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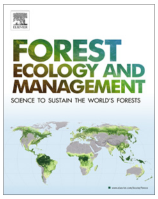

Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty

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ABSTRACT

Observations of increasing global forest die-off related to drought are leading to more questions about potential increases in drought occurrence, severity, and ecological consequence in the future. Dry soils and warm temperatures interact to affect trees during drought; so understanding shifting risks requires some understanding of changes in both temperature and precipitation. Unfortunately, strong precipitation uncertainties in climate models yield substantial uncertainty in projections of drought occurrence. We argue that disambiguation of drought effects into temperature and precipitation-mediated processes can alleviate some of the implied uncertainty. In particular, the disambiguation can clarify geographic diversity in forest sensitivity to multifarious drivers of drought and mortality, making more specific use of geographically diverse climate projections. Such a framework may provide forest managers with an easier heuristic in discerning geographically diverse adaptation options. Warming temperatures in the future mean three things with respect to drought in forests: (1) droughts, typically already unusually hot periods, will become hotter, (2) the drying capacity of the air, measured as the vapor pressure deficit (VPD) will become greater, and (3) a smaller fraction of precipitation will fall as snow. More hot-temperature extremes will be more stressful in a direct way to living tissue, and greater VPD will increase pressure gradients within trees, exacerbating the risk of hydraulic failure. Reduced storage in snowpacks reduces summer water availability in some places. Warmer temperatures do not directly cause drier soils, however. In a hydrologic sense, warmer temperatures do little to cause "drought" as defined by water balances. Instead, much of the future additional longwave energy flux is expected to cause warming rather than evaporating water. Precipitation variations, in contrast, affect water balances and moisture availability directly; so uncertainties in future precipitation generate uncertainty in drought occurrence and severity projections. Although specific projections in annual and seasonal precipitation are uncertain, changes in inter-storm spacing and precipitation type (snow vs. rain) have greater certainty and may have utility in improving spatial projections of drought as perceived by vegetation, a value not currently captured by simple temperature-driven evaporation projections. This review ties different types of future climate shifts to expected consequences for drought and potential influences on physiology, and then explains sources of uncertainty for consideration in future mortality projections. One intention is to provide guidance on partitioning of uncertainty in projections of forest stresses.

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1. Introduction

Observations of global die-off in forests has raised concerns about forest responses to drought and the linkages between drought and climate change (Allen et al., 2010, 2015), leading to

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questions about adapting forest and rangeland management for drought resilience (Vose et al., 2016a). At present, there is substantial disagreement about whether climate change will increase drought occurrence, frequency, or severity (Dai, 2011; Seneviratne et al., 2012; Sheffield et al., 2012; IPCC, 2013; Roderick et al., 2014, 2015; Trenberth et al., 2014; Cook et al., 2015). Despite this uncertainty, there is agreement that forests will be more affected by drought in a warmer environment whether through stronger metabolic demand, reduced opportunity for carbon fixation, thermal mortality, leaf desiccation, or greater potential for cavitation of the fluid transport system within tree stems and branches (e.g. Adams et al., 2009; McDowell et al., 2011; Choat et al., 2012; Anderegg et al., 2013; Allen et al., 2015; Körner, 2015; Mackay et al., 2015).

Significant drought mortality has already occurred in U.S. forests, with the majority of the drought stress and mortality found in western states (Millar and Stephenson, 2015; Clark et al., in press) and a lesser, though still noteworthy, increase in the southeastern U.S. since the late 1990s (Olano and Palmer, 2003; Starkey et al., 2004; Berdanier and Clark, 2016). As an example of the magnitude of effect, the area of forests burned by large fires in the Forest Service's Monitoring Trends in Burn Severity (MTBS) database between 1984 and 2006 in 9 western states (excluding most of CA and NV) was 5.7 Mha (Dillon et al., 2011), and between 1997 and 2010, Bark beetle mortality was estimated at 5.4 Mha (Meddens et al., 2012). Much larger areas have been affected if non-forest lands are considered, if more recent years are added, or for a full accounting of affected regions.

Although "drought" is frequently treated as a technical term quantified with varying metrics, it is used with very broad meaning in public discourse. Inconsistent and variable definitions can make assertions made about shifting drought and drought effects difficult to either question or defend. Simpler concepts, terms like "dry" and "warm" are a useful way to break down meaning about drought that can be more easily tied to typical climate projections for purposes of describing effects on forests at large spatial scales. For example, in the broadest sense, we can examine "dry" and "warm" relative to changing averages. While increasing warmth has high certainty (IPCC, 2013), future precipitation is uncertain in most places, with only general patterns of moistening and drying associated with hemisphere-scale atmospheric circulation being agreed upon features of future climates (Fig. 1). This moisture uncertainty provides slight feedback in temperature uncertainty; for example, some of the drying locations are expected to experience exacerbated warming due to drying. Because increasing temperature is virtually certain, the range of precipitation predictions generates a breadth of potential vegetation outcomes around likely temperature effects.

Although there is uncertainty in precipitation change at annual time scales, some greater certainty exists for shorter time scales, and an improved approach may be to focus on precipitation variability and extremes. Predictions and observations of increasing precipitation variability (Pagano and Garen, 2005; Luce and Holden, 2009; Seager et al., 2012; Hamlet et al., 2013) suggest a future that may be warmer and ***both wetter and drier***, depending on the time scale of examination. We can interpret moisture trends from the perspective of annual averages, seasonal or monthly values, or even shorter time frames such as the hottest days and driest weeks. While an annual scale trajectory might point toward warmer and wetter in a given location, lengthening dry spells between storms would increase the frequency of forest drought stress (Knapp et al., 2008; Heisler-White et al., 2009; Ross et al., 2012) as could drying during the summer season. Focusing on variability shifts our view toward extremes that may shift independently of averages (see, for example, figures in Jentsch et al. (2007), Field et al. (2012), Anderegg et al. (2013)). Although much of the United States is projected to get wetter in general, particularly in forested regions, some specific atmospheric and hydrologic behaviors will likely contribute to increasing dryness for time scales of days to months. These are not typically the time scales associated with mortality of long-lived species, but increased short-term moisture stress on a more regular basis during the growing season creates an important ecological context affecting growth and mortality (e.g. see examples in Knapp et al. (2008), Heisler-White et al. (2009)) contingent on environmental characteristics.

The objective of this synthesis is to identify the physical and hydrologic characteristics of drought that are most relevant for understanding how drought impacts forests from the scale of individual trees up to the forest ecosystem. We also clarify the terminologies used when discussing changing droughts and changing forests and explain the individual roles of precipitation, evapotranspiration, and snowmelt timing in contributing to drought-related stresses.

2. Characterizing specific mechanisms of drought in the context of forest responses

In mechanistic terms, drought relates to the fraction of full soil recharge after each precipitation event (i.e., how much it rains), the frequency of precipitation events (i.e., how often it rains), energy available for evaporation (usually net radiation) and atmospheric demand (i.e. the vapor pressure deficit, or difference between current atmospheric water content and water content at saturation). This balance between soil water supply and tree water demand determines drought severity from the perspective of the forest. Even though drought mortality may arise through external agents like fire (e.g. Littell et al., 2016) or insects and pathogens (Kolb et al., this issue), these are ultimately mediated through plant physiological responses to drought (Phillips et al., this issue).

A large range of physiological processes are implicated in drought mortality and productivity declines, and though the literature highlights substantial uncertainty about process (McDowell and Sevanto, 2010; Sala et al., 2010; Anderegg et al., 2013; Hartmann, 2015; Körner, 2015; McDowell et al., 2015), there is a convergence on two competing alternatives: hydraulic failure, or the formation of air/vapor blockage in xylem (e.g. Sperry, 2000; Sperry et al., 2002), and carbon starvation when stomata allowing gas exchange (and thereby photosynthesis) are kept closed for extended periods (e.g. McDowell et al., 2008). These alternatives reflect the trade-off between strategies that encourage stomatal closure at the cost of reduced carbon fixation versus those that risk hydraulic failure but maximize carbon fixation (e.g. Ambrose et al., 2015). In what may actually represent end-members on a spectrum of diverse strategies, isohydric and anisohydric behaviors are used by trees to regulate risks versus growth in environments of varying aridity (e.g. Franks et al., 2007; Klein, 2014). In short, trees vary in their physiological responses to drought, and geographically and topographically varying differences in climate changes will interact with these physiological responses in potentially unique ways.

Shifts in climate are expected to change hydrology and consequently the nature of soil moisture drought and evaporative demand. Climatic shifts can broadly be characterized as shifts in temperature, which are relatively certain in their magnitude and direct consequence, and shifts in precipitation, which have large uncertainty in magnitude (Table 1). One response to uncertainty is to set aside potential precipitation variability and analyze temperature induced changes conditioned on mild average changes in precipitation. In Table 1, we offer both wetting and drying seasonal trends in precipitation as context, in part because there is spatial variation in seasonal precipitation projections across the

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