Forest Ecology and Management 382 (2016) 168–183

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Using one year post-fire fire severity assessments to estimate longer-term effects of fire in conifer forests of northern and eastern California, USA

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ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 6 October 2016
Accepted 7 October 2016

Keywords:
Basal area
California
Canopy cover
Composite burn index
Fire effects
Severity

ABSTRACT

Fire severity maps derived from immediate or one year post-fire satellite images are commonly used by US federal land managers for making post-fire management decisions and provide fundamental insights into broad scale fire ecology questions. How these maps relate to longer term post-fire conditions in the absence of management actions is an unanswered question, and a key issue for post-fire restoration planning. We characterized field-measured fire effects in forests 5–7 years after fire in severity categories as they were mapped with one year post-fire satellite data. The severity maps we used were produced from a relativized differenced normalized burn ratio (RdNBR) derived from Landsat images and calibrated to three severity metrics: composite burn index (CBI), percent change in basal area (BA), and percent change in tree canopy cover (CC). Relationships of field-measured values with severity generally followed expected patterns. BA of dead trees and shrub cover increased with increasing fire severity. BA of live trees, total tree CC, conifer CC, litter cover, litter depth and duff depth all decreased with increasing severity. When forest type (yellow pine, dry mixed conifer, moist mixed conifer, fir) was added as an interaction term there were differences in the relationships of field-measured values to severity, some of which can be attributed to differences between pine and fir dominated forests. We did not find any difference in live BA between unburned, unchanged, low and moderate severity plots for yellow pine forests; the only significant decrease in live BA was in high severity plots. In contrast, both dry and moist mixed conifer forests showed more or less steadily decreasing live BA with increasing fire severity. For yellow pine dead BA there were no significant differences between unchanged, low and moderate categories, while there was a difference between unchanged and moderate for all other forest types. In the high-severity categories ⩾91% of plots had <10% conifer CC, and ⩾82% of plots had <10% total tree CC. Comparing our 5–7 year post-fire dataset to a separate dataset measured one year post-fire demonstrates that delayed tree mortality occurs at all levels of severity, and notable snag fall (especially pines) is already underway a half-decade after fire. The effects we measured provide useful information for managers interested in planning for post-fire activities up to 5–7 years after fire, including soil erosion abatement, habitat restoration, fuel and snag management, and tree regeneration management.

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1. Introduction

Information describing fire effects is needed by land managers for making post-fire management decisions. However, acquiring plot data to assess fire effects is time consuming, expensive, and can only be collected in limited locations. Employing satellite-acquired images calibrated to field-measured variables is a more cost-effective method for extrapolating field measurements over broader scales (Roller and Bergen, 2000). There is a need, therefore, to establish relationships between satellite derived severity maps and detailed fire effects (e.g., tree mortality, surface fuels, etc.) measured on the ground (Morgan et al., 2014).

Severity maps depicting wildland fire effects are commonly produced from satellite images by the US Federal land management agencies (Eidenshink et al., 2007; Parsons et al., 2010; Miller and Quayle, 2015). These data are currently being used by

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http://dx.doi.org/10.1016/j.foreco.2016.10.017
0378-1127/Published by Elsevier B.V.

land managers in making post-fire management decisions, for monitoring, and for providing insights into basic broad scale fire ecology questions (e.g., van Wagtendonk and Lutz, 2007; Collins et al., 2009; Holden et al., 2009; Dillon et al., 2011; Picotte and Robertson, 2011; Miller et al., 2012a, 2013; Cansler and McKenzie, 2014; Steel et al., 2015). Severity maps derived using similar methods have also been used in other fire prone areas of the world (Hall et al., 2008; Kumar et al., 2008; Tanase et al., 2011; Rivera-Huerta et al., 2016).

There have been two major issues with interpreting many commonly produced severity maps. First, the degree of severity depicted on severity maps is often represented in broad categories such as low, moderate, and high without precise definitions of what the categories mean in terms of individual fire effects, e.g., tree mortality. For example, the composite burn index (CBI), a field-based estimate of fire severity, has been widely used to describe fire effects in mapped categories on some severity maps (e.g., Cocke et al., 2005; Miller and Thode, 2007; Cansler and McKenzie, 2012). The CBI protocol includes separate ocular estimates of individual effects to soils, fuels and four vegetation strata, which are typically integrated into a single composite value (Key and Benson, 2006a). Although CBI was designed to correlate to severity, CBI values are not as meaningful for forest and wildlife management as leaf area index, tree basal area or canopy cover (Cade, 1997; Broham and Bryant, 2005; Boer et al., 2008; Miller et al., 2009a; Kolden et al., 2015). Second, some methodologies used for creating severity maps from satellite images require unique calibrations for each fire because of differences in vegetation types and density (Spanner et al., 1990; Miller and Yool, 2002; Key and Benson, 2006b; Kokaly et al., 2007; Miller and Thode, 2007). Some of the most readily available severity maps in the US are produced by the Monitoring Trends in Burn Severity (MTBS) program (www.mtbs.gov). The MTBS maps are derived from satellite images converted to a satellite index [the differenced normalized burn ratio (dNBR)] that is closely associated to the absolute change pre- to post-fire in chlorophyll (Eidenshink et al., 2007; Miller and Thode, 2007). Chlorophyll content is directly tied to vegetation type and density, however, and therefore a particular change in chlorophyll can represent different severities across fires, and even with the same fire (Miller and Yool, 2002). Consequently, MTBS image analysts, who have no direct knowledge of ground conditions, derive categorical severity maps by choosing satellite index thresholds unique to each fire to delineate severity categories. This methodology leads to uncertainty in the precise definition of the severity categories and an inability to directly compare severity ratings between fires, and can translate into high classification error rates (Kolden et al., 2015). In a study conducted in the Pacific Northwest region of the US, Whittier and Gray (2016) found that MTBS categorical maps reflected lower severity than did tree mortality data on 51% of forest inventory plots.

In an attempt to remedy these issues, Miller and Thode (2007) described a new satellite index, a relativized version of the differenced normalized burn ratio (RdNBR), and for California forests produced calibrations between one year post-fire ("extended assessment") Landsat data and CBI measured in 741 field plots from 14 wildfires. Miller and Thode claimed that their approach allowed for calibrations to field-measured variables to be applied to future fires without further field validation. Subsequently, Miller et al. (2009a) published calibrations of one year post-fire Landsat data to field-measured percent change in canopy cover (CC) and tree basal area (BA) using field data from 16 additional California fires to the Miller and Thode (2007) dataset, and demonstrated that those calibrations as well as their earlier CBI calibration remained valid for other fires in the same study area. Most recently Miller and Quayle (2015) published calibrations of immediate post-fire images ("initial assessments") to CBI, percent changes in tree BA and CC for a suite of California fires.

While there are many examples in the literature of satellite index calibrations to CBI (e.g., Hall et al., 2008; Holden et al., 2009; Picotte and Robertson, 2011; Cansler and Mckenzie, 2012), Miller et al. (2009a) and Miller and Quayle (2015) are the only studies to date that report calibrations to percent change in BA and CC that are being used to produce severity maps routinely used by forest managers beyond the scope of an individual study (e.g., Harvey, 2015). There is a need to better describe how these maps relate to important vegetation and ground surface variables, as well as to understand how these maps relate to field-measured variables over longer time frames. Dunn and Bailey (2016) reported tree mortality and structure attributes within severity categories delineated by MTBS categorical severity maps. As far as we are aware, however, no study to date has described field-measured understory characteristics (i.e., herbaceous and shrub cover) across the full range of mapped severity categories (i.e., low, moderate and high). Hudec and Peterson (2012) is the only study that has described field-measured fuel characteristics in mapped categories of BA change. In addition, no study to this point has differentiated these effects between different forest types (e.g., yellow pine, mixed conifer, fir). Finally, there is a major gap in our understanding about how post-fire forest conditions change over time within the different fire severity categories.

Because the satellites most commonly used to make severity maps measure the reflectance from sun light, the satellite images primarily detect changes to the overstory of closed canopy forests, or a combination of understory and overstory in open canopy forests (Spanner et al., 1990; Stenback and Congalton, 1990). Consequently, satellite derived severity data are highly correlated to first order fire effects to overstory trees, i.e., live conifer BA and canopy cover decrease with increasing severity, but dead conifer BA increases (Hudec and Peterson, 2012; Miller and Quayle, 2015; Dunn and Bailey, 2016). Secondary overstory fire effects and effects to understory fuels, herbaceous plants, shrubs and hardwoods, however, are closely associated with interacting individual plant and plant community responses to fire, successional/life histories, fire intensity and site potential (i.e., biophysical setting) (Agee, 1993; Fites-Kaufman et al., 2006).

It is beyond the scope of this paper to fully describe all possible first and second order effects interactions. However, some generalizations can be made for conifer forests in our study area based upon existing literature. Coarse woody fuels ($\geqslant$1000 h timelag), litter and duff fuel loadings are all initially reduced by fire (Kilgore, 1971; Campbell et al., 2007; Webster and Halpern, 2010; Vaillant et al., 2013; Welch et al., in press). However, litter, duff, and coarse woody fuels all increase with time since fire at rates that are dependent upon tree species, tree diameter, and degree of tree scorch and/or mortality (Webster and Halpern, 2010; Dunn and Bailey, 2012, 2015; Vaillant et al., 2013). A greater extent of exposed soil due to a decrease in litter and duff cover in concert with opened tree canopies, especially in severely burned areas where almost all trees are killed, usually leads to an increase in herbaceous and/or shrub cover (Collins et al., 2007; Wayman and North, 2007; Webster and Halpern, 2010; Abella and Springer, 2015; Welch et al., in press). All of the major hardwood species that occur in the conifer vegetation types in our study sprout after fire (Sugihara et al., 2006). Consequently, hardwood cover initially decreases with fire, but usually recovers within a couple years. In areas where competition with conifers is reduced, hardwood cover can become greater than prior to fire (Cocking et al., 2014; Collins and Roller, 2013; Crotteau et al., 2014).

In this manuscript our principal purpose was to develop a better understanding for how field-measured fire effects 5–7 years post-fire in forests of northern and eastern California, USA, relate to fire