Fires and Postfire Debris/Mudflows Triggered by Landforms in the Colorado Front Range and the Subsequent Impact on and by Humans

Ping Xu

University of Colorado Boulder, Boulder/USA · xup@colorado.edu

Abstract: The warming climate and Colorado's fast-growing population affect the sensitive Rocky Mountain ecosystems that are already fire-prone zones. Increasingly frequent wildfires have been an urgent issue for mountain communities. Rocky Mountain landforms trigger lightning, fire, wind, and debris flows. Fire is an important ecological process; however, fire events produce outputs such as the loss of human life and property, air pollution, and postfire debris/mudflows. Keeping people and infrastructure away from fire prone areas and reducing human-caused fires may be an efficient strategy for adapting to climate challenges. This research suggests the establishment of an open-fire ban zone within the wildland-urban interface of the Front Range, where most of Colorado's population, cultural, and economic centers are located. In remote fire-prone areas, populations should be limited so that large infrequent fires can take their natural course and provide benefits to the ecological process. The research method includes four components: 1) a survey of Colorado wildfires from 2011 to 2016 over 100 acres; 2) a Research Publication Study including fire ecology, postfire debris/mudflows, fire impacts on the environment and humans, as well as climate warming and increasing populations in the Colorado Front Range; 3) field investigations of fire and postfire debris flow sites; and 4) the application of systems thinking, and development of a framework for the prediction models of fire hazards and postfire debris sites.

Keywords: Landforms, wildfire, postfire debris flow, wildland-urban interface, systems thinking, sustainability

1 Introduction

The current warming climate and extreme weather patterns are heavily impacting Rocky Mountain landscapes. Since 1970, the number of large fires per year has doubled and could increase another six-fold in the next two decades (REPORT: WILDFIRES 2013). An increased burn area of two to five times could engulf almost the entire area of the Rocky Mountains in as little as 50 years (BAKER 2009). Roads and 4-wheel drive vehicles bring people to ever more remote areas and high elevations, while tourism and new development in mountain forests create an increased risk of fire ignition.

Increasingly frequent fires and Colorado's fast-growing population affect the sensitive Rocky Mountains ecosystems that are already fire-prone zones. The mountains' beautiful landforms attract visitors and residents, but also trigger lightning, fires, high winds, and debris flows. Fire is an important ecological process, but can also be damaging to humans. This potential should make protecting the Front Range from fire threats a priority for Colorado. Faced with such a complex and difficult challenge, designers and planners should take responsibility for designing to protect human health and property, reduce human-caused fires, and sustain the ecological fire process. Practical implementations first require a comprehensive understanding and synthesis analysis of the fire system. As Carl Steinitz states: *"Geodesign should be*

Journal of Digital Landscape Architecture, 2-2017, pp. 63-74. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-629-1, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537629007.

decision-driven, not data-driven. Before data are gathered, for use in a GIS or otherwise, other issues for the study must be better understood" (STEINITZ 2012).

Natural disasters are often treated as singular events and the systematic connections between relevant components are ignored. This paper emphasizes the interactions between climate, landforms, and human activities. The research method includes four components: 1) a survey of Colorado wildfires from 2011 to 2016 over 100 acres; 2) a Research Publication Study including fire ecology, postfire debris/mudflows, fire impacts on the environment and humans, as well as climate warming and increasing populations in the Colorado Front Range; 3) field investigations of fire and postfire debris flow sites; and 4) the application of systems thinking, and development of a framework for the prediction models of fire hazards and postfire debris sites. According to systems thinking, for a comprehensive analysis we should look at the structure of the system; list all relevant components in a system; emphasize the relationship between them; and elaborate the process in which the system works (LASZLO 1972).

2 Survey of Colorado Wildfires from 2011 to 2016

A survey of Colorado wildfires of over 100 acres taking place between 2011 and 2016 was conducted to collect data on fire time, location, size, cause, damage, and related wind speeds. There was a total of 108 fires and 681,447 acres burned. Table 1 presents a portion of the wildfire survey, compiling those over 2,000 acres. According to Baker, the large and infrequent fires over ten thousand acres are mostly beneficial to the ecological process (BAKER 2009). Figure 1 shows the locations of the fires in Table 1, distinguishing between fires over 10,000 acres and fires under 10,000 acres but over 500 acres, with an emphasis on whether the fires were human-caused or nature-caused, and the region where they occurred.

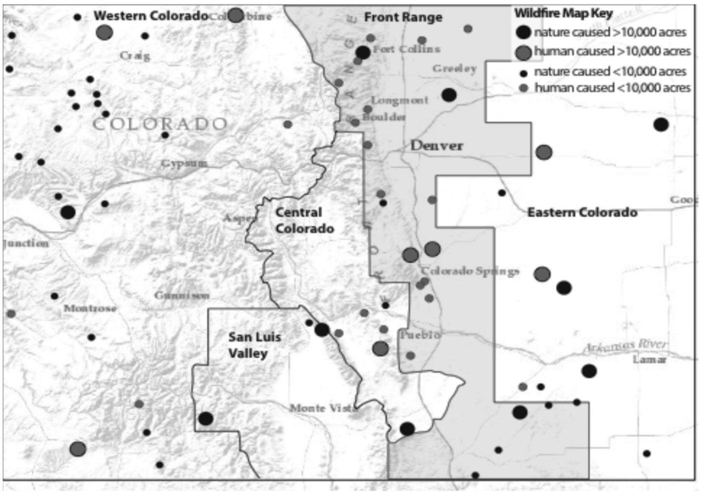

Fig. 1: Map of Colorado regions and wildfires over 500 acres, 2011-2016 (by PING XU)

Table 1: Colorado wildfires over 2,000 acres from 2011 to 2016 (Compiled by PING XU from BELKNAP 2014, INCIWEB 2016 and THE DENVER POST 2016)

Date	Approx. Time	Name	Location	Size, Acres	Damage	Cause	Wind Gusts	Type
February 19, 2011	4:00 PM	Sierra Vista Fire	Southwest of La Junta, Otero County	2,042	none	human	38 mph	grass
March 24, 2011	unknown	Karval Fire	E of Karval, Karval County	12,000	3 buildings	human	44 mph	grass
April 1, 2011	12:00 AM	Crystal Fire	12 mi West of Fort Collins, Larimer County	2,940	13 buildings	human	33 mph	forest
April 7, 2011	10:00 AM	Ft. Lyon Fire	West of Las Animas, Bent County	14,000	2 buildings	lightning	35 mph	grass
May 30, 2011	unknown	Purgatoire Fire	Northeast of Trinidad, Las Animas County	6,140	none	lightning	54 mph	grass
May 31, 2011	7:00 AM	Bear Fire	South of Trinidad, Las Animas County	6,900	none	lightning	47 mph	forest
June 3, 2011	1:00 PM	Salt Fire	South of Las Animas, Bent County	4,500	none	lightning	44 mph	grass
June 5, 2011	1:00 PM	Bear Springs Fire	South of La Junta, Las Animas County	44,662	5 buildings	lightning	38 mph	grass
June 7, 2011	4:00 PM	Callie Marie Fire	South of La Junta, Las Animas County	9,089	none	lightning	38 mph	grass
June 7, 2011	11:00 AM	Shell Complex Fire	15 mi N of Kim, Las Animas County	13,312	7 buildings	lightning	30 mph	grass
June 12, 2011	3:00 PM	Duckett Fire	8 mi Northwest of Westcliffe, Custer County	4,690	7 buildings	human	36 mph	forest
June 29, 2011	1:00 PM	Young Hollow Fire	South of Colorado Springs, El Paso County	2,200	none	human	48 mph	grass
March 18, 2012	1:00 PM	Heartstrong Fire	South of Yuma, Yuma County	24,000	2 buildings	unknown	59 mph	grass
March 26, 2012	2:30 PM	Lower North Fork	1 mi East of Foxton, Jefferson County	4,140	27 buildings, 3 dead	human	80 mph	forest
May 13, 2012	3:00 PM	Little Sand Fire	North of Pagosa Springs, Archuleta County	24,900	none	lightning	32 mph	forest
May 14, 2012	1:00 PM	Hewlett Fire	Northwest of Fort Collins, Larimer County	7,685	none	human	20 mph	forest
May 25, 2012	4:45 PM	Sunrise Mine Fire	3 mi North of Paradox, Montrose County	5,742	none	human	43 mph	forest
June 5, 2012	1:00 PM	West Fork Complex Fire	Northeast of Pagosa Springs, Mineral County	109,615	1 building	lightning	40 mph	forest
June 9, 2012	6:00 AM	High Park Fire	15 mi West of of Fort Collins, Larimer County	87,284	259 buildings, 1 dead	lightning	75 mph	forest
June 22, 2012	4:30 PM	Weber Fire	3 mi South of Mancos, Montezuma County	10,133	none	human	40 mph	forest
June 23, 2012	12:00 PM	Waldo Canyon Fire	West of Colorado Springs, El Paso County	18,947	346 buildings, 2 dead	human	70 mph	forest
June 25, 2012	1:30 PM	Last Chance Fire	Last Chance, Washington County	45,000	11 buildings, 1 firetruck	human	33 mph	grass
June 27, 2012	1:45 PM	Pine Ridge Fire	Northwest of Grand Junction, Mesa County	13,920	none	lightning	46 mph	forest
August 3, 2012	12:15 PM	Wolf Fire	Northwest of Meeker, Moffat Countay	6,100	none	lightning	32 mph	forest
October 9, 2012	2:00 PM	Fern Lake Fire	West of Estes Park, Larimer County	3,498	none	human	70 mph	forest
June 11, 2013	1:15 PM	Royal Gorge Fire	West of Canon City, Fremont County	3,218	20 buildings	human	40 mph	forest
June 11, 2013	2:00 PM	Black Forest Fire	North of Colorado Springs, El Paso County	14,280	548 buildings, 2 dead	human	47 mph	forest
June 19, 2013	5:10 PM	East Peak Fire	Southwest of Walsenburg, Huerfano County	13,572	11 buildings	lightning	54 mph	forest
June 20, 2013	3:30 PM	East Tschuddi Fire	Northwest of Meeker, Rio Blanco County	2,009	none	lightning	54 mph	forest
April 8, 2014	unknown	Yuma County Fire	South of Wray, Yuma County	2,500	none	unknown	33 mph	grass
July 23, 2014	2:30 PM	Alkali Fire	14 mi Northwest of Maybell, Moffat County	20,690	2 buildings	human	40 mph	grass
September 18, 2015	3:00 PM	Kersey Grass Fire	East of Kersey, Weld County	11,669	none	lightning	35 mph	grass
July 8, 2016	6:00 PM	Hayden Pass Fire	20 mi Southeast of Salida, Fremont County	16,754	none	lightning	28 mph	forest
July 19, 2016	4:45 PM	Beaver Creek Fire	24 mi North of Walden, Jackson County	38,380	3 buildings	human	50 mph	forest
August 8, 2016	2:20 PM	Lost Solar Fire	24 mi Southeast of Meeker, Garfield County	4,755	none	lightning	24 mph	forest
October 3, 2016	1:00 PM	Beulah Hill Fire	15 mi Southwest of Pueblo, Pueblo County	5,232	14 buildings	human	40 mph	forest
October 17, 2016	3:45 AM	Junkins Fire	11 mi East of Westcliffe, Custer/Pueblo Counties	18,403	26 buildings	human	70 mph	forest

The Front Range, including Denver, Boulder, Fort Collins, Colorado Springs, and Pueblo, is an economic and cultural area of Colorado located immediately east of the front range of the Rocky Mountains. The region is defined by county lines and contains all of the highest populated counties in the state. It accounts for 82 % of the state's population and creates 86 % of its economic output, making it particularly important when considering wildfire policy (ECON REPORT 2009). Figure 1 shows that within the Front Range area there were 24 fires over 500 acres, two-thirds of which were human-caused, making up 64 % of human-caused fires during that time. Due to the high rate of human caused fires, fire prediction should include detailed analysis of the risk factors for human-caused ignition.

3 Rocky Mountain Landforms Trigger Fires

3.1 Landforms Trigger Lightning, Windstorms, and Fires

Between 2011 and 2016, three of the four largest fires by acreage were caused by lighting strikes (Table 1). Lightning, an electric discharge, causes fires when striking an earth-bound object. The smoke and mist expelled by a large forest fire can cause even more electric charges, starting new fires many kilometers downwind (DUL'ZON 1996). Although lightning can occur anywhere, at any elevation, areas with steep and high elevations, often those over 8,000 feet and below the tree line, in particular, attract lightning strikes that cause fires. The high landforms of the southern Rocky Mountains have the most abundant lightning strikes in the region (BAKER 2009). Fires caused by lightning include the Bear Peak fire at about

8,100 feet, the Cold Springs Fire at 8,770 feet, the multiple fires on Sugarloaf Mountain at 8,917 feet, and the High Park Fire, which started at 8,200 feet. Therefore, the fire prediction model should include a lightning-caused ignition model with elevation overlays.

The Rocky Mountain range also triggers windstorms that spread fires over thousands of acres. Steep and rigid landforms of the Rocky Mountains and the unpredictable weather patterns at high elevations, particularly on mountain crests, are responsible for powerful wind gusts. These high gust speeds can be seen in Table 1, which indicates that the majority of the large fires in this period were spread by wind gusts more than 30 miles per hour, and as high as 80 miles per hour. The highest gust speeds tend to correlate with the fires that are most damaging to human life and property. Downslope windstorms are common late autumn into spring along the Front Range. Downslope winds characterized by unseasonably warm temperatures called Chinook winds. Bora winds involve the transfer of cold air and are accompanied by falling temperatures. (DOESKEN 2003). There is also an increased fire risk in canyons that can form wind tunnels, spreading fire rapidly. These factors contribute to Colorado being the third most at-risk state for wildfires (WILDFIRES 2016). The impact of wind on fast-spreading fires necessitates an understanding of the criteria that generate strong wind patterns when modeling fire hazards.

3.2 Fire Ecology and Postfire Landscape

There are two main on-going debates about fire impacts on mountain ecosystems and humans, and the subsequent management of forest fire policy. One side of the debate argues that fire is an ecological system that plays a key role in shaping the natural landscape, and that this system should not be limited (WUERTHNER 2006). The contrary debate argues that fires should be investigated on a large regional scale with hundreds of years of temporal understanding including the increasing human impacts on and from the system and that policies should be shaped to protect the landscape and people. In the past, fires have been seen as manageable ecological processes in a resilient ecosystem, however, in the Rocky Mountains, this idea is no longer tenable (BAKER 2009).

According to Baker, large and infrequent fire events are a natural ecological process. These fires are part of a larger historical cycle, called the Historical Range of Variability (HRV), which is not affected by people. However, weather warming and expanding populations in mountain areas disrupt the natural cycle and greatly increase fire frequency and size. The Colorado Rockies have never experienced fire exclusion, as the Rocky Mountain landscape triggers fire events naturally. Colorado forests in particular take a long time to recover from fire. In the Rockies, there are few plants with seed banks to aid tree regeneration. The dry weather also impacts the recovery time, and many forests are still recovering from the large fires of the 19th century (BAKER 2009). Fires damage wildlife habitat, water quality, and mutual forests. In addition, the extended periods of recovery on burned slope sides leave them vulnerable to debris/mudflow disasters.

4 Rocky Mountain Landforms Trigger Debris/Mudflows

4.1 Landforms Trigger Rainstorms and Debris/Mudflows

The high elevation and steep landforms of the Rocky Mountains contribute to intense rainstorms. Along the Colorado Front Range catchments of watersheds see heavy summer storms, owing to Gulf/Subtropical Atlantic moisture that moves west across the state, creating extreme weather patterns before reaching the high mountains (DUST 2016). Orographic lift, when air is forced from a low elevation to a high elevation over steep terrain, also creates high precipitation storms in the mountains and canyons of the Front Range (WHITEMAN 2000). The constant and intense rainfalls triggered by these landforms are essential to the creation of debris/mudflow disasters, making weather forecasting an important factor in predicting post-fire debris/mudflows.

Landforms play a significant role in causing debris/mudflows, one of the most dangerous natural hazards (COSTA & WIECZOREK 1987). Based on the author's field investigations of the 2013 Colorado debris/mudflow zones, the discussion of landform patterns emphasizes the three following areas. The first is the debris and runoff catchment where debris and runoff accumulate and debris flows are initiated. The second area is a debris flow track, often a water channel, where debris events develop, generate power, and accelerate downhill. The final area is that of the debris flow fan, which is a receiving or impact area, where the slope has dropped more than 20 %, and the debris is released, potentially damaging property and infrastructure. Debris flow fan sites often have local hills with steep slopes, which have seen fire recently.

With these combined landforms and the author's previous research on debris/mudflow sites, four spatially relevant site prediction models should be used (XU 2016). The basin model includes debris catchments that initiate in mountain basins and terminate in a debris fan. The distance model occurs where flow tracks travel through seven miles of a steep "zig-zag" canyon. The local model is a short track from a local hill with a 35-45 % slope with great potential for damage. The combined model includes criteria from the basin, distance, and local models, where a flow track from a basin passes through a canyon with steep burned hillsides, and points directly to the site at a river confluence. These models are important spatial predictors for debris events, especially where there have been recent fires.

4.2 Postfire Debris/Mudflow Sequence

A common phenomenon in mountain areas is debris/mudflows following wildfires, and is called the postfire debris flow sequence (WELLS 1987). According to the author's field investigations of the 2013 flood impact zones in Colorado Front Range canyons, every high-impact zone experienced a fire before the debris/mudflow, most within two to three years. Fire changes the structure of soil, coating it in burned organic molecules and making it virtually waterproof. Two primary erosion processes cause debris flows in burned watersheds (WELLS 1987). The first process is dry ravel, the downhill movement of debris without the flow of water, damming dry washes and worsening future flows. The second is the formation of rill networks, or small debris flows that branch extensively with little rain. These erosions accelerate and intensify debris/mudflow disasters (WELLS 1987). After a fire, it is crucial to anticipate debris/mudflows and for prediction models, inputting mountain landforms, burn areas, and heavy rain, to prepare residents for the possibility of such a disaster.

When fire burns vegetation from the mountainsides, it kills the groundcover and loosens debris. During heavy rains, the dead trees fall more easily, levering out the soil and producing more debris. The dead timber washes into debris flows, further generating power. Geomorphic research indicates that in a debris/mudflow, a significant amount of heavy timber causes landslides and the destruction of property (RENEAU & DIETRICH 1987).

4.3 Postfire Debris Flow Sequence Case Studies

The town of Poudre Park was impacted by the 2012 High Park fire in Larimer County, Colorado. This historic fire burned more than 87,284 acres over three weeks of time. The blaze destroyed 259 homes, and there was one fatality (SCHULZ 2012). In the 2013 floods, houses on the lower portion of Fall Gulch received the highest impact, and the entire valley was evacuated. The landforms of Poudre Park played a significant role in triggering the debris/mudflows (Figure 2). The town is located on a confluence area, a receiving zone for debris/mudflows. There is a dry wash intersecting the site that originates from a high elevation and passes through three miles of burned hillsides with an average slope of 35 %. This catchment collects enormous debris and runoff, generating debris/mudflows.

Fig. 2: Burned slopes, Poudre Park, Larimer County (JAMES 2013)

The Big Elk Meadows neighborhood in Lyons was affected by a fire in 2002. During the 2013 floods, a house on the hillside was destroyed, the only thing left was the garage buried in mud. The neighboring houses on both sides received no damage. A dry wash behind the site passes through a straight and narrow channel on a hillside with a 45 % slope. The postfire debris flow sequence often leaves a straight track of rock and sand on the impacted land, which can be seen on the Google Map data after debris/mudflows (Figure 3a and 3b).

Fig. 3a and 3b: Photograph and satellite image showing the straight debris track, Big Elk Meadows, Lyons (Photo by PING XU, Basemap from Google Maps 2014)

5 Fire Impact on and by Humans

Although lightning, fire, wind, and debris/mudflows are natural processes, all can have a heavy impact on human life and property. Human developments and activities are in danger, and also a direct contributor to the danger. Colorado wildfires have impacted hundreds of thousands of acres of land, thousands of homes, and taken several lives. Between 2011 and 2016, of the 108 wildfires surveyed, 60 % were caused by humans. As the population of the Front Range grows, more and more people are moving into the wildland-urban interface zone, increasing development of homes and infrastructure, including roads and power lines. Severe winds can blow down large trees with shallow roots and damage power lines, potentially lighting a fire that will be spread rapidly by the strong winds. There is also an increase of tourism in mountain areas. Outdoor activities make Colorado attractive to tourists, but can also spark fires that quickly spread out of control.

In Colorado, since 2011 about 72 forest fires over 100 acres have burned nearly 456,213 acres of forest. If there are an estimated average of 75 trees on each acre, then roughly 34.7 million trees have been burned in the last five years. Burned trees release large amounts of carbon dioxide, and can no longer filter pollutants or produce oxygen. Inhalation of smoke and ash from large wildfires also create serious health threats for the elderly, ill, and those with heart or respiratory conditions (Report: Wildfires 2013). Taking into account the weight of potential impacts to human health in the Front Range, nearby fires should be immediately extinguished.

6 Conclusions and Discussions

According to systems thinking, the comprehensive analysis of fire events should present the structure of the system including listing all relevant components; emphasizing the relationship between them; and elaborating the process in which it works. Figure 4 demonstrates the framework of the fire system where weather warming and increasing populations input to the Rocky Mountain climate, geology, landforms, soil, vegetation, and weather. The resulting fire events lead to outputs including the loss of human lives and property, air pollution, postfire debris/mudflows, as well as some positive ecological effects. The high elevations and landforms in the Colorado Front Range are not just affected by fire, wind, debris, and thunderstorms, but interact with the climate to generate new patterns of such events.

Rocky Mountain landforms also trigger high precipitation storms. These constant and heavy rainfalls in turn trigger debris/mudflow disasters in burned watersheds. Fire changes the soil structure and causes increased erosion in the way of dry ravel and rill networks. Postfire erosions accelerate and intensify a debris/mudflow disaster (WELLS 1987). In the 2013 floods every high-impact zone experienced a fire before the debris/mudflow. These additional factors are important when considering fire impacts and the potential for future disasters.

Implementation of systems thinking for fire and postfire debris flow site prediction models involves careful consideration of all criteria and how they interact to create disasters. Figure 5 demonstrates a framework for models predicting fire hazards and postfire debris sites. Lightning caused ignition and human caused ignition models should be included in fire hazard prediction, along with understanding and mapping of wind and climate models. Prediction of debris/mudflows sites requires an understanding of landform models, mapping of burn areas, and forecasting of heavy rain events. At every level, this system includes characteristics of Rocky Mountain landscapes; thus, prediction models should be responsive to these interconnected local contexts.

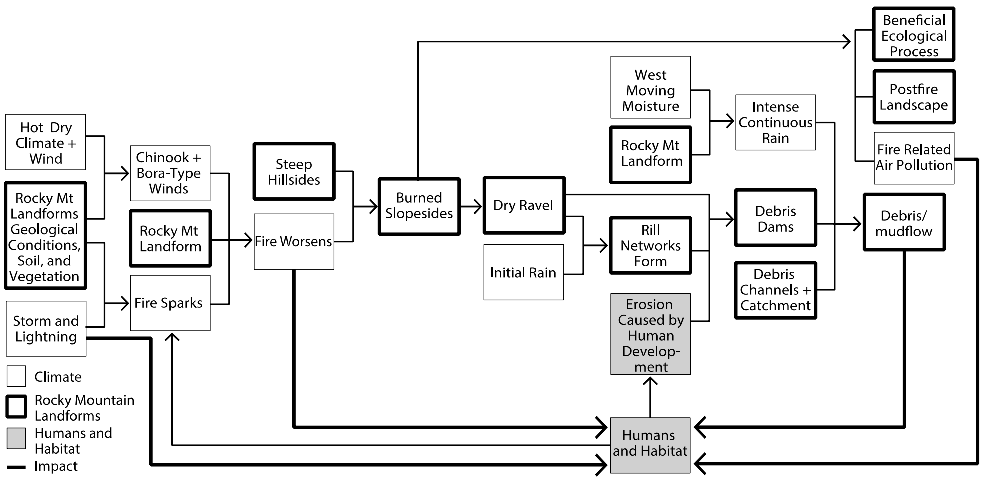

Fig. 4: The fire event system in the Colorado Front Range (by PING XU)

Rocky Mountain landscapes trigger fire events naturally. Large and infrequent wildfires in particular benefit the ecological process. In Colorado's dry climate, forests take a longer time to recover from fire. Fire also leaves the land vulnerable to debris/mudflows. Moreover, the population of the Front Range is expanding rapidly and more and more people are moving to the wildland-urban interface, increasing the risk of human-caused fires. Such fires are not an ecological benefit and can greatly damage human health and property. Equivocating ecological arguments have led to hesitation in banning fires. The factors that lead to accidentally lit fires, such as fireworks and campfires, should be banned unambiguously within the Front Range. Banning human-caused fires will not lead to fire exclusion in Colorado, where nature-caused fires will continue to burn and provide ecological benefit.

Fire is not just an ecological issue. Wildfires are a complex concern that impact many areas, including ecology, air pollution, economics, and human life and health. Large fires and postfire debris/mudflows that threaten human life and property are resource intensive, require massive state and federal funds, and endanger the lives of fire fighters. In Colorado since 2011 wildfires have burned nearly 681,447 acres of land and roughly 34.7 million trees, worsening the greenhouse gas effect. Rocky Mountain forests are also “the lungs” of the United States and too many fires could cause these lungs to fail. Smoke and ash from large wildfires threaten the health of thousands of people, even hundreds of miles away.

Considering the Front Range’s population density and the potential cost, there should be a more effective ban on open fires and efforts to stop any burns immediately.

A synthesis analysis will balance the priorities of ecology and human health and safety in different zones. An open-fire ban zone should be established within the wildland-urban interface of the Front Range, where most of Colorado’s population and economic interests are located. All fires in this area should be stopped immediately upon detection, including campfires, fireworks, debris or pile burning, and other open fires. In more remote fire prone areas, populations should be limited so that large infrequent fires can take their natural course and provide benefits to the ecological process. To better implement the “open-fire ban zone” within of the Front Range there are several suggested strategies:

- Include fire, wind patterns, and postfire debris/mudflow overlays in the site analysis process. Create a warning system to aid preparedness for postfire debris/mudflows in burned watersheds.
- Control development and infrastructure in sensitive fire prone areas in order to reduce human-caused fires, and limit density in the wildland-urban interface. Local governments should also purchase and repurchase fire prone lands and debris/mudflow sites as they become available.
- Ban open fires including fireworks and campfires. Within parks and open space particularly, there should be fire bans and detailed hazard plans for disasters in order to protect visitor’s health and safety.
- Educate residents on the necessity of fire prevention and establish a fire-reporting system using social media, and build a network to efficiently identify and report fires. It is crucial to stop fires upon detection, as they can develop beyond control within hours.
- Establish underground power lines in the wildland-urban interface in order to avoid fires lit by fallen wires. The high wind gusts of the Front Range knock down power lines and cause fires that quickly spread out of control. Although this project may seem a massive

infrastructural undertaking, it would be worthwhile when compared to the potential damages caused by a fire disaster.

With increasingly extreme weather and growing populations, Colorado wildfires will occur more frequently. Nature is hard to control, but human behavior can be modified. Human development and populations are impacted by, but also contribute to, the causes of these disasters. Keeping humans and infrastructure away from fire prone areas and reducing human-caused fires may be an efficient strategy for adapting to climate challenges. Landscape designers, planners, architects, and developers should consider the complexities of this issue as well as what is at stake in order to make better solutions. Implementing systems thinking in re-planning the wildland-urban interface and establishing mitigation strategies with consideration for fire ecology and human safety will help to sustain the beautiful Rocky Mountain landscape.

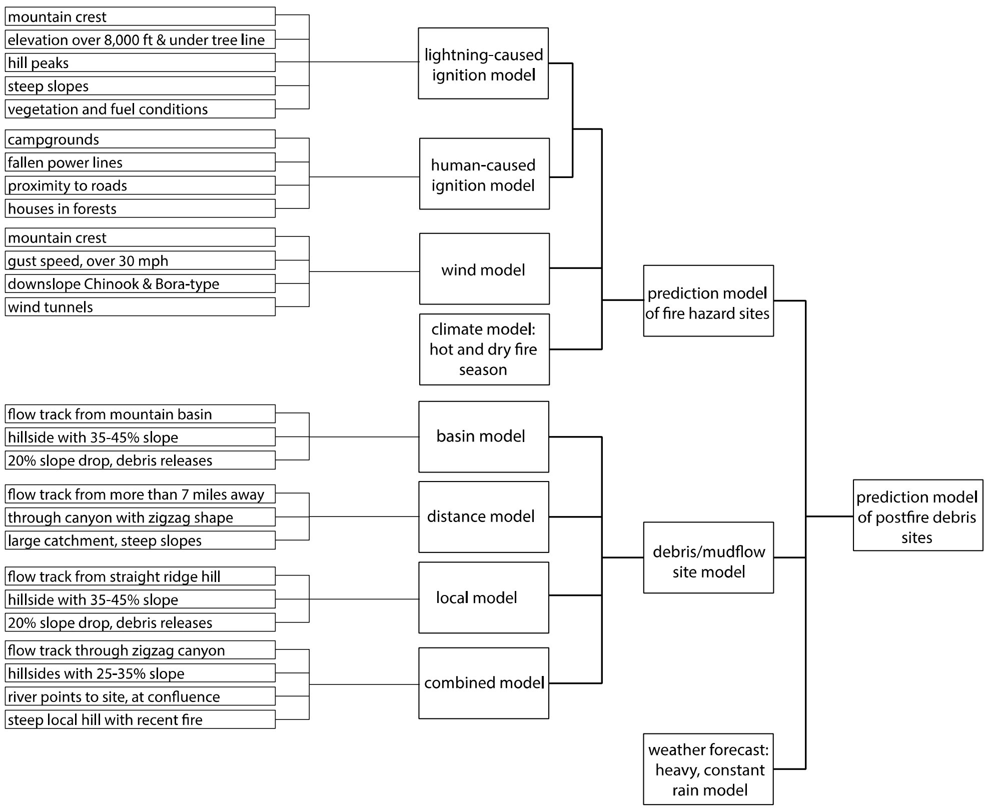

Fig. 5: The framework for the prediction models of fire hazards and postfire debris sites (by PING XU)

Acknowledgements

The author would like to thank Mackinzi Taylor for editing this paper and assisting with the tables.

References

BAKER, W. L. (2009), Fire Ecology in Rocky Mountain Landscapes. IslandPress, Washington/Covelo/London.

BELKNAP, D. (2014), Map: Colorado Wildfires 2008-2012. The Coloradoan. www.coloradoan.com/story/news/local/wildfires/2014/04/17/map-colorado-wildfires-2008-2012/7833433.

COSTA, J. E. & WIECZOREK, G. F. (1987), Debris Flow/Avalanches: Process, Recognition, and Mitigation. The Geological Society of America: Boulder, Colorado.

DOESKEN, N. J. (2003), Climate of Colorado. Colorado State University. http://climate.colostate.edu/climateofcolorado.php.

DUL'ZON, A. A. (1996), Lightning as a source of forest fires, Combustion, Explosion, and Shock Waves. Springer, New York, 32 (5), 134-142.

DUST, D. (2016), Hydroclimatology of the Colorado Front Range. Colorado State University. http://warnercnr.colostate.edu/~ellenw/front_range/hydro.php.

ECON REPORT (2009), Water and the Colorado Economy, Commissioned by: Front Range Water Council. Summit Economics and the Adams Group. http://www.denverwater.org/docs/assets/4bea7503-0237-e833-64a3f4c3447f588c/frwc_econ_report.pdf.

JAMES, L. (2013), Poudre Park hangs tough after two major fires, major flood. North Forty News. www.northfortynews.com/poudre-park-hangs-tough-after-two-major-fires-major-flood.

LASZLO, E. (1972), Introduction to Systems Philosophy, with a foreword by Ludwig von Bertalanffy. Gordon and Breach, Science Publishers, New York.

RENEAU, S. L. & DIETRICH W. E. (1987), The importance of hollows in debris flow studies; examples from Marin County, California. Debris Flow/Avalanches: Process, Recognition and, ed. J. E. COSTA and G. F. WIECZOREK. The Geological Society of America: Boulder, Colorado, 165-179.

REPORT: WILDFIRES (2013), Report: Wildfires & Air Pollution, A Hidden Hazard. Climate Central. http://www.climatecentral.org/news/report-wildfires-and-air-pollution-a-hidden-hazard-16651.

SCHULZ, J. (2012), High Park Fire Update. Larimer County Sheriff. www.larimersheriff.org/press-release/high-park-fire-update-6/.

STEINITZ, C. (2012), A Framework for Geodesign. Esri: Redland, CA.

WELLS, W. G. (1987), The effect of fire on the generation of debris flows in southern California. Debris Flow/Avalanches: Process, Recognition and Mitigation, ed. by J. E. COSTA & G. F. WIECZOREK. The Geological Society of America: Boulder, Colorado, 105-114.

WHITEMAN, C. D. (2000), Mountain Meteorology: Fundamentals and Applications. Oxford University Press.

WILDFIRES (2016), Wildfires. Insurance Information Institute. http://www.iii.org/fact-statistic/wildfires.

WUERTHNER, G. (2006), Wildfire: A Century of Failed Forest Policy. The Foundation for Deep Ecology, Sausalito, CA.

XU, P. (2016), Feng-shui – Ancient Geodesign as a Clue: Identifying Predictive Landform Models of Mountain Flood Impact Zones. Journal of Digital Landscape Architecture, 1-2016, 141-148.

www.inciweb.nwcg.gov/state/6

www.denverpost.com