Forest Ecology and Management 413 (2018) 48–61

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Evaluating and monitoring forest fuel treatments using remote sensing applications in Arizona, U.S.A.

Roy E. Petrakis[a,*], Miguel L. Villarreal[b], Zhuoting Wu[c], Robert Hetzler[d], Barry R. Middleton[a], Laura M. Norman[e]

[a] Western Geographic Science Center, U.S. Geological Survey, Flagstaff, AZ 86001, United States
[b] Western Geographic Science Center, U.S. Geological Survey, Menlo Park, CA 94025, United States
[c] Land Remote Sensing Program, U.S. Geological Survey, Flagstaff, AZ 86001, United States
[d] Bureau of Indian Affairs, San Carlos Agency, San Carlos, AZ 85550, United States
[e] Western Geographic Science Center, U.S. Geological Survey, Tucson, AZ 85721, United States

ARTICLE INFO

Keywords:
Forest management
GIS
Burn severity
Multitemporal Kauth Thomas
Ponderosa pine forests

ABSTRACT

The practice of fire suppression across the western United States over the past century has led to dense forests, and when coupled with drought has contributed to an increase in large and destructive wildfires. Forest management efforts aimed at reducing flammable fuels through various fuel treatments can help to restore frequent fire regimes and increase forest resilience. Our research examines how different fuel treatments influenced burn severity and post-fire vegetative stand dynamics on the San Carlos Apache Reservation, in east-central Arizona, U.S.A. Our methods included the use of multitemporal remote sensing data and cloud computing to evaluate burn severity and post-fire vegetation conditions as well as statistical analyses. We investigated how forest thinning, commercial harvesting, prescribed burning, and resource benefit burning (managed wildfire) related to satellite measured burn severity (the difference Normalized Burn Ratio – dNBR) following the 2013 Creek Fire and used spectral measures of post-fire stand dynamics to track changes in land surface characteristics (i.e., brightness, greenness and wetness). We found strong negative relationships between dNBR and post-fire greenness and wetness, and a positive non-linear relationship between dNBR and brightness, with greater variability at higher severities. Fire severity and post-fire surface changes also differed by treatment type. Our results showed harvested and thinned sites that were not treated with prescribed fire had the highest severity fire. When harvesting was followed by a prescribed burn, the sites experienced lower burn severity and reduced post-fire changes in vegetation greenness and wetness. Areas that had previously experienced resource benefit burns had the lowest burn severities and the highest post-fire greenness measurements compared to all other treatments, except for where the prescribed burn had occurred. These results suggest that fire treatments may be most effective at reducing the probability of hazardous fire and increasing post-fire recovery. This research demonstrates the utility of remote sensing and spatial data to inform forest management, and how various fuel treatments can influence burn severity and post-fire vegetation response within ponderosa pine forests across the southwestern U.S.

1. Introduction

1.1. Fire management history

The practice of forest fire suppression, a result of the early 20th-century concept of fire exclusion (Show and Kotok, 1924), has been applied to forests of the western United States (U.S.) over the past century (Agee and Skinner, 2005; Stephens et al., 2009). This practice has had negative long-term impacts on ponderosa pine (*Pinus ponderosa*) forests and has often led to very dense forests, increasing the potential risk for larger and more severe wildfires (Covington and Moore, 1994; Parsons and DeBeneetti, 1979; Wu et al., 2015). Additionally, periodic droughts as well as elevated temperatures have increased tree mortality (Breshears et al., 2005) and altered phenological patterns (Walker et al., 2015) within forests of the Southwest U.S., increasing their vulnerability to wildfire. Increased fuel moisture stress caused by drought (Abatzoglou and Williams, 2016; Rocca et al., 2014), reduced precipitation during the winter-spring period (Swetnam and

* Corresponding author.
E-mail address: rpetrakis@usgs.gov (R.E. Petrakis).

https://doi.org/10.1016/j.foreco.2018.01.036
Received 14 July 2017; Received in revised form 19 January 2018; Accepted 20 January 2018
0378-1127/ Published by Elsevier B.V.

Betancourt, 1990), and higher spring temperatures and earlier snowmelt (Westerling et al., 2006), have also been shown to increase the potential for more severe and short-term forest wildfire activities, creating additional challenges for forest management.

To address the increased potential fire danger presented by both fire suppression and climate changes in forest ecosystems, recent management efforts have focused on reducing tree density and restoring a historical fire regime through the use of various fuel treatments (Allen et al., 2002; Arno and Fiedler, 2005; Stephens and Ruth, 2005). When compared to untreated areas, treated areas have been shown to have lower tree mortality (Strom and Fulé, 2007) and burn severity (Omi and Martinson, 2002) following a wildfire. In Arizona, both Tribal and Federal agencies have employed fuel treatments on ponderosa pine forests, including the U.S. Forest Service Four Forest Restoration Initiative (4FRI; USDA Forest Service, 2013) and the San Carlos Apache Tribal Forest Resource Program, of the San Carlos Apache Reservation. While the 4FRI program mainly uses a combination of mechanical thinning and prescribed fire to restore forests on a large scale (USDA Forest Service, 2013), the San Carlos Tribal Forest Resource Program manages their forests with the goal of restoring the historical fire regime through additional treatments including commercial harvesting and resource benefit burns (i.e., managed wildfires).

With this research, we examined patterns of satellite measured burn severity and post-fire recovery in ponderosa pine forests following a 2013 fire that burned across different forest fuel treatments on the San Carlos Apache Reservation in Arizona. We provide general information on forest management and fuel treatments used by the San Carlos Apache in the following section.

1.2. Current management techniques

The San Carlos Apache Tribe in east-central Arizona considers its forests as reservoirs of food, water, cultural heritage, as well as commercial products like timber and fuel wood (Tuttle, 2008). Therefore, combinations of fuel treatments and fire patterns are applied in order to support multiple uses of tribal lands, habitats, and resources (Lake et al., 2017). Each treatment is designed to meet the ecological goals of the Tribal Forest Resource Program, including restoring a historical fire regime and improving vegetative conditions. More specific descriptions of treatment approaches can be found in the supplementary data.

Both commercial timber harvesting and thinning treatments of ponderosa pine stands focused on the same areas, either to maintain the desired stand structure or to “push” a stand towards the commercial timber base. Commercial timber harvesting is conducted to selectively remove merchantable trees to support the natural resource economy and to maintain stocking levels and age classes aimed at improving forest condition and growth. Thinning projects are designed to reduce tree density, remove undesirable understory species and ladder fuels, and treat insect and disease problems; as well as potentially lessen the risk of high severity and crown fires (Agee and Skinner, 2005; Allen et al., 2002; Fulé et al., 2001; Pollet and Omi, 2002). The Tribal Forest Resource Program will generally limit all harvesting or thinning treatments to < 40% slopes (San Carlos Apache Tribal Forest Resource Program).

Thinning and harvesting treatments, depending on the type and intensity, can generate large volumes of slash material, which, if left untreated, has the potential to burn at high intensities and could damage the forest (Allen et al., 2002; Graham et al., 1999). On the San Carlos Apache Tribal lands, slash material can reach a depth of ~0.5 m in both thinned and harvested areas (San Carlos Apache Tribal Forest Resource Program). The return interval for commercial timber harvesting on San Carlos Apache lands is ~20 years, while the historical fire return interval for ponderosa pine is around 4–11 years (Kaib, 2001), therefore an additional 1 to 4 fires are needed between harvests.

Prescribed fires are deliberately set and managed with the goal of reducing standing fuels, consuming remnant slash material, as well as lowering the risks and hazards of unplanned and unmanaged wildfire, while considering climate, landscape, and other factors such as air quality (Fernandes and Botelho, 2003; Wade and Lunsford, 1989). They have been found to burn a majority of the forest floor surface fuels, although they can reach crown level and have been shown to increase mortality of ponderosa pines compared to untreated areas (Agee and Skinner, 2005; Stephens and Finney, 2002; Swezy and Agee, 1991). They are generally conducted on forest lands of the San Carlos Apache Reservation 1–3 years after a thinning or harvesting treatment to remove hazard and slash fuels. Whenever possible, the San Carlos Apache Tribe has used prescribed burns in recent years to treat areas outside of thinned and harvested sites in order to restore fire to the broader landscape. However, the prescribed burning program currently has a large backlog of previously harvested or thinned areas needing prescribed fire treatments that cannot currently be executed due to lack of funding. The San Carlos Apache Tribe funds the prescribed burning program through timber sales or other funding sources, which do not currently generate enough revenue to cover the full costs associated with prescribed fire.

Federal and tribal forest management agencies have also allowed for naturally ignited wildfires to burn to help restore a frequent fire regime, including in areas that have experienced rotations of thinning/harvesting or areas where a prescribed burn is planned. These are called “resource benefit wildfires,” to differentiate them from potentially destructive wildfires that are actively suppressed (Harbour, 2010). This approach has been recorded as far back as the late-1960s in California and the early-1970s in southeastern Arizona (van Wagtendonk, 2007). As with prescribed burns, risks are assessed when managing resource benefit fires, including: climate and fuel conditions, landscape characteristics, and anthropogenic constraints such as air quality and overall risk to private property (Williamson, 2007). In remote and inaccessible areas, resource benefit wildfires may be the only management option available to reduce fuel loads.

1.3. Remote sensing of wildfire impacts

Assessing the effects of fuel treatments on fire severity and post-fire vegetation response over a large geographic area using a field sampling approach can be challenging. Therefore, satellite imagery is commonly used to quantify forest burn severity and post-fire vegetation response at the landscape scale (Eidenshink et al., 2007; Key, 2006; Miller and Thode; 2007; Miller and Yool, 2002; Soulard et al., 2016; White et al., 1996), and has been applied to quantify and compare both treated and untreated areas (Finney et al., 2005; van Leeuwen, 2008). The Normalized Burn Ratio (NBR) (Key and Benson, 1999), originally developed by García and Caselles (1991), is used to discriminate burned from unburned vegetation and can assess fire severity by differencing pre- and post-burn images to identify change resulting from fire (Cocke et al., 2005). The NBR has long been used to measure burn severity following a fire (Brewer et al., 2005; Key and Benson, 1999), including within ponderosa pine forests (Epting et al., 2005).

Various quantitative techniques and data sources are used to monitor post-fire vegetation response with remote sensing data (Lentile et al., 2006a, 2006b). For instance, the Tasseled Cap (TC) (Crist and Cicone, 1984; Kauth and Thomas, 1976) and Multitemporal Kauth Thomas (MKT) transformations (Collins and Woodcock, 1996) are particularly useful as they can be used to assess three unique qualities of post-disturbance vegetation conditions from one source of satellite imagery – brightness, greenness, and wetness. Both the TC and MKT variables have been used within remote sensing applications of forests and vegetation disturbances (Cohen and Goward, 2004; Healey et al., 2005; Masek et al., 2008; Rogan et al., 2002; Skakun et al., 2003). Combined, the three variables can provide a more comprehensive analysis of conditions related the post-fire vegetation response through a remote sensing methodology.

Brightness contains the overall weighted sum of spectral data from