Remote Sensing of Environment 210 (2018) 282–296

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Measuring short-term post-fire forest recovery across a burn severity gradient in a mixed pine-oak forest using multi-sensor remote sensing techniques

Ran Meng[a,*], Jin Wu[a], Feng Zhao[b], Bruce D. Cook[c], Ryan P. Hanavan[d], Shawn P. Serbin[a]

[a] Environmental & Climate Sciences Department, Brookhaven National Laboratory, Upton, New York, NY 11973, USA
[b] Department of Geographical Sciences, University of Maryland, 1165 Lefrak Hall, College Park, MD 20742, USA
[c] Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20742, USA
[d] USDA Forest Service, Northeastern Area State & Private Forestry, 271 Mast Rd., Durham, NH 03824, USA

ARTICLE INFO

Keywords:
Burn severity
Species-specific post-fire responses
Fire adaptive strategies
WorldView-2
Vegetation classification
Hyperspectral data
Forest composition and structure

ABSTRACT

Understanding post-fire forest recovery is pivotal to the study of forest dynamics and global carbon cycle. Field-based studies indicated a convex response of forest recovery rate to burn severity at the individual tree level, related with fire-induced tree mortality; however, these findings were constrained in spatial/temporal extents, while not detectable by traditional optical remote sensing studies, largely attributing to the contaminated effect from understory recovery. Here, we examined whether the combined use of multi-sensor remote sensing techniques (i.e., 1 m simultaneous airborne imaging spectroscopy and LiDAR and 2 m satellite multi-spectral imagery) to separate canopy recovery from understory recovery would enable to quantify post-fire forest recovery rate spanning a large gradient in burn severity over large-scales. Our study was conducted in a mixed pine-oak forest in Long Island, NY, three years after a top-killing fire. Our studies remotely detected an initial increase and then decline of forest recovery rate to burn severity across the burned area, with a maximum canopy area-based recovery rate of 10% per year at moderate forest burn severity class. More intriguingly, such remotely detected convex relationships also held at species level, with pine trees being more resilient to high burn severity and having a higher maximum recovery rate (12% per year) than oak trees (4% per year). These results are one of the first quantitative evidences showing the effects of fire adaptive strategies on post-fire forest recovery, derived from relatively large spatial-temporal scales. Our study thus provides the methodological advance to link multi-sensor remote sensing techniques to monitor forest dynamics in a spatially explicit manner over large-scales, with important implications for fire-related forest management and constraining/benchmarking fire effect schemes in ecological process models.

1. Introduction

Global fire emissions are an annual carbon flux of around 2.1 Pg C per year, equivalent to 50%–200% of annual terrestrial carbon sink (Piao et al., 2009; van der Werf et al., 2009; van der Werf et al., 2010). Among these fire emissions, 35% are forest-related (van der Werf et al., 2009; van der Werf et al., 2010). Post-fire forest recovery, a successional process towards the pre-fire structure and function, or to an alternative state, can lead to a significant carbon sink, generating offsets to the large fire-induced carbon losses (Amiro et al., 2003; Hicke et al., 2003; Turner et al., 2016). Such post-fire forest recovery is tightly connected to burn severity, a metric of fire effects on forest composition and structure, showing strong spatial heterogeneity across the landscape (Bolton et al., 2015; Jin et al., 2012; Morgan et al., 2014; Turner et al., 1997). Understanding how forests recover from disturbances such as fire, especially the quantitative relationship between forest recovery rate and burn severity, has long been a central focus for forest ecology and global carbon cycle studies, and is becoming a pressing issue for global change biologists, particularly with increasing frequencies and intensities of fire disturbances under the projected drier and warmer future climate (Bowman et al., 2009; Dale et al., 2001; Harvey et al., 2014; Meng et al., 2015; Turner, 2010; Westerling et al., 2006; Yang et al., 2015; Yang et al., 2017).

Separating post-fire forest canopy recovery from understory recovery is scientifically important, having broad implications for forest management (Castro et al., 2011; Kotliar et al., 2002), understanding

* Corresponding author.
E-mail address: ranmeng@bnl.gov (R. Meng).

https://doi.org/10.1016/j.rse.2018.03.019
Received 1 September 2017; Received in revised form 7 March 2018; Accepted 12 March 2018

fire effects on the terrestrial water cycle (Lewis et al., 2006; Mayor et al., 2007), and for simulating the global carbon cycle in Earth System Models (Fisher et al., 2015; Fisher et al., 2017). Specifically, understory (e.g., shrub, herbaceous, and woody) vegetation can recover quickly after the fire even with high burn severity (Figs. S1 & S2), however this vegetation is not the same, functionally and structurally, as the pre-fire canopy, having large differences in lifeform, productivity and capacity for carbon and water storage (Little and Moore, 1949; Swanson et al., 2011). Thus here we refer post-fire forest recovery to the increase in tree canopy areas during the post-fire period. As we focus on quantifications of post-fire tree canopy area recovery in this study, we define burn severity as the extent of tree canopy area loss by fire following previous studies (Meng et al., 2017; Quintano et al., 2013).

Several previous field-based studies have been conducted to explore the relationship between burn severity and short-term (< 5 years) post-fire forest responses (Balch et al., 2011; Brando et al., 2012; Smith et al., 2016; Sparks et al., 2016). Short-term post-fire recovery is critical for the long-term forest regeneration and can provide important insights about forest dynamics (Mantgem et al., 2006; Meng et al., 2015; Swanson et al., 2011). Although these field-based studies are primarily experiment-based, focusing on the threshold of burn severity in tree mortality at individual tree or coarse stand-scale not directly post-fire forest recovery, their results indicate trees or seedlings canopy areas can recover most from intermediate burn severity before reaching the threshold of burn severity in tree mortality (Brando et al., 2012; Sparks et al., 2016). These results are consistent with forest recovery studies in twenty-four years after the Greater Yellowstone fire with high resolution satellite imagery (see Fig. 8 in Zhao et al., 2016). Additionally, these experiment-based fire studies provide comparable results to other field-based studies examining various other disturbance drivers (e.g., herbivory, drought, and hurricane), also finding that forests recover most under intermediate disturbance impacts during the short-term period, with no or little forest recovery rate under very high disturbance extent (Hoogesteger and Karlsson, 1992; Lloret et al., 2004; Rich et al., 2007). These field-based studies thus collectively suggest that there exist convex relationships between post-disturbance forest recovery rate and disturbance severity during the short-term period (Fig. 1a).

In spite of the community canopy level relationship between forest recovery rate and burn severity, previous field-based studies suggest that the post-fire forest response can also vary across species (Bond and Keeley, 2005; Franklin et al., 2006; Jordan et al., 2003; e.g., Fig. 1a). Such variations in post-fire responses most likely arise from species-specific fire adaptive strategies (Keeley et al., 2011; Pausas and Keeley, 2014). For example, in a mixed pine-oak forest, the dominant pine has thick fire-resilient bark with the ability to recover from crown regrowth or epicormic resprouting; oak stems are more vulnerable to burn heat but can have vigorous sprouts from the root collars (Jordan et al., 2003; Little, 1998). Although these field-based studies shed important insights as to the post-fire recovery process, these studies are laborious, time-consuming, and often only cover small areas given the time and expense of making the observations, and thus are constrained to very limit spatial and temporal extents. Moreover, disturbances often happen in remote regions (e.g., Meng et al., 2015; Serbin et al., 2013) and as such can be difficult to reach for in-situ measurements.

Remote sensing can provide an efficient way for forest fire-related studies over large spatial and temporal scales, and importantly in remote areas (Lentile et al., 2006; White et al., 1996; Zhao et al., 2016). Many studies have used remote sensing measurements to examine how ecosystem-scale post-fire forests recover from different burn severity across a range of biomes, including Boreal (e.g., Goetz et al., 2006; Jin et al., 2012; Serbin et al., 2013), Mediterranean (e.g., Meng et al., 2015; Storey et al., 2016), and Tropical (e.g., Wilson et al., 2015). These previous remote sensing studies primarily relied on using broadband spectral features within the red, near-infrared (NIR), and shortwave near-infrared (SWIR) regions, typically employing spectral vegetation indices (SVIs), such as the Normalized Difference Vegetation Index (NDVI) at medium to coarse spatial scales (i.e., 15 m to 1 km), to track post-fire vegetation recovery (e.g., Epting and Verbyla, 2005; Goetz et al., 2006; Lee and Chow, 2015; Storey et al., 2016). However, SVIs such as NDVI can saturate at a relatively low leaf area index (Myneni et al., 1997) and the observed signal in medium to coarse resolution satellite imagery can be influenced by the rapid understory recovery leading to a misinterpretation of the recovery patterns (e.g., Figs. S1 & S2; Meng et al., 2015; Serbin et al., 2013), and as such cannot sufficiently separate post-fire canopy from understory recovery (Bolton et al., 2015; Serbin et al., 2013; Meng et al., 2015). This results in an incorrect or apparent recovery trend suggesting a positive increasing recovery rate with burn severity (Fig. 1b) that is not matched in field observations (Fig. 1a, Figs. S1 & S2). In particular, very high burn severity fires create large canopy gaps and enhance light availability for understory, facilitating rapid understory growth (Serbin et al., 2013; Bartels et al., 2016). As such, traditional SVIs-based methods tended to overestimate the short-term post-fire forest recovery rate, especially at high burn severity (Meng et al., 2015; Fig. S2), and can lead to an unrealistic relationship between burn severity and post-fire forest recovery rate (Fig. 1b). Additionally, such remote sensing-based studies are often constrained in their spatial resolution (≥ 30 m) to characterize the patchy post-fire landscapes with strong spatial heterogeneity, as post-fire forest structural characteristics and the fire-induced ecological responses often vary at very high spatial resolution (VHR, i.e., < 5 m) (Alonzo et al., 2017; Meng et al., 2017). Thus these studies cannot meet the increasing demand for conducting operational forest management and studying species-specific post-fire forest responses (Kolden et al., 2012; Meng et al., 2017).

The use of multi-sensor remote sensing observations together could provide new and unique opportunities to help bridge these knowledge gaps (Asner et al., 2017; Cook et al., 2013; Meng et al., 2017). For example, sub-orbital (i.e., airborne) remote sensing platforms, leveraging imaging spectroscopy (IS, i.e., passive high-spectral-resolution of "hyperspectral" reflectance) and Light Detection and Ranging (LiDAR, i.e., active ranging measurements to derive canopy heights and structure), enables the simultaneous measurements of forest optical and structural properties at VHR, by which we expect it can help to separate post-fire forest recovery from understory recovery. For example, several recent studies have demonstrated that the combined use of optical and LiDAR remote sensing measurements allows for more accurate species differentiation (Fassnacht et al., 2016). In addition, the increasing availability of VHR satellite data is enabling forest burn severity mapping at much finer spatial scales than previously available, showing improved performances over traditional 30 m Landsat-based methods (Holden et al., 2010; Meng et al., 2017; Mitri and Gitas, 2008). As such, we expect these multi-sensor remote-sensing techniques to facilitate improved quantifications of the species-specific relationships between forest recovery rate and burn severity (Fig. 1c) from the individual tree scale to the landscape as a whole.

The goal of our work was to explore the combined use of these multi-sensor remote sensing techniques to facilitate species-specific short-term forest recovery rate across a burn severity gradient in a spatially explicit manner. We addressed two specific questions: 1) Will the combined use of multi-sensor remote sensing techniques (to minimize the contaminated effect from understory dynamics) be able to extract the convex relationship between post-fire forest recovery rate and burn severity (Fig. 1c) during the short-term post-fire period as expected from field-based studies (Fig. 1a)? 2) Will our novel remote sensing approach allow for the detection of species-specific post-fire forest responses to different levels of burn severity (i.e., oak vs. pine in our study)?