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A forest vulnerability index based on drought and high temperatures

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ABSTRACT

Increasing forest stress and tree mortality has been directly linked to combinations of drought and high temperatures. The climatic changes expected during the next decades – large increases in mean temperature, increased heat waves, and significant long-term regional drying in the western USA – will likely increase chronic forest stress and mortality. The aim of this research is to develop and apply a new forest vulnerability index (FVI) associated with drought and high temperatures across the Pacific Northwest region (PNW; Oregon and Washington) of the USA during the MODIS Aqua era (since 2003). Our technique incorporates the alterations to canopy water and energy exchange processes caused by drought and high temperatures with spatially continuous MODIS land surface temperature (LST) and evapotranspiration (ET), and with Parameter-elevation Relationships on Independent Slopes Model (PRISM) precipitation (P) data. With P and ET, we calculate a monthly water balance variable for each individual pixel normalized by forest type group (FTG), and then difference the water balance with the corresponding normalized monthly mean LST to calculate a monthly forest stress index (FSI). We then extract the pixel-specific (800-m resolution) statistically significant temporal trends of the FSI from 2003 to 2012 by month (April to October). The FVI is the slope of the monthly FSI across years, such that there is a FVI for each month. Statistically significant positive slopes indicate interannual increases in stress leading to expected forest vulnerability (positive FVI) for a given month. Positive FVI values were concentrated in the months of August and September, with peak vulnerability occurring at different times for different FTGs. Overall, increased vulnerability rates were the highest in drier FTGs such as Ponderosa Pine, Juniper, and Lodgepole Pine. Western Larch and Fir/Spruce/Mountain Hemlock groups occupy moister sites but also had relatively high proportion of positive FVI values. The Douglas-fir group had the second largest total area of increased vulnerability due to its large areal extent in the study area. Based on an analysis using imagery viewed in Google Earth, we confirm that areas with increased vulnerability are associated with greater amounts of stress and mortality. The FVI is a new way to conceptualize and monitor forest vulnerability based on first-order principles and has the potential to be generalized to other geographical areas.

1. Introduction

Terrestrial vegetation plays a critical role in water and energy cycles, with transpiration representing about 80 to 90% of terrestrial evapotranspiration (ET) and absorbing a tremendous amount of solar energy (Jasechko et al., 2013; Trenberth, Fasullo, & Kiehl, 2009). Since climate and the distribution of vegetation are so tightly linked (Mather & Yoshioka, 1968; Stephenson, 1990), plants are vulnerable to changes in precipitation, temperature, and related variables when those exceed species-specific physiological stress thresholds (Allen et al., 2010; IPCC, 2013; McDowell & Allen, 2015; Teskey et al., 2015). There is considerable uncertainty in how trees will cope with the rapid changes occurring in the climate system, including increasing global mean temperatures and a changing hydrologic cycle (Hartmann, Adams, Anderegg, Jansen, & Zeppel, 2015; IPCC, 2013; McDowell et al., 2008). The potential for broad-scale climate-induced forest die-off is of particular concern because of large carbon storage in forests, and their key role in providing a variety of other valuable ecosystem services (Breshears et al., 2005; Kurz, Stinson, Rampley, Dymond, & Neilson, 2008; McDowell & Allen, 2015; Millar & Stephenson, 2015; Smith et al., 2014). Urgently needed are remote sensing-based large-area forest stress and mortality detection and attribution techniques that can provide a priori assessments of forest status and trends, as in metrics that can be used to infer a measure of possible future harm (Allen, Breshears, & McDowell, 2015; Smith et al., 2014). Vulnerability metrics should have clear mechanistic links with remotely sensed metrics of vegetation that are sensitive to the changes in climate (Smith et al., 2014).

Globally, forests are showing signs of stress, such as reduced growth and leaf area decline, and increasing tree mortality that can be directly linked to combinations of drought and/or high temperatures (Allen et al., 2010; Anderegg, Kane, & Anderegg, 2013; Breshears et al., 2005;

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Griffin & Anchukaitis, 2014; Martinez-Vilalta, Lloret, & Breshears, 2011; Pravalie, Sîrodoev, & Peptenatu, 2014; Allen et al., 2015; Vicente-Serrano et al., 2014; Steinkamp & Hickler, 2015). In western North America, climate change has been implicated in rapidly increasing background mortality rates during recent decades, with widespread die-offs affecting tree species across regions, environmental gradients, age and structure classes, and disturbance regimes (Breshears et al., 2005; van Mantgem et al., 2009; Vogelmann, Tolk, & Zhu, 2009; Williams et al., 2013). Broad-scale drivers of tree mortality known with high confidence, such as droughts that are hotter and more widespread due to continued warming, imply a future greater level of forest vulnerability, independent of the specifics of mortality mechanism (Allen et al., 2015). Higher rates of climate-induced tree mortality can cause major shifts in ecosystem structure and function (Allen & Breshears, 1998; Breshears et al., 2005) that have varied and long-term consequences on ecological communities (Anderegg et al., 2013; McDowell et al., 2008). Changes in forest structure and composition have important implications for availability and distribution of plant and animal habitat, especially in ecosystems dominated by one or a few foundational tree species (Ellison et al., 2005). Mortality events change the albedo and the latent and sensible heat fluxes, with feedbacks on regional climate (Anderson et al., 2011; Bonan, 2008; Chapin, Randerson, McGuire, Foley, & Field, 2008). Even when mortality is not realized, severe drought has long lasting effects on forests (Anderegg et al., 2015). A growing body of evidence in the literature indicates that there are physical signs of stress and decline that indicate an increased risk of tree mortality. The physical expression of forest stress associated with vulnerability may manifest initially as poor crown condition and/or a decline in leaf area (Dobbertin & Brand, 2001; Solberg, 2004) followed by a reduction in growth (Delucia, Maherali, & Carey, 2000; Pedersen, 1998; Suarez, Ghermandi, & Kitzberger, 2004), and then by the potential increase in susceptibility to insects and fire (Hicke et al., 2012; Westerling, Hidalgo, Cayan, & Swetnam, 2006). The exceptionally severe 2003 European drought produced widespread stress symptoms in many trees (premature leaf fall, yellowing, shedding) and resulted in a large number of weakened individuals (low radial growth and small amounts of stored carbohydrates) followed by increased mortality rates in 2004 and 2005 in areas where weather conditions remained unfavorable (Bréda, Huc, Granier, & Dreyer, 2006). An index that relates climatic drivers of vulnerability directly to physiological stress factors would provide valuable information on forests that are predisposed to increased vulnerability.

Recent observational and experimental studies have highlighted the potential for warmer temperatures to compound the effects of severe drought events and exacerbate regional forest stress and die-off (Adams et al., 2009; Breshears et al., 2005; Griffin & Anchukaitis, 2014; van Mantgem et al., 2009; Williams et al., 2013). The increased energy load from warmer temperatures during severe drought events acts to heat and stress trees (Adams et al., 2009; Breshears et al., 2005; Stephenson, 1990). For example, the precipitation deficits of the 2012–2014 California drought were anonymously low, but not unprecedented. Yet record high temperatures could have exacerbated the drought by approximately 36%, resulting in the most severe drought conditions in over a century of instrumental observations (Griffin & Anchukaitis, 2014). In the southwestern US (SWUS) increasing warm-season vapor pressure deficit (largely controlled by the maximum daily temperature) was found to be the primary driver of an ongoing forest drought-stress event that is more severe than any event since the late 1500s megadrought (Williams et al., 2013). The strong correspondence between temperature-driven forest drought-stress and tree mortality, combined with the relatively high confidence in the projections of continued warming in the SWUS, portends future intensified forest drought stress and increased forest decline (Williams et al., 2013). In a study that estimated vulnerability of 15 tree species in the western USA and Canada to significantly warmed climate conditions, 30% of the species recorded ranges were deemed vulnerable based on the majority of years being unsuitable for the species (Coops & Waring, 2011). Projections for the western USA indicate that far greater chronic forest stress and mortality risk should be expected in coming decades due to the large increases in mean temperature and significant long-term regional drying, as well as the frequency and severity of extreme droughts and heat waves (Allen et al., 2015; Cook, Smerdon, Seager, & Coats, 2014; IPCC, 2013; Jentsch, Kreyling, & Beierkuhnlein, 2007; Moritz et al., 2012). Urgently needed is a remote sensing-based forest vulnerability index (FVI) that explicitly tracks where and when forests are becoming increasingly vulnerable to drought and increased temperature stress, to assess potential climate change impacts on vegetation and associated feedbacks to the climate system (Allen et al., 2015; McDowell et al., 2008; Smith et al., 2014).

The majority of vulnerability assessments derived from space-borne data are conducted a posteriori, such that the disturbances (e.g., drought, wildfire, hurricane) had to occur prior to research being conducted (Smith et al., 2014). Global drought monitoring approaches such as the widely applied Vegetation Temperature Condition Index and the more recently developed Global Terrestrial Drought Severity Index have proven effective at providing information on the extent and severity of drought events (Kogan, 1997; Mu, Zhao, Kimball, McDowell, & Running, 2013). However, these metrics do not track longer term (multiple years to decades) forest stress trends, and lack the ability to deliver a priori information regarding where vegetation is likely becoming increasingly vulnerable to drought and increased temperature stress. An FVI at spatial and temporal scales relevant to land management that could be regularly updated would provide managers with knowledge of where and when forests are under multi-year stress so that proactive remedial actions could be better prioritized to have the greatest effect (Millar & Stephenson, 2015; Smith et al., 2014). Our objectives are to: 1) Develop an FVI that detects where and during which month of the growing season (April through October) forests are likely becoming increasingly vulnerable to climate-induced physiological stress associated with drought and high temperatures, and maps vulnerability across the Pacific Northwest region (PNW; Oregon and Washington) of the USA. 2) Understand the behavior of the FVI relative to its driving factors.

2. Land surface temperature and the biophysical link to plant canopy stress

Climatological data can be developed for two kinds of surface temperatures: near-surface air temperature (T_{air}) and land surface temperature (LST) (Jin & Dickinson, 2010). T_{air} is measured 1.5 m above the ground level at official weather stations with sensors protected from radiation and adequately ventilated (Karl, Miller, & Murray, 2006). Many standard drought monitoring indices, such as the Palmer drought severity index (PDSI), rely on T_{air} from the weather station network. The inequitable distribution of weather stations over the global land surface and the lack of information in areas with sparse or no stations limit the drought monitoring capability and the spatial resolution of the output products based on T_{air} data (Daly et al., 2008; Kogan, 1997; Mu et al., 2007; Mu et al., 2013). Although correlated with T_{air}, LST differs from T_{air} in its physical meaning, magnitude, and measurement techniques (Jin & Dickinson, 2010). LST can be estimated from measurements of thermal radiance coming from the land surface, retrieved from satellite, and mapped globally. LST from the Moderate Resolution Imaging Spectroradiometer (MODIS) measures the canopy foliage temperature in vegetated areas, a unique and useful ecological parameter because critical temperature dependent physiological processes and associated energy fluxes occur in the vegetated canopy. A global analysis of the relationship between remotely sensed annual maximum LST from the Aqua MODIS sensor and the corresponding site-based maximum air temperature for every World Meteorological Organization station on Earth showed that LST is more tightly coupled to the radiative and