Forest Ecology and Management 365 (2016) 137–151

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Spatial and temporal trends of drought effects in a heterogeneous semi-arid forest ecosystem

Timothy J. Assal [a,b,*], Patrick J. Anderson [a], Jason Sibold [c]

[a] U.S. Geological Survey (USGS), Fort Collins Science Center, 2150 Centre Avenue, Fort Collins, CO 80526, USA
[b] Graduate Degree Program in Ecology, Colorado State University, 1401 Campus Delivery, Fort Collins, CO 80523, USA
[c] Department of Anthropology, Colorado State University, 1787 Campus Delivery, Fort Collins, CO 80523, USA

ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 16 January 2016
Accepted 17 January 2016
Available online 1 February 2016

Keywords:
Landsat time-series
Temporal trend analysis
Drought effects
Forest-shrubland ecotone
Rocky Mountain forests

ABSTRACT

Drought has long been recognized as a driving mechanism in the forests of western North America and drought-induced mortality has been documented across genera in recent years. Given the frequency of these events are expected to increase in the future, understanding patterns of mortality and plant response to severe drought is important to resource managers. Drought can affect the functional, physiological, structural, and demographic properties of forest ecosystems. Remote sensing studies have documented changes in forest properties due to direct and indirect effects of drought; however, few studies have addressed this at local scales needed to characterize highly heterogeneous ecosystems in the forest-shrubland ecotone. We analyzed a 22-year Landsat time series (1985–2012) to determine changes in forest in an area that experienced a relatively dry decade punctuated by two years of extreme drought. We assessed the relationship between several vegetation indices and field measured characteristics (e.g. plant area index and canopy gap fraction) and applied these indices to trend analysis to uncover the location, direction and timing of change. Finally, we assessed the interaction of climate and topography by forest functional type. The Normalized Difference Moisture Index (NDMI), a measure of canopy water content, had the strongest correlation with short-term field measures of plant area index ($R^2 = 0.64$) and canopy gap fraction ($R^2 = 0.65$). Over the entire time period, 25% of the forested area experienced a significant (p-value < 0.05) negative trend in NDMI, compared to less than 10% in a positive trend. Coniferous forests were more likely to be associated with a negative NDMI trend than deciduous forest. Forests on southern aspects were least likely to exhibit a negative trend while north aspects were most prevalent. Field plots with a negative trend had a lower live density, and higher amounts of standing dead and down trees compared to plots with no trend. Our analysis identifies spatially explicit patterns of long-term trends anchored with ground based evidence to highlight areas of forest that are resistant, persistent or vulnerable to severe drought. The results provide a long-term perspective for the resource management of this area and can be applied to similar ecosystems throughout western North America.

1. Introduction

Climate shapes vegetation patterns through the balance between energy supply, moisture and the seasonal timing of the two (Stephenson, 1990). In this way, the climate of a region exerts top-down control on ecosystem pattern and process. Ecosystem disturbance, in particular large, infrequent disturbances (Turner and Dale, 1998), are also recognized as a key mechanism of landscape pattern in forests due to the enduring legacies of physical and biological structure that result from these events (Foster et al., 1998). However, disturbance also operates at less conspicuous scales and the range of disturbance impacts are best thought of along a continuum (Sousa, 1984), as legacies can persist at some level regardless of the size or frequency of the disturbance (Turner et al., 1998). Drought and desiccation stress are forms of ecosystem disturbance (Sousa, 1984), yet the spatial and temporal complexity of drought renders identification and quantification very difficult (Vicente-Serrano, 2007).

In the early 2000s, over half of the coterminous United States experienced moderate to severe drought conditions and record breaking precipitation deficits throughout the western part of the country (Cook et al., 2004). These events brought attention to drought vulnerability in semi-arid forests of western North America. Portions of the intermountain west also experienced severe to

* Corresponding author at: USGS, Fort Collins Science Center, Fort Collins, CO 80526, USA.
E-mail address: assalt@usgs.gov (T.J. Assal).

http://dx.doi.org/10.1016/j.foreco.2016.01.017
0378-1127/Published by Elsevier B.V.

extreme drought in 2012 (NOAA, 2012). Severe drought in the early part of the last decade has been identified as the driver of tree stress, dieback and mortality across diverse forest types (Allen et al., 2010; Breshears et al., 2005; Gitlin et al., 2006; Michaelian et al., 2011). These events also contribute to flammability of fuels and decreased snowpack, resulting in longer fire seasons (Littell et al., 2009; Westerling et al., 2006).

The physiological drivers of tree mortality are complex (McDowell et al., 2008) and drought produces a gradient of effects on coniferous and deciduous forests in western North America. Drought can induce direct or indirect tree mortality, however, less conspicuous effects such as loss of productivity can accompany drought as well (Hogg et al., 2008). Forest response to drought is likely dependent on the spatial pattern of forest structure and function (Baguskas et al., 2014; Hope et al., 2014), and the duration of the drought is a key element in plant response (Dorman et al., 2013). Water stress can lead to an increase in plant respiration (Jones and Vaughan, 2010), and plants cope with drought via stomatal closure and reduced leaf area index (LAI) (Hope et al., 2014). A reduction in leaf area leads to a lower photosynthetic capacity and a change in canopy structure. Collectively, these responses result in a decrease in chlorophyll and water content of plant leaves (Jones and Vaughan, 2010). Drought stress is often coupled with multiple, interacting factors (Allen et al., 2010), and lag effects of drought may lead to tree dieback and mortality several years after the drought event (Bigler et al., 2007).

Multiple studies have documented an increase in mortality rates of coniferous species throughout the western United States over the later part of the 20th century (Allen and Breshears, 1998; Breshears et al., 2005; van Mantgem et al., 2009). Increases in mortality rates have been reported across ecosystem type and elevation, among dominant genera and tree size, and at sites with diverse fire histories (Gitlin et al., 2006; van Mantgem et al., 2009). All of these mortality events were driven by increased water deficit associated with drought, but secondary agents such as bark beetle outbreaks have also contributed to conifer mortality in some areas (Bentz et al., 2010; van Mantgem et al., 2009). The dominant deciduous tree in western North American, quaking aspen (*Populus tremuloides*), may have an advantage over coniferous trees during periods of lower moisture due to its clonal root system. However, droughts of long durations are likely to affect the growth of both suckers and mature trees alike (Hessl and Graumlich, 2002). Severe drought in the boreal forest and parkland of western Canada resulted in a two-fold increase in stem mortality and a 30% decrease in regional stem growth in persistent trees (Hogg et al., 2008). Decrease in growth is the result of high levels of twig and branch dieback in the crowns of living trees and productivity is limited by carbon dioxide fixation imposed by leaf stomatal resistance during soil or atmospheric water deficits (Hogg et al., 2000). A phenomenon known as sudden aspen decline (SAD) has been documented in regional aspen forests (Worrall et al., 2008). Rapid and sudden onset of mortality is primarily caused by high temperatures, acute drought and secondary biotic agents (Worrall et al., 2008).

Disturbance alters ecosystem structure by both abrupt, obvious change and through gradual, slow change over some period of time (Assal et al., 2014). Remote sensing offers a powerful medium to capture the pre and post disturbance landscape and detect changes that might not be readily observed, such as drought stress. Spatial, temporal and spectral scales are an important consideration when using remote sensing in ecosystem disturbance studies. Two common multispectral remote sensing platforms used in drought studies are the Moderate Resolution Imaging Spectroradiometer (MODIS) (Abbas et al., 2014; Bastos et al., 2014; Hope et al., 2014) and the Landsat satellites (Huang and Anderegg, 2012; Maselli, 2004; Vogelmann et al., 2009; Volcani et al., 2005). Both platforms are well suited to study ecosystem dynamics at regional scales given the large coverage area per scene. However, subtle changes in forest structure and productivity are difficult to detect with satellite derived observations (Deshayes et al., 2006). Therefore, drought studies require a long-term series of observations, which makes the high temporal resolution of these satellites well suited for this application. Although MODIS has a high-temporal resolution (16-day composite product compared to 16-day revisit time for Landsat), the lower spatial resolution (250–500 m compared to 30 m) precludes its use in highly heterogeneous forest-shrubland ecotones. Trend analysis utilizing time-series of Landsat data is useful to identify, monitor, and assess both abrupt and subtle forest change (Czerwinski et al., 2014; Dorman et al., 2013; Kennedy et al., 2010; Vogelmann et al., 2009).

Forest canopy reflectance is influenced by several biophysical parameters including crown closure, canopy and branch architecture, LAI, the chlorophyll and water content of leaves as well as the understory and exposed soil properties of the stand (Deshayes et al., 2006). Multispectral satellites have spectral bands spanning the visible and infrared wavelengths that can be combined into vegetation indices that are sensitive to differences in these biophysical parameters (Jones and Vaughan, 2010). Living vegetation absorbs radiation in portions of the visible wavelengths and reflects in the near-infrared (NIR); whereas radiation in the shortwave-infrared (SWIR) is absorbed by water content of leaves (Jones and Vaughan, 2010). The NIR and SWIR are sensitive to variations in LAI and the SWIR band is sensitive to water stress during periods of drought (Deshayes et al., 2006). Numerous spectral vegetation indices have been used in disturbance and drought studies, many of which utilize the NIR and/or the SWIR bands. The Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index to document and monitor drought and related impacts in forests (Breshears et al., 2005; Carreiras et al., 2006; DeRose et al., 2011; Lloret et al., 2007; Maselli, 2004; Volcani et al., 2005; Weiss et al., 2004). However, other vegetation indices have utility in disturbance related vegetation dynamics including the Enhanced Vegetation Index (EVI) (Hope et al., 2014; Tüshaus et al., 2014), the Normalized Difference Moisture Index (NDMI) (Goodwin et al., 2008; Meddens et al., 2013), the soil adjusted vegetation index (SAVI) (Tüshaus et al., 2014), and the Tasseled Cap (Czerwinski et al., 2014).

We sought to quantify the spatial and temporal effects of drought in a semi-arid mixed forest ecosystem that is expected to be vulnerable to drought stress and climate change. The effects of climate change and variability are expected to be most rapid and extreme at ecotones, especially in semi-arid forests (Allen and Breshears, 1998; Gosz, 1992). An understanding of the link between climate variability and tree mortality for species near ecotones is an important focus of current research (Kulakowski et al., 2013). Ecotones are important barometers of climate change (NEON, 2000) and stress, dieback and mortality are expected to accompany severe drought in this arid landscape. Recent studies (Crookston et al., 2010; Rehfeldt et al., 2009) predict the current climate profile for several prominent tree species (e.g. aspen, subalpine fir and lodgepole pine) will be greatly limited or no longer present in isolated forests of the Rocky Mountains over the course of the next century. However, regional climate can be influenced by local topography, a concept known as topoclimate (Thornthwaite, 1953). Slope, aspect and other topographic features influence air temperature, water balance, radiation, snowmelt patterns and wind exposure (Dobrowski, 2011) which amplify the effects of drought, particularly in arid landscapes.

The use of temporal remotely sensed data has been effective in monitoring drought induced changes in forests and woodlands (Maselli, 2004; Vogelmann et al., 2012). A primary challenge in spectral change analysis is to segregate long-term vegetation