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Forest drought resistance distinguished by canopy height

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Abstract

How are the survival and growth of trees under severe drought affected by their size? While some studies have shown that large trees are more vulnerable to drought than smaller trees, others found that small trees are the more vulnerable. We explored the potential relationships between canopy height and forest responses to drought indicated by tree mortality, tree ring width index (RWI), and normalized difference vegetation index (NDVI) in the southwestern United States (SWUS) in 2002. In that year many trees had zero tree ring growth due to mortality and dieback, presumably related to drought-stress. With RWI data from a tree ring data base and climate data co-located with the field measurements, we found size-dependent linear correlations between these forest responses and canopy height in SWUS under severe drought condition. During that drought period, both trunk growth (RWI) and leaf growth (NDVI) were positively correlated with canopy height of the smaller trees (less than 18 m) and negatively correlated with canopy height of greater than 18 m. Tree mortality was negatively correlated with canopy height up to 15 m. Both local-scale and regional-scale data are consistent in showing that forests with medium canopy height (around 18 meters) showed the greatest resistance to severe drought. We suggest that negative impacts of severe drought on forests could be modified with active management of canopy structure.

1. Introduction

The frequency of severe drought is increasing all over the world (Cook *et al* 2014), which has caused profound impacts on forest ecosystems (Allen *et al* 2010, Yi *et al* 2015) such as decreased forest productivity (Ciais *et al* 2005, Yi *et al* 2010) and earlier dormant period (Xie *et al* 2015). Forest mortality is likely in a region when drought is so severe that zero annual tree-ring growth occurs across the region (Kolb 2015), which was defined as a drought tipping point by (Huang *et al* 2015). Forests resistance to drought or insects attack are weak around the tipping point (i.e. narrow or missing ring growth) (Kolb 2015, Kane and Kolb 2010, McDowell *et al* 2015), which is likely related to the structure and function of forest (Anderson-Teixeira *et al* 2013).

The impact of drought on forest structure and function may be sensitive to tree size. Greater mortality of small trees may modify future forest succession whereas mortality of large trees causes disproportionate losses of carbon reserve (Phillips *et al* 2010, Lindenmayer *et al* 2012). It has not been clear whether large or small trees would suffer more under drought stress. Particularly, there were two opposite findings of size effects on forest response to drought. Some studies indicated that small trees were more sensitive to water stress (Nakagawa *et al* 2000, Guarín

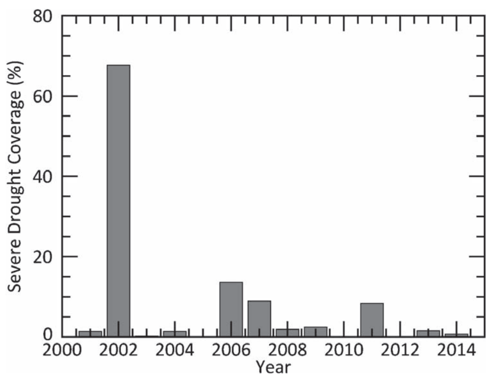

Figure 1. Percentage of severe drought (SPEI <-1.64) area in the southwest United States (SWUS) during 2001–2014. The percentage were calculated by the pixels (half degree) where SPEI value less than -1.64 to the total pixels numbers (22×26) in SWUS.

and Taylor 2005, Zhang *et al* 2017) due to their shallow roots and less access to water in the deep soil. Other studies indicated that drought had a greater impact on large trees (Aber *et al* 2001, Nepstad *et al* 2007, Zhang *et al* 2009, Bennett *et al* 2015), as they have a greater evapotranspiration rate and higher water demand, than smaller trees.

In this study, we attempted to reveal the relationship between the growth of forests in the Southwest and canopy height under severe drought condition. By integrating field measurement data, remote sensing data and climate data, we analyzed the drought responses in different forests with various canopy heights. The objective of this study was answer this question: when a drought reaches the tipping point that may lead to zero tree ring growth, what is the role of canopy height in forest resistance to drought?

2. Data and method

The SWUS (Arizona, New Mexico, Colorado, and Utah) experienced a severe drought event in 2002 (figure 1) (Cook *et al* 2004). The study area in this research was the same as with (Huang *et al* 2015) (figure S1 available at stacks.iop.org/ERL/13/075003/mmedia). Many studies showed this event had a great impact on the local forest ecosystem which resulted in dieback and morality (Floyd *et al* 2009, Ganey and Vojta 2011, Stahl *et al* 2013, Kane and Kolb 2014), and have accumulated multi-source data from ground survey to satellite observation in this region. Pinus edulis (PIED) and Pinus ponderosa (PIPO) are dominant conifer species and will be used to investigate how canopy height impacts coniferous forest responses under severe drought condition in SWUS.

2.1. Data

2.1.1. SPEI data

In this study, we used the Standardized Precipitation Evapotranspiration Index (SPEI) as the indicator for drought intensity to quantify surface water deficit and surplus (Vicente-Serrano *et al* 2010, 2013). SPEI data were obtained from the global SPEI data set, which was based on monthly precipitation and potential evapotranspiration from the Climatic Research Unit (CRU) of the University of East Anglia (http://sac.csic.es/spei/database.html). It provided SPEI timescales between 1 and 48 months, with a 0.5 degree spatial resolution and a monthly temporal resolution (Vicenteserrano *et al* 2010, Beguería and Vicente Serrano 2016). Following results from Huang *et al* (2015), we used the SPEI between the previous September and July of the subject year to reveal the impact of canopy height on forest response under the apparent tipping point of drought in 2002 (SPEI< -1.64) (Huang *et al* 2015) at which tree mortality seems to become frequent.

2.1.2. Mortality data

We obtained data from 10 forest plots with drought-related mortality in the SWUS from the previous studies (figure S1, Floyd *et al* 2009, Negron *et al* 2009, Ganey and Vojta 2011, Stahl *et al* 2013). The data included geographic location, species (PIED and PIPO) and drought-related mortality. We matched those plots to the spatial data by latitude and longitude, and obtained their canopy heights and SPEI values from the pixels where the plots were located. From the ten plots for which we had data, we selected eight plots with SPEI < -1.64 and height > 0 (table S1).

2.1.3. Tree ring data

The International Tree-Ring Data Bank (ITRDB) is the world's largest public archive of tree ring data, managed by NCEI's Paleoclimatology Team and the World Data Center for Paleoclimatology (www.ncdc.noaa.gov/paleo-search/?dataTypeId=18). We have extracted geographic location, species and raw ring width from the ITRDB. Standard chronologies were created with the program AutoRegressive STANdardization by detrending and indexing (standardizing) from tree ring measurement series (Cook 1985). The RWI value of 1000 represents mean growth values while value of 0 represents no growth. We matched those plots to the spatial data by latitude and longitude, and obtained their canopy heights from a 1 km resolution image and SPEI from a 0.5 degree image in the SWUS (figure S1). Eighteen tree ring records from all 35 sites with SPEI < -1.64 and height > 0 were chosen to use in this study (table S2).

2.1.4. Remote sensing data (NDVI and canopy heights)

NDVI: The responses of the subject forest to drought were quantified through use of MODIS NDVI (MOD13A3) (http://modis.gsfc.nasa.gov/) which served to evaluate potential changes in forest leaf activity (Deshayes *et al* 2006). These data have a spatial resolution of 1 km and temporal resolution of monthly and have been widely used for monitoring regional vegetation conditions. The increase in atmospheric or soil water vapor resulted in a lower NDVI signal, which can be interpreted as an actual change in leaf growth (Pinheiro *et al* 2004). In this study, the NDVI change (ΔNDVI) in the drought year of 2002 were calculated pixel by pixel by:

$$\Delta\mathrm{NDVI} = \overline{\mathrm{NDVI}}_{2002\mathrm{GS}} - \overline{\mathrm{NDVI}}_{2001\mathrm{GS}}$$

where $\overline{\mathrm{NDVI}}_{2002\mathrm{GS}}$ represents the optimum growth condition of forest activity in the growing season (July and August) in the drought year of 2002. $\overline{\mathrm{NDVI}}_{2001\mathrm{GS}}$ represents the optimum growth condition of forest activity in the pre-drought year of 2001. As the comparison was over different time periods at the same pixel, it may be assumed to represent the change of growth status caused by the drought.

Canopy height: In this study, we used the spatial-specific forest canopy height data (1 km resolution) (Simard *et al* 2011) (figure S1), derived from LiDAR. This dataset was downloaded from http://landscape.jpl.nasa.gov. It provided estimated canopy height values across the land surface, and had good correlation with the tree height observed in the field at both global and regional scales (Simard *et al* 2011, Zhang *et al* 2014).

Forest map: Conifer forest regions (PIED and PIPO dominated) are defined herein by the International Geosphere Biosphere Programme (IGBP) as the distribution map of the needleleaf forest cover types from the MODIS Land Cover product (MCD12Q1), with a spatial resolution of 500 m in 2002.

2.2. ΔNDVI average

Based on Huang *et al* (2015), SPEI around −1.64 is a threshold below which there would be zero tree ring growth. For this study we selected all the areas with SPEI<−1.64 as the study area which was going through a severe drought. In order to study the relationship between leaf growth change and canopy height under severe drought at the regional scale, ΔNDVI in the region where SPEI <−1.64 were grouped by pixels with the same canopy height. To avoid extreme outliers canopy height categories in which the proportion pixels were less than 1‰ of the total forest pixels, were not included.

2.3. Regression analyses

In order to reveal the relationship between forest response and canopy height under severe drought, three linear regression models of different forest response indicators (drought-related Mortality, RWI and ΔNDVI) and canopy height were established. For the drought-related mortality and RWI, we matched the plots with grid data to get their heights and SPEI and the ΔNDVI were grouped by pixels with the same canopy heights.

All regression analyses were conducted in EXCEL (Microsoft Office 2013). All graphs were made in IDL8.5 and Arcgis10.0.

3. Results and discussion

The relationship between the drought responses and height of forests are shown in figure 2. When the forest heights were less than 18 meters, there was a significant negative ($P < 0.1$) linear correlation between mortality and height, and a significant positive linear correlation between RWI ($P = 0.006$) and height. It is not surprising to see ΔNDVI also has a positive linear correlation with height for the trees <18 m height ($P < 0.001$), as ΔNDVI represents the changing input to forest growth from canopy leaves. This is interpreted to mean that mortality was reduced with the increase in canopy height up to 18 m both RWI and ΔNDVI were increased with the increase in canopy height. It is reasonable to consider short trees to be more sensitive to drought when the canopy height was under 18 meter. Soil water was less available to the shallow root system of short trees, resulting in this weaker drought tolerance (Nakagawa *et al* 2000). On the other hand, when forest heights were over 18 m, both RWI ($P = 0.065$) and ΔNDVI ($P < 0.001$) had significant negative linear correlation with height under severe drought condition. We inferred from these results that there may be a positive correlation between mortality and height above 18 m, although we didn't have mortality data for heights over 18 m. It means both the growth of stem and leaf were reduced with increased height above 18 m, and that the tall trees were more sensitive to drought when the canopy height was above 18 m. This phenomenon may result from the greater water demand in tall trees caused by the longer water transportation path, higher consumption to maintain respiration and the stronger evapotranspiration of leaf surface (Zhang *et al* 2009). It might also be associated with their vulnerability to xylem cavitation under severe drought (Schnitzer and Bongers 2002, Nepstad *et al* 2007).

Above all, our results indicated that forest resistance under severe drought might be inferred from canopy height. Both short and tall forests were sensitive to severe drought, but the medium-height forests had the least reduction in leaf (NDVI) and stem (RWI) growth which indicates greater resistance to severe drought. This resistance may be especially important in an early-middle stage of forest growth as this is the period with the strongest ability to produce and store dry matter, i.e. carbohydrates needed for future growth. For example, light-use efficiency (LUE), which is a key physiological parameter for vegetation primary production, has a significant relationship with stand age (Zhou *et al* 2015). The maximum LUE appeared at the early-middle stage (Zhou *et al* 2015),

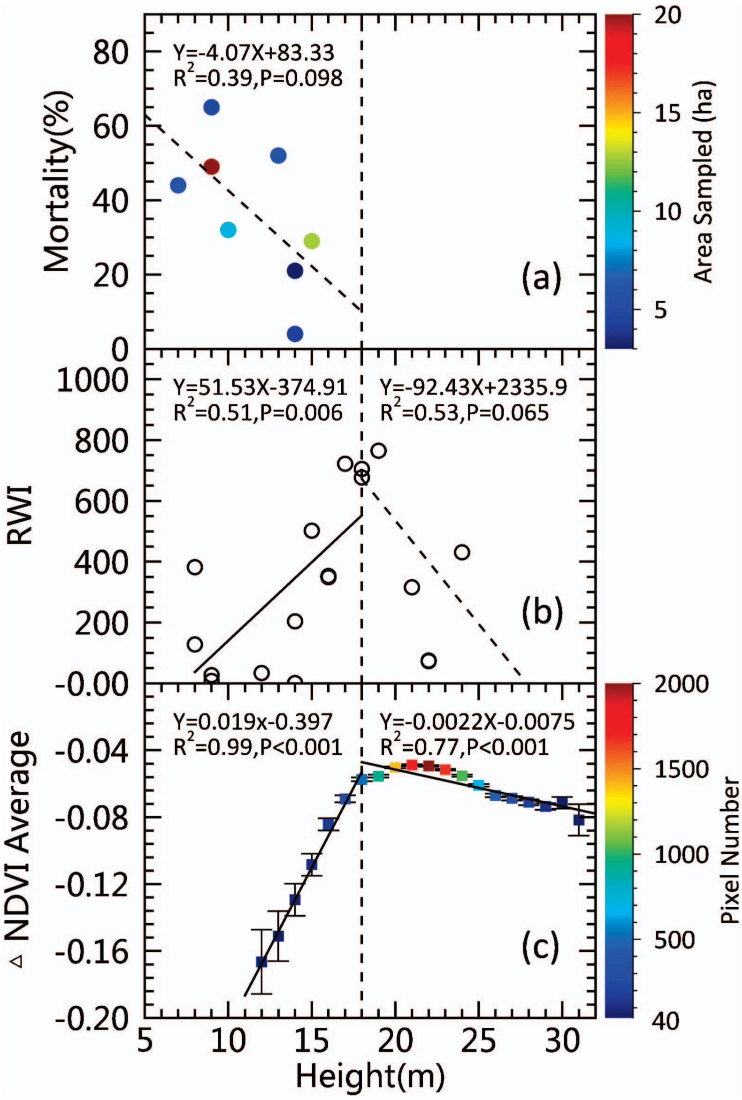

Figure 2. The relationship between forest growth variables and canopy height under severe drought.

when trees can produce and store much more dry matter, as well as water, that is available to support tree metabolism during drought. These reserves would increase with stomatal closure as water supply becomes limited, thereby reducing loss of water reserves in the tree and soil by evapotranspiration, providing increased resistance to water loss during drought (Waggoner and Turner 1971). Another reason for the different resistance might be because medium-size trees have all the advantages of both large and small trees. Compared to the larger trees, medium-size trees have lower water demand, but compared to smaller trees, they have a more developed root system that can seek and absorb more soil water.

Our results helped to reconcile the two opposing hypotheses on size-dependent response to drought and explain why they can coexist. Severe drought had a greater impact on both small and large trees than on medium size trees. The canopy structure should be considered in such research, because the distribution of canopy height may be skewed toward one height class and affect the conclusion. The impact of drought on forest heterogeneity (spatial and temporal) also should be considered. As our results were obtained under severe drought conditions, the conclusion with less severe drought conditions can not be inferred. But it is certain that differences in the drought intensity and duration will have an impact on forest responses (Allen *et al* 2010). Our results also imply that forests with primarily short and tall trees will face a higher risk of death and degradation as a result of climate change. These results should help forest mangers focus more attention on the population dynamics of forests (Bellassen and Luyssaert 2014).

The canopy height data with spatial continuity were derived from the LiDAR rather than from the field observations. Forest heterogeneity and topography will increase the error of height estimation (Lefsky *et al* 2005, Duncanson *et al* 2010, Simard *et al* 2011), but the height data used here was one of the best descriptions of forest vertical structure at regional scales currently available (Simard *et al* 2011). Given the limitation of canopy and tree height from field observations, it is difficult to verify the accuracy of the height data by measuring tree and canopy height over such a large region. From known validation of the global and regional scales (Simard *et al* 2011, Zhang *et al* 2014), it is reasonable to assume that this set of canopy height data correlate well with field observations. At global-scale these canopy height data have a good correspondence with site canopy height at 66 sites from the FLUXNET La Thuille database ($R^2 = 0.69$ and root-mean-square error (RMSE) = 4.36 m). Many forest sites in this database, located in US (Baldocchi 2008), also have a good correlation with the field observation tree height in different parts of China at the regional scale reported by Zhang *et al* (2014) ($R^2 = 0.41$ and RMSE = 3.15 m; $R^2 = 0.64$ and RMSE = 4.18 m). Green *et al* (2013) fused this 1 km resolution canopy height data with higher-resolution land cover data, resulting in 30 m resolution estimates of canopy height. Results at 30 m resolution showed a good correlation with reference to airborne LiDAR data from 262 randomly located 1 km^2 areas within nine study sites ($R^2 = 0.77$) (Green *et al* 2013). It is undeniable that this canopy height data may cause uncertainty in the results, but the canopy heights in our study area ranged from (5–18 m) and (18–31 m), which were larger than the regional and global errors.

4. Conclusion

In this study, we analyzed the characteristics of severe drought responses in forests with different canopy heights based on multi-resource data. Our results demonstrated that when drought reached the tipping point of SPEI < -1.64, the amount of tree mortality and reductions in stem growth (RWI) and leaf growth (NDVI) of the forests was correlated with canopy height in SWUS. Both short and tall forests were more vulnerable and susceptible to drought than medium-height forest stands. The medium height forests had the greatest drought resistance. Considering the increase in the frequency and duration of severe drought in the context of global climate change, more attention needs to be given to canopy structure in forest management and risk assessments in the future.

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