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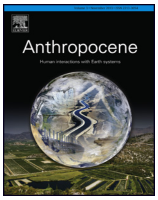

Review

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

American populations, coincided with decreased ENSO variability that favored conditions for fire, temporarily reducing fire activity (Veblen et al., 2000). Significant buildup of fuel and this “fire deficit” exacerbate potential for catastrophic wildfire events (Marlon et al., 2012). Population growth and human encroachment into fire-prone areas contribute to the growing hazards from wildfires on society. Direct human interactions with wildfires have consequently increased. Moritz et al. (2014) noted that human population density is becoming a more significant predictor of fire activity than vegetation density. Fires starting and spreading have increased significantly because humans have replaced lightning as the main ignition source of fires, especially where the urban corridor encroaches upon undeveloped areas. In the United States, the National Interagency Fire Center (https://www.nifc.gov) reports that human-caused fires burn more than 9700 km^2 (2.4 million acres) per year. Over the last few decades, the number of houses in rural areas has decreased (along with an increase in suburban, peri-urban, or urban houses) in the western United States (U.S.) (Fig. 1). Rural areas have reduced by as much as 38% in the 1990s (Fig. 1), with continued urban expansion into fire-prone areas. Perhaps most alarming is the capacity for further development, increased fire risk, and potential perturbations to the wildland-urban systems.

3. Water and society: post-fire interactions

3.1. Fluvial processes after wildfire

Wildfires induce changes in Earth’s surface processes that may pose hazards to human settlements. Post-fire flash floods are a primary hazard for communities downstream (Chong et al., 2004) and can cause damage to life and property and pose significant challenges for short- and long-term management. When fire occurs, the acute loss of vegetation reduces infiltration and enhances soil water repellency and decreases soil cohesion and organic matter (DeBano, 2000; Robichaud, 2000). These alterations ultimately increase runoff and flooding potential (e.g., Rulli and Rosso, 2007; Ebel et al., 2012). Kinoshita and Hogue (2011, 2015) documented elevated streamflow for seven years after fire in southern California (USA), while dry season flow increased for over a decade. Similar increases in flow are observed in Australia (Lane et al., 2012). The magnitude of these changes depends on the characteristics of the fire, watershed properties, patterns of post-fire precipitation, and recovery of the vegetation (Verkaik et al., 2013; Moody et al., 2013).

In addition to altering rainfall-runoff relationships, wildfires also create sediment hazards for people. Burned hillslopes devoid of vegetation increases the availability of sediment for delivery into river channels. Extreme heat from wildfire also decreases the stability of soils and increases erodibility of the topsoil (Moody et al., 2013). These processes make rill erosion (Sheridan et al., 2007), mobilization of dry ravel (Florsheim et al., 1991), and debris flows (Cannon et al., 2001; Nyman et al., 2015) common after wildfire. Suspended sediment concentrations in stream and rivers typically increase by several orders of magnitude (Troendle and Bevenger, 1996; Silins et al., 2009) and bedload after fire has been noted to increase 20-fold (Beaty, 1994). Thus, post-fire river systems typically become transport-limited (Moody and Martin, 2001). Although sediment concentrations may return toward pre-fire levels within several years (Beaty, 1994), fire-related sediment could remain for several hundred years, creating legacy effects (Moody and Martin, 2001). Elevated quantities of sediment, coupled with flashier hydrological regimes, may induce geomorphic responses that include aggradation, incision, bank widening, channel narrowing, and braiding (e.g., Benda et al., 2003).

Wildfires play an important role in biogeochemical cycling, which impacts the air, soil, and water. The remobilization of natural and industrial lead, mercury, and other trace metals and contaminants are released during fire and are more readily transported in waterways, causing environmental health concerns (Odigie and Flegal, 2011, 2014; Burke et al., 2013; Kristensen et al., 2014; Odigie et al., 2016). Water quality typically deceases after wildfires, which may liberate atmospherically deposited contaminants in soils and vegetation, which are then mobilized through erosion, runoff, and sediment transport processes (Kristensen et al., 2014). Increased runoff after fire accelerates mobilization of contaminants, especially in steep topography (Townsend and Douglas, 2004). Nutrient loading in streams are generally elevated after fire (Ranalli, 2004). Nitrates increase up to 40 times (Mast and Clow, 2008; Riggan et al., 1994) along with increases in other metals including lead, cadmium, and mercury (Stein et al., 2012; Burke et al., 2013). Nitrates, metals, and large quantities of sediment itself from burned landscapes contribute substantially to pollutant loads downstream. These pollutants have significant implications for water management, including the quality of drinking water (Riggan et al., 1994; Stein et al., 2012; Burke et al., 2013).

Post-fire changes in runoff, sediment regimes, and water quality also affect the overall health of biotic ecosystems downstream. The resilience of ecosystems and biological communities largely

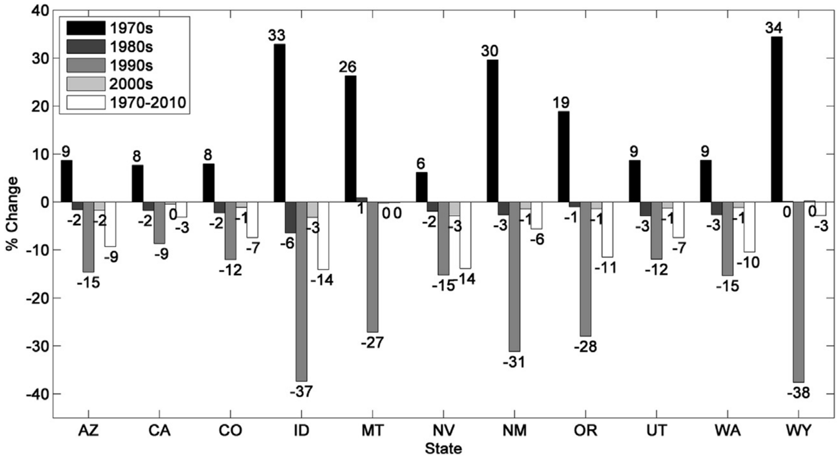

Fig. 1. Percentage change in rural areas in western U.S. between 1970 and 2010 for each decade, where AZ = Arizona, CA = California, CO = Colorado, ID = Idaho, MT = Montana, NV = Nevada, NM = New Mexico, OR = Oregon, UT = Utah, WA = Washington, WY = Wyoming.
Data Source: U.S. Census, 2015.

determines the capacity of organisms to adapt and recover (Vieira et al., 2004; Romme et al., 2011). Fire can cause mortality in aquatic fauna (e.g., Rieman et al., 1997), although most studies have found negligible or indiscernible direct impacts to organisms such as fish (Rinne, 1996; Jones et al., 1993), amphibians (Dunham et al., 2007), benthic macroinvertebrates (Minshall et al., 1997; Bêche et al., 2005), and periphyton (Earl and Blinn, 2003; Malison and Baxter, 2010). Causes of direct mortality from wildfire include increases in stream temperature (Minshall et al., 1997; Dunham et al., 2007) and toxicity from ash (Spencer and Hauer, 1991; Rinne, 1996) or fire retardant (Jones et al., 1989). In contrast, the loss of riparian vegetation and large floods following fire mobilizes sediment and degrades aquatic habitat, posing indirect effects on organisms (e.g., Bozek and Young, 1994; Pettit and Naiman, 2007). Aquatic organisms that show short-term declines often recover within 1–4 years post-fire (Rieman et al., 1997; Bêche et al., 2005). Recovery of stream ecosystems occurs as vegetation re-establishes and sediment sources decline (Robichaud et al., 2009). Human-induced alterations to landscapes (Neville et al., 2009), however, can amplify the detrimental effects of wildfire and diminish the resilience of ecosystems (Isaak et al., 2010).

3.2. Societal and human interactions with post-fire fluvial processes

Urban expansion into fire-prone areas heightens human exposure to water inundation, degraded water quality and public health risks, and debris flow related hazards and in turn increases overall social vulnerability (Montz, 2000; Suriya and Mudgal, 2012). Social vulnerability to flooding at both household and community scales is influenced by an affected group's exposure to the hazard (e.g., whether the home or community is located in a flood plain), sensitivity to the perturbation (e.g., whether there are preexisting health or mobility challenges present), and capacity to adapt and respond to the flood event (e.g., whether financial resources are available to assist the recovery process) (Adger, 2006; Blaikie et al., 2014). Cannon and DeGraff (2009) note how these aspects of social vulnerability are particularly acute for residents in the wildland-urban interface; including short-term flood risks associated with the movement of water and sediment and also longer term health impacts associated with water-born illnesses and disease (Tapsell et al., 2002). Hazardous debris flows can affect areas beyond the burned area perimeter up to two years after the fire (Wagner et al., 2013). For example, the storm following the 2003 Old and Grand Prix fire in California (USA) triggered over sixty debris flows and was responsible for sixteen deaths (Santi et al., 2011). In southeast Australia, the rapid and destructive fluvial processes after the 2003, 2006, and 2009 fires in Victoria impacted lives, local businesses, private property, and transportation infrastructure as debris flows and flash flooding swept away cars, killed a fire fighter, destroyed homes, and buried roads (Nyman et al., 2011). Furthermore, sedimentation of waterways can pose negative impacts on drinking water quality and challenge water providers' ability to deliver safe, clean drinking water to communities (Smith et al., 2011; Emelko and Sham, 2014). Globally, these social vulnerabilities have been shown to disproportionately impact poor, minority and marginalized communities (Rawson and Colten, 2007; Tretter and Adams, 2012).

Large-scale erosion within watersheds can increase sedimentation of reservoirs and damage critical water resource infrastructure (Meixner and Wohlgemuth, 2004; Nyman et al., 2011) leading to considerable costs. Hazard mitigation and prevention create management expenses for diverse stakeholders including homeowners and local agencies (Merz et al., 2010) through city bonds, local fees, state and local taxes, personal expenses, and rising insurance premiums (Jensen, 2006). Activities addressing the risks from altered fluvial systems contribute to financial pressures within already overburdened municipal agencies (Blonksi et al., 2002; Loomis, 2004). The U.S. Forest Service and other land management agencies have spent millions of dollars on post-fire emergency watershed stabilization measures, which are intended to minimize hydrologic damage to natural habitats as well as to roads, bridges, reservoirs and irrigation systems (http://www.gao.gov/index.html). For example, the effects of storm events following the 2002 Hayman and the 2012 High Park Fires in Colorado (USA) filled reservoirs with sediment and caused intake shutdowns (Warziniack and Thompson, 2013). Removing sediment from Denver Water's reservoirs cost $28 million and the High Park Fire led to rate increases to fund capital improvements necessary for maintaining a viable drinking water source (Warziniack and Thompson, 2013).

Managing water and debris related hazards require coordination from individuals and institutions with expertise across the social and physical sciences. As a first step, risk assessments are crucial to identify and map social risks on the landscape and to ensure resources are distributed appropriately before and after hazardous events (Plate, 2002). In parts of Europe and the U.S., for example, the Burned Area Emergency Response (BAER) program is used to identify and mitigate imminent threats to human life and safety, property, and critical natural and cultural resources (Young and Rust, 2012). Second, technical mitigation approaches within watersheds can reduce the likelihood of catastrophic flood outcomes. These include improvements to water infrastructure (e.g., piping, pumps, improved water filtration), bank stabilization (e.g., hydro- mulching, sediment traps, riparian treatments, log deflectors and seeding to accelerate vegetation regrowth) and stream channeling and debris control techniques (Robichaud, 2000; Emelko and Sham, 2014). Third, planning approaches within urbanizing environments can help manage and reduce future social vulnerabilities (Hamin and Gurran, 2009). These include new zoning regulations, which can significantly limit new developments in high risk landscapes such as floodplains, and also the implementation of strict building codes and land use restrictions (e.g., setbacks and surface permeability requirements) that can help local stakeholders withstand hazardous events and minimize flood impacts (Berke and Smith, 2009). Fourth, preparedness measures, such as improved education and warning systems are essential for alerting communities to impending threats and guiding their movement to safety (López-Marrero and Tschakert, 2011; De Graff, 2014).

It is increasingly accepted that integrated management approaches – including the aforementioned steps – are necessary when building community resilience to the threat of water and sediment related hazards (Berke and Campanella, 2006). Integrated risk management approaches should synthesize best practices from governments, land managers, planners, scientists and citizens (Aerts et al., 2008; Ashley and Blanksby, 2007). Furthermore, key feedback loops linking economic decisions, environmental impacts, planning policy, and social vulnerability should be acknowledged and addressed as part of these integrated management efforts (Peterson et al., 2014; Chin et al., 2015). Under this approach, the goal is to not only prevent hazardous events from occurring, but also to accept the inevitability of periodic flooding and minimize their impacts in the "Anthropocene" (Hamin and Gurran, 2009; Liao, 2012).

4. Through the lens of the Waldo Canyon Fire

The Waldo Canyon Fire (Fig. 2) began on 23 June 2012 and burned 74 km^2 of land, mostly in the Pike National Forest near the city of Colorado Springs, Colorado. The fire was contained on 10 July 2012. About 19% of the burn was classified as high severity, 40% moderate severity, and 41% low severity (Young and Rust, 2012).

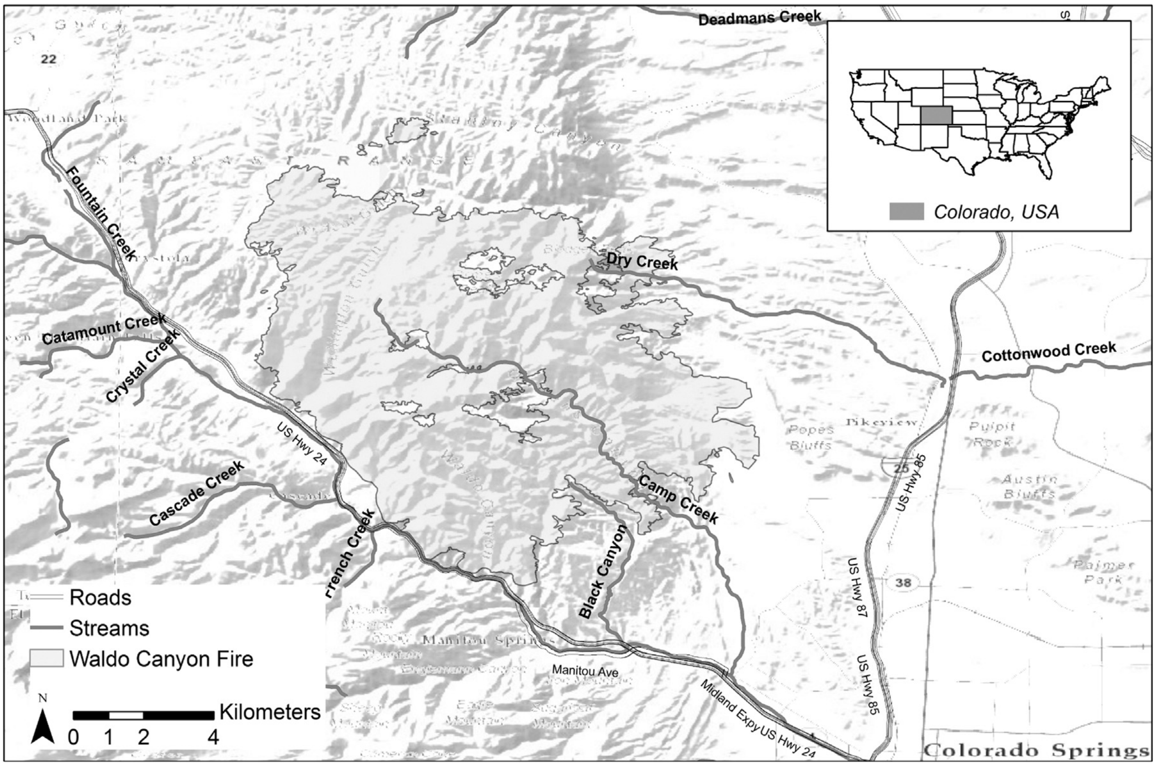

Fig. 2. Waldo Canyon Fire in Colorado, USA and surrounding cities (Woodland Park, Manitou Springs, and Colorado Springs), main roads, and streams.

Most notable about the Waldo Canyon Fire, however, was the potential for high social impacts due to the proximity of the fire to a large city (Colorado Springs with a population of 433,570 people and nearby communities (Fig. 3a–d)). More than 32,000 residents were evacuated, including 22,000 people within a two-hour period on 26 June 2012 (Martin, 2013). The fire damaged or destroyed 347 homes, mostly in the Mountain Shadow neighborhood, and killed an elderly couple. Insurance claims from loss and damage totaled $353 million. Closure of businesses (e.g., Fig. 3c) escalated millions of dollars. In addition, the U.S. Forest Service reportedly spent $13 M fighting the fire. The City of Colorado Springs recorded over $4 M in overtime wages during and after the fire. The Colorado Springs Utilities spent more than $2.7 M restoring damaged utilities. In light of these diverse and significant costs, the Waldo Canyon Fire was, at the time of occurrence, considered the most expensive in state history (Wineke, 2012). The costs continued to mount into the years following the fire, as efforts focused on mitigating and treating the secondary effects (Fig. 3c), including flash floods and sediment debris (Fig. 3d).

Besides the high economic costs, the Waldo Canyon Fire was also an example of complex and intense human interactions with wildfire. The close proximity to a large city created an unprecedented collaboration between agencies (at multiple levels) in the post-fire efforts to manage potential risks and hazards to residents (El Paso County, 2013). These agencies focused primarily on mitigating the risks and hazards of flash floods and sediment/debris flows (El Paso County, 2013). At the Federal governmental level, the agencies included the U.S. Forest Service (USFS), Federal Emergency Management Agency (FEMA), and Natural Resources Conservation Service (NRCS). Organizations at the city, county, and state levels (the cities of Colorado Springs, Manitou Springs, and El Paso County) also worked alongside local agencies such as the Colorado Springs Utilities, non-profit organizations (e.g., Coalition for the Upper South Platte), and private landowners. These agencies collaborated to implement projects to stabilize hillslopes and slow erosion (i.e. detention basins, reshaped channels). The Colorado Department of Transportation (CDOT) also installed mitigation and advanced warning systems for flash floods. Decision-making, therefore, played an important role in how the burned landscape would recover, and in turn how the recovery process would affect human communities.

In addition, direct human interactions with post-fire processes also characterized the Waldo Canyon Fire. These human actions focused on intervention measures to inhibit the natural processes following fire that would produce erosion, flash floods, and ultimately hazardous to society. Activities included the application of retardants and treatment (e.g., aerial straw and wood chip mulching) (Fig. 4a and b) during and immediately after fire to prevent potential erosion. Direct manipulation of hillslope and river channels also continued several years after the fire (Fig. 4c–f) to retard movement of sediment down barren hillslopes into stream channels and block sediment transportation toward downstream residential communities. By 2013, there were 45 sediment detention basins (Fig. 4e–f), about 10 km of modified river channels, 89 manual treatments, and 2383 debris deflectors, totaling over $30 M (El Paso County, 2013). Similarly, private landowners also built two tall debris fences at the base of a burned watershed that cost over $1.5 M (Fig. 4c and d; Chin et al., 2015).

Although attempts to mitigate potential hazards associated with post-fire effects (as described in previous sections above) are often given high priority to alleviate immediate human concerns, they confound causal connections and make predictions of post-fire processes difficult (Gresswell, 1999). Artificial manipulation of burned landscapes also affects the cycle of natural recovery within ecosystems, many of which have demonstrated remarkable resiliency (e.g., Yellowstone after the 1988 fire; Romme et al., 2011). Moreover, despite the significant activities implemented after the Waldo Canyon Fire, extremely heavy rainfall and steep granite terrain still produced hazardous flooding that contributed to additional loss of life, property, and critical public infrastructure

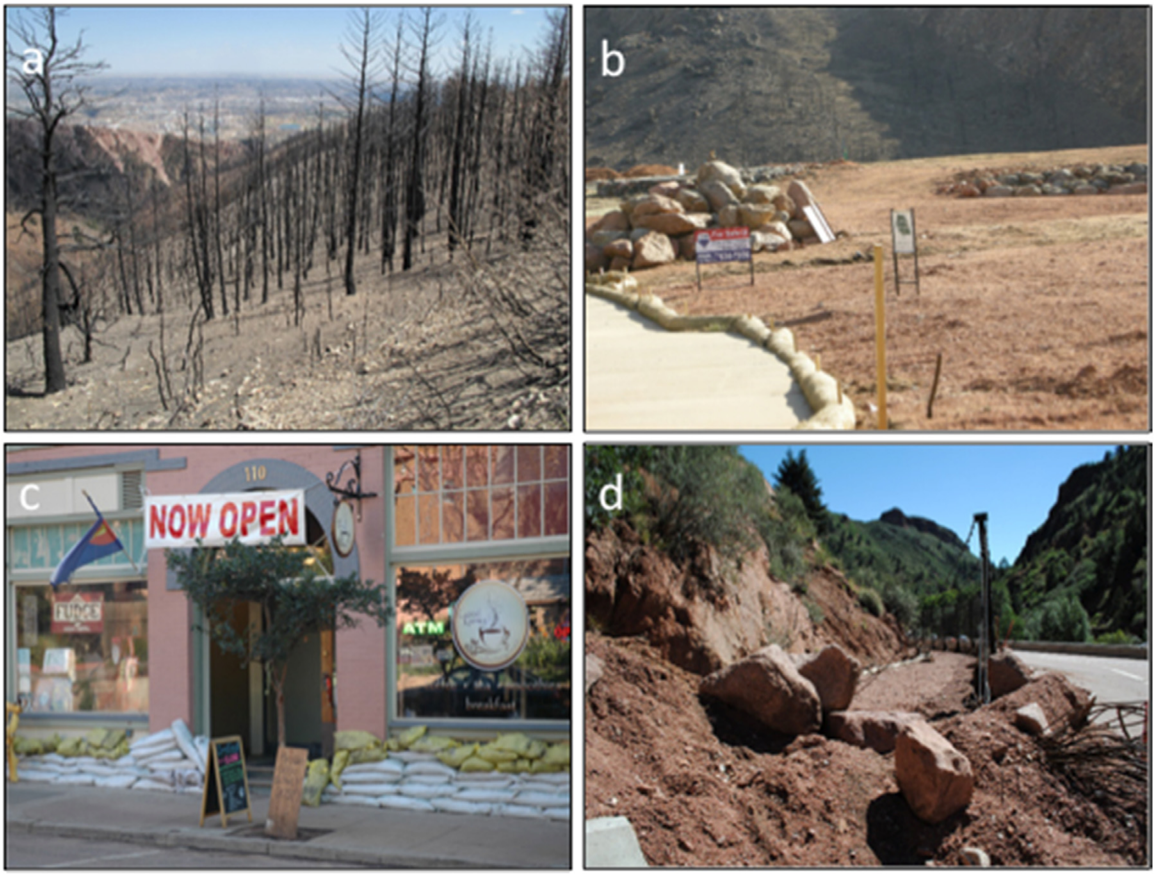

Fig. 3. Human impacts of Waldo Canyon Fire: (a) burned forest with Colorado Springs in background (photo taken April 2013); (b) vacant land for sale where homes once stood, against burned forest (photo taken April 2013); (c) coffee house (and other businesses) in Manitou Springs re-open after damage from flash floods induced by fire (photo taken August 2013); (d) debris from Waldo Canyon onto US Highway 24, the main road between Colorado Springs and Woodland Park (photo taken September 2013).

in the summers of 2012 and 2013 (EL Paso 2013 and CDOT 2014). Thus a need exists to understand the response and influence of human activities in the post-fire recovery process and to incorporate them in predictive models. This understanding requires linking theories from the bio-physical and social sciences.

5. Toward integrative studies on wildfires in the "Anthropocene"

5.1. Core themes

The core themes common to investigating hydro-geomorphic, ecological and social (environmental governance) systems (Wohl et al., 2014) provide a path for integrating the fluvial and social dimensions of wildfires. These themes include *connectivity*, *feedbacks*, *tipping points or thresholds*, and *resiliency*. As open systems, the connectivity of landscape components largely controls the traits of the system (Bracken and Croke, 2007; Bracken et al., 2013). Bio-physical systems adjust over time to disturbances such as hydrologic events (Poff et al., 1997) and human activity, including land-use changes (e.g., Chin, 2006). These systems exhibit varying degrees of resilience and feedback mechanisms that regulate their behavior (Corenblit et al., 2011; Chin et al., 2014a), including complex, non-linear responses characterized by thresholds (Schumm, 1979). Correspondingly, social or governance systems show connectivity in the flows of information and communication, with decision processes often eliciting feedback loops (Gerlak, 2013; Peterson et al., 2014). The concept of adaptiveness in social systems (Folke et al., 2005, 2010) relates to the idea of resiliency in natural systems. Adjustments to perturbations through feedback mechanisms also characterize social systems, including thresholds that may be crossed. These themes, therefore, are considered promising foci for interdisciplinary research linking across physical and social aspects of human-landscape systems, including the effects of wildfire (Harden et al., 2014).

5.2. Applying the Interactive, Integrative and Iterative Framework to the Waldo Canyon Fire

The Interactive, Integrative, and Iterative (III) Framework for Human-Landscape Change provides a useful conceptual tool to link questions centering on connectivity, feedbacks, tipping points/thresholds, and resiliency. The III framework (Chin et al., 2010, 2014b) focuses on the core interactions among physical, biological, and social processes in response to perturbations within landscapes—such as human-induced soil erosion, clear-cutting, or installation and removal of dams in rivers. In this case, wildfires (the perturbation) may be sufficiently strong to tip the system across a threshold (left box Fig. 5). The resulting adjustments within the interacting systems (processes) ultimately change the conditions of vulnerability and resilience in bio-physical systems and human communities (right box Fig. 5; e.g. elevated streamflows and impacted communities). The environmental and human context in which the perturbation occurs (top arc Fig. 5) determines the initial vulnerability and resilience of the human and bio-physical systems to the perturbation. It also contributes the background processes (e.g., perceived risk) that determine the resulting conditions of the biophysical and human systems after adjustment to the perturbation. The changes, in turn, elicit environmental responses and modifications in human actions

Fig. 4. Human responses to Waldo Canyon Fire: (a) aerial mulching after containment of fire (helicopter is seen in sky, top left of center; photo taken 16 September 2012) (b) straw treatment from aerial application (photo taken 16 September 2012) (c) sediment fence over 6 m (20 ft) tall, constructed upstream of residential community (photo taken March 2013 showing construction workers on fence); (d) sediment and wood behind fence after storm (photo taken 6 July 2013); (e) in-channel modification: sediment basins (photo taken 30 June 2013); (f) sediment basin filled after storms (photo taken 13 July 2013).

that potentially feed back to the original causes (bottom arc Fig. 5). Feedback responses at various levels (local and regional) occur through policy along with mitigation and adaptation strategies to environmental stress, as well as behavioral changes.

The III Framework for Human-Landscape Change is particularly useful for conceptualizing problems in the "Anthropocene" and anticipating solutions for the future, even though it is just one of several frameworks that bridge disciplinary divides in tackling complex environmental systems (see, for example, theory on social-ecological systems; Berkes et al., 2003). Distinct from other frameworks, the III model explicitly identifies the physical, as opposed to ecological, landscape processes (Wohl et al., 2014). The framework emphasizes adjustments over time through interacting impacts and feedbacks in response to disturbances in the system—resulting in iterative changes in system states in the evolution of the landscape (Fig. 6). When applied iteratively, the III is useful for articulating and understanding changing human-landscapes over time, and thus for anticipating changes that will occur on Earth's surface. (after Chin et al., 2010). It also considers the longer-term, cumulative changes that characterize the evolution of geomorphic systems, including legacy effects from past disturbances (Wohl and Merritt, 2007; James, 2013) that pose varying initial conditions of vulnerability and resilience. For example, Moody and Martin (2001) found that residence times for eroded sediment after a

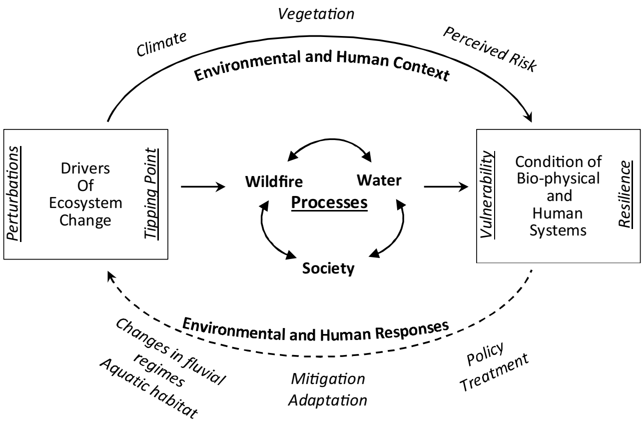

Fig. 5. The Interactive, Integrative, and Iterative (III) Framework for Human-Landscape Change as applied to the wildfire, water, and society nexus. It provides an integrative view that links impacts with feedbacks. The top arc represents the background environmental and human processes regardless of the perturbations. The middle arrow represents naturally resulting processes and conditions after a perturbation. The bottom arc represents environmental and human feedback responses.

wildfire in the Colorado Front Range exceeded 300 years, much greater than the recurrence interval of fire in the area. The erosional and depositional features, therefore, become legacies from wildfire and serve as new initial conditions for subsequent wildfire and flood sequences during landscape evolution.

The III concept provides a conceptualization of the complex human-landscape interactions induced by the Waldo Canyon Fire. Ignition in an urban-fringe location (the perturbation, left box; Fig. 5) causes post-fire floods and debris flows and reduced biological habitats and water quality. At the same time, interacting environmental and human processes include application of aerial retardants to inhibit erosion and post-fire management responses such as straw and wood mulch (Fig. 4). These interactions may elicit feedbacks among the social and bio-physical processes themselves. Regardless, the perturbation and adjustment processes would result in reduced resilience and increased vulnerability in both bio-physical and human systems (right box, Fig. 5). Such degraded conditions may prompt further human and environmental responses (bottom arc; Fig. 5).

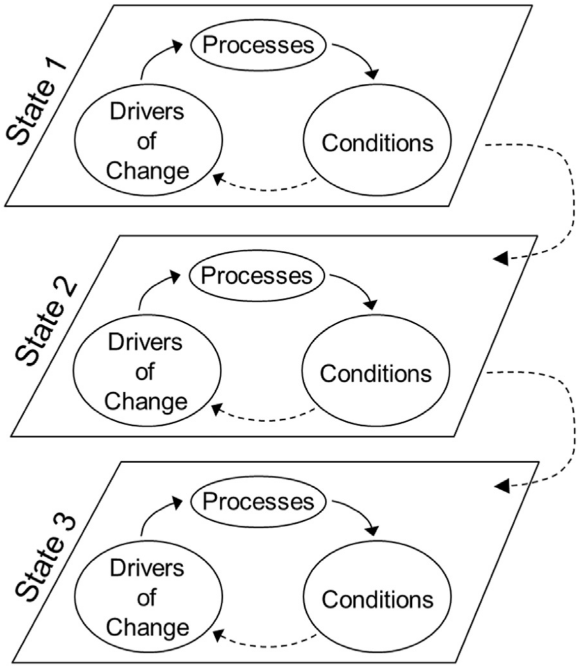

Fig. 6. Iterative states in the evolution of human-landscape systems produced by interacting impacts and feedbacks. New states occur when thresholds are crossed and the system does not return to pre-disturbance conditions (after Chin et al., 2010). In this context, State 1 represents post-fire adjustments and responses (i.e. Fig. 5), State 2 occurs when the system is no longer able to recover to pre-fire conditions, and State 3 is a potential new equilibrium.

An example of a complex human response to the risks and hazards following the Waldo Canyon Fire was the construction of large debris nets (Fig. 4c and d; bottom arc Fig. 5; mitigation and adaptation) to protect property and lives. Instead of facilitating recovery of the burned landscapes, the debris net interrupted sediment transport and prevented coarse particles from propagating downstream. The decreased roughness caused further channel erosion, which prompted the landowners to pave the river channel (Chin et al., 2015). The additional human response of paving the eroded river channel segment changed the form and function of the river system further, acting as a tipping point in the system, whereby a return to a pre-fire state (i.e. recovery) is no longer possible. In this case, the post-fire landscape reaches State 2 (Fig. 6).

As scientific knowledge advances regarding the complex human-landscape interactions following wildfires, the environmental impact of post-fire practices and sustainable management strategies may emerge. Over time, these changing interactions may enable the burned system to regain some of its connectivity and lost functions, even though this “recovery” may be partial. Such iterative states could continue until the landscape system reaches a new equilibrium (State 3; Fig. 6). Or, in the case of persistent human interruption, the system may remain in a perpetual state of adjustment.

5.3. Posing integrative research questions

The case of the Waldo Canyon Fire underscores the need to understand the multiple dimensions of human interactions with wildfire within an integrated framework capable of articulating these interactions. The complex interactions include humans affecting the cycle of wildfires, to wildfires impacting people, to responses such as strategies for mitigating hazards from wildfires. Therefore, to fully understand and anticipate how fire-prone landscapes will evolve under increasing human intervention, – i.e., in the “Anthropocene,” – new approaches are needed to *connect* the impacts of fire with the human responses to the fire and understand how these responses, in turn, affect the landscape. The use of conceptual frameworks that emphasize *interacting impacts and feedbacks* (Fig. 5) are critical, while recognizing that multiple *thresholds* within both adjusting natural and human processes will make predictions of change difficult. Moreover, conceptual frameworks must accommodate incomplete “recovery” of ecosystems when they are subjected to persistent, multiple human-caused drivers of change. Instead, iterative sequences of new stable states (i.e., Fig. 6, repeated new definitions of “normal” (Collins et al., 2012)) will likely characterize the evolution of fire-prone landscapes. Such an integrative approach highlights common core themes for investigating wildfire, hydro-geomorphic, and social (governance) systems, as outlined above.

Accordingly, we pose a series of interconnected example research questions within this framework, deriving from the Waldo Canyon case study, at the intersection of post-fire, fluvial and social systems. These questions illustrate an integrated, interdisciplinary approach to tackling post-fire research in the new era (Fig. 7).

A. Initial state of landscape before disturbance (pre-historical context)

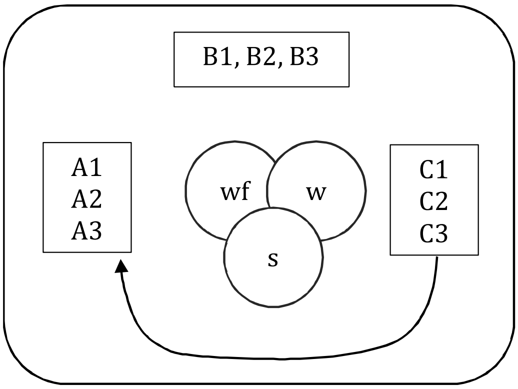

Fig. 7. An integrated interdisciplinary approach for post-fire research. The interacting processes are defined as wf = wildfire, w = water, s = social. Letters and numbers refer to research questions in text, where "A" is the initial state of landscape before disturbance; "B" is the interactions among bio-physical and social processes induced by wildfire; and "C" is the human responses and changing human-landscape systems over time. The bottom arrow is analogous to the bottom arc in Fig. 5, where human responses provide feedbacks to the original state of the landscape.

A1. What is the fire regime in the area and have climate change and human activity influenced this regime?

A2. How has forest management influenced the hydrological, geomorphological and biotic systems?

A3. How has the built landscape evolved and contributed to human disturbances?

B. Interactions among natural and social processes induced by fire

B1. How do biotic communities interact with sediment dynamics and channel morphology in varying degrees of burn?

B2. How do these biotic and geomorphic interactions vary with runoff response?

B3. How do fire management treatments and policies affect the dynamic hydro-geomorphological-biotic interactions and responses?

C. Management responses and changing human-landscape systems over time

C1. What are the trajectories of landscape change under different forest policy and management regimes?

C2. What are the feedbacks between altered landscape processes and human behaviors?

C3. How do changing landscapes affect the ecosystems services that they provide, and how do feedback responses trigger decisions that influence further change?

Tackling these questions requires interdisciplinary expertise in paleoecology and climate science (A1), hydrology (A2, B2, B3, C1), geomorphology (A2, B1, B2, B3, C1), ecology (A2, B1, B2, B3, C1), human geography/sociology (A3, C1, C2), economics (C2, C3), and political/decision science (A2, C2, C3). In this integrated approach, answering questions using knowledge from one discipline will improve the ability to answer other disciplinary questions. For example, knowing the fire cycle and the influence of climate change (A1) will help us understand the time scales of process adjustments (B1, B2) — i.e., the time frame for a possible stable state in the evolution of the landscape (Fig. 6) — which will yield insight into the trajectories of landscape change under different policy regimes (C1), as well as changes in ecosystem services (C3). Echoing Beschta et al. (2004), such an interdisciplinary approach will contribute to a timely and holistic understanding of wildfires, while accounting for inevitable and increasing human interactions (Gresswell, 1999; Wohl, 2013).

6. Outstanding needs, challenges, and opportunities

An urgent need exists to understand the interactions and feedbacks among wildfire, water processes, and society. First, we need to develop predictive understanding of the coupled hydrological, geomorphic and ecological responses within burned landscapes, using interdisciplinary knowledge amassed over the past several decades. Such information is vital for understanding the fundamental processes, functions, and feedback relationships altered by fire, and ultimately for maintaining healthy ecosystem services for human communities in the face of change. Second, in an era of intense human interaction with landscapes, we need to fully integrate human activities into these coupled responses. This approach entails better understanding of the historical context of human impacts, policies, and management practices under which landscapes have evolved, as well as ongoing wildfire mitigation. Third, in light of critical concerns for human safety and welfare in fire-prone areas, we need to develop policies and strategies for risk mitigation and adaptation (i.e., bottom arc Fig. 5; Chapin et al., 2006). Recognizing that disturbance is itself an agent of recovery, strategies should place priority on enhancing capacity for burned landscapes to recover (Beschta et al., 2004), rather than on changing the trajectory of recovery.

Challenges to address the needs outlined above remain with respect to data, theory and methods. Abundant and diverse types of observational data, such as field-based or remotely-sensed information exist across various ecosystems, spatial and temporal-scales, and research disciplines. To advance the integrative science of wildfire, humans, and river systems, we must synthesize and analyze historical pre- and post-fire information across multiple disciplines and also develop new data and methods that can complement existing datasets. Tackling broadly interdisciplinary research questions also requires collaboration among diverse scientists; especially in bridging the social-natural scientific divide, where different languages, data, and tools to address the same problem exist (Bracken and Oughton, 2006). Particular difficulties arise when quantitative models are capable of representing only portions of human-landscape interactions, necessitating the use of mixed methods (Lach, 2014). Modelers therefore need to collaborate with scientists who work on the ground to fill in gaps in models; domain scientists must learn computational thinking and sufficiently understand mathematical models to improve model parameterization.

An emergent set of integrative analytic and modeling tools, such as simulation approaches, provide the ability to integrate data from multiple temporal and spatial scales and various fields of research. These tools enable the incorporation of feedbacks from human behavior and decision-making (Barton et al., 2010; Zvoleff and An, 2014; Chin et al., 2015). The U.S. National Research Council (2011) noted the critical importance of successfully incorporating human interaction in modeling the mechanics of Earth surface systems. These modeling tools provide a new avenue for addressing complex interactions associated with the nexus of wildfires, water, and society — and in general, for answering a grand challenge recently identified: *How will Earth's surface evolve in the "Anthropocene*?" (National Research Council (NCR), 2010).

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