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Review

Wildfire, water, and society: Toward integrative research in the "Anthropocene"

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ABSTRACT

Across the globe wildfires are increasing in frequency and magnitude under a warming climate, impacting natural resources, infrastructure, and millions of people worldwide every year. At the same time, human encroachment into fire-prone areas has increased the potential for ignition, as well as risks and damages to human communities. In an era of intensifying human activities on Earth – the "Anthropocene" – societal interactions with post-fire landscapes are becoming normal. Independent theories derived from individual disciplines no longer apply in cases where human interactions are intense. A holistic approach that accounts for interactions between natural and human systems is necessary to understand the altered dynamics of post-fire landscapes. Focusing on the intersection of fire, water, and society, this review explores an integrative research framework to couple post-fire fluvial and human processes. We overview the trends in wildfires and growing impacts on humans, how fluvial processes and systems are altered by wildfires, and the potential hazards for human settlements. This review is a basis for integrating societal concerns, such as vulnerability, economic impacts, and management responses. We then link disciplinary questions into broad interdisciplinary research through an integrative framework. The 2012 Waldo Canyon Fire (Colorado, USA) provides an illustrative case with intense human interactions, both during and after the fire, to formulate critical questions within the integrative framework. Utilizing emergent integrative conceptual frameworks and tools will assist scholars in meeting the challenges and opportunities for broad collaboration, which are necessary to understand and confront wildfires characteristic of the "Anthropocene".

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1. Introduction

Humans are changing Earth's surface at unprecedented rates; at the same time, humans must respond to this rapid change. Maintaining healthy ecosystem services require that we understand both human impacts and responses and anticipate how interacting landscapes evolve into the future. One process undergoing rapid change is human interactions with wildfires. Across the globe, wildfires are increasing in frequency and magnitude under a warming climate, impacting natural resources, infrastructure, and millions of people every year (Bowman et al., 2009). Simultaneously, human encroachment into fire-prone areas has increased the potential for ignition, as well as risks and damages to human communities, and therefore costs to society (Gorte, 2013). In summer 2012, several wildfires raged across the Colorado Front Range (USA), including the High Park Fire near Fort Collins and the Waldo Canyon Fire near Colorado Springs that displaced hundreds of residents. The Waldo Canyon Fire caused $353 million in damages and two fatalities. At the time it was ranked as the most costly fire in Colorado history, only to be matched the following summer by the Black Forest Fire (El Paso County, 2013). These events raise urgent questions about how landscapes respond to disturbance and force us to rethink how society responds to altered landscapes. This increasing societal interaction with wildfires is becoming a common phenomenon during the "Anthropocene"—an era dominated by human activity.

Understanding landscapes that are increasingly burned and subjected to intense human interactions requires a holistic and integrated approach. Traditionally, research on the biophysical effects of wildfire has emphasized acute impacts, including runoff and hillslope erosion, stream sedimentation, altered water quality, and degraded biological habitat (Gresswell, 1999; Shakesby and Doerr, 2006; Smith et al., 2011; Moody et al., 2013). Separately, literature on human dimensions of wildfires has addressed issues of vulnerability (e.g., Simon, 2012) while also focusing on human responses to the risks and outcomes of fires (e.g., Haight et al., 2004; Cohen, 2010). To fully understand and predict how fire-prone landscapes will evolve with human interactions, we need to develop conceptual and modeling frameworks that emphasize interacting impacts and feedbacks (Bolte et al., 2007; Chin et al., 2014a), while also recognizing that full "recovery" of ecosystems is likely not possible (Vieira et al., 2004). Rather, iterative sequences of alternative stable states (i.e., new "normals"; Collins et al., 2012) may characterize the evolution of landscapes subjected to multiple human-caused drivers of change.

Using the 2012 Waldo Canyon Fire in Colorado (USA) as an illustrative case, we outline potential research directions necessary for understanding the coupling between Earth's surface processes and human activities. The research directions call for a range of interdisciplinary expertise from the natural and social sciences and engineering to understand the complex changes induced by fire. Systems approaches to tackling wildfires are beginning to emerge (e.g., Johnson et al., 2013) and include ways for humans to coexist with wildfires (Moritz et al., 2014). A need exists to catalyze such research by explicitly highlighting fruitful directions for interdisciplinary collaboration. We recognize that human interactions with wildfires are often greatest during and immediately after fires. Thus, we focus on changes resulting from post-fire effects, such as post-fire floods and debris flows at the intersection of fire, water, and society.

First, we discuss wildfires in the "Anthropocene" that point toward a continuing surge in severe wildfires across the American west, concomitant with increasing damages and impacts on human populations. Second, we briefly review key fluvial processes that pose hazardous impacts to humans following wildfire. This review encompasses water quality and hydrology, fluvial geomorphology, and stream ecology, serving as a basis for integrating knowledge from the social sciences. Third, we also discuss societal impacts and responses to the hazards produced by fluvial processes, focusing on vulnerability, economic implications, and management. Finally, using the case of the Waldo Canyon Fire, we explore overlapping topical areas that may facilitate interdisciplinary understanding and potential areas for integration. This integration allows us to pose new research questions within a systems-level framework. We discuss outstanding research needs, theoretical and methodological challenges, and implications for managing fire-prone landscapes and ecosystems in the "Anthropocene."

2. Wildfires in the "Anthropocene"

Wildfires are common and natural occurrences across the world (Paton et al., 2015). Wildfires are necessary to maintain healthy ecosystems to recycle nutrients, improve soil condition, and initiate plant succession (Keane et al., 2008). In mediterranean climates, for example, natural fire frequencies range from 10–15 years in Australia, 10–20 years in South Africa, to 40–60 years in California, USA (Davis and Richardson, 2012; Kruger et al., 2012). In the Front Range of Colorado (eastern slopes of the Rocky Mountains), wildfires burn frequently (average return interval $<$30 years) in low elevation ponderosa pine forests; while in some subalpine forests, fires have not been noted in over 400 years (Sibold et al., 2006).

Wildfire patterns are influenced by climatology and anthropogenic climate change. Records of fire activity, spanning millennia, suggest that levels of burned biomass before the 1850's corresponded to changes in climate and fuel loads (Marlon et al., 2012). Coupled with the variability in El Niño Southern Oscillation (ENSO), warming climate trends of the 20th and 21st centuries have made mid- to high-elevation forests particularly susceptible to wildfires. Novel mixtures of plants that establish under altered climate can contribute to exacerbated fire conditions (Seastedt et al., 2008). For example, high severity crown fires result from the accumulation of fuel and the availability of fuel ladders that carry fire to the top of the forest canopy. Spracklen et al. (2009) noted that, under future climate projections, larger fires are expected, with up to a 175% increase in the Rocky Mountains from 2000 to 2050.

Human activities have also altered wildfire regimes through fire suppression efforts and artificial ignition of fires around the world. Although discerning the degree of human versus climate influence in the historical records is challenging, an uncharacteristic increase in the occurrence of fires in Colorado (USA) is apparent as soon as Euro-American settlers arrived. Settlers provided ample opportunities for ignition through prospecting, salvage logging, and clearing land for ranching (Veblen et al., 2000). Fire suppression efforts after the 1920s, along with the displacement of Native