


# Dynamic responses of tree-ring growth to multiple dimensions of drought

Shan Gao<sup>1,2,3</sup>  | Ruishun Liu<sup>4</sup> | Tao Zhou<sup>1,2</sup> | Wei Fang<sup>3</sup> | Chuixiang Yi<sup>3,5</sup> | Ruijie Lu<sup>1</sup> | Xiang Zhao<sup>6</sup> | Hui Luo<sup>1,2</sup>

<sup>1</sup>State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing, China

<sup>2</sup>Key Laboratory of Environmental Change and Natural Disaster of Ministry of Education, Academy of Disaster Reduction and Emergency Management, Beijing Normal University, Beijing, China

<sup>3</sup>School of Earth and Environmental Sciences, Queens College, City University of New York, Queens, New York

<sup>4</sup>College of Resources and Environment, Northwest A&F University, Yangling, China

<sup>5</sup>Earth and Environmental Sciences Department, the Graduate Center of the City University of New York, New York City, New York

<sup>6</sup>State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences, Beijing, China

## Correspondence

Tao Zhou, State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China. Email: tzhou@bnu.edu.cn

## Funding information

National Natural Science Foundation of China, Grant/Award Number: 41571185, 41621061; Fundamental Research Funds for the Central University, Grant/Award Number: 2015KJJC33; China Scholarship Council; City University of New York, Grant/Award Number: PSC-CUNY ENHC-48-33, PSC-CUNY CIRG- 80209-08 22

## Abstract

Droughts, which are characterized by multiple dimensions including frequency, duration, severity, and onset timing, can impact tree stem radial growth profoundly. Different dimensions of drought influence tree stem radial growth independently or jointly, which makes the development of accurate predictions a formidable challenge. Measurement-based tree-ring data have obvious advantages for studying the drought responses of trees. Here, we explored the use of abundant tree-ring records for quantifying regional response patterns to key dimensions of drought. Specifically, we designed a series of regional-scaled “natural experiments,” based on 357 tree-ring chronologies from Southwest USA and location-matched monthly water balance anomalies, to reveal how tree-ring responds to each dimension of drought. Our results showed that tree-ring was affected significantly more by the water balance condition in the current hydrological year than that in the prior hydrological year. Within the current hydrological year, increased drought frequency (number of dry months) and duration (maximum number of consecutive dry months) resulted in “cumulative effects” which amplified the impacts of drought on trees and reduced the drought resistance of trees. Drought events that occurred in the pregrowing seasons strongly affected subsequent tree stem radial growth. Both the onset timing and severity of drought increased “legacy effects” on tree stem radial growth, which reduced the drought resilience of trees. These results indicated that the drought impact on trees is a dynamic process: even when the total water deficits are the same, differences among the drought processes could lead to considerably different responses from trees. This study thus provides a conceptual framework and probabilistic patterns of tree-ring growth response to multiple dimensions of drought regimes, which in turn may have a wide range of implications for predictions, uncertainty assessment, and forest management.

## KEYWORDS

cumulative effect, drought dimensions, legacy effect, probabilistic patterns of tree growth, response to drought process, tree-ring, water balance

## 1 | INTRODUCTION

Drought is one of the most economically and ecologically disruptive extreme events, one that impacts terrestrial ecosystem processes

profoundly especially under the current warming climate (Allen, Breshears, & McDowell, 2015; Anderegg et al., 2015, 2016; Choat et al., 2012; Cook, Ault, & Smerdon, 2015; Yi et al., 2012). Higher air

temperature causes a greater atmospheric demand for water, which exacerbates the water stress upon vegetation during a drought (Novick et al., 2016). Among all vegetation types, forests are potentially the most susceptible to drought based on the hydraulic corollary of vascular plant physiology (McDowell & Allen, 2015). Increasing focus has been placed on widespread drought-induced tree mortality and forest declines that cause a significant reduction in carbon flux from the atmosphere to the land (Wei, Yi, Fang, & Hendrey, 2017; Yi, Pendall, & Ciais, 2015; Yi et al., 2010), which have been investigated from diverse perspectives and on different scales using a wide variety of approaches (Adams et al., 2009; Allen et al., 2015; Barbeta et al., 2015; Bhuyan, Zang, Vicente-Serrano, & Menzel, 2017; Dobbertin, 2005; Dorman, Svoray, Perevolotsky, & Sarris, 2013; González-Cásares, Pompa-García, & Camarero, 2017; He et al., 2017; Huang et al., 2015; Luo et al., 2018; Xu et al., 2018; Yi et al., 2018). However, detailed and locally specific conclusions and hypothetical mechanisms derived from in situ experiments or event-based observations are difficult to be applied at the regional to global scales, while regional- to global-scaled studies tend to simplify or abstract the processes of climate–vegetation interplay, which may cause uncertainties or even paradoxes. These hold back the development of process-based models and leave unclear the dynamic patterns of forest responses to drought and their underlying mechanisms.

Drought is a multiscale phenomenon and thus it is difficult to be quantified (Mckee, Doesken, & Kleist, 1993; Vicente-Serrano et al., 2013; Wei et al., 2014; Zargar, Sadiq, Naser, & Khan, 2011). Multiple dimensions, namely severity, frequency, duration, timing, and geographic extent have been used to characterize drought (Zargar et al., 2011), and each dimension could plausibly affect tree stem radial growth to some extent. Drought has been predicted to be longer, more frequent, more severe and more unseasonal during ongoing global climate change (Cook et al., 2015; Halwatura, Lechner, & Arnold, 2015; Spinoni, Naumann, Carrao, Barbosa, & Vogt, 2014; Yi et al., 2015). It is therefore urgent that we quantify how tree stem radial growth responds dynamically to each dimension of drought, so that more accurate modeling and predictions could be developed.

It is crucial but challenging to quantify the impact of each dimension of drought on trees. Observations give an overall picture of the patterns of forests respond to drought dimensions (Allen et al., 2010, 2015). Extreme droughts affect trees' vigor and structure considerably (Rosbakh et al., 2017). In addition to these immediate impacts, their long-lasting legacy effects could delay trees' recovery, and increase vulnerability to future droughts (Anderegg et al., 2013, 2015; Wu et al., 2017). Increase of drought frequency exposes trees to drought more frequently, which may augment the risk of forest die-off (Mueller et al., 2005). Droughts with longer duration could cause accumulated hydraulic deterioration, which may lead to mortality. In situ controlled experiments provide insight into the physiological mechanisms of tree responses to drought; we could monitor selected physiological indicators of saplings for their changes over time under the controlled water stress conditions (Anderegg & Anderegg, 2012; Barbeta et al., 2015; Ditmarova, Kurjak, Palmroth,

Kmet, & Strelcova, 2009; Ryan, 2011). However, varied responses were reported among saplings (Ambrose et al., 2015; Rosbakh et al., 2017; Ryan, 2011), which attest to the difficulty in predicting individual drought responses. Moreover, the disparate physiological responses to drought between saplings and mature trees (Anderegg & Anderegg, 2012; Bennett, McDowell, Allen, & Anderson-Teixeira, 2015), in addition to limited specimens and experimental durations, make it difficult to generate regional-scaled predictions.

In regional- to global-scaled studies, drought indices are preferred for characterizing drought since they are readily usable numerical values that are calculated by assimilating drought indicators (Mckee et al., 1993; Vicente-Serrano, Beguería, & López-Moreno, 2010; Zargar et al., 2011; Zhou, Yi, Bakwin, & Zhu, 2008). Correlation and regression analyses between drought indices and indicators of forest vitality or tree growth have been the most common methods used to date in exploring how forests respond to drought (Breshears et al., 2005; Vicente-Serrano et al., 2013) and other important topics such as the dominant timescales (Andujar, Krakauer, Yi, & Kogan, 2017; Vicente-Serrano, Camarero, & Azorin-Molina, 2014; Vicente-Serrano et al., 2013), biome sensitivities (González-Cásares et al., 2017), time-lag effects (Wu et al., 2015), while consensus was rarely achieved. Although severity of drought has received the most attention among all drought dimensions in such analyses, it is worth noting that drought is a process. A complete process contains extensive and complex information that goes beyond a single value. Therefore, more detailed process-based research is needed at the regional scale.

In this study, we sought to clarify how tree stem radial growth responds to each dimension of drought by designing a series of regional-scaled “natural experiments,” based on 357 tree-ring chronologies from southwest USA and location-matched monthly water balance anomalies. Southwest USA is an ideal region for drought related research. Ring width indices (RWI) were used to indicate tree stem radial growth while monthly water balance anomalies were used to quantify the key dimensions of drought. Specifically, we reassembled tree-ring specimens based on a series of drought scenarios with chosen drought dimensions and the corresponding patterns of tree-ring growth were analyzed. The contrasting distribution patterns of RWIs under different drought scenarios should shed new light on our understanding of drought regimes at the regional scale.

## 2 | MATERIALS AND METHODS

### 2.1 | Study region

The study region, located in the southwest of United States, includes the states of Utah, Colorado, Arizona and New Mexico (Figure 1). The topography is mainly comprised of the Colorado Plateau, which is surrounded by mountains and deserts. The climate of the region depends mainly on elevation and topography, therefore has large spatial gradients in both temperature and precipitation (Allen, Betancourt, & Swetnam, 1998; Biederman et al., 2017); low elevation is

arid desert climate, while higher elevations feature alpine climates and have large tracts of alpine trees. Southwest USA is a typical region for researching tree-ring response to drought since forests there are mainly limited by water deficits.

## 2.2 | Tree-ring data

A total of 357 tree-ring chronologies of three major tree species (*Pseudotsuga menziesii*, *Pinus ponderosa*, *Pinus edulis*) were obtained from the International Tree-Ring Data Bank (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>; Table 1). These trees were mainly distributed at the elevation range of 1,300–3,200 m. Tree-ring growth patterns across species and space are generally coherence (Williams et al., 2012). Standard chronologies were obtained directly from the International Tree-Ring Data Bank or developed from raw tree-ring width when they were unavailable. To develop standard chronologies, long-term trends caused by aging and increasing trunk diameter were removed mostly by negative exponential curves using ARSTAN program (Cook, 1985). After standardization, all chronologies were scaled to a standard mean (RWI = 1,000) and comparable variance, therefore spatial heterogeneities among tree-ring sites were largely eliminated. Processed chronologies after the year 1902 were selected for further analyses.

## 2.3 | Climate data

Monthly gridded climate data (precipitation [P] and potential evapotranspiration [PET]) from 1901 to 2013 for each tree-ring site were obtained from the Climate Research Unit, TS v.4.01 (<https://crudata.uea.ac.uk/cru/data/hrg/>). We calculated the monthly water balance ( $D_m$ ) of each site (Equation 1) and its annual water balance ( $D_y$ ) (Equation 2). In this research, hydrological year—beginning in October of the previous year and ending in September of the current year—was used (Fang, Frank, Zhao, Zhou, & Seppa, 2015; Salzer & Kipfmüller, 2005; Williams, Michaelsen, Leavitt, & Still, 2010) to

obtain a more reasonable correspondence between hydrological processes and tree phenology. To explore how water balance variability controls tree-ring growth, we used monthly and annual water balance anomalies (respectively,  $D_m$  anomaly and  $D_y$  anomaly), which were calculated by Equations 3 and 4. Water balance anomalies described the departure from a long-term average, which effectively normalizes the data, thus enabling more meaningful comparisons to be made with respect to normality, both for different sites within a region and different periods within a hydrological year.

$$D_m^j = P_i^j - PET_i^j, \quad (1)$$

$$D_y = \sum_{i=1}^{12} D_m^j, \quad (2)$$

$$D_m \text{ anomaly}_i^j = D_m^j - \overline{D_m^j}, \quad (3)$$

$$D_y \text{ anomaly}_j = \sum_{i=1}^{12} D_m \text{ anomaly}_i^j. \quad (4)$$

For the  $i$ th month of a hydrological year at the  $j$ th tree-ring site,  $\overline{D_m^j}$  represents 113-hydrological year-mean (from year 1901 to 2013) water balance for  $i$ th month at  $j$ th site.

## 2.4 | Dimensions of droughts

Drought can be characterized by multiple dimensions, that include its severity, duration, frequency, and timing (Zargar et al., 2011). In our study, we used monthly water balance anomaly condition to quantify each dimension of droughts.

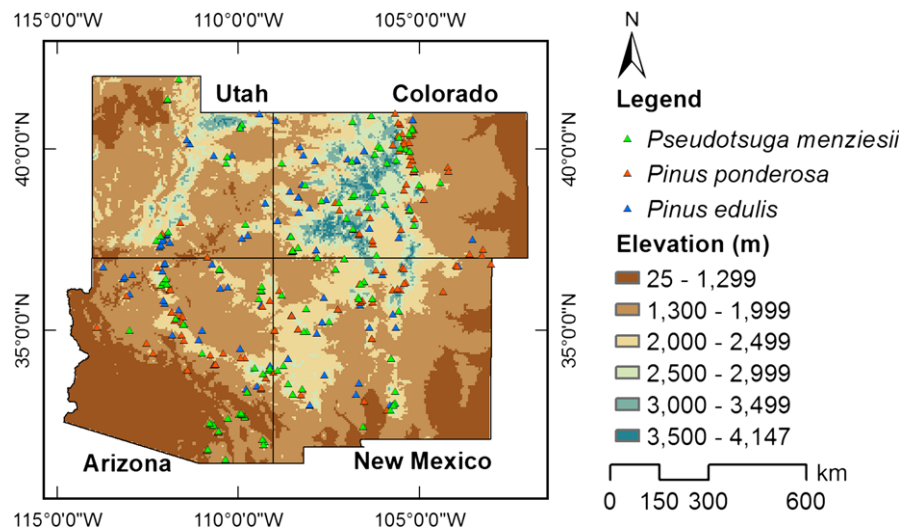
Severity: Monthly water balance anomaly ( $D_m$  anomaly) equal to or below a drought threshold.

Frequency: Number of months within a hydrological year (i.e., from October of the previous to September of the current year) that have a monthly water balance anomaly below a threshold.

Duration: Number of consecutive months within a hydrological year that monthly water balance anomaly below a certain severity.

Timing: Onset time of drought within a hydrological year.

**FIGURE 1** Distribution of tree-ring sites used in Southwest USA. A total of 357 tree-ring sites of three major tree species (*Pseudotsuga menziesii*, *Pinus ponderosa*, *Pinus edulis*) were included



Species code	Species Latin name	Number of sites (used/total)	Chronology	Number of site years	Elevation distribution (m)
PSME	<i>Pseudotsuga menziesii</i>	127/128	1902–2012	10,388	1,750–3,200
PIPO	<i>Pinus ponderosa</i>	126/129	1902–2011	10,628	1,433–2,896
PIED	<i>Pinus edulis</i>	104/104	1902–2011	8,658	1,377–2,956
Total	3	357/361	1902–2012	29,969	1,377–3,200

**TABLE 1** General information of chronologies used in this study

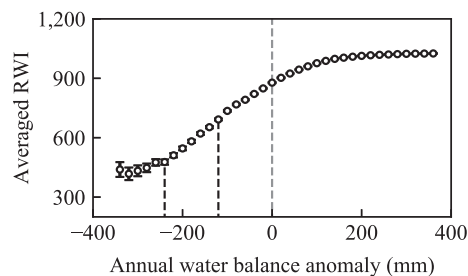
Note. We removed two PIPO chronologies with field measured elevations equal to 0, one PIPO chronology with an unusual format, and one PSME chronology lacking years after 1901.

We defined three levels of monthly drought severity: SI ( $D_{m,anomaly} \leq 0$ ), SII ( $D_{m,anomaly} \leq -10$  mm/month), and SIII ( $D_{m,anomaly} \leq -20$  mm/month). To determine these thresholds more objectively, we set the accumulated annual water balance threshold every 20 mm and plotted the averaged RWI formed below each threshold (Figure 2). When the water balance threshold was approximately  $-240$  mm/year, the changed rates of averaged RWI slowed down; therefore, the strongest severity we set was below  $-20$  mm/month, while the weakest was set to below 0 mm/month, which we considered as under the normal condition for tree-ring growth in this region.

## 2.5 | Natural experiments using existing tree-ring dataset

Our tree-ring database was formed with 357 standard chronologies from year 1902 to 2012, resulting in a total of 29,969 site-years. Each site-year was considered as an individual specimen impacted by the water balance condition. To better illustrate how different dimensions of drought may impact tree-ring growth, we first set up hypothetical water balance conditions, and then picked out RWI specimens from the database formed under the accordant conditions, so that the most likely characteristics of RWI distribution for the study region could be revealed.

To examine whether droughts in previous hydrological year have strong legacy effects on RWIs of current year and to compare the



**FIGURE 2** Averaged ring width indices (RWIs) formed under the annual water balance anomaly thresholds. Annual water balance anomaly thresholds were set every 20 mm and averaged RWIs formed below those thresholds were calculated. Error bars represent standard errors of averaged RWIs

effects of droughts in current and in previous hydrological years on tree growth, we designed two major drought scenarios. In the first scenario, we only controlled the drought conditions of current hydrological year, keeping them equivalent (Figure 3a). In the second scenario, we only controlled previous hydrological year drought conditions, keeping them equivalent (Figure 3b). Episodes of drought were subdivided into three severities whose annual water balance anomalies were below 0,  $-120$ ,  $-240$  mm, respectively. The distributions of RWI specimens formed under those drought scenarios were presented, independent sample  $t$  tests were conducted to test significant differences.

To examine how drought frequency affects tree stem radial growth, we first counted the number of months whose  $D_{m,anomaly}$  was below a certain severity for each site-year, and then RWI specimens under the same drought frequencies were grouped, averaged, and compared (Figure 4).

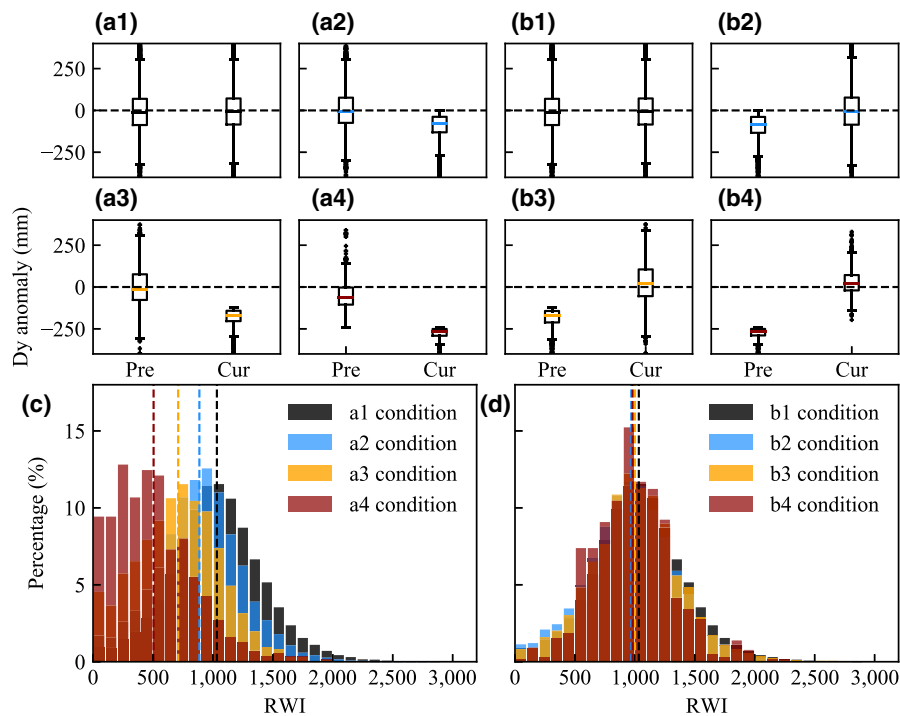
To examine how drought duration affects tree stem radial growth, we first grouped RWI specimens according to certain drought frequencies, and then grouped them according to continuous drought durations with fixed frequencies (Figure 5a,b). Independent sample  $t$  tests were conducted to test significant differences among groups.

To examine how drought onset timing affects tree stem radial growth, two drought scenarios were designed: one with continuous drought that mainly occurred between October of the previous year and March of the current year (i.e., the pre-growing season; Figure 6a); the other with continuous drought that mainly occurred between April and September of the current year (i.e., growing season) (Figure 6b). RWI specimens under those two drought scenarios were grouped, averaged, and compared using independent sample  $t$  tests.

## 3 | RESULTS

### 3.1 | Are there interannual drought legacy effects on RWI specimens?

Droughts of current hydrological year had significant impacts on RWIs, as drought severity increased, the impacts on RWIs strengthened. Under the three increased drought severity conditions, the regional mean RWI decreased from 1,033 to 887, 710, and 505,



**FIGURE 3** Contrasting impacts of the annual water balance condition ( $D_y$  anomaly) of the current and previous hydrological year on tree-ring growth (RWIs). To assess the impact of  $D_y$  anomaly of the current hydrological year on tree-ring growth, scenarios a1–a4 were designed, holding the  $D_y$  anomaly of the previous hydrological year constant while that of the current hydrological year had four severity levels (= a1 as control, and a2–a4 representing an increasing severity of drought). The a2, a3 and a4 conditions were current hydrological year water balance anomalies below 0, –120, and –240 mm respectively. Sample sizes for the a1–a4 conditions were 29,313, 15,538, 4,497, and 562, respectively. To assess the impact of  $D_y$  anomaly of the previous hydrological year on tree stem radial growth, scenarios b1–b4 were designed, keeping  $D_y$  anomaly of the current hydrological year constant while that of the previous hydrological year had four severity levels (= b1 as control, and b2–b4 representing an increasing severity of drought). The b2, b3, and b4 conditions were previous hydrological year water balance anomalies below 0, –120, –240 mm respectively. The sample sizes of b1–b4 condition were 29,313, 15,831, 4,749, and 650, respectively. (c) Effect of the current hydrological year drought with varying severities on tree stem radial growth. Independent sample t tests were conducted, and significant differences were found between RWIs under a1 condition and those under the a2–a4 conditions ( $p < 0.001$ ). (d) Effect of the previous hydrological year drought with varying severities on tree stem radial growth. Significant differences were found between RWIs under the b1 condition and those under b2–b4 conditions ( $p < 0.001$ )

respectively (Figure 3c). Compared to the impacts on RWIs from current hydrological years, previous hydrological year drought apparently had smaller impacts, and an increase in drought severity did not make much differences, as the regional mean RWI varied around 1,000 at no more than 50 above and below that value (Figure 3d).

### 3.2 | How does drought frequency in different severities affect tree-ring growth?

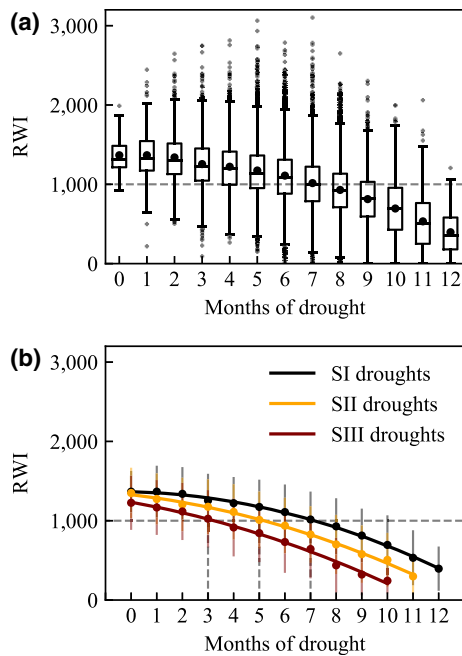
Ring width indices specimens formed under the same drought frequency condition in SI severity condition were grouped and presented (Figure 4a). Regional mean RWI generally decreased with an increase of drought frequency within a hydrological year. As droughts occurred for more than 7 months within a hydrological year, regional mean RWI started to drop below the standard mean (RWI = 1,000) and as droughts occurred for more than 9 months within a hydrological year, the missing rings (RWI = 0) appeared more regularly.

Severity of drought amplified the effect of drought frequency on RWI specimens. Droughts with high frequency but low severity

could have similar effects on RWIs as droughts with low frequency but with high severity. For example, a RWI mean of c. 1,000 could be formed under a 7-month/year frequency in SI severity droughts, but for SII severity droughts it only required a 5-month/year frequency; similarly, for SIII severity droughts only 3-month/year frequency was needed (Figure 4b).

### 3.3 | How does drought duration affect tree-ring growth?

We compared the effects of continuous droughts and random droughts on RWIs (Figure 5a,b). Given the same drought frequency (number of dry months of the hydrological year), RWIs that formed under continuous droughts (indicated by the dashed lines) were generally lower than those formed under random droughts (indicated by the solid lines). This suggested that continuous droughts tend to have a stronger impact on RWIs. Weaker droughts of longer duration could have a similar impact on RWIs as stronger droughts do. For instance, under a 7-month/year drought frequency condition, continuous SI droughts resulted in a regional mean RWI of 820,



**FIGURE 4** Effect of drought frequency in different drought severities on ring width indices (RWI) specimens. (a) Boxplots of RWI specimens under different drought frequency in the SI severity condition. On each box, the central bar indicates the median, the black dot indicates RWI mean, the bottom and top edges indicate the 25th and 75th percentiles; the whiskers extend to all data points except outliers (which are plotted individually using “+”). (b) Effect of drought frequency in different drought severity on RWI specimens, where dots represent RWI means formed under different drought frequencies and error bars represent their standard deviations. SI, SII, and SIII drought severity levels indicate monthly water balance anomalies below 0,  $-10$ ,  $-20$  mm, respectively

similar to that of random SII droughts (RWI = 826; Figure 5d), despite the mean  $D_v$  anomaly of random SII droughts (orange dashed line) being 102 mm lower than that of continuous SI droughts (black dashed line, Figure 5c). Under the same drought frequency condition, as drought severity became stronger, the difference between the effects of continuous droughts (dashed lines in Figure 5b) and random droughts (solid lines in Figure 5b) on RWIs gradually dissipated, which points to legacy effects.

### 3.4 | How does the timing of drought affect tree-ring growth?

To examine how timing of drought may affect regional RWIs, we designed two hypothetical intra-annual water balance conditions: continuous droughts mainly occurred in pregrowing season (Figure 6a) or in growing season (Figure 6b). RWI specimens were reassembled accordingly under both scenarios. Although the mean value for the  $D_v$  anomaly of pregrowing season droughts was comparable to those of growing season droughts (blue vs. orange dashed lines in Figure 6c,e,g), the adverse impact of pregrowing season droughts on RWIs was much larger than the impact of growing

season droughts (blue vs. orange dashed lines in Figure 6d). This disparity increased with greater drought severity—regional mean RWI decreased from 642 under SI droughts to 397 under SII droughts and 311 under SIII droughts (Figure 6f,h)—while for growing season droughts, increase of severity of droughts had little impacts on regional mean RWI (Figure 6d,f,h).

## 4 | DISCUSSION

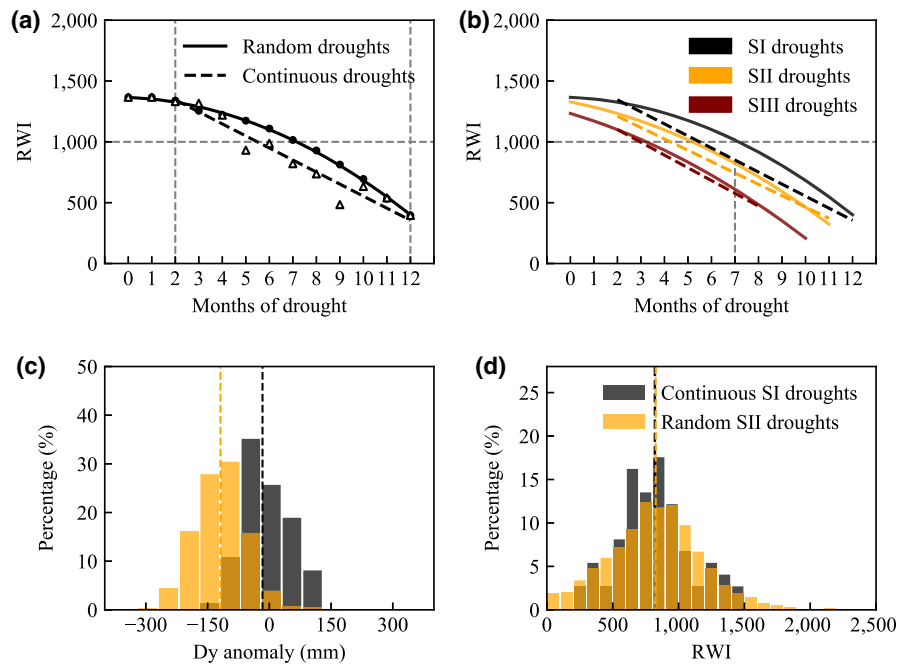
### 4.1 | Tree stem radial growth responses to drought dimensions

Having drought in the hydrological years immediately prior to the current ones exerted certain impacts on tree-ring growth of the current year. Our results showed that regional mean RWI was reduced from an average of 1,033 to 970 (Figure 3d), which is comparable to the studies of interannual legacy effects from Anderegg et al. (2015) and Wu et al. (2017). Previous studies reported that correlations between vegetation indices (e.g., RWI, NDVI) and drought indices (e.g., SPEI) were tested significant at a timescale over 24 months (Li et al., 2015; Luo et al., 2018; Vicente-Serrano et al., 2014). Nevertheless, even when the previous hydrological year was under extreme drought conditions, its impact on current year RWIs were much less than the impact from drought in the current hydrological year (Figure 3c). This result underscores the critical importance of the current year's water balance condition on tree stem radial growth.

Within a hydrological year, drought legacies of the pregrowing seasons had significantly higher impacts on current year RWI formation than that of the growing seasons, and these legacy effects increased with an increasing drought severity (Figure 6). This result, echoing previous studies, suggests that tree-ring width is primarily determined by the water condition of pregrowing season (Barnes et al., 2016; Fang et al., 2015; Hagedorn et al., 2014; Rigling, Bräker, Schreiber, & Schweingruber, 2002). We speculate that if there is enough water accumulation in the pregrowing season, a tree can effectively turn stored nonstructural carbon (NSC) into new tissue when reaching the suitable temperature for growth, therefore, wider early wood could be formed; otherwise the NSC would be consumed. Studies on seasonal wood formation showed that early wood width was positively correlated with precipitation from the previous winter and current spring to early summer, which could affect late wood formation and make the early wood more sensitive than late wood to drought (Julio Camarero, Miguel Olano, & Parras, 2010; Pasho, Julio Camarero, & Vicente-Serrano, 2012)—this is consistent with our speculation. Early wood is generally wider and brighter than late wood, which likely means wider ring widths, and so pregrowing season droughts could have larger impacts on tree-ring formation. Here, we also want to emphasize that the relatively small impacts of growing season droughts on tree-ring width do not necessarily mean that growing season droughts have less impact on tree physiology.

Our result also showed that as drought severity increased, the impact of drought duration became harder to be detected

**FIGURE 5** Effect of drought duration in different drought severities on ring width index (RWI) specimens. (a) Comparison of the random and continuous droughts' effects on RWI specimens. (b) Comparison of the random and continuous droughts in different severities on RWI specimens. (c) Comparison of the annual water balance of continuous SI droughts and random SII droughts under 7-month/year frequency condition; sample sizes were 74 and 2,690, respectively.  $D_y$  anomaly of continuous SI droughts was significantly higher than that of random SII droughts ( $p < 0.001$ ). (d) Cumulative effects of continuous SI droughts on RWIs under a 7-month/year frequency condition. No significant difference was found between RWIs under continuous SI and random SII droughts



(Figure 5b), which suggested that the delayed impacts of drought legacies increased with drought severity (Reichstein et al., 2013). Drought severity could influence trees' physiological responses (Ryan, 2011), as many physiological indicators respond to severe drought but not mild drought events (Ditmarova et al., 2009; Rosbakh et al., 2017). After experiencing an extreme drought event, trees may enter a malfunctioned state and need more time and water accumulation to adjust and recover (Pan, Yuan, & Wood, 2013) from legacy effects, thus losing their sensitivity to droughts of longer duration.

Legacy effects of trees responses to drought have been found to vary significantly at the global scale, some studies reported that forest ecosystems did not show apparent legacy effects or legacy effects  $< 3$  months (Wu et al., 2015), some reported around 5 months (Luo et al., 2016), some reported 8–10 months in semiarid and subhumid regions and shorter in arid and humid regions (Vicente-Serrano et al., 2013), some reported over 24 months (Li et al., 2015; Luo et al., 2018; Vicente-Serrano et al., 2014; Wu et al., 2017). These discrepancies were then attributed to diverse climate characteristics and forest types. Yet most of those reported results were processed using correlation methodology, in which drought legacy effects were considered constant on a fixed timescale (Mitchell et al., 2016). In our research, we did not address the exact timescale of the drought legacy effect, but we did show that legacy effects could be largely influenced by both the onset timing and severity of drought. Therefore, drought legacy effects should be considered as a dynamic process in further studies.

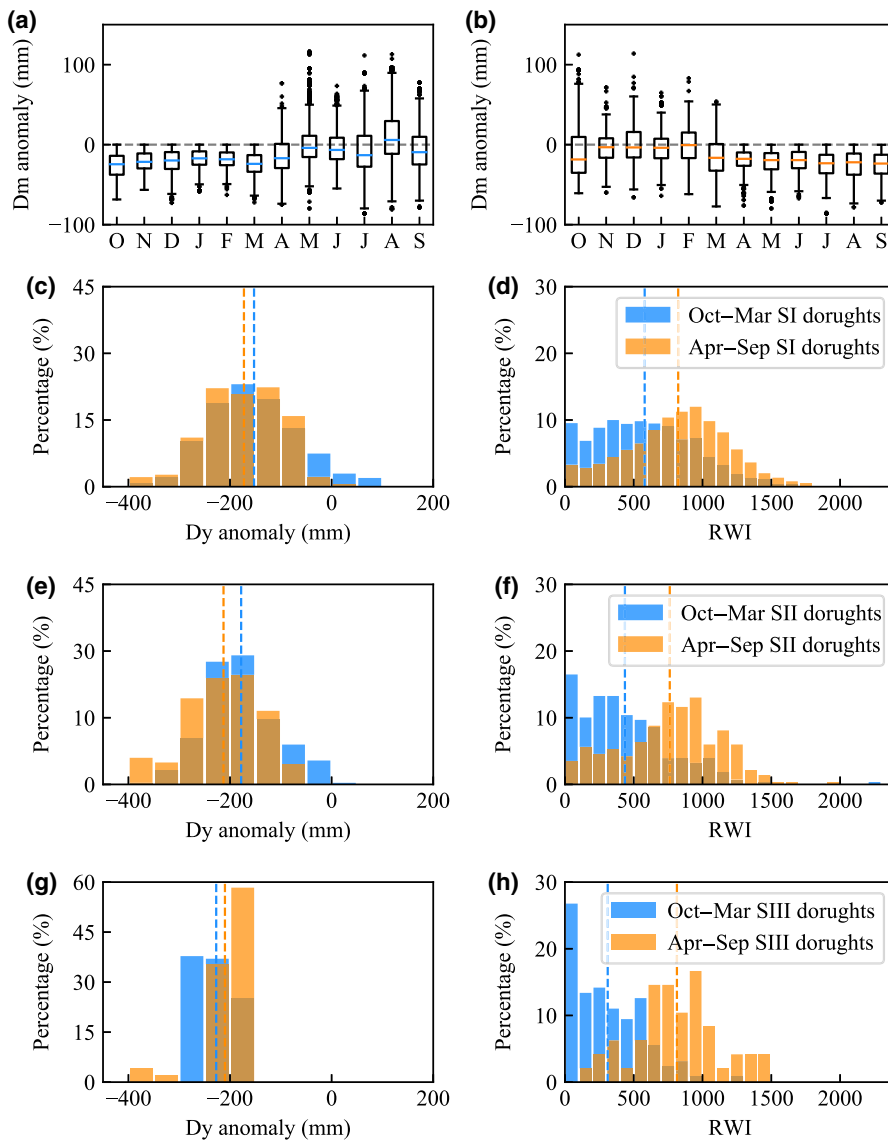
As drought frequency or duration increased within a hydrological year, repeated or continuous mild droughts could have similar impacts on tree stem radial growth with severe droughts (Figures 4b and 5b). This suggested that increasing the drought frequency and duration could result in "cumulative effects" which would reduce trees' resistance, thus amplifying the impacts of drought on trees.

Previous observations and experiments have showed that prolonged drought gradually pushed trees to a more vulnerable state and, when increased in frequency, exposed the trees to a higher probability of mortality (Adams et al., 2009; Allen et al., 2015; Mueller et al., 2005). Conceptual frameworks for investigating cumulative effects exist and these are well accepted (Allen et al., 2015; McDowell et al., 2011; Mitchell et al., 2016); this study contributes to this topic further by describing such cumulative effects in a relatively clear, quantitative way.

The interplay of multiple dimensions of drought has made the impacts of drought on trees extremely complex and difficult to model and predict accurately. Even if the total water deficits are the same, difference among drought processes could result in considerably different responses from the affected trees. These results help us to reconsider the validity and rationality of building climate-growth relationships by pure statistics alone and using these relationships to reconstruct and predict drought events and impacts (Fang et al., 2015; Mitchell et al., 2016; Sheppard et al., 2004). Drought indices have been widely used to simplify the drought process, and they are efficient tools for communicating drought levels among involved entities (Zargar et al., 2011), but we should be aware that such simplifications could also introduce uncertainties and bias. Coupling the drought process with tree physiology and phenology would significantly improve our ability of predicting resulting complex phenomena, such as drought-induced tree mortality and forest dieback.

## 4.2 | The evaluation for designing natural experiments

Regional-scaled "natural experiments" offer a straightforward and transparent method to explore regional response of trees to climate variability, and they have the potential to allow for more detailed



**FIGURE 6** Effect of onset timing and severity of drought on ring width indices (RWIs). (a) Monthly water balance condition of continuous SI droughts in the pregrowing season (blue center lines indicate medians, the bottom and top edges indicate the 25th and 75th percentiles, the whiskers extend to all data points except outliers which are plotted individually using “+”). (b) Monthly water balance condition of continuous SI droughts in the growing season (orange center lines indicate medians). (c, e, g) Comparison of annual water balance  $D_y$  anomalies of pregrowing season (blue bars) and growing season (orange bars) drought scenarios under SI, SII, and SIII levels of drought severity. A significant difference in the  $D_y$  anomaly between pregrowing and growing seasons was found under each severity. (d, f, h) Impact of drought onset timing on RWIs for SI, SII, and SIII severity. A significant difference in the RWIs between pregrowing and growing seasons was found under each severity level. Sample sizes for the pregrowing season and growing season for SI were 1,731 and 1,485 (c, d), for SII they were 279 and 284 (e, f), for SIII they were 127 and 48 (g, h), respectively

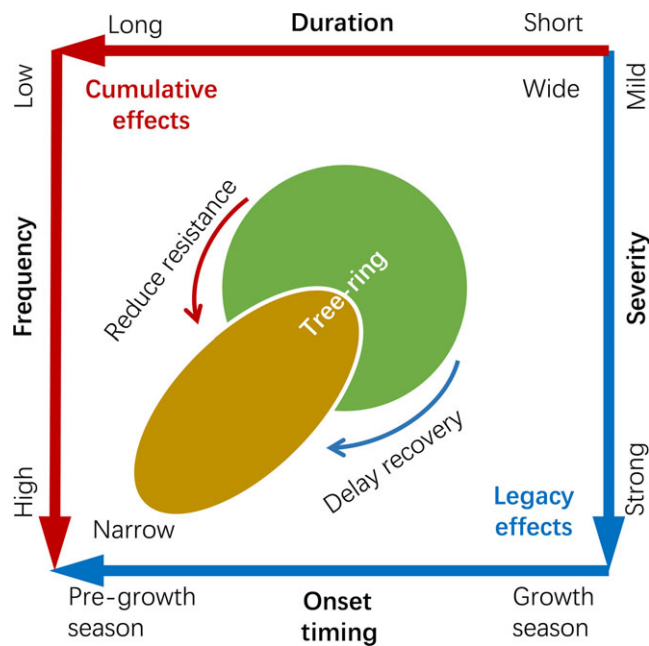
analyses (such as interspecies comparisons) when data are abundant. Inspired by the experimental approach with clear control and randomized design, natural experiments are observational studies with ad hoc designs. Full spectrum of spatial and temporal dynamics in natural condition resembles a complete randomized exposure, while the ad hoc designs of drought scenarios allow us to test the effect of the focal factor while controlling other factors (Dunning, 2008; Petticrew et al., 2005; Rutter, 2007). In our case, the normalized tree-ring data (RWIs) was the dependent variable and the water balance condition was the independent factor that we could control with ad hoc design/selection.

Tree-rings, formed under a variable climate, are suitable for discerning the impacts of drought process since they are direct measures of stem growth and have both advantages of data availability and continuity, spatially and temporally. Hence, using tree-rings to conduct regional-scaled “natural experiments” could generate tenable results. Nevertheless, the accuracy of this approach will be affected by the quantity and distribution of tree-ring sites. Therefore,

on the basis of existing International Tree Ring Data Bank (ITRDB), updated regularly, adding new sites to develop a more evenly distributed network could improve our ability to conduct regional- to global-scale explorations.

Southwest USA is an ideal region for investigating how tree stem radial growth responds to drought process, not only because of its densely distributed tree-ring sites, but also owing to its characteristic intra-annual water balance conditions (Supporting Information Figure S2). First of all, water deficit is the most limiting factor for tree stem radial growth in the Southwest USA (Adams & Kolb, 2005; Hidalgo, Dracup, MacDonald, & King, 2001; Kolb, 2015), and this was basis of our study approach. Second, the correlation between monthly water balance anomalies ( $D_m$  anomaly) and RWIs is mostly positive (Supporting Information Figure S2a), suggesting that water deficit limits tree-ring growth there all year round. This is also important because inconsistent limiting effects would cause interference when studying the impacts of drought processes. Third, variation in the monthly water balance anomaly ( $D_m$  anomaly) was roughly





**FIGURE 7** Conceptual diagram of how different dimensions of drought affect tree stem radial growth

constant within a hydrological year (Supporting Information Figure S2b), suggesting that each month could be treated equally when designing drought scenarios. Finally, a variable climate could result in diverse tree-ring samples, which are helpful for reducing bias in natural experiments (Rutter, 2007). With these “near-standard” water balance characteristics, it was reasonable to extract relatively general response patterns of tree stem radial growth to drought process. Nevertheless, might these patterns also be found in other regions with different climate types?

Mediterranean climate areas, for instance, with hot, dry summers and cool, wet winters, are very different from Southwest USA where the climate is driven by a summer monsoon. After examining interannual water balance conditions (Supporting Information Figures S1, S3 and S5), California with Mediterranean climate (Köppen, 2011) is suitable in general for testing response patterns of tree-ring to drought process (Supporting Information Figures S4, S5 and Table S2), but still the variations of monthly water balance anomaly differ greatly within a hydrological year (Supporting Information Figure S5b). Nevertheless, the response pattern of tree-ring growth to different dimensions of drought in California did show similarity to that in Southwest USA (Supporting Information Figure S6), which strengthened our initial conclusions.

In summary, as drought frequency, duration and severity increased, regional mean RWIs decreased (Figure 7). Within a hydrological year, increasing the frequency and duration would result in drought “cumulative effects,” which reduce trees’ resistance and gradually push them into a more vulnerable state, thereby amplifying the impacts of drought on trees (Figure 7). Water balance condition of current year is critical to tree stem radial growth and pregrowing

season droughts could profoundly affect later radial growth. Both the onset timing and severity of drought strengthened its “legacy effects,” which reduce trees’ resilience and make it harder for them to recover completely from drought (Figure 7). Therefore, it is important to study drought as a process and complex regime with multiple dimensions. We suggest that intra-annual water balance conditions be thoroughly studied for mechanism-based simulations and predictions of forest response to drought, before attributing uncertainties to spatial heterogeneity, vegetation differences, and climate change.

#### ACKNOWLEDGEMENTS

We acknowledge contributors to the International Tree-Ring Data-bank for tree-ring data. We thank anonymous reviewers for their constructive comments and suggestions for improving this manuscript. This study was supported by the National Natural Science Foundation of China (grant numbers 41571185 and 41621061), the Fundamental Research Funds for the Central University (grant numbers 2015KJJC33), with additional financial support from the China Scholarship Council. C.Y. was supported by the City University of New York (PSC-CUNY ENHC-48-33 and PSC-CUNY CIRG- 80209-08 22).

#### ORCID

Shan Gao  <http://orcid.org/0000-0002-1452-8741>

#### REFERENCES

- Adams, H. D., Guardiola-Claramonte, M., Barron-Gafford, G., Villegas, J. C., Breshears, D. D., Zou, C. B., ... Huxman, T. E. (2009). Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences*, 106, 7063–7066. <https://doi.org/10.1073/pnas.0901438106>
- Adams, H. D., & Kolb, T. E. (2005). Tree growth response to drought and temperature in a mountain landscape in northern Arizona, USA. *Journal of Biogeography*, 32, 1629–1640. <https://doi.org/10.1111/j.1365-2699.2005.01292.x>
- Allen, C. D., Betancourt, J. L., & Swetnam, T. W. (1998). Landscape changes in the southwestern United States: techniques, long-term data sets, and trends. In *Perspectives on the land use history of North America: A context for understanding our changing environment* (pp. 71–84). Lafayette, LA: U.S. Geological Survey.
- Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, 6, 1–55.
- Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., ... Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259, 660–684. <https://doi.org/10.1016/j.foreco.2009.09.001>
- Ambrose, A. R., Baxter, W. L., Wong, C. S., Naesborg, R. R., Williams, C. B., & Dawson, T. E. (2015). Contrasting drought-response strategies in California redwoods. *Tree Physiology*, 35, 453–469. <https://doi.org/10.1093/treephys/tpv016>

- Anderegg, W. R. L., & Anderegg, L. D. L. (2012). Hydraulic and carbohydrate changes in experimental drought induced mortality of saplings in two conifer species. *Tree Physiology*, *33*, 252–260.
- Anderegg, W. R. L., Klein, T., Bartlett, M., Sack, L., Pellegrini, A. F. A., Choat, B., & Jansen, S. (2016). Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe. *Proceedings of the National Academy of Sciences*, *113*, 5024–5029. <https://doi.org/10.1073/pnas.1525678113>
- Anderegg, W. R. L., Plavcová, L., Anderegg, L. D. L., Hacke, U. G., Berry, J. A., & Field, C. B. (2013). Drought's legacy: Multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology*, *19*, 1188–1196. <https://doi.org/10.1111/gcb.12100>
- Anderegg, W. R. L., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., ... Pacala, S. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*, *349*, 528–532. <https://doi.org/10.1126/science.aab1833>
- Andujar, E., Krakauer, N. Y., Yi, C., & Kogan, F. (2017). Ecosystem drought response timescales from thermal emission versus shortwave remote sensing. *Advances in Meteorology*, *2017*, 1–10. <https://doi.org/10.1155/2017/8434020>
- Barbeta, A., Mejía-Chang, M., Ogaya, R., Voltas, J., Dawson, T. E., & Peñuelas, J. (2015). The combined effects of a long-term experimental drought and an extreme drought on the use of plant-water sources in a mediterranean forest. *Global Change Biology*, *21*, 1213–1225. <https://doi.org/10.1111/gcb.12785>
- Barnes, M. L., Moran, M. S., Scott, R. L., Kolb, T. E., Ponce-Campos, G. E., Moore, D. J. P., ... Dore, S. (2016). Vegetation productivity responds to sub-annual climate conditions across semiarid biomes. *Ecosphere*, *7*, e01339. <https://doi.org/10.1002/ecs2.1339>
- Bennett, A. C., McDowell, N. G., Allen, C. D., & Anderson-Teixeira, K. J. (2015). Larger trees suffer most during drought in forests worldwide. *Nature Plants*, *1*, 15139. <https://doi.org/10.1038/nplants.2015.139>
- Bhuyan, U., Zang, C., Vicente-Serrano, S., & Menzel, A. (2017). Exploring relationships among tree-ring growth, climate variability, and seasonal leaf activity on varying timescales and spatial resolutions. *Remote Sensing*, *9*, 526. <https://doi.org/10.3390/rs9060526>
- Biederman, J. A., Scott, R. L., Bell, T. W., Bowling, D. R., Dore, S., Garatuza-Payan, J., ... Goulden, M. L. (2017). CO<sub>2</sub> exchange and evapotranspiration across dryland ecosystems of southwestern north America. *Global Change Biology*, *23*, 4204–4221. <https://doi.org/10.1111/gcb.13686>
- Breshears, D. D., Cobb, N. S., Rich, P. M., Price, K. P., Allen, C. D., Balice, R. G., ... Meyer, C. W. (2005). Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, *102*, 15144–15148. <https://doi.org/10.1073/pnas.0505734102>
- Choat, B., Jansen, S., Brodribb, T. J., Cochard, H., Delzon, S., Bhaskar, R., ... Zanne, A. E. (2012). Global convergence in the vulnerability of forests to drought. *Nature*, *491*, 752–756. <https://doi.org/10.1038/nature11688>
- Cook, E. R. (1985). *a time series analysis approach to tree ring standardization*. Tucson, AZ: University of Arizona.
- Cook, B. I., Ault, T. R., & Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the american southwest and central plains. *Science Advances*, *1*, e1400082.
- Ditmarova, L., Kurjak, D., Palmroth, S., Kmet, J., & Strelcova, K. (2009). Physiological responses of norway spruce (*Picea abies*) seedlings to drought stress. *Tree Physiology*, *30*, 205–213.
- Dobbertin, M. (2005). Tree growth as indicator of tree vitality and of tree reaction to environmental stress: A review. *European Journal of Forest Research*, *124*, 319–333. <https://doi.org/10.1007/s10342-005-0085-3>
- Dorman, M., Svoray, T., Perevolotsky, A., & Sarris, D. (2013). Forest performance during two consecutive drought periods: Diverging long-term trends and short-term responses along a climatic gradient. *Forest Ecology and Management*, *310*, 1–9. <https://doi.org/10.1016/j.foreco.2013.08.009>
- Dunning, T. (2008). Improving causal inference—strengths and limitations of natural experiments. *Political Research Quarterly*, *61*, 282–293. <https://doi.org/10.1177/1065912907306470>
- Fang, K., Frank, D., Zhao, Y., Zhou, F., & Seppa, H. (2015). Moisture stress of a hydrological year on tree growth in the tibetan plateau and surroundings. *Environmental Research Letters*, *10*, 034010. <https://doi.org/10.1088/1748-9326/10/3/034010>
- González-Cásares, M., Pompa-García, M., & Camarero, J. J. (2017). Differences in climate–growth relationship indicate diverse drought tolerances among five pine species coexisting in northwestern mexico. *Trees*, *31*, 531–544. <https://doi.org/10.1007/s00468-016-1488-0>
- Hagedorn, F., Shiyatov, S. G., Mazepa, V. S., Devi, N. M., Grigor'ev, A. A., Bartish, A. A., ... Moiseev, P. A. (2014). Treeline advances along the Urals mountain range – driven by improved winter conditions? *Global Change Biology*, *20*, 3530–3543. <https://doi.org/10.1111/gcb.12613>
- Halwatura, D., Lechner, A. M., & Arnold, S. (2015). Drought severity–duration–frequency curves: A foundation for risk assessment and planning tool for ecosystem establishment in post-mining landscapes. *Hydrology and Earth System Sciences*, *19*, 1069–1091. <https://doi.org/10.5194/hess-19-1069-2015>
- He, M., Shishov, V., Kaparova, N., Yang, B., Bräuning, A., & Griebinger, J. (2017). Process-based modeling of tree-ring formation and its relationships with climate on the tibetan plateau. *Dendrochronologia*, *42*, 31–41. <https://doi.org/10.1016/j.dendro.2017.01.002>
- Hidalgo, H. C., Dracup, J. A., MacDonald, G. M., & King, J. A. (2001). Comparison of tree species sensitivity to high- and low-extreme hydroclimatic events. *Physical Geography*, *22*, 115–134.
- Huang, K., Yi, C., Wu, D., Zhou, T., Zhao, X., Blanford, W. J., ... Li, Z. (2015). Tipping point of a conifer forest ecosystem under severe drought. *Environmental Research Letters*, *10*, 024011. <https://doi.org/10.1088/1748-9326/10/2/024011>
- Julio Camarero, J., Miguel Olano, J., & Perras, A. (2010). Plastic bimodal xylogenesis in conifers from continental Mediterranean climates. *New Phytologist*, *185*, 471–480. <https://doi.org/10.1111/j.1469-8137.2009.03073.x>
- Kolb, T. E. (2015). A new drought tipping point for conifer mortality. *Environmental Research Letters*, *10*, 031002. <https://doi.org/10.1088/1748-9326/10/3/031002>
- Köppen, W. (2011). The thermal zones of the earth according to the duration of hot, moderate and cold periods and to the impact of heat on the organic world. *Meteorologische Zeitschrift*, *20*, 351–360. <https://doi.org/10.1127/0941-2948/2011/105>
- Li, Z., Zhou, T., Zhao, X., Huang, K., Gao, S., Wu, H., & Luo, H. (2015). Assessments of drought impacts on vegetation in China with the optimal time scales of the climatic drought index. *International Journal of Environmental Research and Public Health*, *12*, 7615–7634. <https://doi.org/10.3390/ijerph120707615>
- Luo, H., Zhou, T., Wu, H., Zhao, X., Wang, Q., Gao, S., & Li, Z. (2016). Contrasting responses of planted and natural forests to drought intensity in yunnan, china. *Remote Sensing*, *8*, 635. <https://doi.org/10.3390/rs8080635>
- Luo, H., Zhou, T., Yi, C., Xu, P., Zhao, X., Gao, S., & Liu, X. (2018). Stock volume dependency of forest drought responses in yunnan, china. *Forests*, *9*, 209. <https://doi.org/10.3390/f9040209>
- McDowell, N. G., & Allen, C. D. (2015). Darcy's law predicts widespread forest mortality under climate warming. *Nature Climate Change*, *5*, 669–672. <https://doi.org/10.1038/nclimate2641>
- McDowell, N. G., Beerling, D. J., Breshears, D. D., Fisher, R. A., Raffa, K. F., & Stitt, M. (2011). The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology & Evolution*, *26*, 523–532. <https://doi.org/10.1016/j.tree.2011.06.003>
- Mckee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Eighth Conference on Applied Climatology*, *17*, 179–184.

- Mitchell, P. J., O'Grady, A. P., Pinkard, E. A., Brodribb, T. J., Arndt, S. K., Blackman, C. J., ... Tissue, D. T. (2016). An ecoclimatic framework for evaluating the resilience of vegetation to water deficit. *Global Change Biology*, 22, 1677–1689. <https://doi.org/10.1111/gcb.13177>
- Mueller, R. C., Scudder, C. M., Porter, M. E., Trotter III, R. T., Gehring, C. A., & Whitham, T. G. (2005). Differential tree mortality in response to severe drought: Evidence for long-term vegetation shifts. *Journal of Ecology*, 93, 1085–1093. <https://doi.org/10.1111/j.1365-2745.2005.01042.x>
- Novick, K. A., Ficklin, D. L., Stoy, P. C., Williams, C. A., Bohrer, G., Oishi, A. C., ... Phillips, R. P. (2016). The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change*, 6, 1023–1027. <https://doi.org/10.1038/nclimate3114>
- Pan, M., Yuan, X., & Wood, E. F. (2013). A probabilistic framework for assessing drought recovery. *Geophysical Research Letters*, 40, 3637–3642. <https://doi.org/10.1002/grl.50728>
- Pasho, E., Julio Camarero, J., & Vicente-Serrano, S. M. (2012). Climatic impacts and drought control of radial growth and seasonal wood formation in *Pinus halepensis*. *Trees*, 26, 1875–1886. <https://doi.org/10.1007/s00468-012-0756-x>
- Petticrew, M., Cummins, S., Ferrell, C., Findlay, A., Higgins, C., Hoy, C., ... Sparks, L. (2005). Natural experiments: An underused tool for public health? *Public Health*, 119, 751–757. <https://doi.org/10.1016/j.puhe.2004.11.008>
- Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., ... Wattenbach, M. (2013). Climate extremes and the carbon cycle. *Nature*, 500, 287–295. <https://doi.org/10.1038/nature12350>
- Rigling, A., Bräker, O., Schneider, G., & Schweingruber, F. (2002). Intra-annual tree-ring parameters indicating differences in drought stress of *Pinus sylvestris* forests within the Erico-pinion in the Valais (Switzerland). *Plant Ecology*, 163, 105–121. <https://doi.org/10.1023/A:1020355407821>
- Rosbakh, S., Leingärtner, A., Hoiss, B., Krauss, J., Steffan-Dewenter, I., & Poschlod, P. (2017). Contrasting effects of extreme drought and snowmelt patterns on mountain plants along an elevation gradient. *Frontiers in Plant Science*, 8, 01478. <https://doi.org/10.3389/fpls.2017.01478>
- Rutter, M. (2007). Proceeding from observed correlation to causal inference—the use of natural experiments. *Perspectives On Psychological Science*, 2, 377–395. <https://doi.org/10.1111/j.1745-6916.2007.00050.x>
- Ryan, M. G. (2011). Tree responses to drought. *Tree Physiology*, 31, 237–239. <https://doi.org/10.1093/treephys/tpr022>
- Salzer, M. W., & Kipfmüller, K. F. (2005). Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, U.S.A. *Climatic Change*, 70, 465–487. <https://doi.org/10.1007/s10584-005-5922-3>
- Sheppard, P. R., Tarasov, P. E., Graumlich, L. J., Heussner, K. U., Wagner, M., Sterle, H., & Thompson, L. G. (2004). Annual precipitation since 515 BC reconstructed from living and fossil juniper growth of north-eastern Qinghai province, China. *Climate Dynamics*, 23, 869–881. <https://doi.org/10.1007/s00382-004-0473-2>
- Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., & Vogt, J. (2014). World drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology*, 34, 2792–2804. <https://doi.org/10.1002/joc.3875>
- Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23, 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
- Vicente-Serrano, S. M., Camarero, J. J., & Azorin-Molina, C. (2014). Diverse responses of forest growth to drought time-scales in the northern hemisphere. *Global Ecology and Biogeography*, 23, 1019–1030. <https://doi.org/10.1111/geb.12183>
- Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., ... Sanchez-Lorenzo, A. (2013). Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences*, 110, 52–57. <https://doi.org/10.1073/pnas.1207068110>
- Wei, S., Yi, C., Fang, W., & Hendrey, G. (2017). A global study of GPP focusing on light-use efficiency in a random forest regression model. *Ecosphere*, 8, e01724. <https://doi.org/10.1002/ecs2.1724>
- Wei, S., Yi, C., Hendrey, G., Eaton, T., Rustic, G., Wang, S., ... Valentini, R. (2014). Data-based perfect-deficit approach to understanding climate extremes and forest carbon assimilation capacity. *Environmental Research Letters*, 9, 065002. <https://doi.org/10.1088/1748-9326/9/6/065002>
- Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., ... McDowell, N. G. (2012). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3, 292–297.
- Williams, A. P., Michaelsen, J., Leavitt, S. W., & Still, C. J. (2010). Using tree rings to predict the response of tree growth to climate change in the continental United States during the twenty-first century. *Earth Interactions*, 14, 1–20. <https://doi.org/10.1175/2010EI362.1>
- Wu, X., Liu, H., Li, X., Ciais, P., Babst, F., Guo, W., ... Ma, Y. (2017). Differentiating drought legacy effects on vegetation growth over the temperate northern hemisphere. *Global Change Biology*, 24, 504–516.
- Wu, D., Zhao, X., Liang, S., Zhou, T., Huang, K., Tang, B., & Zhao, W. (2015). Time-lag effects of global vegetation responses to climate change. *Global Change Biology*, 21, 3520–3531. <https://doi.org/10.1111/gcb.12945>
- Xu, P., Zhou, T., Zhao, X., Luo, H., Gao, S., Li, Z., & Cao, L. (2018). Diverse responses of different structured forest to drought in Southwest China through remotely sensed data. *International Journal of Applied Earth Observation and Geoinformation*, 69, 217–225. <https://doi.org/10.1016/j.jag.2018.03.009>
- Yi, C., Mu, G., Hendrey, G., Vicente-Serrano, S. M., Fang, W., Zhou, T., ... Xu, P. (2018). Bifurcated response of a regional forest to drought. *Expert Opinion on Environmental Biology*, 7(2), 1000153.
- Yi, C., Pendall, E., & Ciais, P. (2015). Focus on extreme events and the carbon cycle. *Environmental Research Letters*, 10, 070201. <https://doi.org/10.1088/1748-9326/10/7/070201>
- Yi, C., Ricciuto, D., Li, R., Wolbeck, J., Xu, X., Nilsson, M., ... Zhao, X. (2010). Climate control of terrestrial carbon exchange across biomes and continents. *Environmental Research Letters*, 5, 034007. <https://doi.org/10.1088/1748-9326/5/3/034007>
- Yi, C., Rustic, G., Xu, X., Wang, J., Dookie, A., Wei, S., ... Pinter, K. (2012). Climate extremes and grassland potential productivity. *Environmental Research Letters*, 7, 035703. <https://doi.org/10.1088/1748-9326/7/3/035703>
- Zargar, A., Sadiq, R., Naser, B., & Khan, F. I. (2011). A review of drought indices. *Environmental Reviews*, 19, 333–349. <https://doi.org/10.1139/a11-013>
- Zhou, T., Yi, C., Bakwin, P. S., & Zhu, L. (2008). Links between global CO<sub>2</sub> variability and climate anomalies of biomes. *Science in China Series D: Earth Sciences*, 51, 740–747.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Gao S, Liu R, Zhou T, et al. Dynamic responses of tree-ring growth to multiple dimensions of drought. *Glob Change Biol*. 2018;00:1–12. <https://doi.org/10.1111/gcb.14367>