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Changing spatial patterns of stand-replacing fire in California conifer forests☆

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ABSTRACT

Stand-replacing fire has profound ecological impacts in conifer forests, yet there is continued uncertainty over how best to describe the scale of stand-replacing effects within individual fires, and how these effects are changing over time. In forests where regeneration following stand-replacing fire depends on seed dispersal from surviving trees, the size and shape of stand-replacing patches are critical metrics that are difficult to describe and often overlooked. We used a novel, recently-developed metric that describes the amount of stand-replacing area within a given distance of a live-tree patch edge, in order to compare fires that may be otherwise similar in fire size or the percentage of stand-replacing effects. Specifically, we analyzed 477 fires in California pine, fir, and mixed-conifer forests between 1984 and 2015 and asked whether this metric, the stand-replacing decay coefficient (SDC), has changed over time, whether it is affected by fire management, and how it responds to extreme weather conditions at the time of the fire. Mean annual SDC became smaller over time (significantly so in the Sierra Nevada region), indicating that stand-replacing patches became larger and more regularly shaped. The decrease in SDC was particularly pronounced in the years since 2011. While SDC is correlated with percent high-severity, it is able to distinguish fires of comparable percent high-severity but different spatial pattern, with fires managed for suppression having smaller SDC than fires managed for resource benefit. Similarly, fires managed by the US Forest Service had smaller SDC than fires managed by the National Park Service. Fire weather also played an important role, with higher maximum temperatures generally associated with smaller SDC values. SDC is useful for comparing fires because it is associated with more conventional metrics such as percent high-severity, but also incorporates a measure of regeneration potential – distance to surviving trees at stand-replacement patch edges – which is a biological legacy that directly affects the resilience of forests to increasingly frequent and severe fire disturbances. We estimate that from 1984 to 2015, over 80,000 ha of forestland burned with stand-replacing effects greater than 120 m in from patch edges, denoting areas vulnerable to extended conifer forest loss due to dispersal limitation. Managing unplanned ignitions under less extreme weather conditions can achieve beneficial "fine-grained" effects of stand-replacing fire where regeneration limitation is less of a concern. Because SDC is a useful single metric to compare fires, we introduce a web application (stevensjt.shinyapps.io/sdc_app) to calculate SDC for any high-severity spatial layer that may be of interest.

1. Introduction

In forests, overstory tree mortality from fire is an important ecological process that catalyzes change in forest structure, fuel loads, vegetation diversity and wildlife habitat suitability (Swanson et al., 2011). Tree mortality from fire is a binary process (a tree is top-killed or not), but it is spatially correlated: weather, fuel or topographic conditions that lead to the mortality of one tree also increase the likelihood of mortality for neighboring trees (Collins et al., 2007; Thompson and Spies, 2010). When a patch of adjacent trees are all top-killed by fire, this is termed "stand-replacing fire". This term is scale-independent – stand-replacing fire can refer to sub-ha stands of ≤100 trees, or to many-ha stands of > 10,000 trees – but the implications of the spatial scale of stand-replacing fire are profound.

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Forest resilience, defined as long-term ecosystem persistence and capacity to recover following perturbation (e.g. stand-replacing fire), depends on ecological memory in the form of tree propagules (Holling, 1973; Johnstone et al., 2016). In forests where the dominant tree species have evolved to propagate after being top-killed by fire, (e.g. via basal re-sprouting in oaks (*Quercus* spp.) or serotinous cones in Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia*)), resilience is maintained even in large stand-replacing patches. In forests where the dominant tree species lack these adaptations (e.g. many western mixed-conifer forest types), tree propagules generally must arrive via surviving trees on the edges of stand-replacing patches, and the size and shape of these patches becomes critical. Forest resilience is reduced when contiguous stand-replacing patches become larger because tree regeneration towards patch interior is slowed by dispersal limitation, and the likelihood of future stand-replacing fire within these patches increases (Stevens et al., 2014; Chambers et al., 2016; Coppoletta et al., 2016; Johnstone et al., 2016; Welch et al., 2016).

What drives much of the concern over stand-replacing fire in mixed-conifer forests is not an intrinsically negative effect of stand-replacing fire, but the potential for large-scale tree regeneration failure and persistent type-conversion (Millar and Stephenson, 2015). As such, there have been numerous attempts to quantify trends in the extent of stand-replacing fire in contemporary wildfires and infer how climate and forest management practices (e.g. historical fire suppression and fire-fighting tactics) might influence these trends (Miller et al., 2009b, 2012b; Miller and Safford, 2012; Cansler and McKenzie, 2014; Harvey et al., 2016b; Picotte et al., 2016).

Most efforts to quantify trends in stand-replacing fire rely on interpretation of satellite-based vegetation change indices, particularly the differenced Normalized Burn Ratio (dNBR) (Key and Benson, 2006) and a version of that ratio relativized to pre-fire vegetation cover (RdNBR) (Miller and Thode, 2007). Burn severity (the amount of dominant vegetation killed or consumed by fire within a given area) can be estimated by calibrating this ratio to field-derived data on canopy cover loss from fire, basal area loss from fire, or other composite field indices of burn intensity (Miller et al., 2009a). Modern burn severity classifications transform a continuous variable (e.g. RdNBR) into a discrete variable, generally at a 30-m LANDSAT pixel resolution (e.g. "low", "moderate" or "high" severity), based on threshold values associated with particular field conditions (e.g. $\leq$20%, 20–70%, or > 70% basal area mortality). Field validations of post-fire conifer stands mapped as "high-severity", whether using a 70% or a 90% basal area mortality threshold, indicate these areas generally have > 95% basal area mortality, with 100% basal area mortality being by far the most common condition greater than 30 m from the edge of a patch mapped as "high-severity" (Miller and Quayle, 2015; Lydersen et al., 2016). Thus, areas of "high-severity fire" mapped in this way are reasonable approximations of "stand-replacing fire".

More recently, the term "mixed-severity" has become popular to describe individual fires, or characteristic effects of multiple fires (i.e. fire regimes), wherein some fraction of burned area experiences stand-replacing effects delineated in distinct patches (Hessburg et al., 2016). While portions of a fire's area that are mapped as low or moderate severity still have some tree mortality, individual "mixed-severity fires" are commonly described as those with 20–70% of the fire area mapped as high-severity (Perry et al., 2011). This approach relies upon the concept that patches of stand-replacing fire of *ecologically meaningful size* are those mapped as "high-severity" at 30-m resolution (Collins et al., 2017). Mixed-severity fires are therefore comprised of discrete patches of stand-replacing fire, eventually filled in by grass, shrubs, or tree regeneration, surrounded by surviving forest that burned at low- to moderate-severity. While the "patchy" nature of mixed-severity fires leads to a wide range of potential stand-replacing patch sizes and shapes, the conventional definition of a mixed-severity fire says nothing about these attributes. Percent high-severity is a useful way to measure fire effects and compare among multiple fires, as it is easily derived and interpreted (Miller et al., 2009b). However, fires where the stand-replacing effects are concentrated in a few large patches are much more susceptible to dispersal limitation of regenerating conifers, and therefore prolonged type conversion to non-forest vegetation, compared to fires with a similar percent high severity but more smaller patches (Crotteau et al., 2013; Kemp et al., 2016; Welch et al., 2016). For instance, the 2013 Rim Fire in California's Sierra Nevada had a relatively modest proportion of burned area mapped as high severity (~35%) but contained some of the largest contiguous patches of stand-replacing fire found anywhere in the modern record (Lydersen et al., 2017). Thus, there is a need to update previous research on trends in the modern burn severity record by accounting explicitly for the size and shape of stand-replacing patches (Collins et al., 2017).

Our objective was to document trends in stand-replacing patch configuration in California's mixed-conifer forest ecoregion over the past 33 years, using a novel metric developed to describe how much stand-replacing patch area remains with increasing distance inward from patch edges (Collins et al., 2017). The stand-replacing decay coefficient (SDC) is related to fire size, high-severity area, and proportion high-severity, as well as conventional landscape metrics such as patch edge:area ratio (Collins et al., 2017). However, this metric is more biologically relevant than traditional metrics because it explicitly accounts for distance to seed source within stand-replacing patches, and as a single metric it distinguishes among fires that may be similar in terms of fire size or proportion high-severity but differ strongly in aggregate distance to seed source, without needing to specify an arbitrary dispersal limitation distance (Collins et al., 2017). Thus SDC can more directly identify fires that are vulnerable to long-term conifer forest loss and potential type-conversion.

In this paper, we present analyses that build on previous work investigating trends in burn severity and differences among land management agencies in California (Miller and Safford, 2012; Miller et al., 2012b). More specifically, we include all mapped forest fires > 80 ha that occurred in northwestern California and the Sierra Nevada from 1984 through 2015, which spans two historic multi-year droughts (1987–1992, 2011–2015), to investigate (1) whether fires with different managing agencies and management objectives differed in SDC independently of fire size and proportion high-severity, (2) how average SDC for these fires changed over time, and (3) the role of weather conditions in determining SDC. These results illustrate how a process-based quantification of fire effects can be used to describe changing fire regimes, and this could assist forest managers in developing desired conditions in western US forests that once burned with frequent, low-moderate severity fire regimes.

2. Methods

Fire behavior and effects are influenced by a multitude of factors, including, but not limited to, past forest management actions, topography, weather and climate. Fires within California are managed primarily by three different agencies; the National Park Service (NPS), US Forest Service (USFS) and the California Department of Forestry and Fire Protection (CAL FIRE). These agencies support very different land management objectives and as such, have different fire management directives. For example, Yosemite, and Sequoia and Kings Canyon National Parks have allowed many lightning-ignited fires to burn under specified conditions to meet resource-management objectives since the early 1970s (van Wagtendonk, 2007). Although some National Forests allow some 'resource benefit' fires in more remote, higher-elevation areas, most fires are still suppressed (Stephens and Ruth, 2005). Fires managed by CAL FIRE generally occur at lower elevations in the wildland urban interface (WUI), and therefore are always aggressively suppressed. Beyond potential differences in fire management approaches, the lands these agencies manage have quite different forest management histories. The combined effect of these differences would be expected to result in different fire patterns among these agencies.

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