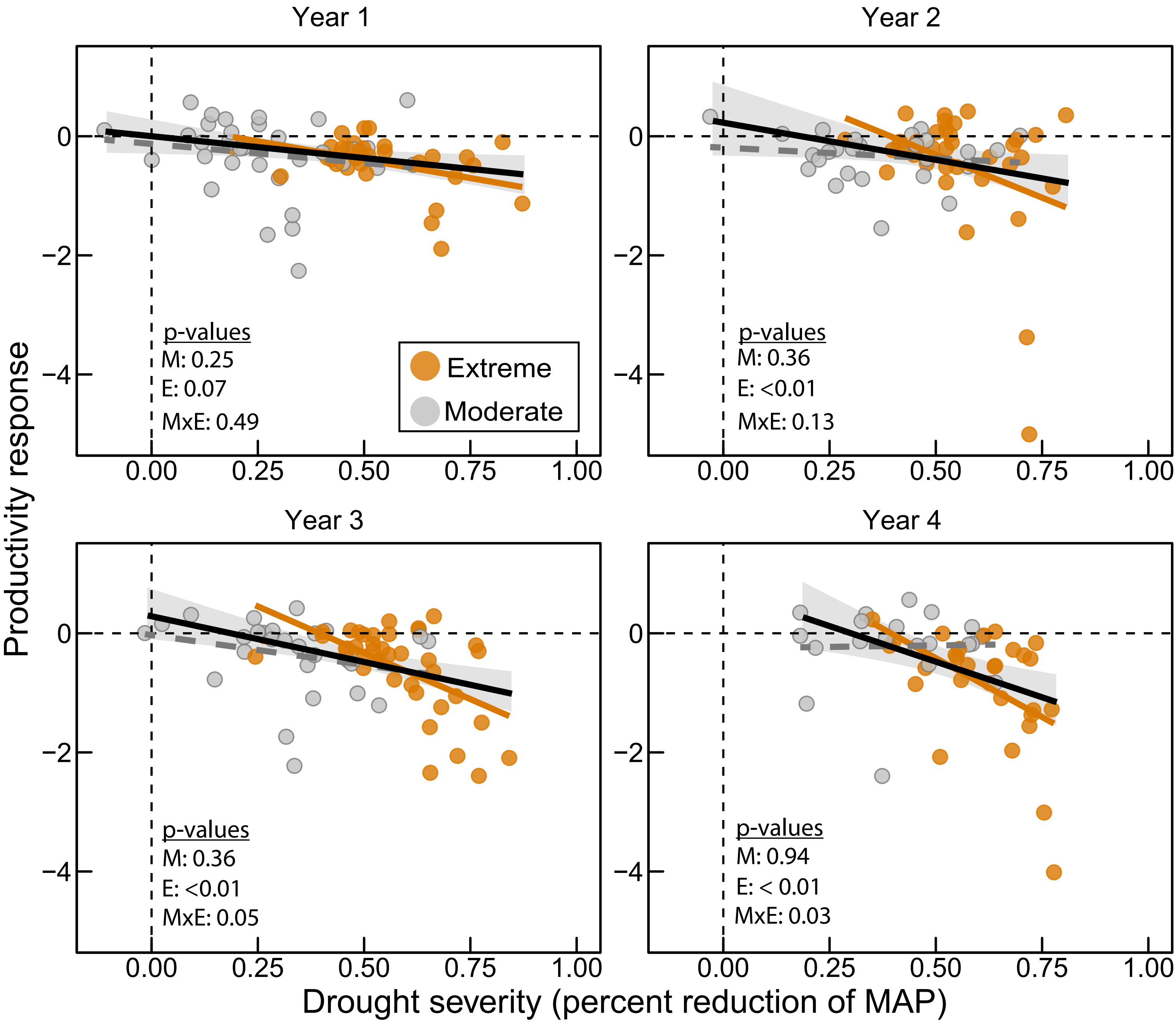
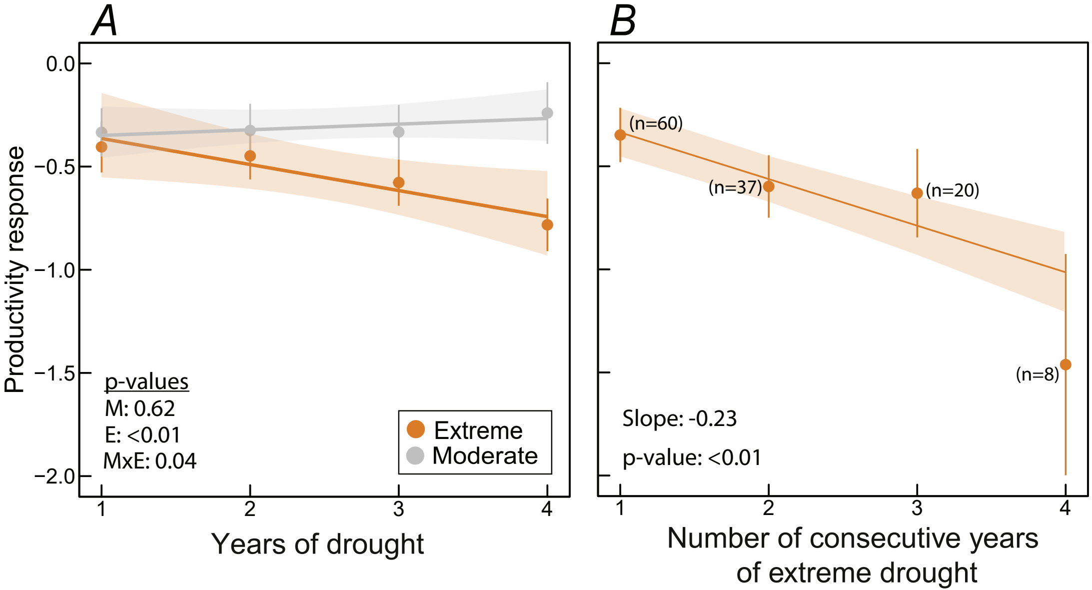
freiburg.de
hulun.cn
esw.ca
jrnchi.us
teshio.jp
passogavia.it
cedartrait.us
naqu.cn
kinsella.ca
ukulingadrt.za
bange.cn
hong.cn
biddulph.ca
matador.ca
spvdrt.ar
credom.au
rhijn.nl
credoj.au
allmendb.ch
xilin.cn
ciempoz.es
norm.cn
purdue.us
oreac.us
brookdale.ca
marcdrt.ar
kernnu.ca
allmendo.ch
hard.us
ayora.es
kernb.ca
torla.es
chilcasdrt.ar
−3
−2
−1
0
1
Avg productivity response
1
2
3
4
Treatment year
extreme year
moderate year
no data
C
Productivity response
Years of drought
2
0
−2
1
2
3
4
a,b
a
a,c
a
a,c
b
a
a,c
b
c
a
a,c
Vegetation type
Annual (n=8)
Herbaceous Perennial (n=52)
Woody Perennial (n=14)



Year 1
Year 2
Year 3
Year 4
Productivity response
Drought severity (percent reduction of MAP)
0
−2
−4
0.00
0.25
0.50
0.75
1.00
p-values
M: 0.25
E: 0.07
MxE: 0.49
Extreme
Moderate
p-values
M: 0.36
E: <0.01
MxE: 0.13
p-values
M: 0.36
E: <0.01
MxE: 0.05
p-values
M: 0.94
E: < 0.01
MxE: 0.03



A
B
0.0
−0.5
−1.0
−1.5
−2.0
Productivity response
p-values
M: 0.62
E: <0.01
MxE: 0.04
Extreme
Moderate
1
2
3
4
Years of drought
(n=60)
(n=37)
(n=20)
(n=8)
Slope: -0.23
p-value: <0.01
Number of consecutive years of extreme drought

Science
AAAS

Supplementary Materials for

Drought intensity and duration interact to magnify losses in primary productivity

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Materials and Methods

Experimental design

The International Drought Experiment (IDE) is a globally distributed network of drought experiments in grassland and shrubland ecosystems. At each site in the network, passive precipitation reduction treatments were designed to simulate a year-round, statistically extreme, 1-in-100-year drought event. This was achieved by adjusting the reduction in precipitation imposed at each site according to the mean and standard deviation based on the previous 100 years of local climate data or interpolated data from the Terrestrial Precipitation Analysis tool (*51*). This site-specific method accounted for historical precipitation patterns and variability, allowing for proportional adjustments in precipitation reduction to ensure a consistent level of historical drought severity appropriate for each site (see Fig. 1B; *29*). Drought conditions were imposed using infrastructure typical for short-statured ecosystems (*52*), consisting of open-sided shelters, each at least 2m × 2m in size, with transparent roofs constructed with strips of corrugated polycarbonate or acrylic. Three or more replicates of these shelters were established at each site, along with an equal number of unsheltered control (ambient precipitation) plots

Since precipitation was manipulated passively, achieving the target drought treatment in any given year depended on ambient precipitation. If ambient precipitation was at or below a site's mean annual precipitation (MAP) for a year of drought treatment, then the target level of 1-in-100-year drought was met or even surpassed for a particular site, and we refer to the drought treatment as "extreme". However, if ambient precipitation was above MAP for a year of drought treatment, then the target level was not met, and we refer to the drought treatment as "moderate". We based the moderate and extreme categories on well-known classification schemes of drought intensity utilized by the US Drought Monitor and NOAA (*53*), which are based on ranges of percentile statistics, as well as values for Standard Precipitation and Standardized Precipitation-Evapotranspiration Indices (SPI/SPEI). The target 1-in-100-year drought (ambient precipitation at or below MAP) is best represented by the US Drought Monitor/NOAA (*53*) "Extreme" (D3) and "Exceptional" (D4) drought intensity categories, as these encompass the 0-5% range. Our moderate category encompasses the full range of percentiles attributed to non-extreme drought in the US Drought Monitor/NOAA classification schemes (*53*): "Severe" (D2, 5-10%), "Moderate" (D1, 10-20%), "Abnormally Dry" (D0, 20-30%) and "Neither Wet or Dry" (30-70%).

Over the duration of the experiment, the reliance on ambient precipitation created sequences of moderate and extreme intensity droughts at each site, but the order of these sequences varied among sites (Fig. 1B). Across the network, some sites experienced primarily moderate droughts, while others experienced 1-, 2-, 3-, or 4-years of extreme drought. This allowed us to assess how grassland and shrubland ecosystems would respond to single or multiple sequential years of extreme drought. Because drought treatments began at different times of year across the large number of IDE sites, the first year of drought treatment was standardized as the first sampling period that included an entire growing season (median 375 days, range 200 - 565 days) after initiation of the drought treatments. This conservative cutoff for the first treatment year ensured enough time for the first treatment year to be comparable in length to the second (566 to 930 days), third (931 to 1,295 days), and fourth years (1,296 to 1,660 days) of treatment. The 74 sites included in our analyses imposed at least three consecutive years of the drought treatment.

Aboveground net primary productivity response

Aboveground net primary productivity (hereafter referred to as productivity) was estimated destructively by clipping all current year's aboveground herbaceous growth and/or non-destructively by estimating herbaceous and woody biomass allometrically using methods appropriate for each particular site (*54*). We relied on investigators to decide what measurement approach was best suited to their study system. Destructive and non-destructive measures were made at peak biomass in subplots (equal to no more than 25% of a subplot harvested each year to avoid resampling) located under each rainout shelter or in control plots at each site. For each treatment plot in each year, we quantified the productivity response to drought (hereafter referred to as productivity response) as the natural log of drought plot productivity divided by the average (at least 4 years, median 5 years) productivity in control plots. We used site averaged productivity to minimize the impacts of anomalous levels of ambient precipitation in any given year (*27,55*).

Climate data

Daily precipitation data were obtained from multiple sources. We used the highest resolution data available for each site by favoring data sources in the following order: submitted by site PI, Global Historical Climate Network (GHCN; *56*), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; *57*), and Multi-Source Weighted-Ensemble Precipitation (MSWEP; *58*).

Drought severity

Drought severity was calculated using both the percent precipitation reduction reported by site data contributors along with daily precipitation data. Drought severity was defined as the amount of rainfall that the drought treatment plots received each year expressed relative to MAP (modified from *27*).

$$Drought\ severity = \frac{MAP - 365\ day\ precip\ in\ treatment\ plots}{MAP}$$

Therefore, higher drought severity values indicate greater reductions of precipitation relative to MAP.

Statistical analyses

We used a linear mixed effects model to test productivity responses to the drought treatment over time across multiple vegetation types, with vegetation type, treatment year, and their interaction as predictor variables. IDE sites were classified into three main vegetation types based on species abundance data provided by site PIs: annual, herbaceous perennial, and woody perennial/shrubland (see table S1). To control for repeated measures at sites and geographic clustering, we used site nested within geographic region as defined by the Intergovernmental Panel on Climate Change (*31*) as random effects.

We tested for relationships between productivity responses and a broad suite of abiotic and biotic variables. We selected these variables because they have been shown to be determinants of ecosystem response to environmental perturbations, including drought: species richness (*59*), abundance of key growth forms (graminoids; *60*), soil texture (*61*), MAP (*26*), mean annual temperature (MAT; *62*), mean aridity index (*63*), interannual precipitation variability (*33*,*64*), seasonality (*65*), and previous and current year drought severity (*27,66,67*). Species richness and abundance of graminoids were obtained from site-submitted community data from the control plots. These data were available for 46 of 66 total perennial dominated sites. Sand content of soils was derived from Batjes et al. (*68*), MAP was derived from Beck et al. (*58*), aridity was calculated as MAP divided by potential evapotranspiration (*69*), interannual precipitation variability was derived from Beck et al. (*58*) and quantified as the coefficient of variation of annual precipitation over a 50-year period, and the seasonality index was calculated as the sum of the absolute value of deviations of monthly rainfall from mean monthly rainfall divided by total annual precipitation over a 50-year period as described by Walsh and Lawler (*70*). Previous and current year drought severity were quantified as the precipitation received by drought treatment plots in the previous 366-730 days and 1-365 days respectively prior to the biomass sampling period and scaled to MAP as described in the drought severity section above. For each of these variables in each treatment year, we fit linear mixed effects models predicting productivity response with each variable separately using IPCC region as a random effect. We chose to fit separate models for each variable because many of the predictor variables were correlated, and we did not expect interactions among variables. We did not explicitly correct for multiple comparisons because not all sites were represented in all models. Instead, we took a conservative approach to the interpretation of these models and focused on the explanatory power of variables relative to each other instead of their explanatory power independent of all other factors.

We used model selection to test whether the history of drought severity in prior years of the experiment had direct or interactive effects on the response of productivity for years two, three, and four of the experiment. We performed forward model selection using the stepAIC function in the MASS package (v. 7.3-58.1; *71*) beginning with the null model productivity response ~ 1. The full models tested for each year were: year 4 productivity response ~ year 4 drought severity * year 3 drought severity * year 2 drought severity * year 1 drought severity; year 3 productivity response ~ year 3 drought severity * year 2 drought severity * year 1 drought severity; year 2 productivity response ~ year 2 drought severity * year 1 drought severity. To control for geographic clustering, IPCC region was used as a random effect. This process identified a best model for years two, three, and four of the experiment (table S4).

For each year separately, we used a linear mixed effects model predicting productivity response with drought severity and extreme vs. moderate drought intensity categories to assess the impacts of drought severity on productivity response and whether there was an interaction between the continuous drought severity variable and the moderate vs. extreme categories. To control for geographic clustering, IPCC region was used as a random effect.

We tested whether productivity responses were different over the duration of the experiments by fitting a model predicting productivity response with treatment year, drought extremity, and their interaction. Sites nested within IPCC regions were used as random effects. To test the effect of consecutive years of extreme drought on productivity response, we first summarized data by categorizing each treatment period by the number of consecutive extreme drought years prior to the sampling period. For example, the sampling period in the second year of treatment would be considered two consecutive years of extreme drought only if both the first and second year of treatment were extreme. If the first year of treatment was not extreme, the sampling period in the second year of drought treatment would be categorized as a single year of extreme drought. Further, a site might have multiple entries in the same category if, for instance, the first and third year of treatment were extreme and the second year was moderate. In this case, both the first and third year of treatment for that site would be in the single consecutive year of drought category. Therefore, the number of data points in each year of treatment decreases for each consecutive year of drought treatment as the odds of consecutive years throughout the time series become less likely. With these categories defined, we used a linear mixed effects model to test whether productivity response changes with the number of consecutive years of extreme drought. Sites nested within IPCC region were set as random effects to control for multiple data points from the same site and geographic clustering.

For 49 sites for which species presence and absence data were available for both the pretreatment year and at least one treatment year, we assessed whether species gains, species losses, or changes in species richness differed between sites that experienced extreme vs. moderate drought intensities. We used the RAC_change function in the CODYN package (*72*) to calculate the number of species gained, species lost, and changes to species richness for drought and control plots relative to pretreatment values and scaled by the total number of species at the site. Next, we calculated a response ratio as drought minus control plots at each site for species losses, gains, and changes in richness. Finally, for each measure of species change, we tested the linear mixed effect model: species change response ratio ~ extreme vs moderate * number of treatment years. Site nested within IPCC region were set as random effects to control for multiple data points from the same site and geographic clustering. We used the same subset of 49 sites with species presence and absence data (pretreatment and during drought treatments) to test whether sites with more species losses incurred greater productivity response. For each of the four treatment years, we analyzed the data with a linear mixed effects model: productivity response ~ species losses. IPCC region was set as a random effect to account for multiple sites within the same region.

Data transformations, statistical analyses, and data visualization were performed with R (v. 4.2.2; *73*) including the tidyverse package (v. 2.0.0; *74*). Mixed effects models were created using the nlme package (v. 3.1-160; *75*) and the emmeans package (*76*) was used for summarization of those models.

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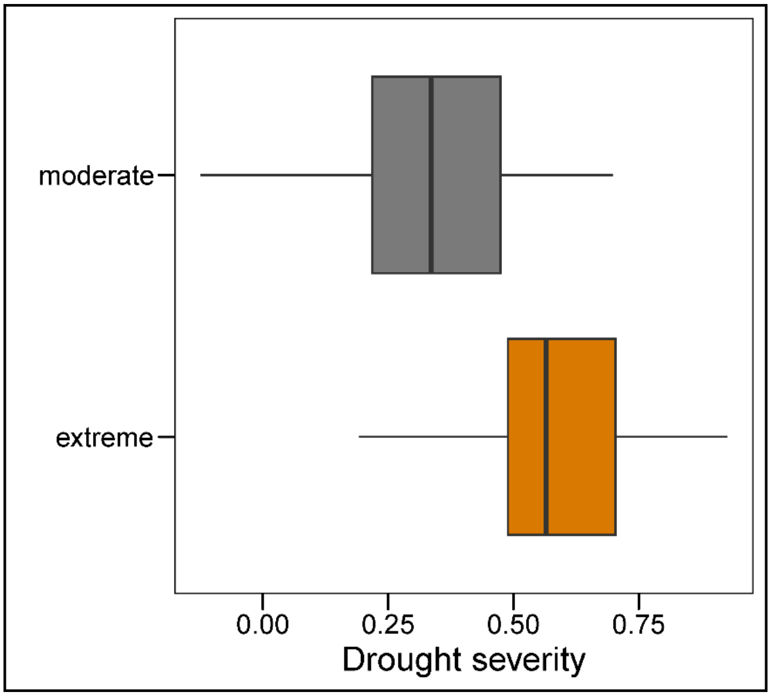

Fig S1. Drought severity (*23*) for moderate and extreme droughts, averaged across 74 International Drought Experiment (IDE) sites and all years of the experiment. Solid, vertical line denotes median. Boxes and whiskers denote percentiles of data in 25% increments. Drought severity was statistically different for the two categories of drought intensity ($p < 0.001$). Mean drought severity was 0.36 for the moderate and 0.58 for extreme drought intensity categories.

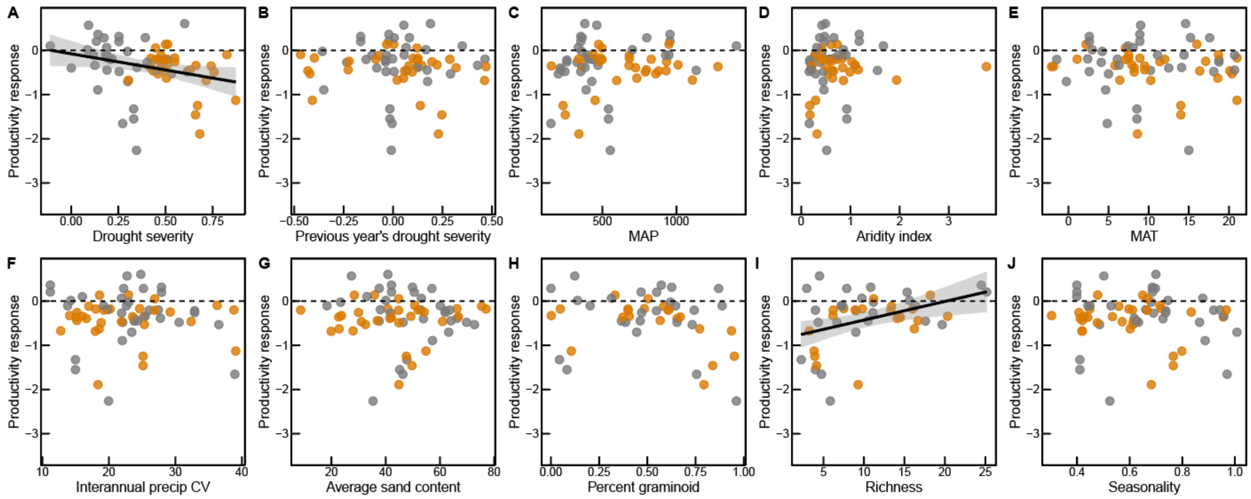

Fig. S2. Relationships between productivity response to the first year of drought and abiotic and biotic environmental variables. Orange points denote sites that experienced extreme drought, grey points denote sites that experienced moderate drought. Solid regression lines denote significant slopes in the model for that variable (see table S2).

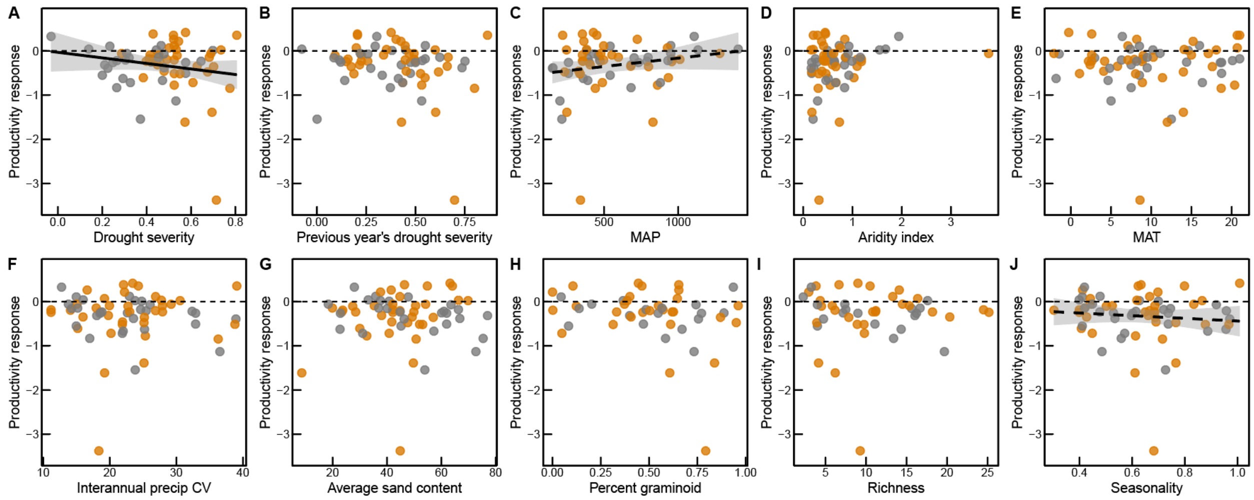

Fig. S3. Relationships between productivity response to the second year of drought and abiotic and biotic environmental variables. Orange points denote sites that experienced extreme drought, grey points denote sites that experienced moderate drought. Solid regression lines denote significant slopes in the model for that variable (see table S2), and dashed regression lines denote marginal significance in the model (0.10 > p > 0.05).

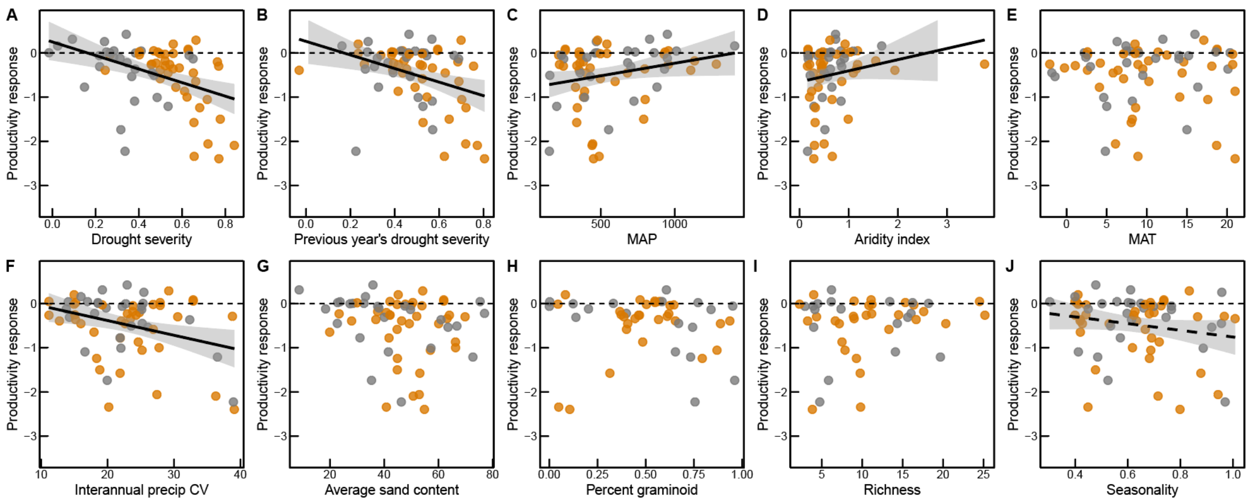

Fig. S4. Relationships between productivity response to the third year of drought and abiotic and biotic environmental variables. Orange points denote sites that experienced extreme drought, grey points denote sites that experienced moderate drought. Solid regression lines denote significant slopes in the model for that variable (see table S2), and dashed regression lines denote marginal significance in the model (0.10 > p > 0.05).

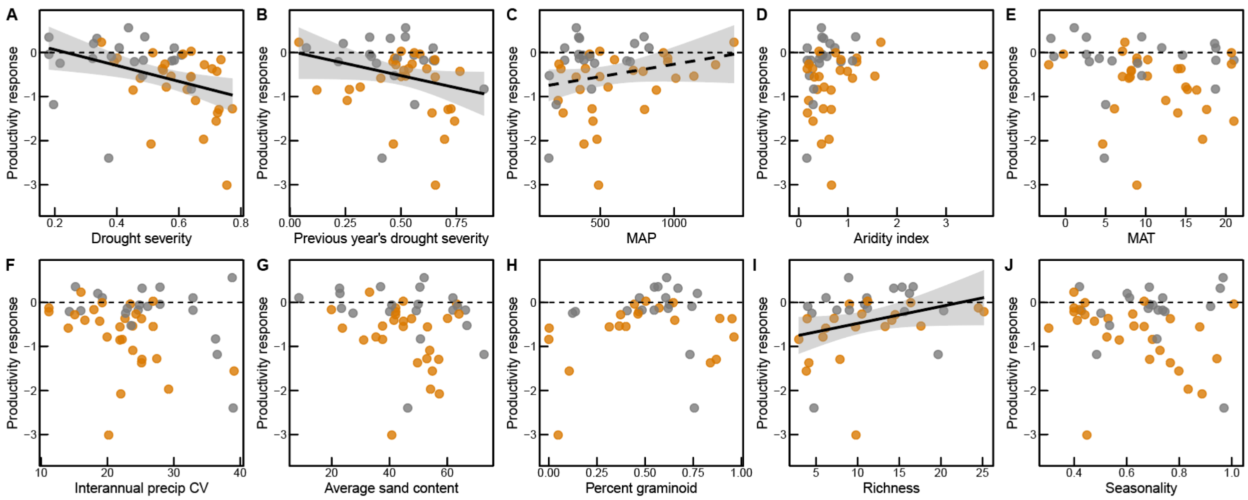

Fig. S5. Relationships between productivity response to the fourth year of drought and abiotic and biotic environmental variables. Orange points denote sites that experienced extreme drought, grey points denote sites that experienced moderate drought. Solid regression lines denote significant slopes in the model for that variable (see table S2), and dashed regression lines denote marginal significance in the model (0.10 > p > 0.05).

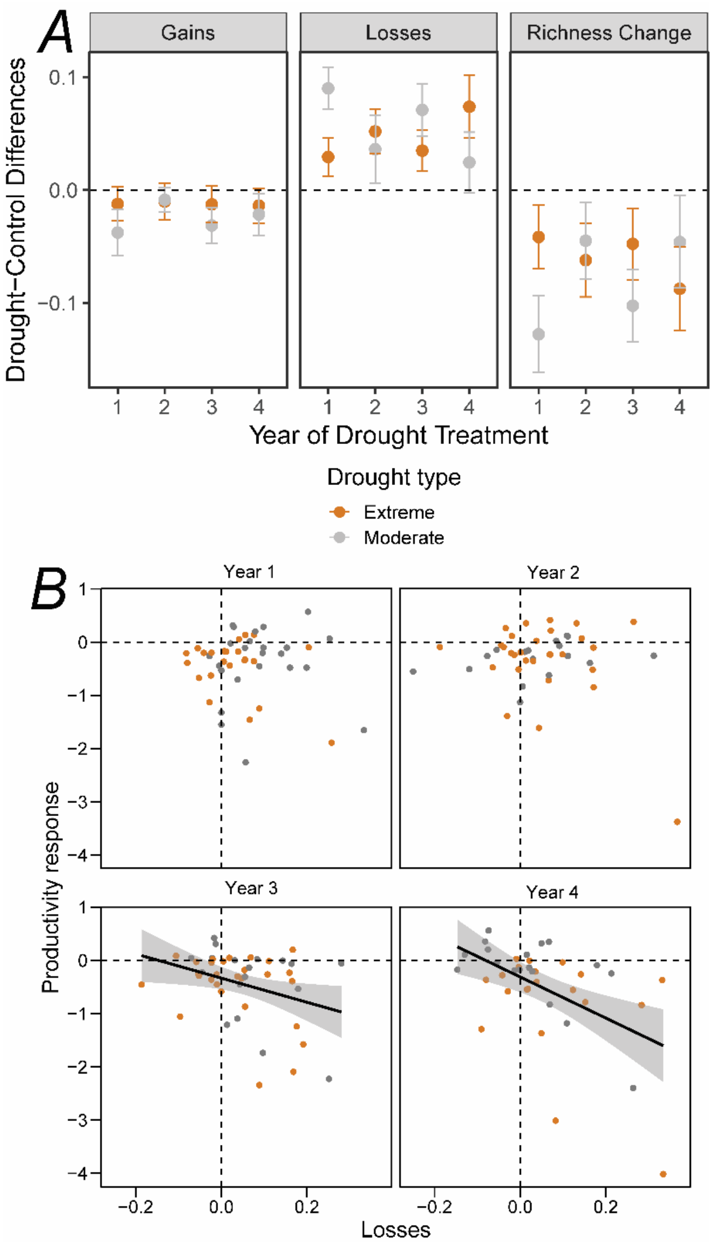

Fig S6. A) Species gains, losses, and changes in richness with drought for the 49 International Drought Experiment (IDE) sites for which pretreatment and species presence/absence data were available. Gains, losses, and richness change are expressed as a fraction of the total species at the sites, and the y-axis is expressed as the difference between drought and control plots (*23*). Averages across sites are separated by the intensity of drought treatment compared to historical values (*i.e.,* extreme or moderate, see Main text). Species gains, losses, or richness change did not significantly differ between the drought extremity categories or over time (tables S8, S9). B) Relationships between species losses and productivity response for 49 IDE sites for which pretreatment and species data were available. Each panel shows a different year of the drought treatment (one through four) and regression lines are only shown where significant (table S10).

Table S1. Summary of 74 IDE sites in this study. Information provided includes the site name, site codes that combine the site names and two-letter country codes, two-letter country codes, continent, vegetation type, latitude (decimal), longitude (decimal), mean annual precipitation (MAP; mm), mean annual temperature (MAT; °C), target proportion of annual precipitation reduced over the duration of the experiment (Target reduction), and average actual proportion of precipitation reduced over the duration of the experiment (Actual reduction).

Site name	Site code	Country	Continent	Vegetation type	Latitude	Longitude	MAP	MAT	Target reduction	Actual reduction
Allmend Brachy	allmendb.ch	CH	Europe	Herbaceous.Perennial	46.7457	7.5885	957	8.9	0.32	0.35
Allmend Ovina	allmendo.ch	CH	Europe	Herbaceous.Perennial	46.7457	7.5885	957	8.9	0.33	0.36
Antelope	antelope.us	US	North America	Herbaceous.Perennial	35.584	-111.513	215	12.5	0.50	0.32
Ayora Experimental Station	ayora.es	ES	Europe	Woody.Perennial	39.11532	-0.95025	381	14.6	0.75	0.67
Bad Drought	baddrt.de	DE	Europe	Herbaceous.Perennial	51.39214	11.87797	489	8.9	0.55	0.55
GCN-Bange	bange.cn	CN	Asia	Herbaceous.Perennial	31.38333	90.2333	428	-0.3	0.50	0.52
Bayreuth_DroughtNet	bayrdrt.de	DE	Europe	Herbaceous.Perennial	49.922	11.5838	724	8.2	0.40	0.47
BFL	bfl.us	US	North America	Herbaceous.Perennial	30.28401	-97.7787	861	20.4	0.50	0.42
Biddulph	biddulph.ca	CA	North America	Herbaceous.Perennial	51.9098	-106.716	354	2.6	0.48	0.39
Brookdale	brookdale.ca	CA	North America	Herbaceous.Perennial	50.051	-99.92	474	2.2	0.32	0.31
McDowell Mountain	capmcd.us	US	North America	Annual	33.64434	-111.72	204	24.0	0.66	0.59
White Tank Mountain	capwhite.us	US	North America	Annual	33.60439	-112.498	204	24.0	0.66	0.55
Cedar Creek Savanna	cedarsav.us	US	North America	Herbaceous.Perennial	45.39715	-93.1803	682	7.5	0.43	0.34
Cedar Creek Trait	cedartrait.us	US	North America	Herbaceous.Perennial	45.40268	-93.1892	682	7.5	0.43	0.33
Los Cerrillos	cerrillos.ar	AR	South America	Woody.Perennial	-29.9503	-65.8736	390	21.0	0.50	0.51
Chacra Experimental Patagones	chacra.ar	AR	South America	Woody.Perennial	-40.7231	-62.8989	400	14.4	0.50	0.40
Changling	chang.cn	CN	Asia	Herbaceous.Perennial	44.75	123.75	445	6.1	0.70	0.68
Charleville	charleville.au	AU	Australia	Herbaceous.Perennial	-26.36	146.15	451	21.0	0.65	0.79
Las Chilcas Drt	chilcasdrt.ar	AR	South America	Herbaceous.Perennial	-36.1632	-58.1556	950	16.0	0.50	0.44
Ciempozuelos	ciempoz.es	ES	Europe	Woody.Perennial	40.1899	-3.60139	364	15.2	0.44	0.45
Cobar	cobar.au	AU	Australia	Annual	-31.77	145.56	354	18.9	0.65	0.74
Cowichan Drt	cowidrt.ca	CA	North America	Herbaceous.Perennial	48.8083	-123.632	1134	10.2	0.50	0.50
CredoJ	credoj.au	AU	Australia	Woody.Perennial	-30.47	120.81	260	18.8	0.60	0.57
CredoM	credom.au	AU	Australia	Woody.Perennial	-30.47	120.81	260	18.8	0.60	0.57
EE Elva	elvadrt.ee	EE	Europe	Herbaceous.Perennial	58.25921	26.35527	680	5.8	0.62	0.63
ESW	esw.ca	CA	North America	Herbaceous.Perennial	43.08	-81.34	1012	7.9	0.45	0.47
Freiburg	freiburg.de	DE	Europe	Herbaceous.Perennial	48.01985	7.82738	934	11.4	0.35	0.47
Granite Cover	gmgranite.us	US	North America	Annual	34.77741	-115.652	220	29.3	0.66	0.83
Molar Junction	gmmolar.us	US	North America	Annual	34.77749	-115.646	220	29.3	0.66	0.82
Hardware Ranch	hard.us	US	North America	Woody.Perennial	41.61472	-111.567	462	9.0	0.47	0.31
HOIDE	hoide.de	DE	Europe	Woody.Perennial	54.5504	13.1039	541	8.5	0.40	0.36
GCN-Hongyuan	hong.cn	CN	Asia	Herbaceous.Perennial	32.83	102.58	703	3.0	0.50	0.27
GCN-Hulunber	hulun.cn	CN	Asia	Herbaceous.Perennial	49.333	119.9516	360	-1.8	0.50	0.38
HYIDE	hyide.de	DE	Europe	Woody.Perennial	54.5515	13.1016	541	8.5	0.40	0.37
Jena	jenadrt.de	DE	Europe	Herbaceous.Perennial	50.93778	11.53036	597	10.3	0.66	0.70

JRN_Chihuahuan	jrnchi.us	US	North America	Woody.Perennial	32.54978	-106.77	247	18.1	0.70	0.71
Kernen_burned	kernb.ca	CA	North America	Herbaceous.Perennial	52.16978	-106.531	354	2.6	0.48	0.31
Kernen_unburned	kernnu.ca	CA	North America	Herbaceous.Perennial	52.16973	-106.531	354	2.6	0.48	0.31
Kinsella	kinsella.ca	CA	North America	Herbaceous.Perennial	53.03	-111.56	406	2.4	0.45	0.32
Konza	konzadrt.us	US	North America	Herbaceous.Perennial	39.10688	-96.6091	830	12.0	0.60	0.38
Mar Chiquita Drt	marcdrt.ar	AR	South America	Herbaceous.Perennial	-37.7152	-57.4245	928	20.7	0.50	0.43
Matador	matador.ca	CA	North America	Herbaceous.Perennial	50.7	-107.73	358	4.2	0.48	0.37
Mattheis	mattheis.ca	CA	North America	Herbaceous.Perennial	50.9	-111.88	329	4.1	0.55	0.48
Monte Oriental	morient.ar	AR	South America	Woody.Perennial	-39.683	-64.8543	383	14.1	0.47	0.50
Naposta	naposta.ar	AR	South America	Herbaceous.Perennial	-38.4239	-62.2879	553	15.0	0.44	0.42
GCN-Naqu	naqu.cn	CN	Asia	Herbaceous.Perennial	31.6437	92.0097	430	-1.4	0.50	0.36
Northeast Normal	norm.cn	CN	Asia	Herbaceous.Perennial	44.57	123.52	470	6.3	0.41	0.22
Nyngan	nyngan.au	AU	Australia	Herbaceous.Perennial	-31.64	146.65	441	18.7	0.65	0.77
Oklahoma (KAEFS-OK)	oklah.us	US	North America	Herbaceous.Perennial	34.98	-97.53	880	16.4	0.43	0.34
ORE IDE AA	oreaa.us	US	North America	Woody.Perennial	42.184	-121.015	497	7.1	0.41	0.53
ORE IDE AC	oreac.us	US	North America	Woody.Perennial	42.183	-121.015	497	7.1	0.41	0.53
Potrok Aike Drt	paike.ar	AR	South America	Herbaceous.Perennial	-51.916	-70.4074	202	5.0	0.54	0.45
Passo Gavia	passogavia.it	IT	Europe	Herbaceous.Perennial	46.35391	10.48934	1281	-2.1	0.43	0.48
Purdue Wildlife Area	purdue.us	US	North America	Herbaceous.Perennial	40.4457	-87.0505	950	11.1	0.40	0.27
Rhijnauwen	rhijn.nl	NL	Europe	Herbaceous.Perennial	52.07352	5.175666	797	9.5	0.51	0.53
Rio Mayo	riomayo.ar	AR	South America	Woody.Perennial	-45.3977	-70.3059	155	9.5	0.67	0.54
SantaCruzHigh	scruzh.us	US	North America	Annual	37.02	-122.08	745	13.9	0.60	0.25
SantaCruzLow	scruzl.us	US	North America	Annual	36.95269	-122.064	745	13.9	0.60	0.78
SantaCruzMiddle	scruzm.us	US	North America	Annual	36.95269	-122.064	745	13.9	0.60	0.35
Sevilleta_Black	sevblack.us	US	North America	Herbaceous.Perennial	34.33752	-106.691	249	14.0	0.66	0.68
Sevilleta_Mixed	sevmixed.us	US	North America	Herbaceous.Perennial	34.35984	-106.691	234	14.0	0.66	0.67
Shortgrass Steppe Drt	sgsdrt.us	US	North America	Herbaceous.Perennial	40.80528	-104.715	341	8.6	0.66	0.71
SLP	slp.us	US	North America	Herbaceous.Perennial	30.0849	-97.1723	931	20.1	0.50	0.38
San Pablo Valdes Drt	spvdrt.ar	AR	South America	Herbaceous.Perennial	-42.6537	-64.1716	221	20.7	0.50	0.45
Syferkuil (DroughtAct Limpopo)	syferkuil.za	ZA	Africa	Herbaceous.Perennial	-23.8499	29.70066	478	17.1	0.66	0.63
Teshio Experimental Grassland	teshio.jp	JP	Asia	Herbaceous.Perennial	44.91819	142.0195	1108	6.4	0.25	0.17
Torla	torla.es	ES	Europe	Herbaceous.Perennial	42.651	-0.06553	1405	7.4	0.20	0.10
Ukulinga IDE	ukulingadrt.za	ZA	Africa	Herbaceous.Perennial	-29.6705	30.40135	733	18.6	0.50	0.33
GCN-Urat	urat.cn	CN	Asia	Herbaceous.Perennial	41.41667	106.9667	152	4.8	0.50	0.30
Validate	validate.fr	FR	Europe	Herbaceous.Perennial	45.72222	3.022222	790	8.2	0.68	0.73
GCN-Xilinhot	xilin.cn	CN	Asia	Herbaceous.Perennial	43.54959	116.7434	338	1.1	0.50	0.50
GCN-Yanchi	yanchi.cn	CN	Asia	Herbaceous.Perennial	37.31	106.93	337	8.1	0.50	0.51

Yarramundi Drt	yarradrt.au	AU	Australia	Herbaceous.Perennial	-33.6136	150.7381	800	17.6	0.65	0.58
GCN-Youyu	youyu.cn	CN	Asia	Herbaceous.Perennial	39.98806	112.3216	390	4.6	0.50	0.40

Table S2. Summary of models using abiotic and biotic environmental variables to predict productivity response in each of the four years of drought treatment. Int = intercept; Drt. Sev = drought severity; Prev Yr Drt. Sev = Previous Year's Drought Severity; MAP = mean annual precipitation; AI = aridity index; MAT = mean annual temperature; CV = coefficient of variation of precipitation; Sand = average percentage soil sand content; Prop Gram = average proportion of total cover attributable to all graminoids; Seasonality = seasonality of precipitation. See *23*.

Year 1						
	Est.	SE	t	p	R2m	R2c
Int	-0.08	0.14	-0.54	0.59	0.08	0.08
Drt. Sev	-0.73	0.32	-2.31	**0.03**		
Int	-0.37	0.07	-5.35	<0.01	0.001	0.001
Prev Yr Drt. Sev	-0.08	0.31	-0.25	0.8		
Int	-0.58	0.15	-3.84	<0.01	0.04	0.07
MAP	0.0004	0.0002	1.57	0.12		
Int	-0.43	0.11	-3.92	<0.01	0.007	0.007
AI	0.09	0.13	0.69	0.49		
Int	-0.31	0.13	-2.42	0.02	0.005	0.005
MAT	-0.01	0.01	-0.55	0.59		
Int	-0.25	0.24	-1.03	0.31	0.004	0.004
CV	-0.01	0.01	-0.53	0.6		
Int	-0.3	0.23	-1.32	0.19	0.002	0.002
Sand	-0.001	0.005	-0.35	0.73		
Int	-0.13	0.18	-0.72	0.48	0.05	0.07
Prop Gram	-0.48	0.32	-1.49	0.15		
Int	-0.81	0.16	-4.9	<0.01	0.17	0.17
Richness	0.04	0.01	3.02	**<0.01**		
Int	-0.22	0.25	-0.87	0.39	0.01	0.01
Seasonality	-0.23	0.39	-0.60	0.55		
Year 2						
Int	0.39	0.3	1.31	0.19	0.1	0.24
Drt. Sev	-1.59	0.57	-2.79	**<0.01**		
Int	-0.09	0.22	-0.37	0.72	0.03	0.1
Prev Yr Drt. Sev	-0.75	0.49	-1.53	0.13		
Int	-0.73	0.23	-3.21	<0.01	0.05	0.16
MAP	0.001	0.0004	1.83	0.07		
Int	-0.56	0.17	-3.35	<0.01	0.03	0.12
AI	0.28	0.19	1.48	0.14		
Int	-0.64	0.2	-2.29	0.03	0.004	0.07
MAT	0.01	0.02	0.49	0.63		
Int	-0.14	0.37	-0.38	0.71	0.01	0.08
CV	-0.01	0.02	-0.68	0.5		

Int	-0.33	0.34	-0.99	0.33	0.001	0.06
Sand	-0.001	0.01	-0.18	0.86		
Int	-0.07	0.13	-0.55	0.59	0.04	0.05
Prop Gram	-0.33	0.24	-1.39	0.18		
Int	-0.19	0.13	-1.42	0.17	0.004	0.004
Richness	-0.005	0.01	-0.43	0.67		
Int	0.29	0.39	0.74	0.46	0.05	0.12
Seasonality	-1.04	0.59	-1.78	0.08		
Year 3						
Int	0.19	0.22	0.88	0.39	0.14	0.44
Drt. Sev	-1.4	0.4	-3.48	**<0.01**		
Int	0.23	0.25	0.92	0.36	0.1	0.47
Prev Yr Drt. Sev	-1.43	0.45	-3.2	**<0.01**		
Int	-0.93	0.2	-4.75	<0.01	0.12	0.55
MAP	0.001	0.0002	3.31	**<0.01**		
Int	-0.71	0.16	-4.44	<0.01	0.07	0.47
AI	0.36	0.15	2.48	**0.02**		
Int	-0.47	0.2	-2.32	0.02	<0.01	0.4
MAT	<0.01	0.02	0.06	0.95		
Int	0.41	0.31	1.3	0.2	0.12	0.45
CV	-0.04	0.01	-3.01	**<0.01**		
Int	-0.17	-0.28	-0.6	0.56	0.02	0.4
Sand	-0.01	0.01	-1.29	0.2		
Int	-0.48	0.21	-2.22	0.04	0.0003	0.41
Prop Gram	0.05	0.33	0.13	0.89		
Int	-0.67	0.2	-3.26	<0.01	0.03	0.44
Richness	0.02	0.02	1.37	0.18		
Int	0.28	0.39	0.70	0.49	0.07	0.46
Seasonality	-1.10	0.55	-1.99	0.05		
Year 4						
Int	0.68	0.4	1.7	0.1	0.19	0.19
Drt. Sev	-2.39	0.72	-3.32	**<0.01**		
Int	0.15	0.37	0.51	0.69	0.09	0.09
Prev Yr Drt. Sev	-1.48	0.69	-2.15	**0.04**		
Int	-1.01	0.27	-3.79	<0.01	0.07	0.1
MAP	0.001	0.0004	1.83	0.08		
Int	-0.78	0.19	-4.12	<0.01	0.04	0.04
AI	0.3	0.22	1.34	0.19		
Int	-0.44	0.24	-1.85	0.07	0.01	0.01
MAT	-0.01	0.02	-0.74	0.46		
Int	-0.14	0.46	-0.3	0.77	0.02	0.02
CV	-0.02	0.02	-1.04	0.31		

Int	-0.09	0.44	-0.21	0.83	0.03	0.03
Sand	-0.01	0.01	-1.21	0.24		
Int	-0.65	0.28	-2.37	0.03	0.02	0.06
Prop Gram	0.44	0.47	0.94	0.36		
Int	-0.89	0.26	-3.41	<0.01	0.12	0.27
Richness	0.04	0.02	2.17	**0.04**		
Int	-0.12	0.47	-0.26	0.80	0.02	0.02
Seasonality	-0.72	0.70	-1.03	0.31		

Table S3. Pairwise contrasts between each unique combination of three vegetation types (annual, herbaceous perennial, woody perennial) and treatment year. Results correspond to Figure 1C. See *23*.

contrast	estimate	SE	df	t.ratio	p.value
year 1 Annual - years 2 Annual	2.08	0.36	192	5.78	<0.01
year 1 Annual - year 3 Annual	1.41	0.36	192	3.92	0.01
year 1 Annual - year 4 Annual	-1.9	0.46	192	-4.17	0
year 1 Annual - year 1 Herbaceous perennial	-0.26	0.34	53	-0.77	1
year1 Annual - year 2 Herbaceous perennial	-0.19	0.34	53	-0.57	1
year 1 Annual - year 3 Herbaceous perennial	-0.12	0.34	53	-0.36	1
year 1 Annual - year 4 Herbaceous perennial	-0.04	0.34	53	-0.12	1
year 1 Annual - year 1 Woody perennial	-0.41	0.4	53	-1.03	1
year 1 Annual - year 2 Woody perennial	-0.52	0.4	53	-1.32	0.97
year 1 Annual - year 3 Woody perennial	-0.4	0.4	53	-1.01	1
year 1 Annual - year 4 Woody perennial	-0.33	0.42	53	-0.78	1
year 2 Annual - year 3 Annual	-0.67	0.36	192	-1.86	0.78
year 2 Annual - year 4 Annual	-3.98	0.46	192	-8.74	<0.01
year 2 Annual - year 1 Herbaceous perennial	-2.34	0.34	53	-6.91	<0.01
year 2 Annual - year 2 Herbaceous perennial	-2.27	0.34	53	-6.71	<0.01
year 2 Annual - year 3 Herbaceous perennial	-2.2	0.34	53	-6.51	<0.01
year 2 Annual - year 4 Herbaceous perennial	-2.12	0.34	53	-6.16	<0.01
year 2 Annual - year 1 Woody perennial	-2.49	0.4	53	-6.29	<0.01
year 2 Annual - year 2 Woody perennial	-2.6	0.4	53	-6.58	<0.01
year 2 Annual - year 3 Woody perennial	-2.48	0.4	53	-6.27	<0.01
year 2 Annual - year 4 Woody perennial	-2.41	0.42	53	-5.77	<0.01
year 3 Annual - year 4 Annual	-3.31	0.46	192	-7.27	<0.01
year 3 Annual - year 1 Herbaceous perennial	-1.67	0.34	53	-4.94	0
year 3 Annual - year 2 Herbaceous perennial	-1.61	0.34	53	-4.74	0
year 3 Annual - year 3 Herbaceous perennial	-1.54	0.34	53	-4.53	0
year 3 Annual - year 4 Herbaceous perennial	-1.45	0.34	53	-4.22	0
year 3 Annual - year 1 Woody perennial	-1.82	0.4	53	-4.6	0
year 3 Annual - year 2 Woody perennial	-1.93	0.4	53	-4.89	0
year 3 Annual - year 3 Woody perennial	-1.81	0.4	53	-4.58	0
year 3 Annual - year 4 Woody perennial	-1.74	0.42	53	-4.17	0.01
year 4 Annual - year 1 Herbaceous perennial	1.64	0.44	53	3.74	0.02
year 4 Annual - year 2 Herbaceous perennial	1.71	0.44	53	3.89	0.01
year 4 Annual - year 3 Herbaceous perennial	1.78	0.44	53	4.05	0.01
year 4 Annual - year 4 Herbaceous perennial	1.86	0.44	53	4.19	0.01
year 4 Annual - year 1 Woody perennial	1.49	0.48	53	3.09	0.11
year 4 Annual - year 2 Woody perennial	1.38	0.48	53	2.85	0.19
year 4 Annual - year 3 Woody perennial	1.5	0.48	53	3.11	0.11
year 4 Annual - year 4 Woody perennial	1.57	0.5	53	3.14	0.1

year 1 Herbaceous perennial - year 2 Herbaceous perennial	0.07	0.14	192	0.48	1
year 1 Herbaceous perennial - year 3 Herbaceous perennial	0.14	0.14	192	0.97	1
year 1 Herbaceous perennial - year 4 Herbaceous perennial	0.22	0.15	192	1.41	0.96
year 1 Herbaceous perennial - year 1 Woody perennial	-0.15	0.27	53	-0.55	1
year 1 Herbaceous perennial - year 2 Woody perennial	-0.26	0.27	53	-0.97	1
year 1 Herbaceous perennial - year 3 Woody perennial	-0.14	0.27	53	-0.51	1
year 1 Herbaceous perennial - year 4 Woody perennial	-0.07	0.3	53	-0.22	1
year 2 Herbaceous perennial - year 3 Herbaceous perennial	0.07	0.14	192	0.49	1
year 2 Herbaceous perennial - year 4 Herbaceous perennial	0.15	0.15	192	0.97	1
year 2 Herbaceous perennial - year 1 Woody perennial	-0.21	0.27	53	-0.8	1
year 2 Herbaceous perennial - year 2 Woody perennial	-0.33	0.27	53	-1.22	0.98
year 2 Herbaceous perennial - year 3 Woody perennial	-0.2	0.27	53	-0.76	1
year 2 Herbaceous perennial - year 4 Woody perennial	-0.13	0.3	53	-0.45	1
year 3 Herbaceous perennial - year 4 Herbaceous perennial	0.08	0.15	192	0.52	1
year 3 Herbaceous perennial - year 1 Woody perennial	-0.28	0.27	53	-1.06	1
year 3 Herbaceous perennial - year 2 Woody perennial	-0.4	0.27	53	-1.48	0.94
year 3 Herbaceous perennial - year 3 Woody perennial	-0.27	0.27	53	-1.02	1
year 3 Herbaceous perennial - year 4 Woody perennial	-0.2	0.3	53	-0.68	1
year 4 Herbaceous perennial - year 1 Woody perennial	-0.37	0.28	53	-1.32	0.97
year 4 Herbaceous perennial - year 2 Woody perennial	-0.48	0.28	53	-1.74	0.84
year 4 Herbaceous perennial - year 3 Woody perennial	-0.36	0.28	53	-1.29	0.98
year 4 Herbaceous perennial - year 4 Woody perennial	-0.28	0.31	53	-0.93	1
year 1 Woody perennial - year 2 Woody perennial	-0.11	0.27	192	-0.42	1
year 1 Woody perennial - year 3 Woody perennial	0.01	0.27	192	0.03	1
year 1 Woody perennial - year 4 Woody perennial	0.08	0.3	192	0.26	1
year 2 Woody perennial - year 3 Woody perennial	0.12	0.27	192	0.45	1
year 2 Woody perennial - year 4 Woody perennial	0.19	0.3	192	0.64	1
year 3 Woody perennial - year 4 Woody perennial	0.07	0.3	192	0.23	1

Table S4. Summary of results from model selection process. The Year column denotes the year of the experiment in which productivity (ANPP) was collected, the Winning model column denotes the model chosen through the model selection process described in the Methods. Estimate, SE, df, t-value, and p-value denote the model results for drought severity for each of the winning models. R^2m and R^2c denote the marginal and conditional r-squared for each model, respectively.

Year	Winning model	Estimate	SE	df	t-value	p-value	R^2m	R^2c
4	ANPP response ~ Drought severity in year 4	-2.39	0.72	32	-3.32	<0.01	0.19	0.19
3	ANPP response ~ Drought severity in year 3	-1.40	0.40	46	-3.50	<0.01	0.15	0.42
2	ANPP response ~ Drought severity in year 2	-1.56	0.57	46	-2.74	<0.01	0.10	0.23

Table S5. Summary of model results predicting productivity response with drought severity. Main effects refer to the slope of the drought severity-productivity response relationship for sites experiencing either extreme or moderate drought in a given year. Extreme-Moderate contrasts assess whether the slopes of the main effects differed from one another. These statistics correspond to results shown in Figure 2. Bolded p-values indicate significance at α ≤ 0.05. See *23*.

Year	Main effect or contrast	Estimate	SE	df	t.ratio	p-value
1	Extreme	-1.235	0.657	44	-1.877	0.067
1	Moderate	-0.638	0.551	44	-1.158	0.253
1	Extreme-Moderate	-0.596	0.858	44	-0.695	0.490
2	Extreme	-3.064	1.101	44	-2.783	**0.007**
2	Moderate	-0.840	0.904	44	-0.928	0.358
2	Extreme-Moderate	-2.224	1.458	44	-1.525	0.134
3	Extreme	-3.004	0.731	44	-4.108	**0.001**
3	Moderate	-0.694	0.744	44	-0.933	0.355
3	Extreme-Moderate	-2.309	1.119	44	-2.062	**0.045**
4	Extreme	-3.954	1.222	30	-3.235	**0.002**
4	Moderate	0.099	1.208	30	0.082	0.935
4	Extreme-Moderate	-4.053	1.718	30	-2.358	**0.025**

Table S6. Summary of model predicting productivity response with the number of treatment years and whether drought was categorized as extreme vs. moderate. These statistics correspond to results shown in Figure 3A. See Main text and *23* for details.

Main effect or contrast	Estimate	SE	df	t.ratio	pvalue
Extreme	-0.127	0.048	178	-2.61	**<0.01**
Moderate	0.026	0.052	178	0.492	0.62
Extreme x Moderate	-0.153	0.074	178	-2.046	**0.04**

Table S7. Summary of model predicting productivity response with the number of consecutive extreme drought years. These statistics correspond to results shown in Figure 3B.

	Estimate	SE	df	t.value	p.value	R^2m	R^2c
Intercept	-0.11	0.16	64	-0.7	0.48	0.06	0.41
Number of continuous extreme years	-0.23	0.07	64	-3.31	**<0.01**		

Table S8. Summary of model contrasting three metrics of species change (species gains, species losses, and richness changes) for the extreme and moderate drought categories in each of the four drought years. These statistics correspond to results shown in Figure S6A. See *23*.

Metric	Model term	Value	Std.Error	DF	t-value	p-value
Species gains	(Intercept)	-0.01552	0.014444	122	-1.07473	0.28
	Moderate	-0.01877	0.017164	122	-1.09371	0.28
	Year 2	0.009319	0.015153	122	0.614959	0.54
	Year 3	0.006696	0.01582	122	0.423258	0.67
	Year 4	-0.0112	0.017019	122	-0.6583	0.51
	Moderate:Year 2	0.009718	0.024394	122	0.398382	0.69
	Moderate:Year 3	-0.00451	0.025444	122	-0.17717	0.86
	Moderate:Year 4	0.028821	0.025341	122	1.137311	0.26
Species losses	(Intercept)	0.042577	0.019916	122	2.137868	0.036
	Moderate	0.031999	0.025595	122	1.250237	0.216
	Year 2	0.003363	0.022832	122	0.147313	0.886
	Year 3	-0.00517	0.023732	122	-0.21803	0.83
	Year 4	0.029746	0.025588	122	1.162491	0.25
	Moderate:Year 2	-0.03302	0.036472	122	-0.90542	0.37
	Moderate:Year 3	-0.00573	0.037802	122	-0.15162	0.88
	Moderate:Year 4	-0.08168	0.037913	122	-2.15439	**0.033**
Richness Change	(Intercept)	-0.06006	0.029387	122	-2.04387	0.043
	Moderate	-0.04664	0.035753	122	-1.30449	0.19
	Year 2	0.008698	0.031639	122	0.274909	0.78
	Year 3	0.013722	0.032998	122	0.415856	0.68
	Year 4	-0.0383	0.035518	122	-1.07827	0.28
	Moderate:Year 2	0.0369	0.050845	122	0.72574	0.47
	Moderate:Year 3	-0.0021	0.052957	122	-0.03962	0.97
	Moderate:Year 4	0.10585	0.052828	122	2.003682	**0.047**

Table S9. Summary of model contrasting three metrics of species change (species gains, species losses, and richness change) between sites that experienced extreme and moderate drought in each of the four treatment years. These statistics correspond to results shown in Figure S6A. See *23*.

Metric for contrast between extreme and nominal	Treatment year	Estimate	SE	df	t.ratio	p.value
Species gains	1	0.02	0.02	122	1.1	0.28
	2	0.01	0.02	122	0.5	0.61
	3	0.02	0.02	122	1.3	0.19
	4	-0.01	0.02	122	-0.5	0.6
Species losses (extreme-moderate contrast)	1	-0.01	0.03	122	-1.3	0.21
	2	0.001	0.03	122	0.04	0.97
	3	-0.03	0.03	122	-1	0.32
	4	0.05	0.03	122	1.8	0.08
Richness change	1	0.05	0.04	122	1.3	0.19
	2	0.01	0.04	122	0.3	0.79
	3	0.05	0.04	122	1.3	0.19
	4	-0.06	0.04	122	-1.5	0.14

Table S10. Summary of model predicting productivity response to drought with species losses for each of the four treatment years. These statistics correspond to results shown in Figure S6B. See *23*.

Treatment year	Model term	estimate	SE	df	t.ratio	p.value
1	intercept	-0.37	0.11	28	-3.48	0.002
	losses	-0.68	0.99	28	-0.68	0.5
2	intercept	-0.02	0.06	28	-0.34	0.74
	losses	-0.96	0.78	28	-1.23	0.23
3	intercept	0.03	0.04	27	0.68	0.5
	losses	-2.38	0.91	27	-2.63	**0.014**
4	intercept	0.01	0.06	21	0.14	0.89
	losses	-3.86	1.09	21	-3.54	**0.002**