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Review of broad-scale drought monitoring of forests: Toward an integrated data mining approach ☆

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A B S T R A C T

Efforts to monitor the broad-scale impacts of drought on forests often come up short. Drought is a direct stressor of forests as well as a driver of secondary disturbance agents, making a full accounting of drought impacts challenging. General impacts can be inferred from moisture deficits quantified using precipitation and temperature measurements. However, derived meteorological indices may not meaningfully capture drought impacts because drought responses can differ substantially among species, sites and regions. Meteorology-based approaches also require the characterization of current moisture conditions relative to some specified time and place, but defining baseline conditions over large, ecologically diverse regions can be as difficult as quantifying the moisture deficit itself. In contrast, remote sensing approaches attempt to observe immediate, secondary, and longer-term changes in vegetation response, yet they too are no panacea. Remote sensing methods integrate responses across entire mixed-vegetation pixels and rarely distinguish the effects of drought on a single species, nor can they disentangle drought effects from those caused by various other disturbance agents. Establishment of suitable baselines from remote sensing may be even more challenging than with meteorological data. Here we review broad-scale drought monitoring methods, and suggest that an integrated data-mining approach may hold the most promise for enhancing our ability to resolve drought impacts on forests. A big-data approach that integrates meteorological and remotely sensed data streams, together with other datasets such as vegetation type, wildfire occurrence and pest activity, can clarify direct drought effects while filtering indirect drought effects and consequences. This strategy leverages the strengths of meteorology-based and remote sensing approaches with the aid of ancillary data, such that they complement each other and lead toward a better understanding of drought impacts.

Contents

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1. Introduction

Drought is a well-known driver of ecosystem change, yet its occurrence, effects and long-term implications are difficult to recognize and track over large areas (Panu and Sharma, 2002; Hogg et al., 2008). In forests, the reduced moisture levels and high temperatures associated with drought contribute directly to tree stress and mortality (Wang et al., 2012; Anderegg et al., 2013; Millar and Stephenson, 2015). Drought also impacts forests indirectly, by altering the frequency and severity of disturbances such as insect outbreaks or wildfire (Schowalter et al., 1986; Mattson and Haack, 1987; Meyn et al., 2007; Raffa et al., 2008; Trouet et al., 2010; Martínez-Vilalta et al., 2012). Whether these impacts are direct or secondary, insights from monitoring are typically limited in space and time and inferential in nature. Local observations may be subject to fine-scale nuances that make them unrepresentative of the larger scale. In contrast, broad-scale monitoring of impacts is usually restricted in detail unless change persists long enough to be recognized or until specific changes can be confirmed on the ground with broad-scale surveys.

Fundamentally, our ability to characterize broad-scale drought impacts flows from two types of data: meteorology-based measures and remote-sensing-based measures. Each of these data streams is constrained in its applicability for forests. A multitude of meteorology-based indicators have been developed to estimate moisture deficits in agricultural landscapes, but they may not adequately depict the effects of those deficits across species or vegetation types that exhibit diverse drought responses (Mishra and Singh, 2010; Vicente-Serrano et al., 2012; Peters et al., 2015). As forests and their constituent tree species can have widely disparate levels of drought tolerance, no one indicator is likely to capture the full range of anticipated impacts (Svoboda et al., 2004; Mishra and Singh, 2010; Martínez-Vilalta et al., 2012). For effective national- or regional-scale analysis, multiple indicators may be required (Steinemann, 2003; Anderson et al., 2011; AghaKouchak et al., 2015; Park et al., 2016).

Alternatively, remote-sensing-based measures track short-term drought responses by exploiting known differences in reflected radiation between stressed and unstressed vegetation (Peters et al., 1991, 2002; Zhang et al., 2013; Mildrexler et al., 2016). However, short-term stress may not be a sufficient indicator of drought impacts that sometimes take years to emerge (Pasho et al., 2011; Mendivelso et al., 2014; Park et al., 2016). Such slow or delayed responses can reduce our confidence in attributing observed changes to drought, as vegetation changes can result from a number of stressors, including some (e.g., insects and diseases, wildfire) that are influenced by, and therefore confounded with, drought (Westerling et al., 2006; Bigler et al., 2007; Buma and Wessman, 2011; Anderegg et al., 2015). Regardless, attribution of changes observed by remote sensing is challenging without the aid of ancillary data or modeling (Cohen et al., 2016). Even when attribution is possible, the ecological implications of direct and indirect drought effects can be convoluted, since these disturbances may constitute an important and cyclical natural dynamic at timescales that may not be recognized using remote sensing technologies (Peterson et al., 1998; Gunderson, 2000).

Drought impacts are also difficult to resolve in successionally, compositionally, or structurally complex landscapes because deciduous and evergreen trees, shrubs, and grasses that comprise these landscapes are not equally sensitive or responsive to drought (Hanson and Weltzin, 2000; Lobo and Maisongrande, 2006; Sims et al., 2014). This is especially true of recently disturbed areas, where the vegetation is in various stages of recovery, as dominant seral species may respond differently to drought through time (Sousa, 1984). Varied responses also occur in highly fragmented landscapes where forest, agriculture, and development are intermixed (Laurance, 2004; Ewers and Didham, 2006). In such places, it can be problematic to define appropriate baseline conditions for comparison to current observations.

With more than a century of recorded measurements, meteorological station data can provide a robust understanding of baseline conditions at sites, and conditions can be modeled between stations using known topography and meteorological relationships. From this context, it is possible to infer the adaptations of species to climatic regimes and their potential responses to moisture and temperature extremes. However, the relevance of historical climate can be difficult to ascertain in places where forest structure or composition have changed. Additionally, because climate conditions vary across time scales, the appropriate timespan for meaningful climatic baselines is debatable (Lamb and Changnon, 1981; Livezey et al., 2007; Wilks, 2013). Drought-associated tree mortality can sometimes cause rapid changes in forests (Mueller et al., 2005; Wang et al., 2012), but a long-term successional perspective may be necessary to discern the relative importance of observed changes over the lifespans of trees. Having a relevant temporal context is particularly critical because applicable remotely sensed data have only been available for a few decades, or roughly a third of the time that ground-station-based meteorological data have been available on a wide scale (Choi et al., 2013). While this shorter observation window from remote sensing may limit what we can glean from historical patterns of drought and drought response (AghaKouchak et al., 2015), products derived from satellite data could help to characterize similarities and differences among droughts during recent years, which might be the most relevant time period for some locations of interest.

Near-real-time drought impact monitoring has previously been implemented for agricultural and rangeland systems (Tadesse et al., 2005; Brown et al., 2008), but monitoring impacts is more complicated for forests. Neither meteorological indices nor short-term observations from remote sensing, even if used in combination, are likely to be sufficient. For forests, knowledge of both direct and indirect drought impacts, as well as their interactions, is critical (Anderegg et al., 2015; Trumbore et al., 2015), as are insights into the differing drought sensitivities of forest species and communities. Fortunately, a number of ancillary datasets are available that can enhance interpretations and improve predictions, despite the complex drivers involved. For example, landcover or vegetation maps can inform expectations of drought sensitivity. Similarly, datasets that track recent disturbances can isolate various potential causes of change. Fine-resolution datasets, such as data collected by systematic field surveys, may be required to understand specific drought impacts. When integrated, these data streams can reduce the uncertainties associated with drought impacts in forested ecosystems.

In this paper, we review important strengths and weaknesses of commonly used meteorology- and remote-sensing-based mea-