Collected Abstracts
for
AGU Chapman Conference

Synthesizing Empirical Results to Improve Predictions of Post-wildfire Runoff and Erosion Responses

Updated: 07 August 2013

YMCA Conference Center
Estes Park, Colorado, USA
25-31 August 2013

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Front Cover: Photo of post-wildfire runoff in Rendija Canyon in 2001 after the 2000 Cerro Grande fire near Los Alamos, New Mexico, USA. Photo used with permission from Thomas M. Trujillo.

AGU Chapman Conference

Synthesizing Empirical Results to Improve Predictions of Post-wildfire Runoff and Erosion Responses

Post-wildfire science is generally not recognized as a discipline in its own right, so the intention of this Chapman Conference is to bring together experts from the field of post-wildfire research, the meteorological and hydrological modeling field, other fields of related research, and young career scientists: to (1) address current priority research issues facing the post-wildfire community, and (2) to synthesize the existing empirical data in a quantitative manner that will improve or provide additional post-wildfire model components. These components are designed to predict the hazards associated with post-wildfire runoff and erosion response, but also will provide input for assessing impacts on downstream ecosystems and water quality, and will assist the fire-effects community and land managers in the decision-making process.

This Chapman Conference will be held at the conference center at the YMCA Camp of the Rockies in Estes Park from 25-31 August 2013. The priority research issues are grouped into the following five topic sessions:

1. **Organizational framework: Post-wildfire response domains**
2. **Precipitation: Meso-scale rainfall characterization**
3. **Infiltration: Effects of soil properties on infiltration**
4. **Runoff: Linking precipitation and basin morphology to post-wildfire response**
5. **Soil and sediment: Erosion and transport**

There will be invited talks and posters as well as contributed talks and posters over the course of five days so that there will be ample time for in-depth discussions oriented toward resolving issues. Two half-day field trips are planned: (1) to view potential post-wildfire response domains along an elevation gradient on Monday, 26 August 2013, and (2) to visit to the National Center for Atmospheric Research to learn about meteorological research and atmospherically driven wildfire propagation models on Tuesday, 27 August 2013.

Co-conveners

John Moody, Research Hydrologist, jamoody@usgs.gov,
U.S. Geological Survey, National Research Program, Boulder, Colorado, USA.

Pete Robichaud, Research Engineer, probichaud@fs.fed.us,
U.S. Forest Service Rocky Mountain Research Station, Moscow, Idaho, USA.

Rick Shakesby, Reader in Physical Geography, r.a.shakesby@swansea.ac.uk,
Swansea University,Wales, UK.

Sue Cannon, Research Geologist, cannon@usgs.gov,
U.S. Geological Survey Landslide Hazards Program, Golden, Colorado, USA.

Deborah Martin, Research Hydrologist, damartin@usgs.gov,
U.S. Geological Survey, National Research Program, Boulder, Colorado, USA.

Program Committee

Topic #1. Organizing framework: Post-wildfire response domains

Deborah Martin, U.S. Geological Survey, Boulder, Colorado, USA
John Moody**,** U.S. Geological Survey, Boulder, Colorado, USA

Topic #2. **Precipitation**: **meso-scale rainfall characterization**

John Moody, U.S. Geological Survey, Boulder, Colorado, USA
Dave Gochis, University Center for Atmospheric Research, Boulder, Colorado, USA
Dave Jorgensen, NOAA Severe Storms Lab, Norman Oklahoma, USA
David Dunkerley, Monash University, Melbourne, Australia
Uldis Silins, University of Alberta, Alberta, Canada

Topic #3. Infiltration: Effects of soils properties on infiltration

Rick Shakesby, Swansea University**,** Swansea, UK
Jorge Mataix-Solera, University of Miguel Hernández, Alicante, Spain
Fred Pierson, U.S. Agricultural Research Service, Boise, Idaho, USA
Lea Wittenberg, University of Haifa, Haifa, Israel
Artemi Cerdà, University of Valencia, Valencia, Spain

Topic #4. Runoff: Linking precipitation and basin morphology to post-wildfire response

Pete Robichaud, U.S Forest Service, Moscow, Idaho, USA
Uldis Silins, University of Alberta, Alberta, Canada
Antonio Ferreira, Escola Superior Agrária de Coimbra, Coimbra, Portugal
Jacob Keizer, Universidade de Aveiro, Aveiro, Portugal
Gary Sheridan, University of Melbourne, Melbourne, Australia
Charlie Luce, U.S. Forest Service, Boise, Idaho, USA

Topic #5. Soil and sediment: Erosion and transport

Sue Cannon, U.S. Geological Survey, Golden, Colorado, USA
Lea Wittenberg, University of Haifa, Haifa, Israel
Erkan Istanbulluoglu, University of Washington, Seattle, Washington, USA
Antonio Ferreira, Escola Superior Agrária de Coimbra, Coimbra, Portugal
Susana Bautista, University of Alicante, Alicante, Spain

Young Career Scientist Committee

Brian Ebel, Visiting Fellow, University of Colorado, Boulder , Colorado., USA
Cathelijne Stoof, Post-doctoral associate, Cornell University, Ithaca, New York, USA.
Petter Nyman, University of Melbourne, Melbourne, Australia.
Merche Bodí, University Miguel Hernandez, Alicante, Spain.
Joseph Wagenbrenner, PhD student, Washington State University, Pullman, Washington Rocky Mountain Research Station, Moscow, Idaho, USA.

Acknowledgments

This Chapman Conference was supported by:

Updated:

6 Aug. 2013

Post-wildfire Chapman Conference Program

2013	Sunday 25-Aug	Monday 26-Aug	Tuesday 27-Aug	Wednesday 28-Aug	Thursday 29-Aug	Friday 30-Aug
0750--0800		Welcome & Field Trip Intro	Introduction	Introduction	Introduction	Introduction
0800-0820			*Summary for Topic #1*	*Summary for Topic #2*	*Summary for Topic #3*	*Summary for Topic #4*
0820-0840		Half-day field trip				
0840--0900			**Brian Ebel**	**Cathelijne Stoof**	**Joe Wagenbrenner**	**Gary Sheridan**
0900--0920			**Gabriel Sidman**	**Merche Bodí**	**Kevin Hyde**	
0920--0940			**Dave Gochis**	**Stefan Doerr**	**Jason Williams**	**Jason Kean**
0940--1000		Front Range Post-wildfire Response Domains				
1000--1020			Poster BREAK	Poster BREAK	Poster BREAK	Poster BREAK
1020--1040						
1040--1100			**David Dunkerley**	**Vicki Balfour**	**Ryan Bart**	**Naama Tessler**
1100--1120				**Karletta Chief**	**Dave Goodrich**	**Peter Jordan**
1120--1140			**Ana Barros**			
1140--1200				**Li Chen**	**Sim Reaney**	**Roman DiBiase**
1200--1220		Box Lunch	Box Lunch			
1220--1240	Travel & Registra-tion			LUNCH	LUNCH	LUNCH
1240--1300						
1300--1320		**Set up posters**	Half-day field trip			
1320--1340	and			Measure Soil Hydraulic Properties onsite	**Petter Nyman**	**Erkan Istanbullouglu**
1340--1400		**Deborah Martin**	National Center for Atmospheric Research NCAR Boulder, Colorado		**Christoph Langhans**	
1400--1420	Young Career Scientist Activity	**Sue Cannon**			**Rene Van der Sant**	Poster BREAK
1420--1440		**Grant Meyer**			Poster BREAK	
1440--1500		**Ann Youberg**				
1500--1520		Poster BREAK			**Cristina Santin**	**Take down posters**
1520--1540					**Dennis Staley**	*Summary for Topic #5*
1540--1600		**Uldis Silins**	Coupling Atmospheric-Wildland Fire Modeling			
1600--1620		**Dave Scott**		Meeting of Young Career Scientists	Meeting of Working Groups	Meeting of Working Groups
1620--1640		**Tom Veblen**				
1640--1700		**Susana Bautista**				
1700-1800		OPEN		Working Groups	Working Groups	Working Groups
1800-1930	Aspen Dining Hall	Group Dinner in Walnut Room **Rick Shakesby**	Aspen Dining Hall	Aspen Dining Hall	Aspen Dining Hall	Banquet in Walnut Room **Pete Robichaud**

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 1	Morning		
26 August	0750-0820	**General Welcome Meeting**	***Teddy's Teeth Room Ground Floor Ramshorn Lodge***
Monday	0820-1300	**Field Trip: Local Post-wildfire Response Domains**	
Day 1	Afternoon	**Topic #1: Post-wildfire Response Domains**	
Monday	1300-1340	**Set up Posters**	**Lily Lake Room Ramshorn Lodge**
	1340-1400	**Deborah Martin** **US Geological Survey**	
	1400-1420	**Sue Cannon** **US Geological Survey**	**Hydro-geomorphic Responses to Wildfire in southern California**
	1420-1440	**Grant Meyer** **University of New Mexico**	**Postfire response domains and the relative Importance of post-wildfire erosion in the USA Rocky Mountains**
	1440-1500	**Ann Youberg** **Arizona Geological Survey**	**Hydrologic and geomorphic responses of burned basins in the southwestern U.S.**
	1500-1540	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1540-1600	**Uldis Silins** **University of Alberta**	**High latitude post-fire response domains: Boreal, Tiaga, and Arctic**
	1600-1620	**Dave Scott** **University of British Columbia**	**The hydrologic and erosion response to wildfire in humid watersheds in the winter and summer rainfall regime areas of South Africa**
	1620-1640	**Tom Veblen** **University of Colorado**	**Post-wildfire response domains in the Patagonian-Andean region of Chile and Argentina**
	1640-1700	**Susana Bautista** **University of Alicante**	**The Mediterranean domain: the land of fire recurrence**
	1700-1800	**OPEN**	
	1800-1930	**Group Dinner in Walnut Room**	
	1830-1900	**Plenary Speaker** **Rick Shakesby** **Swansea University**	**Twenty-five years of wildfire experience and questioning "established truths"**

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 2	Morning	**Topic #2: Precipitation**	
27 August	0750-0800	**Introduction**	***Teddy's Teeth Room Ground Floor Ramshorn Lodge***
Tuesday	0800-0840	**Deborah Martin** **US Geological Survey**	**Summary session for Topic #1** **Post-wildfire Respons Domains**
	0840-0900	**Brian Ebel** **University of Colorado**	**What's the Difference: A Novel Method For Connecting Precipitation and Infiltration**
	0900-0920	**Gabriel Sidman** **University of Arizona**	**The effects of varying rainfall representations of post-fire runoff resonse in the KINEROS2/AGWA model**
	0920-1000	**Dave Gochis** **National Center for Atmospheric Research**	**Factors leading to heavy precipitation during the warm season in complex terrain**
	1000-1040	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1040-1120	**David Dunkerley** **Monash University**	**How do the spatial scale and temporal patterns of precipitation influence hydrologic response?**
	1120-1200	**Ana Barros** **Duke University**	**On the Space-Time Organization of Precipitation and Hydrologic Response in Mountainous Regions - Examining Opportunities for Improving the Predictability of Post-wildfire Floods and Debris Flows**
Day 2	Afternoon		
	1200-1800	**Field trip: National Center for Atmosphic Research--Wildfire Models driven by the Atmosphere--Janice Coen**	
	1800-1930	Dinner	Aspen Dining Hall

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 3	Morning	**Topic #3: Infiltration**	
28 August	0750-0800	**Introduction**	***Teddy's Teeth Room Ground Floor Ramshorn Lodge***
Wed-	0800-0840	**John Moody**	**Summary session for Topic #2**
nesday		**US Geological Survey**	**Precipitation**
	0840-0900	**Cathelijne Stoof** **Cornell University**	**Can pore-clogging by ash explain post-fire runoff and erosion?**
	0900-0920	**Merche Bodí** **University of Valencia**	**Effects of Ash on infiltration**
	0920-1000	**Stefan Doerr** **Swansea University**	**Water repellency and soil hydraulic properties**
	1000-1040	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1040-1100	**Vicki Balfour** **University of Montana**	**The evolution of wildfire ash and implications for post-fire infiltration**
	1100-1140	**Karletta Chief** **University of Arizona**	**Change in soil structure and Hydraulic properties in a wooded-shrubland ecosystem following a prescribed fire**
	1140-1220	**Li Chen** **Desert Research Institute**	**Modeling post-wildfire rainfall-infiltration-runoff: current state, challenges, and some new approaches**
	1220-1320	**LUNCH**	**Aspen Dining Hall**
	1320-1600	**Measure soil hydraulic properties on site**	
	1600-1700	**Meeting of Young Career Scientists**	
	1700-1800	**OPEN**	**Meeting of Working Groups**
	1800-1930	Dinner	Aspen Dining Hall

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 4	Morning	**Topic #4: Runoff**	
29 August	0750-0800	**Introduction**	***Teddy's Teeth Room Ground Floor Ramshorn Lodge***
Thursday	0800-0840	**Rick Shakesby** **Swansea University**	**Summary session for Topic #3** **Infiltration**
	0840-0900	**Joe Wagenbrenner** **US Forest Service**	**Changes in runoff following wildfire in eastern Arizona**
	0900-0920	**Kevin Hyde** **University of Montana**	**Vegetation as a first-order control on post-wildfire erosion: A cross-scale study integrating field and satellite data**
	0920-1000	**Jason WIlliams** **US Agriculture Research Ser.**	**Significance of connectivity and post-wildfire runoff**
	1000-1040	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1040-1100	**Ryan Bart** **San Diego State University**	**A mixed modeling approach for combining post-wildfire streamflow and erosion change results**
	1100-1140	**Dave Goodrich** **ARS Tucson, Arizona**	**Determining contributing area for post-wildfire runoff and how it changes with rainfall characteristics**
	1140-1220	**Sim Reany** **Durham University**	**Physical causes of rainfall threshold and connectivity for post-wildfire runoff**
	1220-1320	**LUNCH**	**Aspen Dining Hall**
Day 4	Afternoon	**Topic #5: Soil and Sediment Erosion and Transport--part 1**	
29 August	1320-1340	**Petter Nyman** **Melbourne University**	**Modeling wildfire effects on sediment availability on hillslopes**
Thursday	1340-1400	**Christoph Langhans** **Melbourne University**	**Modelling the distribution of sediment loads from post-wildfire debris flows in SE Australia**
	1400-1420	**René Van der Sant** **University of Melbourne**	**Wildfires are the key to unlocking sediment stored in channels**
	1420-1500	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1500-1520	**Cristina Santin** **Swansea University**	**The organic component in post-wildfire sediments: Erodibility, transport and implications for the global carbon cycle**
	1520-1600	**Dennis Staley** **US Geological Survey**	**Characterizing the primary material sources and dominant erosional processes for post-wildfire debris-flow initiation in a headwater basin using multi-temporal terrestrial laser scanning data**
	1600-1700	**OPEN**	**Meeting of Working Groups**
	1700-1800	**OPEN**	**Meeting of Working Groups**
	1800-1930	Dinner	Aspen Dining Hall

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 5	Morning	**Topic #5: Soil and Sediment Erosion and Transport--part 2**	
30 August	0750-0800	**Introduction**	***Teddy's Teeth Room Ground Floor Ramshorn Lodge***
Friday	0800-0840	**Pete Robichaud** **US Forest Service**	**Summary session for Topic #4** **Runoff**
	0840-0920	**Gary Sheridan** **Melbourne University**	**Post-wildfire soil erodibility**
	0920-1000	**Jason Kean** **US Geological Survey**	**How does post-wildfire runoff become a debris flow? Insights from observations and modeling of debris-flow surge initiation, magnitude, and frequency**
	1000-1040	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1040-1100	**Naama Tessler** **University of Haifa**	**Changes in flow characteristics in burnt areas after forest management**
	1100-1140	**Peter Jordan** **BC Ministry of Forest**	**Post-wildfire debris flows in southern British Columbia**
	1140-1220	**Roman DiBiase** **Calif. Institute of Technology**	**Quantifying sediment storage by vegetation in steep bedrock landscapes: Implications for post-wildfire sediment yield**
	1220-1320	**LUNCH**	**Aspen Dining Hall**
	1320-1400	**Erkan Istanbulluoglu** **University of Washington**	**Modeling post-wildfire sediment supply**
	1400-1500	**POSTER BREAK**	**Lily Lake Room Ramshorn Lodge**
	1500-1520		**Take down posters**
	1520-1600	**Sue Cannon** **US Geological Survey**	**Summary session for Topic #5** **Soil and Sediment Erosion and Transport**
	1600-1700	**OPEN**	**Meeting of Working Groups**
	1700-1800	**OPEN**	**Meeting of Working Groups**
	1800-1930	**Banquet in Walnut Room**	
	1830-1900	**Banquet Speaker** **Pete Robichaud** **US Forest Service**	**What cool ideas I learned this week that could be incorporated into post-wildfire models**
	1900-1930	**Awards**	

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
Day 6 31 August Saturday	Morning	**Departures and possible post-conference field trips**	

INVITED POSTERS

Artemi Cerdà **University of Valencia**	**Long-term monitoring of infiltration rates during post-wildfire period in eastern Spain**
Antonio Ferreira **ESAC, Coimbra, Portugal**	**How do plantation forests change post-wildfire runoff and erosion**
Charlie Luce **US Forest Service**	**Scaling of post-wildfire debris flows: Relationships to aquatic ecology and atmospheric processes**
Lee MacDonald **Colorado State University**	**Causes of post-wildfire runoff and surface erosion: What we know and what should we do?**
Lea Wittenberg **University of Haifa**	**Modeling short and long term water repellency effects on post-wildfire infiltration and runoff**

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	

CONTRIBUTED POSTERS

Jordan Adams Tulane University	Synthesizing terrestrial LiDAR and rainfall-runoff models to explore sediment transport controls in a burned watershed in Arizona, USA
Garrett Altmann University of Alaska, Fairbanks	Surface water dynamics of shallow lakes following wildfire in Alaska's boreal forests
Erica Bigio University of Arizona	The variability in historic fire regimes over the late Holocene for a site in the southwestern Colorado, USA
Daniel Brogan Colorado State University	Erosion, deposition, and stream channel response after the 2012 High Park Fire
Bill Elliot US Forest Service	Using fire and erosion tools to predict wildfire risk and sediment yield
Charles Ichoku National Atmospheric and Space Agency	Biomass burning in northern sub-Saharan Africa and its potential impact on surface water dynamics
Dan Malkinson University of Haifa	An idealized model of plant and soil dynamics
Randy McKinley US Geological Survey	Wildfire burn severity assessments fromsatellite data: A review of available products and user considerations
Mary Ellen Miller Michigan Tech.	Rapid response tools and datasets for post-fire erosion modeling: Lessons learned from the Rock House and High Park Fires
Caitlin Orem University of Arizona	Using airborne and terrestrial LiDAR to quantify and monitor post-fire erosion following the Las Conchas fire, Jemez Mountains, New Mexico
Sandra Ryan US Forest Service	Tracking post-wild fire changes in instream sedimentation, channel dynamics, and large wood loading

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	
		Francis Rengers University of Colorado	Monitoring the Spatial Distribution of Wildfire Erosion Processes
		Karin Riley University of Montana	Drivers of debris-laden flow volume: the role of fire severity and basin topography
		Sarah Schmeer Colorado State University	Post-wildfire erosion response and recovery, High Park fire, Colorado
		Scott Shahverdian Colorado State University	Mechanisms and controls on post-High Park fire sediment delivery in the South Fork Cache la Poudre Basin: Preliminary Results
		Brian Sheppard University of Arizona	Effect of wildland fire on runoff and erosion in semi-arid rangelands
		Rose Shillito Desert Research Institute	Hydrophobicity following wildfire on an arid, alluvial soil
		Gabriel Sidman University of Arizona	Modeling the effect of fuel treatments on post-wildfire runoff and erosion: A case study at Zion National Park
		Victoria Stempniewicz Northern Arizona University	Use of sediment derived paleoflood records to analyze prehistoric depositional characteristics of a fire-susceptible forested watershed
		Micheal Stone University of Waterloo	Biological modification of sediment transport processes in wildfire impacted river systems
		Diana Vieira University of Aveiro	Strengths and weaknesses of the revised Morgan-Morgan-Finney model in predicting post-wildfire erosion
		Pete Wohlgemuth US Forest Service	Hillslope erosion and small watershed sediment yield before and after a wildfire in southern California
		Dave Young US Forest Service	Erosion and sedimentation in the 2012 Bagley fire, eastern Klamath Mountains, northern California, USA
		Ahmed Zegrar University of Oran	Analysis of forest fires impact in semi-arid zones and identification of deseritication process in Algeria

AGU Chapman Conference
Post-wildfire Runoff and Erosion Response
Schedule of Talks and Posters: 25-31 August 2013

updated: 6 August 2013

Day	Time	Speaker	Title of Presentation
		Invited Talk	
		Contributed Talk	

DEMO POSTERS

Bill Elliot US Forest Service	ERMiT and WEPP Technology
Brian Sheppard University of Arizona	Automated geospatial watershed assessment tool (AGWA): Developing model parameters using precipitation and runoff records from gauged watersheds
Gabriel Sidman University of Arizona	Automated geospatial watershed assessment tool (AGWA) Computer demonstration of applications for fire management and rapid post-fire watershed assessment

Synthesizing Terrestrial LiDAR and Rainfall-Runoff Models to Explore Sediment Transport Controls in a Burned Watershed in Arizona, USA

Jordan M. Adams, Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA, jadams15@tulane.edu

Nicole M. Gasparini, Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA, USA, ngaspari@tulane.edu

Stephen DeLong, United States Geological Survey, Menlo Park, CA, USA, sdelong@usgs.gov

Ann Youberg, Arizona Geological Survey, Tucson, AZ, USA, ann.youberg@azgs.az.gov

After wildfire, many landscapes experience short-term, but rapid, geomorphic changes due to increased sediment transport rates. These higher rates are a result of dramatically more intense fluvial and hillslope processes than those prior to wildfire. Reduced infiltration, vegetation removal and loss of surface sediment cohesion are some of several factors that drive heightened susceptibility to erosion following wildfire. Numerical models that are currently used to predict landscape response to wildfire often poorly predict post-fire runoff and erosion because they are empirical and difficult to calibrate. Improvements to current models and subsequent development of new models can help predict events that cause extensive property damage and put lives at risk. In 2011, the Horseshoe 2 Fire burned several thousand hectares of land in southeastern Arizona. Immediately post-fire, terrestrial LiDAR surveys were taken across a 2.7 ha area of small watershed in the Chiricahua Mountains. Four repeat surveys were also taken over the following eight months, offering a unique opportunity to identify the spatial distribution of areas and volumes of erosion and deposition during four time periods. Post-processing of these three-dimensional point clouds removed vegetation and downed tree limbs, providing high accuracy 5 cm digital elevation models (DEMs). By utilizing these DEMs and 2 mm tipping-bucket precipitation gauge data in the HEC-HMS rainfall-runoff model, processes that drive erosion post-fire can be examined.

In this case, the first rain storm to cause significant erosion after the wildfire on July 11th, 2011, with 54.4 mm falling in 1.63 hours (I_{30} = 72.4 mm, 5-yr return interval). LiDAR analysis immediately before and after this storm showed 669 m^3 of material moved down the hillslopes and through the surveyed channels. Figure 1 shows the topographic change that occurred throughout the watershed as a result of erosion. Physical parameters such as percent imperviousness, and process methods used in the model, such as the kinematic wave or Muskingum flow routing methods, are explored to understand how they affect runoff production, fluvial discharge and the magnitude and patterns of sediment transport across the area. Discharge values generated in HEC-HMS drive the one-dimensional sediment transport model HEC-RAS. HEC-RAS uses flow properties to calculate sediment flux throughout a stream network and updates channel geometry based on the Exner equation. Model runs are repeated under different conditions in an attempt to recreate the sediment transport patterns observed in the DEMs. For example, the effects of percent imperviousness on sediment

transport are highlighted by systematically increasing the percent imperviousness of the watershed. By quantifying the impacts of different parameters and processes on the pattern and magnitude of post-fire erosion, future post-wildfire erosion events can be better predicted. Further, these results could be used in the development of more robust post-fire runoff models that could eventually be used to better understand the different processes driving burned and unburned erosion events, or extrapolated to simulate long-term geomorphic change driven by post-wildfire transport processes.

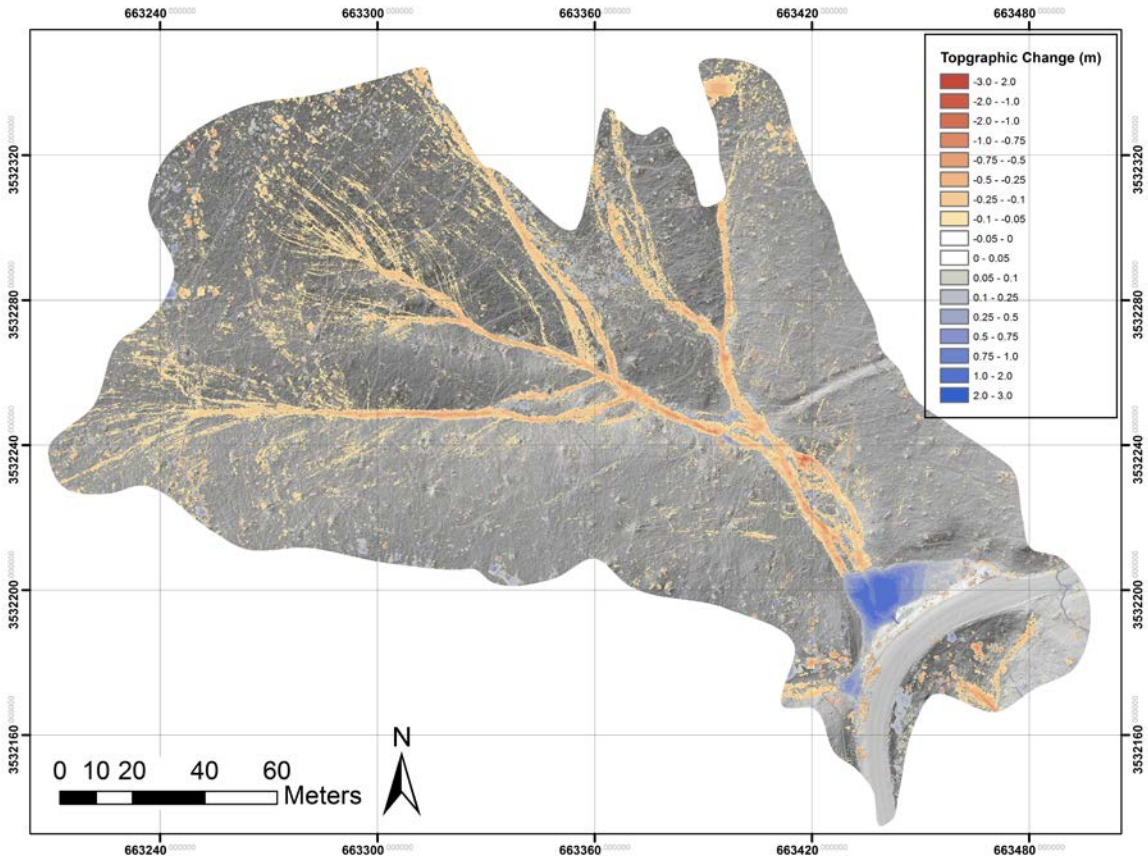

Figure 1: Topographic change between June 21, 2011 and July 19, 2011. The first significant rainfall event after the Horseshoe 2 fire occurred on July 11, 2011. This analysis shows significant deposition in the basin and erosion throughout the stream network.

Surface Water Dynamics of Shallow Lakes Following Wildfire in Alaska's Boreal Forests

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John H. Fox, Department of Natural Resources and Agricultural Sciences, University of Alaska Fairbanks, Fairbanks, AK, USA, jdfox@alaska.edu

Kenji Yoshikawa, Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK, USA, kyoshikawa@alaska.edu

Wildfire is ubiquitous in interior Alaska, and is the primary disturbance regime affecting thawing permafrost and ecosystem processes in boreal forests. An average area of ~400,000 hectares burns annually in Alaska and 96% of these wildfires are in the interior portion of the state. This region is associated with discontinuous permafrost, and wildfire has a profound effect on the insulating vegetation that regulates the thickness of the seasonally thawing active layer located above the permafrost. Since surface and near-surface hydrology is strongly affected by permafrost, changes in the active layer thickness and permafrost extent may mark a distinct change of character in surface hydrology. An increase in the depth of the active layer and subsequent permafrost thaw may result in the drainage of small lakes as unfrozen patches of ground, known as talik, create lateral and vertical drainage pathways. Soils can also develop a characteristic of water repellency following wildfire, which can reduce infiltration capacities by increasing the hydrophobicity of feather-moss derived organic matter. As a consequence, water may not penetrate readily, and accelerated overland flow will result in increased stream flow, erosion, and ponding. We hypothesized that wildfire disturbance resulting in the removal of insulating vegetation down to bare mineral soil will facilitate the lake area expansion in the first 1-2 years following wildfire due to increased overland flow, while shrinking and drying of boreal lakes through talik drainage will occur in the longer term (> 3 years) as the active layer deepens, subsequently breaching permafrost.

In this study, we used remote sensing (Landsat TM/ETM+) and GIS to examine lake dynamics following wildfire in four sub-regions of Interior Alaska. Our study sites were selected based on their association with abundant lakes, discontinuous permafrost, low relief, previous lake studies, and historical wildfire incidence between 1950 and 2010. Surface

hydrology in boreal Alaska is characterized by several large, braided rivers, streams, lakes, ponds, fens, and bogs occurring throughout the region. The continental climate of Interior Alaska is strongly influenced by the orographic effects of the bounding Brooks Range to the north and Alaska Range to the south, which result in semi-arid conditions with annual precipitation rates ranging from < 200 mm to > 500 mm. The two-year, 30-minute maximum precipitation intensity for Fairbanks, a site representative of boreal Alaska, is 13.1 mm h^{-1}. Surface geology in these four study areas consists of alluvial or lacustrine plains mostly derived from glacial sediment, featuring a soil erodibility K-factor of 0.37 to 0.43 t-ha-h/ha-MJ-mm. Our analysis was constrained to nearly level areas with slope gradients of less than 0.05. Vegetation community throughout this region is controlled by aspect, elevation, soil type, soil moisture, permafrost, and succession stage following disturbance. These factors result in a mosaic of black spruce forests, birch and aspen woodlands, sedge meadows, and grasslands persisting throughout boreal Alaska, with an average fire return interval of 198 years for black spruce forests.

Changes in the post-wildfire lake area were examined in the short-term (0-5 years), mid-term (5-10 years), and long term (> 10 years) periods from 1984-2010. The relation between lake area change and burn severity as a function of radiant surface temperature was also explored. Using Landsat band 6 (thermal IR), we were able to calculate radiant surface temperature and identify areas most severely impacted by wildfire. Despite these observations, we found that thermal IR is difficult to be used as a strong indicator of burn severity due to the acquisition time being subject to wide ranging daily and seasonal temperatures that affect radiant surface emissivity.

Results indicate that disturbance from wildfire has the most profound effect on lake area changes during the short-term (0-5 years) period following wildfire, with the majority of lake area differences displaying increases in size within the first two years following a wildfire. No significant effect from wildfire was detected during the mid-term (5-10 years) period, while long-term (>10 years) differences in mean lake areas between burn and control groups resulted in stabilization and/or decreases consistent with other long-term lake studies. Burn severity had the greatest effect within the two years after fire; with radiant temperature increases in burn areas of 3˚-7˚C measured during this period. As vegetation re-established in burn areas, radiant temperature differences between burn and control areas were less than 1˚C. Lake area increases displayed positive correlations with radiant temperature increases within the first five years following wildfire, while there was no correlation between radiant temperature change and decreasing lake area changes during this same period. These findings negated our initial hypothesis that severe wildfires would facilitate lake drainage through removal of insulating vegetation, deepening of the active layer, and increased drainage of taliks.

The Evolution of Wildfire Ash and Implications for Post-fire Infiltration

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Changes in the properties of an ash layer with time may affect the amount of post-fire runoff, particularly by the formation of surface crusts. The formation of depositional crusts by ash has been observed at the pore- and plot-scale, but the causes and temporal evolution of ash layers and the associated crusts have not yet been thoroughly investigated. In particular, it is uncertain whether crust formation due to mineralogical transformations and associated crystal growth within the ash is caused by exposure of the ash to air, or whether rainfall is necessary to wet the ash. Increases in the density of the ash as it collapses under its own weight, compaction by raindrops, and chemical transformations within the ash may increase the potential for forming an ash crust and the associated decrease in infiltration. Furthermore, the rate and causes of the temporal evolution of the ash layer is largely unknown. Over the longer-term, however, ash crusting effects will decrease as the ash layer is removed by wind and water erosion, while in the short-term ash crusting can contribute to the observed changes in post-fire runoff.

This study addresses these topics by studying the evolution over time of highly combusted ash layers from two wildfires in the Northern Rockies. More specifically, this research is designed to assess the potential for ash crusts to form and thereby contribute to the observed decreases in infiltration after forest fires. Nine sites were established in two Montana wildfires that burned at high severity in 2011, and these were the Avalanche-Butte and West Riverside fires. The study sites had similar tree canopies and hence are presumed to have had similar amounts of mixed pine fuels prior to burning. Three plots were established in each site to track the evolution of ash properties over time with different exposure to rainfall. The control plot was exposed to natural rainfall, the second plot was completely sheltered from rainfall by a canopy, and the third plot was exposed to rainfall but protected from raindrop impact by covering the ash surface with a fine mesh screen. The ash layer in each plot was sampled weekly over a two-month period, and the data collected for the ash layer included color, thickness, bulk density, infiltration, and water repellency. Soil water repellency and surface ground cover were also measured each week. Weekly ash samples were taken and analyzed for particle size, particle density, and porosity. X-ray diffraction analysis was used to identify the minerals within the ash samples and changes in ash composition associated with hydration. This design allowed us to distinguish the effects of natural rainfall on ash properties and ash crust formation as compared to rainfall with minimal raindrop impact, and the exposure of the ash layer to moist air but no rainfall.

Preliminary results indicate that high-combustion ash can evolve due to post-fire rainfall. Sites that exhibited a visible ash crust (natural and screen) also displayed a significant decrease in effective porosity, bulk density, and hydraulic conductivity. These decreases in ash layer characteristics were attributed to raindrop compaction and ash

hydration resulting in the formation of carbonate crystals, which decreased effective porosity and flow within the ash layer. The initial effective porosity was high for all plots with values of 86 % ± 5, 86 % ± 2 and 87 % ± 3 for natural, cover and screen respectively. An order of magnitude decrease was documented within natural and screen plots following the first post-fire rainfall event; 73 % ± 5 and 71 % ± 4. Further decreases in porosity over time were not recorded in natural and screen plots after this initial decrease. Covered plots did not exhibit significant changes in effective porosity throughout the course of the study. The mean initial hydraulic conductivity was 830 ± 500, 610 ± 220 and 760 ± 250 mm h^{-1} for natural, cover and screen plots respectively. Following the first rainfall event hydraulic conductivity within natural and screen plots decreased an order of magnitude, from 360 mm h^{-1} to 36 mm h^{-1}, while cover plots indicated no significant change. During this same time period, inorganic carbon content more than doubled from 11 to 26% and bulk density significantly increased from 0.22 to 0.39 g cm^{-3} within natural and screen plots.

While raindrop impact increased the robustness of the ash crust, mineralogical transformations must occur to produce a hydrologically relevant ash crust. These preliminary results indicate that post-fire rainfall is an important control on the properties of the ash layer after burning and on crust formation. The observed changes over time mean that the timing of sampling can affect whether the ash layer is affecting post-fire infiltration and runoff. The formation of post-fire ash crusts could prove beneficial to post-fire hazard mitigation by stabilizing the ash layer, reducing aeolian mixing and erosion.

On the Space-Time Organization of Precipitation and Hydrologic Response in Mountainous Regions - Examining Opportunities for Improving the Predictability of Post-wildfire Floods and Debris Flows

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Topography strongly modulates the hydrometeorology of mountainous regions over a large envelope of spatial and temporal scales including isolated heavy rainfall from convective systems in headwater catchments to the diurnal cycle at the river basin scale. In turn, the spatial and temporal organization of rainfall drives the hydrologic response at the event scale. For small basins (catchments < 1,000 km^2) rainfall-runoff response is further modulated by basin geomorphology, and soil, and land-use and land-cover heterogeneities. Whereas land-surface attributes such as topography and soil hydraulic properties are typically considered temporally stationary, this is not the case in mountainous regions with landslide and debris flow activity and, or where wildfires change the soil composition and hydraulic properties and land-cover, and consequently rainfall-runoff response (e.g. Moody et al. 2013).

In the way of a preamble, we first review here the principal modes of space-time organization of orographic precipitation systems for mountains around the world, and examine the fingerprints of orographic land-atmosphere feedbacks on the spatial patterns of regional hydroclimate, landform and land-cover (e.g. Barros, 2013). Next, we present recent process studies using a high resolution hydrologic model (3D-LSHM) to simulate and forecast flashfloods and debris flows in the Southern Appalachians (Tao and Barros 2013a and 2013b) forced by Quantitative Precipitation Estimates (QPE) and Quantitative Precipitation Forecasts (QPF). Finally, we implement postwildfire changes in model parameters and ancillary data based on Ebel et al. (2012) including transient spatial patterns of ash deposits using recent rainfall erosivity estimates as well as model simulated overland flow to examine changes in hydrologic response at different time-scales and for different storm regimes.

The 3D-LSHM was originally developed as column model for investigating land-atmosphere interactions in the context of hydroclimatology studies at spatial resolution of 1-25 km^2 (Devonec and Barros, 2002; Yildiz, 2001; Yildiz and Barros, 2007; Yildiz and Barros, 2009), and has evolved over the years into a spatially distributed hydrologic model solving the coupled water and energy balance equations including coupled surface-subsurface interactions at very high spatial resolution (250×250 m^2). The 3D-LSHM consists of three coupled modules: a vertical Land Surface Hydrology Model (LSHM), a two-dimensional Surface Flow Routing Model (SFRM), and a two-dimensional Lateral Subsurface Flow Routing Model (LSFRM). There is no explicit interaction between the local and regional groundwater systems (closed basin assumption). At each location, the vertical soil column consists of both an unsaturated zone and a conditionally saturated zone. The unsaturated zone is discretized into three layers, of which the 1st layer is the superficial soil

zone at the land–atmosphere interface, the 2nd and 3rd layers are root layers. Distributed overland flow is estimated either from rainfall excess (Horton) mechanism or saturation excess (Dunne) mechanism for each grid element at each time step and subsequently routed by the SFRM, which relies on a one-dimensional kinematic wave approximation along the down-slope direction, assuming a linear flow surface across grid cells (Yildiz and Barros, 2007). The Muskingum-Cunge method of variable parameters is utilized for the channel routing without significant backwater effects, and subsurface flow, comprising interflow and baseflow, is then laterally routed by the LSFRM. A multi-cell approach is adopted and modified for subsurface flow routing. Soil parameters (i.e. saturated hydraulic conductivity K_{sat}, porosity ϕ, field capacity θ_{fc} and wilting point θ_{wp}) are extracted from existing databases (e.g. STATSGO) database for each location and vegetation parameters are extracted frome remote sensing products (e.g. MODIS).

Rainfall forcing from the National Severe Storms Laboratory Next Generation Multi-sensor QPE (Q2) spatial rainfall ($1\times1 km^2$) product and from the operational QPF product from the National Weather Service National Digital Forecast Database (NDFD, 5×5 km^2) were used as model forcing. QPE products are generated by optimally blending radar and raingauge observations, whereas QPF products strongly rely on NWP (Numerical Weather Prediction). Optimal QPE products (Q2+) were derived by merging Q2 with rainfall observations from a high density raingauge network in the Great Smoky Mountains (GSMRGN) and subsequently used as "rainfall truth" to characterize operational QPF errors, and QFEs in three headwater catchments with different topographic and hydro-geomorphic characteristics. Deterministic QFE results agree well with observations regarding both total water volume and peak flow indicating that the distributed model without calibration captures well the dominant physical processes when the rainfall forcing is optimal. The impact of Q2+ uncertainty with regard to the space-time structure of storm rainfall was subsequently evaluated through Monte Carlo replicates of the QPEs to generate QFE distributions. A critical result of this study was to characterize the rapid and large interflow response during flashfloods under pre-wildfire conditions, and its sensitivity to uncertainty in space-time rainfall structure used as forcing. There are two key aspects of this uncertainty that are particularly relevant here: first, the quality of the measurements or model forecasts; second, the need to integrate and downscale observations and model forecasts to the required very high spatial resolution and short time scales. A discussion of alternative physically-based and statistical downscaling techniques will be presented.

Because debris flows associated with rainstorms are a frequent and devastating hazard in the Southern Appalachians, the model was used to study the hydrologic conditions associated with three recent events in two vulnerable headwater catchments that experience frequent debris flows, the Big Creek Basin and the Jonathan Creek Basin in the Upper Pigeon River Basin, North Carolina: an extremely heavy summertime convective storm in 2011; a persistent winter storm lasting several days; and a severe winter storm in 2009. These events were selected due to the optimal availability of rainfall observations, availability of detailed field surveys of the landslides shortly after they occurred, which can be used to evaluate model predictions, and because they are representative of events that cause major economic losses in the region. The model results substantiate that independently of the hydrometeorological regime, interflow is a useful prognostic of conditions necessary for the

initiation of slope instability, and should therefore be considered explicitly in landslide hazard assessments. Moreover, the relation between slope stability and interflow are strongly modulated by the topography and catchment specific geomorphologic features that determine subsurface flow convergence zones, which are the iniation points.

Following the hydrologic impacts framework provided by Ebel et. al (2012), we subsequently proceed to simulating synthetic post-wildfire conditions by changing soil vertical structure through the addition of an ash layer, and by changing vegetation characteristics, specifically vegetation density, leaf area index, and areal vegetation fraction. In order to simulate the transient evolution of the surface ash layer, and specifically its spatial patterns, recent estimates of rainfall erosivity derived from disdrometer data (Angulo-Martinez and Barros, in preparation), and a simple model of sediment mobility by overland flow were introduced in the model. The flash-flood and debris flow case-studies were repeated for post-wildfire conditions and a detailed analysis of changes in hydrologic processes is conducted focusing on feedbacks between changes in spatial and temporal patterns of interflow and overland flow. Results will be synthesized aiming at providing physical insight into the physical basis for the observed post-wildfire rainfall-runoff response, including the dependence on rainfall intensity above a threshold and catchment recovery (reduction of the ash layer depth and spatial extent, and vegettaion recovery).

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A Mixed Modeling Approach for Combining Post-wildfire Streamflow and Erosion Change Results

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Numerous studies have examined the effect of wildfire on streamflow and erosion. However, as each study is unique with different physiographic properties, meteorological conditions, vegetation types, and fire characteristics; streamflow and erosion responses are only representative of the specific location and conditions that produced the response. There is a need to statistically combine the empirical results from multiple watershed studies in order to make generalizations about the effect of wildfire on streamflow and erosion and identify watershed variables that may affect post-fire response. This understanding may be used to help predict future responses to wildfire in both gauged and ungauged watersheds. In this paper, a new technique, mixed modeling, is introduced for combining the results of individual post-fire studies. Mixed modeling is a statistical approach that is similar to regression analysis, but includes random effects, which allow inferences to be drawn about a hypothetical population of studies from which the observed studies are sampled. Mixed models are particularly useful for modeling data that is organized at more than one level (e.g. runoff events nested within watersheds) and can account for runoff events being more correlated within watersheds than between watersheds. Using post-fire changes in total annual streamflow as an example, I demonstrate how a mixed model can be used to combine the results of six paired-watershed studies in central California in order to produce a regional estimate of post-fire change. In addition, I show how mixed models may be applied to quantitatively combine the results of previously published post-fire change studies. This latter application, which is termed meta-analysis, exploits the numerous post-fire change studies in the literature to potentially produce a more powerful estimate of the true effect of wildfire on streamflow and erosion than any study alone can produce. Finally, some of the challenges with the application of mixed modeling for post-fire streamflow and erosion change studies are described.

The Mediterranean Domain: the Land of Fire Recurrence

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Wildfire is a common and natural disturbance in Mediterranean regions worldwide, where they have burned for millennia. As a consequence, many plants have acquired adaptive mechanisms to persist and regenerate after wildfires, contributing to the reduction in the recovery time required for post-wildfire soil protection. In addition, wildfire is a primary factor promoting flammable ecosystems deviating from the physiognomy that could be expected according to the climate of the region. Thus, vast areas of Mediterranean shrublands have the potential to be forest, but frequent wildfires are largely responsible for maintaining the dominance of shrubs. The dominant natural ecosystems in the Mediterranean Basin (oak forest and shrublands) share some qualities common to other Mediterranean regions: they are highly resilient to fire and are able to cope with the natural high fire-recurrence regimes observed in these areas. However, one of the most relevant differences between the Mediterranean Basin and other Mediterranean regions in the world is the millenary impact of intense land use, including burning, woodland clearing, grazing, terracing, and cultivation, which has resulted in strongly human-modified landscapes with consequences for the Mediterranean fire and hydro-geomorphic regimes. On the one hand, human activities have created a heterogeneous mosaic of land uses and land cover types that are not equally fire-prone, retarding the spread of fire and resulting in relatively small areas burned by individual wildfires. On the other hand, intense land use by humans, which often included uprooting of oaks and other resprouting species, combined with frequent fires, has lead to changes in vegetation towards ecosystems dominated by seeder species. These ecosystems are in turn more susceptible to the risk of wildfire and less resilient than those dominated by non-seeder species, resulting in longer windows of disturbance, and therefore longer post-wildfire periods with soils exposed to erosive agents.

Climate in the Mediterranean Basin favors highly frequent wildfires and post-wildfire soil erosion. The intensity of the seasonal (summer) drought, particularly when it follows particularly wet winter and spring seasons - and the associated accumulation of fuel load – explains a significant proportion of the annual variability in total area burned. Precipitation falls mainly in autumn, with highly erosive rainfalls commonly falling after summer wildfires. Wildfire impact on runoff and erosion can be severe not only when erosive storms occur shortly after a wildfire, but also when a post-fire drought period inhibits vegetation recovery, so that the critical period for post-fire runoff and sedimentation may last several years after a wildfire. The erosive potential of precipitation is exacerbated by the mountainous character of a large part of the land in the Mediterranean Basin, where young mountain ranges from the Alpine orogeny dominate the landscape. Post-wildfire erosion rates (e.g., the first year after wildfire) at plot and catchment scales in the Mediterranean Basin are rarely higher than 10 Mg ha^{-1}, and very often lower than 1 Mg ha^{-1}, although values as high as 20-30 Mg ha^{-1} have been reported for some pine and mixed pine-oak forests at the plot scale. Given the low available soil depth (often less than 30 cm) and the slow soil formation rate in the Mediterranean region, these values have been considered to represent moderate to high soil loss rates.
Climate, land use, topography and frequent wildfires have jointly contributed to sustained soil losses over millennia that have led to very thin and stony soils in most of the Mediterranean forests, woodlands and shrublands. Although there is not much empirical support to unravel the relative role played by each of those factors, comparisons of

erosion rates between burned areas and overexploited rangelands in the Mediterranean Basin suggest that grazing, woodland clear-cutting and marginal agriculture have been much more important drivers of soil erosion than wildfires. In recent decades, however, the fire regime in this region is rapidly changing towards more frequent and larger wildfires. For example, in eastern Spain, average fire return interval for the 1973-2006 period was 49 years, eight times shorter than in the previous 100 years and some areas have been burnt more than six times in the last 25-30 years. Wildfire size is also increasing in the region, where average wildfire size has changed from 126 ha (1973-1972) to 535 ha (1973-2006). This change in wildfire regime has mainly resulted from rapid land-use changes (mostly agricultural land abandonment and extensive reforestation programs) that increased cover and spatial continuity of forests and shrublands in areas with former low fire hazard. Furthermore, marginal agricultural land, often located in steep, terraced slopes is the first to be abandoned, increasing the proportion of land that is particularly vulnerable to fire hydro-geomorphic impact. Every year about 50,000 forest fires occur in southern Europe, burning approximately 0.5 million hectares of rural land. In some years, these area burned figures of the entire region have been reached in one single country, such as the extensive forest fires in Spain in 1994. The current climate change trend in the Mediterranean, towards longer summer droughts and intensification of extreme events (both drought and heavy rainfalls) has set the conditions for larger impacts of wildfires.

NetMap: Information to Support Pre- and Post-wildfire Planning for Resource Managers

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Wildfire management in the western United States focuses on protecting lives, homes and other infrastructure, as well as shielding large tracts of forests from destruction. In addition, protecting aquatic habitats and municipal water supplies from wildfire impacts, including erosion and sedimentation, is becoming increasingly important. One pre fire strategy is fuel reduction, including building fire breaks at critical locations. Post fire strategies include targeted erosion control, stream habitat protection, and road maintenance and abandonment. Thus, pre and post wildfire planning could benefit greatly from ready access to tools and databases that provide geospatial information on habitats and fire related stressors across a range of disciplines (fire managers, foresters, silviculturalists, biologists, hydrologists, engineers, soil scientists, hydrologists). Spatially explicit information is particularly useful in pre fire planning and post fire (BAER) activities when it identifies areas that have the highest potential for erosion, channel sedimentation and consequent impacts to aquatic habitats and other sensitive areas, including homes and highways. Such types of information, however, are not often readily available.

Although much is known about the relations among wildfire, hillslope erosion and channel sedimentation, there are critical gaps in knowledge involving soil properties and erosion response, mesoscale rainfall characteristics and erosion timing/magnitude, and relations between sediment supply (usually large and punctuated) and sediment transport/storage in rivers (Moody et al. 2013). These research topics may require years of effort to resolve. Additionally, in some cases such knowledge may be difficult to incorporate into predictive models designed to operate at watershed to landscape scales where spatial information on soils, mesoscale rainfall patterns, and in-channel sediment transport/storage conditions will be difficult to quantify. Nevertheless, and in the interim, managers and planners require information now about how wildfires may impact watersheds with large differences in fuels, topography, climate, soils, stream network geometry and aquatic habitats, inclusive of threatened and endangered species, both in pre-fire and post fire planning modes.

To address the "information now" issue across federal and state agencies in the western U.S., Earth Systems Institute has developed 'NetMap', a suite of tools coupled to standardized digital watersheds in both ArcGIS and online formats. NetMap takes a necessarily 'coarse grained' approach that utilizes widely available spatial data on fire intensity (Flammap), burn severity (BARC maps), topography and derived river networks (DEMs), climate and simple models of erosion and sediment delivery.
NetMap allows analysts to consider how fire risk (probability and intensity) affects watershed resources and infrastructure including erosion (landslides, debris flows and surface erosion), roads, sediment delivery, channel/floodplain sedimentation, and fish habitats. The

habitat-stressor tool in NetMap, in the context of fire, incorporates habitats (aquatic, riparian, terrestrial) and stressors (fire, erosion, roads) in a matrix of cumulative frequency distributions. Managers and planners use the distributions to specify exceedance levels of interest (e.g., values of habitat quality or stressor intensity above a certain [percentile] magnitude). For example, a manager can quickly search for a habitat-stressor intersection that involves the top 5% of fire intensity (e.g., 95th percentile = 5% exceedance) and the top 5% of post fire erosion potential, and where that pair intersects the top 5% of fish habitat quality or sensitivity, even using coarse grained information. In effect, planners search for locations where wildfire-related stressor extremes overlap, singly or in combination, with the best (highest exceedance) habitats. As new research becomes available about how fires impact watersheds, it could be incorporated into NetMap and in other models, given that new understanding can be parameterized and that the necessary data to run more detailed models become available.

The Variability in Historic Fire Regimes over the Late Holocene for a Site in the Southwestern Colorado, USA

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We reconstructed wildfire regimes over the past ~ 4,000 years using a combination of tree-ring and alluvial-sediment records for an area burned by the 2002 Missionary Ridge fire in the southern Rocky Mountains. The study area is located just north of Durango, Colorado in the western San Juan Mountains, and represents a bimodal precipitation regime characteristic of the southwestern US. Average annual precipitation is 49.10 cm. The precipitation regime is dominated by winter frontal storms (60% of annual precipitation as winter snowfall) and a weak monsoon system (30% of annual moisture) brings rainfall as convective storms in the summer months. In the study area, the wildfire burned 30,000 ha in 2002, and up to 50% of the burned area was a mosaic of moderate and high-severity burned categories. During the summer following the wildfire, debris flows and sediment-laden floods were generated from several low-order tributary basins, and these were in response to convective storms of short-duration (< 2 hours) and high-frequency (16.5 mm/hour). These erosion responses exposed alluvial stratigraphy with many charcoal-rich deposits in the incised stream channels and alluvial fans of several basins.

This research focuses on seven basins (1 – 10 km^2) ranging from an elevation of 2030 m to 3000 m with ponderosa pine and mixed conifer forest cover, where we sampled alluvial-sediment deposits in the valley bottoms and alluvial fans of each basin. Charcoal-rich sediments were collected from several stratigraphic exposures in each basin, and charcoal from individual deposits was submitted for radiocarbon dating. We observed increased fire-related sedimentation between -700 and -200 BC (2700 – 2200 cal yr BP), 550 – 725 AD, 900 – 1280 AD and 1470 – 1650 AD. Sediment characteristics were used to categorize historic post-wildfire responses as streamflow, hyperconcentrated flow and debris flow, and we evaluated the relative charcoal content and quality for all deposits. We used charcoal and sediment characteristics to interpret the past wildfires as low or high-severity for each basin, and evidence of both low and high-severity wildfires was observed during each peak in sedimentation.

We also sampled fire-scarred trees and forest demography plots from adjacent hillslopes within four of the basins. The tree-ring data provide annually-resolved wildfire regime information for the past 500 years. These data indicate that low-severity surface

wildfires burned every 11 - 14 years on south-facing slopes, while on the north-facing slopes, mixed and high-severity wildfires had longer return intervals (~ 30 - 40 years). Over the past 500 years, the comparison of the tree-ring record with paleoclimate records suggests that the most extensive low-severity wildfires were associated with annual drought. Whereas, the larger and more severe wildfires represented by the alluvial-sediment record are associated with multi-decadal length droughts. Furthermore, the peaks in fire-related sedimentation (fire activity) may be associated relatively cooler and wetter climatic conditions during the century preceding the peak. We review the current wildfire regime of infrequent, high-severity wildfires (i.e. Missionary Ridge Fire) with the range of historical wildfire regimes, and discuss changes in wildfire regimes over the late Holocene.

Effects of Ash on Infiltration

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The recent marked increase in the number of studies quantifying the effects of ash on water repellency, infiltration, runoff and soil erosion, and on the analysis of its physical and chemical properties, are shedding light on the different roles ash plays in the hydrological processes immediately after a wildfire. It is now clear that, in the presence of ash, the traditional infiltration theories for soils require modification, and we now know that after a wildfire the infiltration process is driven by a two-layer system: the soil and the ash layer.

Variable infiltration responses have been reported in this two-layer system. These can be attributed to three main factors: i) ash depth and type (e.g. composition, particle size, hydrological properties); ii) soil type (e.g. particle size, porosity); and iii) rainfall characteristics (timing, duration and intensity).
Due to its high porosity and low bulk density (0.18 – 0.96) the ash layer is able to hold a great quantity of water of around 70-80 % of its weight (Bookter, 2006; Cerdà and Doerr, 2008; Goforth et al., 2005; Massman et al. 2008; Moody et al., 2009; Woods and Balfour, 2008; Bodí et al. 2012). The saturated hydraulic conductivity is also often higher than the rainfall intensity and therefore overland flow is delayed and reduced with respect to bare soil. Few measurements of saturated hydraulic conductivity have been carried out on ash from wildfires and typical values range from 84 to 380 mm h^{-1} (Woods and Balfour, 2008, 2010; Bodí et al. 2012; Ebel et al. 2012). The only reported exceptions of ash increasing overland flow have been reported when ash is water repellent (Gabet and Sternberg, 2008; Bodí et al., 2011b) or when it has formed a crust (Cerdà, 1998; Onda et al., 2008; Woods and Balfour, 2008; Bodí et al., 2011a; Balfour and Woods). The latter is particularly common for ash with a high $CaCO_3$ content (ash produced at high temperature), which tends to compact and form a crust during or after the first rain storm. Hydraulic conductivity of crusted or water repellent ash have not been quantified, but confirmations of higher overland flow have been observed by Woods and Balfour (2008), Onda et al. (2008) and Bodí et al. (2011a). In such cases, the ash layer may prevent infiltration and cause Hortonian (infiltration excess) overland flow.

These exceptions aside, the infiltration rate of ash is generally greater than that of the underlying soil. Ponding is therefore more likely at the soil/ash interface (Kinner and Moody, 2010, Ebel et al. 2012) and the ash layer will thus delay overland low runoff proportionally to its thickness (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Larsen et al., 2009; Zavala et al., 2009; Bodí et al., 2012). Once ash is saturated, overland flow by saturation excess of the ash layer may start as well as subsurface flow between the ash

and soil. A number or scenarios may subsequently occur:

i) In cases where the soil had been water repellent and become gradually wettable (Zavala et al. 2009; Bodí et al. 2012), or where ash prevents soil from crusting and compaction (Woods and Balfour, 2008; Ebel et al. 2012), the infiltration rate of the two-layer system can become similar or even greater than would be the case for bare soil, and thus, overland flow may be reduced (Cerdà and Doerr, 2008; Woods and Balfour, 2008; Larsen et al. 2009; Bodí et al., 2011a; Bodí et al., 2012).

ii) Depending on the texture, particle size and pore structure of soil and ash, ash may clog the soil pores, thereby reducing the soil infiltration capacity and increasing overland flow respect bare soil (Balfour and Woods, 2007; Larsen et al., 2009; Woods and Balfour, 2010).

iii) Following prolonged or successive rains, ash may lose its structure or may be entirely removed from a burned site. This would reduce or eliminate any two-layer effects, whereas the effect of ash incorporation into the soil pore space could be expected to be longer-lived (Onda et al. 2008; Woods and Balfour, 2008).

Overall, however, the deposition, properties and redistribution of ash may exhibit sufficient spatial variability to suggest that all these effects on soil hydrology may affect a burned hillslope or catchment at the same time at different locations. Indeed our knowledge on the production, properties and effects of ash to date is far too limited to allow detailed predictions about its net hydrological or geomorphological effects at hillslope or catchment scales.

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Erosion, Deposition, and Stream Channel Response after the 2012 High Park Fire

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One of the most critical concerns after large, high-severity wildfires is the headwater erosion and downstream deposition with the resulting effects on water quality, aquatic habitat, and reservoir sedimentation. The goal of this research is to monitor post-fire channel morphology and recovery at different spatial scales after the June 2012 High Park Fire west of Fort Collins, Colorado. The two primary watersheds studied are Hill Gulch and Skin Gulch (~ 14-15 km^2). They are very similar as they burned 62-68% at moderate to high severity, drain northwards into the Cache la Poudre River, and are characterized by intermittent stream flow. These watersheds are about seven kilometers apart. The data collected includes: airborne LiDAR surveys of the watershed topography, terrestrial LiDAR surveys of channel heads and selected in-channel locations, and repeat surveys of elevations at monumented cross-sections and associated longitudinal elevation profiles.

In mid-July 2012, prior to the installation of any rain gages, a high-intensity thunderstorm produced tremendous channel erosion and localized deposition of over 0.5 m in the middle and lower portions of Skin Gulch. This deposition includes some boulder-sized material just below an inter-tributary confluence and mostly finer material further downstream. In April 2013, a series of unusually large spring snowstorms generated extensive snowmelt runoff that incised up to ~0.7 m through these deposits and transported much of the finer fraction out of the watershed. LiDAR data and field measurements are being used with a two-dimensional hydraulic model (FaSTMECH) to simulate the initial flood responsible for most of the deposition in Skin Gulch. FaSTMECH (Flow and Sediment Transport with Morphological Evolution of Channels) solves the quasi-steady St. Venant equations over an orthogonal curvilinear grid with spatially-variable roughness, and it has the capacity to simulate mixed-grain-size sediment transport and bed evolution. We will use this model to estimate the discharge, flow field, and local sediment transport capacity during this thunderstorm. Much less erosion and deposition has been observed in Hill Gulch since the wildfire, as this area was not subjected to the same rainfall intensities. However, field observations and the downstream cross-section data show the same pattern of low-order channel erosion and downstream deposition after summer thunderstorms, followed by incision from sustained high snowmelt runoff in spring 2013. Our observations indicate that: a) the high spatial variability of rainfall from thunderstorms is the first-order control on post-fire erosion and deposition; b) moderate post-wildfire rainstorms can produce geomorphically significant stream channel change; c) spring snowmelt can greatly contribute to post-fire channel recovery.

Hydro-geomorphic Responses to Wildfire in southern California

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In the Mediterranean-type climate of southern California, wildland fires are among the most destructive watershed disturbances. Wildfire-prone areas in Southern California can be considered to be part of three physiographic provinces, one precipitation regime, and four primary fire regimes, the combination of which results in diverse hydrologic and geomorphic responses of recently burned watersheds to rainfall.

The three physiographic provinces are defined primarily by groupings of several mountain ranges into the Coast Ranges, the Transverse Ranges, and the Peninsular Ranges. Watersheds in the Transverse Ranges are typically steep and rugged, with gradients greater than 50% in their higher reaches, and the great majority of gradients >30%. The largest volume (>500,000 m^3), and widespread and abundant post-wildfire debris flows have been documented in the San Gabriel and San Bernardino Mountains of the Transverse Ranges. The Transverse Ranges are the result of active tectonic movement with uplift rates up to ~25 mm y^{-1}, resulting in active and perpetual movement of material from hillslopes into channels, including both dry ravel and colluvium. It is rare to achieve sediment supply-limited conditions in this setting, particularly following wildfires. Smaller (10,000 m^3<volume>100,000 m^3) and less widespread and abundant debris flows have been documented in localized steeplands within the Coast and Peninsular Ranges. These more spatially diverse responses may be attributed to relatively fewer steep, rugged watersheds in these two provinces. Preliminary examination of values of soil properties extracted from the small-scale STATSGO and SURGO soil survey databases, including percent organic matter, clay content, K-factor and saturated conductivity, did not identify differences sufficient to explain the varying debris-flow responses of the three physiographic provinces.

The Mediterranean-type climate in southern California is typified by hot, dry summers and mild, rainy, winters. Although southern California falls into the Pacific, Medium precipitation regime, with I_{30}^{2yr} generally ranging between 20 and 36 mm h^{-1}, precipitation accumulations are strongly correlated with elevation, with I_{30}^{2yr} values up to 45 mm h^{-1}recorded at the higher elevations throughout. Values of I_{30}^{2yr} from areas in Transverse Ranges known to have produced post-wildfire debris flows and floods range from between about 30 and 45 mm h^{-1}, while values from such areas in the Coastal and Peninsular Ranges range between 20 and 35 mm h^{-1}. Within the Transverse Ranges, debris flows and sediment-laden flows have been triggered from recently burned areas in response to long-duration, low-intensity frontal storms with about 100 mm of rainfall in 20 hours, and convective cells of short-duration, high-intensity rainfall embedded within frontal storms and isolated convective rainfall cells with measured I_{30} values as low as 15 mm h^{-1} and up to 75 mm h^{-1}. Ongoing research is indicating the importance of rainfall peaks of less than 5 minutes in the generation of post-fire debris flows, pointing to the significance of infiltration-excess (rather than saturation-excess) runoff processes in recently-burned areas.

In southern California, wildfires start naturally during late summer and fall in response to lightning strikes. However, most wildfires in this setting are ignited by human activity, so they can be expected at any time of year. The largest wildfires occur in the summer during and following years of low rainfall and in the fall during Santa Ana wind events.

Southern California is host to four primary fire regimes, each characterized by specific Mediterranean vegetation assemblages, and each with distinctive implications for post-wildfire hydrologic responses. Chaparral is the most extensive native plant community, and typically grows at elevations between about 800 and 1400 m. Chaparral consists of hard-leaved shrubs shaped by summer drought, mild, wet winters, and wildfires that naturally burn every 30 to 90 plus years, but more frequently with the effects of human ignitions. Chaparral often grows in a continuous stand of dense vegetation, and small, fine leaves, lots of litter and peeling bark can render the landscape quite flammable. Wildfires in chaparral usually burn hot, produce tall flames and copious embers, and spread rapidly. In some settings, more frequent fires over the same areas have led to conversion to non-native grasslands. Much of the sediment incorporated into post-wildfire debris flows and sediment-laden floods is eroded from hillslopes and channels within the Chaparral fire regime.
Sage scrub is composed of drought deciduous, soft-leaved fragrant shrubs such as California sagebrush (*Artemesia californica*), buckwheat (*Eriogonum sp.),* and a variety of sage species, with a burn frequency of 20 to 120 years. Sage scrub is found in the coastal valleys, plains, and sandy interior foothills below 800 m elevation. Rainfall threshold conditions that result in debris flows from recently burned areas in such coastal valleys have been found to be approximately 20% higher than those for steep, inland areas. Similarly, the volumes of those debris flows that do occur are generally an order of magnitude less than those produced from steep, inland areas.

Montane forests**,** pine- and fir-dominated communities grow at higher elevations in southern California's mountain areas, generally above approximately 1400 m, and experience fire frequencies between approximately 5 and 80 years. In recent years, drought combined with beetle and disease infestations have increased the number of dead trees, and thereby the fire frequency in montane forests in this region. Many post-wildfire debris flows originate in the higher-elevation reaches of watersheds occupied by montane forests.

Riparian forests consist of willows (*Salix sp*.), sycamores (*Plantanus sp*.), cottonwoods (*Populus sp*.), alders (*Alnus sp*.), coast live oaks (*Quercus sp*.), and other trees and plants that are along streams in southern California. Riparian forests can found in narrow canyons, providing important structural support to stream banks, or along broad, wooded corridors. Historically, these wet areas acted as fire breaks during wildfires, with fire recurrence intervals between approximately 5 and 40 years. In recent years, exotic species, including type of large grass (*Arundo sp*.) and Tamarisk (*Tamarix sp*.), have occupied such areas in dense stands. In summer, when water levels recede, these plants may dry out and become dormant, thus becoming potential fuels for fires. Such previously natural fire breaks can be turned into flaming corridors, rapidly fueling the spread of a wildfire. *Arundo* and Tamarisk both recover very quickly after a wildfire, much faster than the native trees, and are thus able expand their range along the river or creek. The loss of structural

support to stream banks through this process may also affect the volume of materials that can be eroded from burned watersheds by debris flows or floods.

Long-Term Monitoring of Infiltration Rates During the Post-wildfire Period in Eastern Spain

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The impact of wildfire on soil properties, infiltration and surface wash usually is studied during the year after a wildfire (Cerdà, 1998). This is the period called the "window of disturbance" by Moody and Martin (2001a; b). However, there are physical (e.g. aggregate stability), chemical (e.g. pH) and biological (e.g. fungi) soil properties that are highly dynamic, and then, the erosional and hydrological soil response can be very variable. Infiltration is the key process of the hydrological cycle that exerts control on the runoff generation, soil erosion, and plant recovery as determine by the soil water availability (Cerdà, 1996). To know the temporal changes of the infiltration rates after a wildfire will shed some light on the long-term evolution of post-fire ecosystems.

The Serra Grossa study area is a Cretaceous limestone parent material relief with typical convex-straight-concave slope morphology with maximum slope angle of 15º in the middle slope tram. The vegetation is a typical Mediterranean maquia: *Quercus ilex*, *Pistacia lentiscus* and *Juniperus oxycedrus*, but floristic composition is related to the fire frequency. *Ulex parviflorus*, *Cistus albidus* and *Rosmarinus officinalis* are very frequent during the decade after the wildfires. Plants and soil are distributed in a patchy like mosaic. Soils are usually shallow (< 15 cm) and distributed in the pockets developed by the dissolution of the limestone (Cerdà, 1997). Mean annual temperature is 16 ºC with warm winters and hot dry summers. Mean annual rainfall is 688 mm, although the 24-hours rain event record is 720 mm in the nearby meteorological station of Gandia. The 30-minutes maximum rain intensity is 90 mm h^{-1} and 60 mm h^{-1} for 60-minute maximum rain intensity. Soils suffered overgrazing and the overexploitation for fuel during millennia. Since the 60s, the land abandonment triggered the plant recovery, and as a consequence also the recurrent wildfires every one to two decades.

Soil infiltration rates were measured by means of simulated rainfall experiments (0.25 m^2 plots, 55 mm h^{-1} during one hour) and cylinder infiltrometer (7 mm in diameter) measurements in a typical Mediterranean Scrubland since 1990 until 2012. Ten experiments and ten measurements were carried out during the wet and dry season. The results show that the infiltration rates measured using the cylinder infiltrometer did not show any change during the study period, whereas those measured using the simulated rainfall indicated a reduction of the steady-state infiltration rates from 53.54 mm h^{-1} before the wildfire (20 years after the last one) to 34.43 mm h^{-1} the winter after the wildfire. The window of disturbance lasted for 2 years (summer season) and for 4 years (winter season). On average, for the 23 years of measurements, the steady-state infiltration rate was reduced 1.67 %, although for the 2 years after the wildfire the reduction reached a peak of 35.45 %.

The impact of wildfire on the infiltration capacity of soils is a short-term effect that lasts 2 to 4 years after the wildfire. Long-term measurements in this region of Spain, demonstrate that there are no effects when wildfires occur once every two decades.

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Modeling Post-Wildfire Rainfall-Infiltration-Runoff Processes: Current State, Challenges and Some New Approaches

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Wildfire can dramatically change hydrological responses of a watershed to rainfall events. In recent years, post-wildfire hydrology has attracted increasing attentions in the hydrologic community, with modeling post-wildfire rainfall-infiltration-runoff one of the central topics. Current approaches for modeling wildfire effects on watershed hydrology, in particular post-fire runoff and stream flow, generally apply certain type of "modifier" to original parameters to account for the fire effects. The effectiveness of this approach needs to be evaluated.

Several currently available approaches for peak flow and runoff hydrograph simulation were examined using historic pre- and post-fire data from San Dimas Experimental Forest (SDEF), San Dimas, California. These methods were chosen based on the complexity of the underlying modeling mechanisms ranging from simple empirical peak flow approaches to conceptual and eventually physically-based models. It was found from this study that empirical models work well in the geographical areas for which they were developed or calibrated, but may not be applicable for predictions outside these areas due to the lack of hydrological mechanisms. In our cases, the conceptual model examined outperformed the physically-based model for pre-fire conditions whereas in post-fire conditions the result is the opposite. Analysis suggests that this may be a result of the temporary change of the dominant runoff generation mechanism due to fire effects.

The analysis indicates that current techniques for simulating post-wildfire runoff have not come to a matured state. Physical mechanisms of infiltration and runoff have not been effectively incorporated into current models. Therefore, large gaps exist between the needs and capability of post-wildfire hydrologic simulation. Soil property changes and associated alteration in infiltration, increased surface heterogeneity, scaling of infiltration and runoff, slope and sediment/debris effects, are among the major challenges we are facing. To improve current techniques for post-wildfire hydrology and apply them for real world cases, we are bounded to enhance our understanding of the physical mechanisms and develop approaches to parameterize the model.

A recently developed rainfall-infiltration-runoff modeling approach may contribute to the progress of post-wildfire hydrologic simulation. This approach consists of a two-dimensional runoff routing module using the diffusion wave method, and an infiltration module using a recently developed two-layer infiltration model. This distributed, physically-based model is expected to fill some gaps between the complex reality and current technical capability, such

as naturally incorporating surface heterogeneity, dealing with layered soil profiles due to burning, and accounting for detailed contributing area for runoff generation and runoff routing pathways as well as runoff connectivity. However, major challenges still exist to extend the model application from plot or hillslope scales to watershed scales.

Changes in Soil Structure and Hydraulic Properties in a Wooded-Shrubland Ecosystem Following a Prescribed Fire

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Pre- and post-fire measurements were made for a low-intensity prescribed fire in a semiarid, shrub-woodland transition zone. There were two objectives. First, to determine changes in near-saturated hydraulic conductivity (K_f measured with a tension infiltrometer), air permeability (k_a measured with an air permeameter), and soil physical properties at shrub undercanopy and interspace microsites immediately before and after a fall burn and for a 13-mo period. Second, to quantify the importance and effect of post-fire soil structure on hydraulic properties using pre- and post-fire measurements. At undercanopy microsites, structure deteriorated from a moderate to a weak subangular blocky structure after the fire that broke down to a structureless soil 10 mo later. At interspace microsites, post-fire soil structure deteriorated from a moderate-strong subangular blocky structure with hard dry consistency to a weak subangular blocky structure with soft dry consistency. After 10 mo, the intercanopy maintained a weak-moderate soil structure that became structureless-weak after 13 mo. Immediately after the fire, at both microsites, there was incomplete organic combustion, a decrease in bulk density, and an increase in k_a. However, at undercanopy microsites, there was no significant change in K_f even though there was a slight to moderate hydrophobicity (using water drop penetration times 60-180 s and 180-600 s, respectively), whereas at interspace microsites where no water repellency existed, K_f increased. These changes may be a result of expansion of vaporized water through soil pores that broke up aggregates, deteriorating soil structure. Thus, mechanisms that contributed to changes immediately and after the first year post-fire may be different for low-intensity burns than for higher intensity burns.

Quantifying Sediment Storage by Vegetation in Steep Bedrock Landscapes: Implications for Post-wildfire Sediment Yield

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Predicting landscape response to wildfire demands a quantitative understanding of erosion processes. However, existing models for hillslope sediment production and transport do not apply to landscapes with patchy soil and slopes that exceed the angle for sediment stability. Here we investigate the hypothesis that patchy soil cover is stable on steep slopes due to local roughness such as vegetation dams that trap sediment upslope. We develop a new theory and test it using tilt-table experiments and field measurements of sediment accumulation behind unburned and burned vegetation from the San Gabriel Mountains in southern California, USA.

Results show that trapped sediment volume scales with the cube of dam width over 3 orders of magnitude in dam width, with a similar scaling for both field and laboratory measurements. Trapped volumes are greatest for hillslopes that just exceed the friction slope and are independent of hillslope gradient for gradients greater than about twice the friction slope. Measured sediment volumes behind burned vegetation dams indicate a loss of at least 75% relative to unburned dams, and when expanded to the catchment scale, our measurements match records of post-fire sediment yield from nearby retention basins.

Contrary to existing models, our observations indicate that in steep landscapes, wildfire-induced sediment yield is driven by transient storage and release of sediment by vegetation dams, rather than increased bedrock-to-soil conversion rates. Without a feedback between soil production and wildfire, fire may play little role in long-term landscape evolution, and increasing fire frequency in response to climate change may not result in heightened sedimentation hazards due to supply limitations.

Water Repellency and Soil Hydraulic Properties

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Soil water repellency (hydrophobicity) has been documented under a wide range of vegetation types and climates and particularly following wildfires. It is of considerable interest to land managers, hydrologists and soil scientists concerned with the effects of wildfire because (i) it can be induced, enhanced or destroyed during burning and (ii) it can change soil hydraulic properties including a marked reduction in infiltration rate. This reduction in infiltration is commonly presumed to be the primary cause of the increases in runoff and erosion that are often observed at a range of scales following wildfire.

It is widely accepted that water repellency is caused by the presence of organic compounds with hydrophobic properties on soil particle surfaces. These compounds reduce the surface tension of particle surfaces to values lower than that of water (~0.074 N m^{-1}), which means that water is more strongly attracted to itself than to the mineral surface and will therefore not spread. The net effect is that water is not drawn into dry soil pores by suction (i.e. capillary forces), but instead repelled.

During burning, hydrophobic substances in the litter and topsoil can be volatized and condensed in the soil, inducing or, perhaps more commonly, intensifying water repellency that was already present. However, where burning heats soil in excess of ~270° (or more if there is a lack of oxygen), these compounds are destroyed and soils rendered wettable. In most cases any increases or elimination of repellency tends to be confined to the top few millimeters or centimeters of the soil, increasing further the often highly spatially and temporally variable patterns of water repellency. Repellency is typically most pronounced under dry conditions and often disappears following prolonged wet weather. The duration and amount of rainfall needed to reduce or eliminate soil water repellency varies with soil type and the severity and persistence of soil water repellency. A soil-specific 'critical water content', which can range from 5-30% (vol.), is thought to demarcate wettable and water repellent states.

Water repellency severity (how 'strongly' water is repelled) can be assessed by measuring the contact angle between a water drop and the soil surface or by the Molarity of an Ethanol (MED) droplet method. Timing how long a water drop takes to infiltrate (Water Drop Penetration Time; WDPT), in turn, determines how long repellency persists when in contact with water. Other methods, such as the time required for a known volume of water to infiltrate over a known area, or the pressure required to force water into soil, provide an integrated measure of soil wettabiliy that is governed by water repellency and other soil physical characteristics.

Burning also induces a series of other changes to soils, (e.g. to texture, organic content, aggregate stability) and the loss of vegetative cover, which may be just as important as water repellency in causing the observed increases in runoff and erosion following wildfire. These factors make it challenging to assess the role of soil water repellency in post-wildfire hydrology and erosion processes. This is particularly so at larger scales due to the high spatial variability of many factors involved and the difficulty in characterizing the counteracting role of wettable soil patches, ash, bioturbation, soil

cracks, and burnt-out tree roots in reducing the surface runoff engendered by strongly water repellent patches.

This contribution aims to provide (i) an overview of soil water repellency, its assessment and the effects of burning on soil water repellency; (ii) an evaluation of its relative importance in predictions of post-wildfire runoff and erosion responses; and (iii) suggestions for addressing remaining research gaps in relation to i and ii.

How do the Spatial Scale and Temporal Patterns of Precipitation Influence Hydrologic Response?

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Precipitation exhibits spatial and temporal variability over a wide range of scales. In seeking to understand the hydrologic response of burned landscapes, the variability that might be linked to the precipitation regime warrants careful analysis. Likewise, a significant part of the precipitation may be intercepted or reach the soil surface as drip and stemflow, and such fluxes will be time-varying as litter and standing vegetation regenerate. It is necessary therefore to understand the temporally-changing nature of effective precipitation regimes and not only the properties of the open-field precipitation as recorded at a meteorological observing station. The temporal structure of precipitation can exert a major influence on water partitioning at the soil surface, and convective rainfall that is at its most intense in the early stages of an event may, for example, yield much less overland flow than steady rain of the same depth. Surface ponding depths are also affected by the temporal structure of rainfall, and this in turn modulates the intensity of drop splash on exposed soil. Plants can deliver spatially-focused stemflow at rates that are an order of magnitude greater than the intensity of the open-field precipitation, and these localized fluxes can affect a number of landscape processes including slope stability and scour by overland flow. The delivery of stemflow itself depends strongly on the temporal structure of the rainfall (and on the state of regeneration of foliage), and on the intensity and timing of bursts of intense rain within an event. Thus, post-fire hydrology research needs to be cognizant of the important influence on landscape response that may be exerted by the spatio-temporal aspects of precipitation.

What's the Difference: A Novel Method for Connecting Precipitation and Infiltration

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One of the grand challenges in hydrology is accurately measuring subsurface fluxes to better understand how precipitation is partitioned into infiltration and runoff. Measuring infiltration flux is particularly challenging in wildfire-affected environments. Here we present measurements of infiltration from a field site within the 2010 Fourmile Canyon fire made by using a "difference infiltrometer". This method combines a co-located rainfall gage with a runoff gage that measures surface runoff from an enclosed plot (~ 1 m^2), with the difference between rainfall and runoff (area-corrected) being the time-varing infiltration rate. Calculated time-variable infiltration rates and unsaturated soil properties were used to inversely-estimate the effective saturated hydraulic conductivity, K_s [mm h^{-1}], using a one-dimensional (1D) vertical model of unsaturated water flow (Hydrus 1D, Šimùnek et al., 2008) for a two-layer soil system and a subset of cyclonic (long duration, low intensity) and convective (short-duration, high intensity) storms (i.e. a split-sample approach). These estimates of the effective saturated hydraulic conductivity (which includes any water repellency effects and the effects of spatial variability within the plot) were then used to predict the infiltration and runoff for the remaining cyclonic and convective storms. This enabled us to use the 1D model as a 'virtual instrument' to understand the post-wildfire infiltration, during a variety of storms, within the unsaturated zone.

Our results indicated that the two-layer model of the fire-affected soil performed better than the one-layer model. Runoff started at a relatively small critical rain depth (1.4-2.5 mm) that was similar for cyclonic and convective storms, and that infiltration was confined to a depth less than 50 mm. The effective saturated hydraulic conductivity, K_s, was relatively small with the value for the upper layer (7 mm thick) ranging from 0.13 to 5.2 mm h^{-1} and the value for the lower layer (7-380 mm thick) ranging from 0.001 to 0.43 mm h^{-1}. Additionally, the coupled analysis of simulated and observed infiltration suggests that the temporal characteristics of storm profiles can be more important than soil-hydraulic properties for disturbed systems where near-surface effective saturated hydraulic conductivities are relatively low (order 1-10 mm h^{-1}). The conjunctive use of 1D unsaturated flow models with time-varying infiltration rates may prove useful for parameter estimation for watershed-scale rainfall-runoff modeling. The difference infiltrometer provides a method for measuring time-varying infiltration rates, and a method for long-term monitoring of changes in infiltration rates after wildfires.

Citation:

Šimùnek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M.Th., 2008. The HYDRUS-1D software package for simulating the one dimensional movement of water, heat, and multiple solutes in variably-saturated media, Version 4.0 x, Hydrus Series 3. Department of Environmental Sciences, University of California Riverside, Riverside, 330 p.

Using Fire and Erosion Tools to Predict Wildfire Risk and Sediment Yield

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Forests deliver a number of ecosystem services, including clean water. When forests are disturbed by wildfire, the timing and quantity of runoff can be altered, and water quality can be severely degraded. A modeling study for the 5500 km^2 Mokelumne River Watershed in California was conducted to determine the risk of wildfire and the associated potential sediment yield from forest hillslopes following a wildfire - and to calculate the potential reduction in sediment yield that might result from fuel reduction treatments.

The first step was to predict wildfire severity under current vegetation conditions with the FlamMap fire spread prediction tool. FlamMap uses a current vegetation database, topography, and wind characteristics to predict the speed, flame length, and direction of a simulated flame front for each 30-m pixel on the landscape. To incorporate wind, FlamMap uses a single wind speed and direction as an input, as specified by the users. From this input, a second model (Wind Ninja) determines the variability in speed and direction across the landscape as influenced by topography. FlamMap is very sensitive to wind speed in both the predicted fire intensity and rate of spread. The next step was to delineate hillslope polygons in the watershed (approximately 6 ha) with GeoWEPP (a geospatial interface for the WEPP model) using a 30-m digital elevation model. The flame length values were aggregated for each polygon to obtain predicted fire intensity. The distribution of flame lengths was compared to the distribution of fire severity of a recent fire within the basin. On that fire (the 2005 Power Line Fire), the observed distribution of fire severity was 12 percent unburned, 41 percent low severity burn, 29 percent moderate severity, and 18 percent high severity. The predicted flame length distribution (including unburned) was categorized to give the same distribution of severity as the Power Line Fire across the basin.

A cross walk table was developed for ground cover remaining after the fire, and soil erodibility properties as a function of fire severity and prefire vegetation. For forest conditions, the ground cover amounts for low, moderate and high severity conditions were 60 percent, 45 percent, and 15 percent, respectively. For low and moderate severity conditions, the WEPP "Low Severity" soil file distributed with the WEPP model was used. For high severity conditions, the WEPP "High Severity" soil file was used. The ground cover assumptions are conservative, but the goal was to be able to identify differences in predicted sediment yield and not necessarily absolute values.

The soil files for running the WEPP model are made up of two parts. The first part describes the erodibility (interrill erodibility, rill erodibility, critical shear and effective saturated hydraulic conductivity) and these values vary with fire severity and vegetation as well as texture. The WEPP soil database includes 8 different vegetation categories, and they are, in order of increasing erodibility: Forest, Young Forest, Shrub, Bunch Grass, Sod Grass,

Low Severity Fire, High Severity Fire, and Skid Trail. The erodibility values have been measured for a number of forest and rangeland soils following wildfire, as well as unburned, using rainfall and runoff simulation. The second part of the soil file is a soil profile with the depth of as many layers as desired, and for each layer, the sand and clay fractions, cation exchange capacity, and organic matter content. These values were obtained from the STATSGO soils database for the basin.

The climate file to run WEPP has daily values for maximum, minimum and dew point termperatures, wind speed and direction, and solar radiation. If a day has precipitation, the file contains the depth, duration, peak intensity, and time to peak intensity for a single storm for the day. The climate is generally stochastically generated from weather statistics from nearby weather stations, and then modified to reflect greater amounts of precipitation at higher elevations, based on the PRISM database, and cooler temperatures based on adiabatic lapse rate. The occurrence of a wet day is determined by a Markov Chain model with separate probabilities for a wet day following a wet day and a wet day following a dry day. On a wet day, the amount of precipitation is randomly generated from the mean precipitation on a wet day for a given month, and the standard deviation and skew of that value. The WEPP model contains a daily time step for plant growth, evapotranspiration, deep seepage and shallow lateral flow. On a wet day, if the average temperature is below freezing, precipitation is assumed to be snow fall, and a snowpack may accumulate. If there is precipitation or snow melt when the temperature is above freezing, the infiltration rate is estimated sub hourly and the soil water content updated. If runoff is predicted, sediment detachment, transport, deposition, and yield are calculated for each hillslope polygon, and for the upland channels. For this study, eight different stochastic climates were generated to account for weather variability within the basin with annual precipitation ranging from 800 to 1400 mm. A modified batching version of GeoWEPP was used to predict the sediment yield from each hillslope polygon and sub watershed consisting of around 50 hillslope polygons in the designated study area.

Estimated hillslope sediment yield rates ranged from 0 to more than 100 Mg/ha the first year following the modeled wildfire, and were typical of observed values measured after other fires in California that ranged from 2.5 to 32 Mg ha^{-1} the year following a wildfire from watersheds that had drier climates than in the study basin. The polygons that generated the greatest amount of sediment or that were critical for reducing fire spread were identified, and these were “treated” by reducing the amount of fuel available for a wildfire. The erosion associated with these fuel treatments was estimated using WEPP. FlamMap and WEPP were run a second time to determine the extent to which the imposed treatments reduced fire intensity and hence fire severity and the predicted erosion rate. The results allowed managers to quantify the net reduction in sediment yield due to the prescribed treatments. Modeling also identified polygons with the greatest net decline in sediment yield, with the expectation that these polygons would have the highest priority for any fuel reduction treatments. The model predictions will allow resource managers to calculate the net change in hillslope sediment yield due to any given fuel reduction treatment. An economic value can then be assigned to the predicted net change in sediment delivered. The estimated avoided costs due to the reduction in sediment delivery can then be used to carry out the optimal fuel treatments.

The approach of combining fire modeling with erosion modeling presents a new tool in understanding wildfire effects on soil erosion risks by predicting fire severity and the associated risk of erosion from current vegetation, topographic and climatic conditions. This approach opens up new research needs to validate the assumptions relating predicted fire intensity to soil erodibility. The approach also revisits the challenge in all hillslope models of trying to determine a single erodibility value to represent a hillslope in post fire conditions that likely has a large spatial variability in soil erodibility. This approach has been expanded to predict the likelihood of a fire occurring in a given pixel, and the likelihood of and volume of sediment delivered from subwatersheds by debris flows in the same basin. Future modeling activities need to be developed to route the sediment transported from eroding hillslopes and debris flows through stream channel systems, and delivering sediment to points of interest like reservoirs or water intakes for domestic or other uses. The approach also underscores the importance of obtaining information on the depth and properties of soils in forest watersheds. Such information is often limited due to the inaccessibility of many forested areas.

ERMiT and WEPP Models

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The Water Erosion Prediction Project (WEPP) Model is a distributed physically-based hydrology and erosion model. We have developed several interfaces for the model to aid in evaluating post wildfire runoff, erosion and sediment delivery risks at the hillslope and watershed scale. The four post-wildfire applications we will demonstrate are:

Model	Attributes
Disturbed WEPP	Online single slope interface to the WEPP model for predicting average annual erosion from forest management and following wildfire.
ERMiT	Online single slope interface to the WEPP model for predicting the probability of a given depth of runoff and sediment delivery amount from a single storm. ERMiT incorporates the effectiveness of mulching, seeding, and log erosion barriers on reducing sediment delivery.
Peak Flow Calculator	Online interface to the NRCS Curve Number method for predicting peak flow rates based on runoff amounts predicted by ERMiT or other software.
Online Watershed Interface	Online interface to a GIS that divides a watershed into representative hillslopes, runs WEPP for each hillslopes, and then routes the detached sediment through the stream system. Can input a fire severity map. Also provides watershed properties for the Peak Flow calculator.

How do Plantation Forests Change Post-Wildfire Runoff and Erosion?

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Commercial forest crops have become dominant in many Mediterranean regions, replacing pristine forest areas and changing significantly the vegetation and soil characteristics, the management practices and their impacts on soil characteristics, and therefore induced significant changes on soil hydrological and erosion processes. The key feature of introducing plantation forests is the loss of diversity, at various levels, not only in terms of biodiversity, but also in what concerns the homogenization of the litter layer and the soil organic matter, along with the homogenization of the soil structure, due to the frequent mechanic interventions. Furthermore, the reduction of species, will contribute to the increase in the homogenization, due to the little diversity at the root system level, the litter layer and the vegetation aerial structure.
This level of homogenization is frequently pointed as the main reason for the difficulties found in forest fire combat, especially if the commercial forest stands are not properly managed and there are no breaks in the forest continuity. The progression of wildfire can be dramatic and the areas burned in many poorly managed areas are frequently wider. It has been demonstrated that size plays an important role in the soil and water degradation processes.

The homogenization produced by plantation forests is also enhanced following forest fires. The formation of a more continuous water repellent layer, for a number of exotic commercial trees, especially in non-limestone areas, where several authors have reported the non occurrence of water repellence after wildfire, overlaid by a hydrophilic ash layer, significantly increases overland flow production, erosion yields and the runoff peak flows at the catchment level. This continuity is responsible for an abnormal inter-scale response. Normally extreme hydrologic events have the tendency to “fade away” (i.e. rainfall intensities concentrated in a small area will decrease when larger areas are included with lower intensities) when progressing from the pedon scale to the slope scale to the catchment scale. However, the continuity of the water repellent area resulting from the homogenization produced by plantation forests and enhanced by wildfire, can actually produce an increase in overland flow from the pedon to the slope and to the catchment scale resulting in unsuspected and unusual peak flows.

Factors Leading to Heavy Precipitation During the Warm Season in Complex Terrain

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During the warm season heavy rainfall is usually associated with local isolated convective systems or larger, mesoscale-scale systems. Isolated convective systems are typically of smaller spatial dimensions of around a few km in horizontal extent and lifecycles ranging of up to an hour or so. They are often associated with quiescent or 'light wind' conditions and therefore don't tend to move very quickly. In contrast, larger, more organized convective systems can have spatial extents up to many 10s of kilometers (e.g. 'mesoscale), persist for several hours and move or propagate on the order of 5-20 m/s. The discrimination between these two kinds of convective systems is somewhat arbitrary and frequently events possess characteristics of both regimes and both regimes can generate brief or sustained intense rainfall rates that drive flooding and erosion responses. The key ingredients to developing convective rainfall are (1) a certain amount of atmospheric instability, (2) moisture to produce clouds and precipitation, (3) convergent circulations to feed or sustain a convective storm and (4) some kind of trigger which initiates the convective circulation. In regions without appreciable topography, convective triggers can be difficult to identify. Sometimes triggers are related to land cover characteristics while other times they are related to subtle boundary layer wind features. Sometimes, convection triggers are seemingly stochastic. In contrast, in regions with substantial topography variations in radiation forcing across sloping landscapes drives local and regional thermal circulations which are often strong enough to trigger and sustain convective storms. Juxtaposition of many key ingredients over complex terrain regions provides a very favorable environment for convective rainfall. Such conditions are common throughout the western U.S. in the spring and summer, especially following the onset of the North American Monsoon circulation, which transports moisture into the southwestern parts of the inter-mountain west.

Particular vulnerabilities exist when these kinds of intense, slow-moving convective systems move across recently burned landscapes. Burned landscapes can influence the response of the landscape to a given rainfall input and also, at times, the strength of the convective circulation itself. Alterations of the surface characteristics such as surface reflectance or 'albedo' along with changes in vegetation structure and function can intensify the background thermal circulations in complex terrain regions. In such cases they may also serve to localize core areas of convection or ascent and impart a persistence influence on the storm circulation. Combined with an increased potential for runoff generation in burned landscapes, enhanced convection potential in such regions amplifies the chances for more severe impacts, in terms of flooding and erosion in recently burned areas.

In this overview talk the basic conceptual frameworks for analyzing and predicting heavy rainfall in warm season convective regimes will be presented. The basic physical ingredients for heavy precipitation formation will be discussed with emphasis on which ingredients are more relevant for different precipitation regimes. The specific role of land surface forcing on convective processes in complex terrain including the role of fire-burned landscapes will also be

discussed. Findings from recent research efforts will be synthesized in the context of creating skillful forecasts of heavy precipitation and what barriers and opportunities exist for improving forecast skill.

Determining Contributing Area for Post-wildfire Runoff and How It Changes With Rainfall Characteristics

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The adoption of physically-based infiltration and routing models as components of distributed watershed models may improve estimates of post-fire watershed response to rainfall. However physically-based infiltration models in particular require rainfall data with high temporal and spatial resolution which is often lacking. Radar derived rainfall data has demonstrated it can overcome some of these problems, but still has a number of inherent limitations due to mountain blockage and weather dependent reflectivity-rainfall (Z-R) relations. In addition, the spatial variability of infiltration model parameters must also be recognized and accounted for. Over large areas nationally available soils maps are available with typical soil polygons having areas less than 10 km^2. When these data are coupled with pedo-transfer functions (Rawls et al., 1982) they can be used to provide initial estimates for soil hydraulic properties at these scales. However, numerous observations also indicate large variability in soil hydraulic properties on the scale of meters (e.g. under-canopy to inter-canopy). Representing this level of spatial variability by discretizing the watershed into smaller modeling elements is impractical at this time. Therefore, a model that can simulate infiltration from rainstorms on areas exhibiting random variation in saturated hydraulic conductivity (or the capillary drive parameter - Smith and Goodrich, 2000) has been incorporated into the KINEROS2-AGWA watershed modeling suite (Goodrich et al., 2012; Semmens et al., 2008 – also see www.tucscon.ars.ag.gov/kineros and www.tucson.ars.ag.gov/agwa).

This infiltration algorithm is based on a point infiltration model that includes options for both the Green-Ampt or Smith-Parlange infiltration functions and a continuum in-between. These functions use the saturated hydraulic conductivity based on data from soil texture and pedo-transfer functions, pre- and post-burned rainfall simulator plot derived parameters, or from calibration when pre- and post-wildfire rainfall-runoff observations are available. AGWA automatically changes the saturated hydraulic conductivity and hydraulic roughness as a function of pre-burn land cover and fire severity. These post-fire parameter changes were derived from cases where good pre- and post-wildfire rainfall-runoff data were available. In these cases event-based calibration was conducted to estimate pre- and post-

wilfire parameters (Canfield et al., 2005; Goodrich et al., 2005; also see Sheppard et al., 2013 – this conference).

The interaction of this model with temporal and spatial rainfall variability for unburned and burned conditions will be examined using data from the densely instrumented USDA-ARS Walnut Gulch Experimental Watershed (WGEW). It is useful to illustrate how KINEROS2 represents a watershed via overland flow (hillslope) and channel model elements to understand the space-time interactions between rainfall, infiltration, and contributing runoff area. A schematic of WGEW subwatershed 11 in map form, contributing areas, and model elements is depicted in Figure 1. By approximating the watershed in this way, 1-D continuity, momentum and erosion equations can be used instead of 2-D equations. Finite difference methods are used to solve these equations interactively with the infiltration equation at each finite difference node. The number of nodes on each model element is typically between 10 and 15.

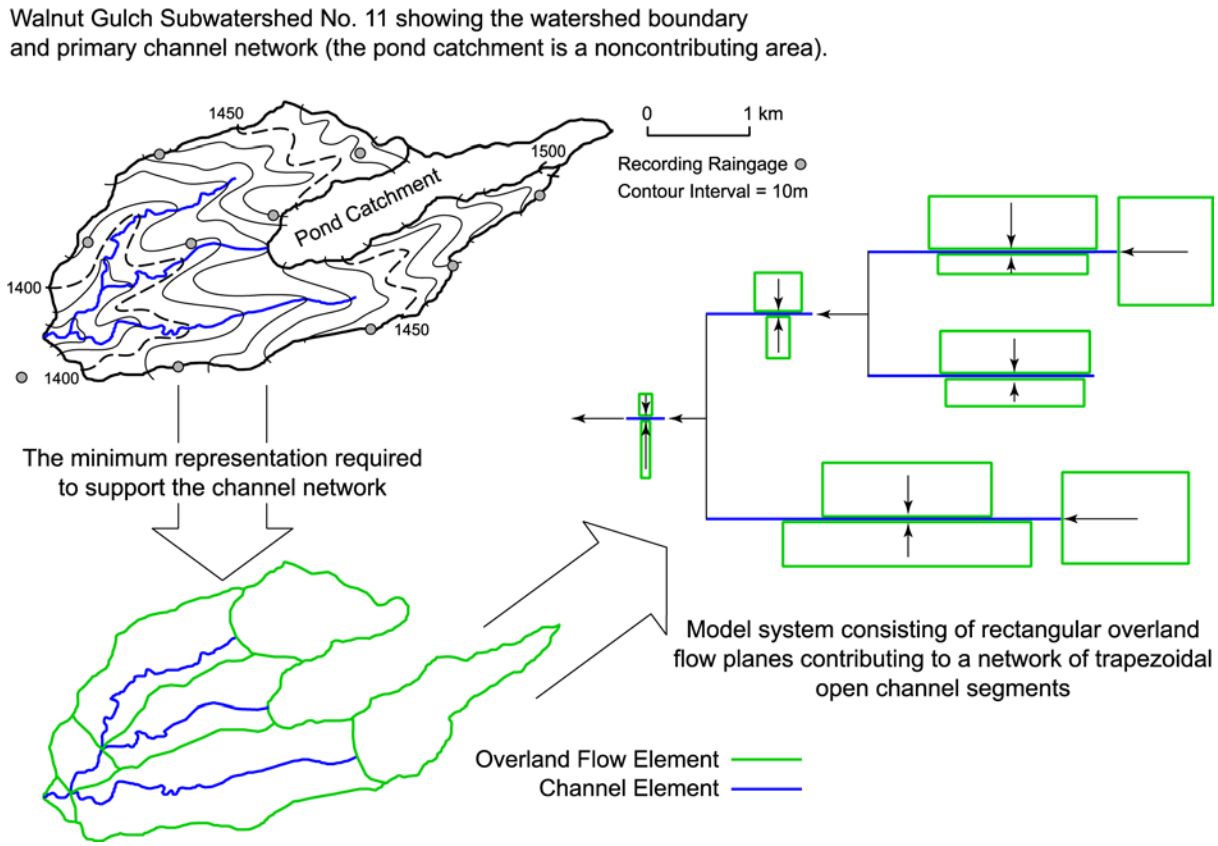


Figure 1. Illustration of how topographic data and channel network topology is abstracted into the simplified geometry defined by KINEROS2 model elements. Note that overland-flow elements (with either curvilinear or uniform slope profiles) are dimensioned to preserve average flow length, and therefore the width of overland flow elements contributing laterally to channels generally do not match the channel length.

In KINEROS2 the rainfall data is entered as time-accumulated depth or time-intensity breakpoint pairs. A time-depth pair simply defines the total rainfall accumulated up to that time. A time-intensity pair defines the rainfall rate until the next data pair. Rainfall is

modeled as spatially uniform but temporally variable over each overland flow model element, but varies between elements if there is more than one rain. The spatial and temporal variability of rainfall is expressed by interpolation from rain gauge locations to each overland flow element. An element's location is represented by a single pair of x,y coordinates at the centroid of the element (computed by AGWA). The interpolation scheme locates the three closest rain gauges which enclose the element's centroid coordinates; if such a configuration does not exist, it looks for the two closest gages from the centroid. If only one gauge exists, spatially uniform, but temporally variable rainfall is applied over all the modeling elements.
If three rain gauges are used for the interpolation, the intensity at any time is represented by a plane passing through the intensities above the three gauges for a given time step, and the interpolated intensity for the overland flow element is the intensity above its centroid coordinates (Figure 2). In essence a piece-wise planar representation of the rainfall intensity field is formed over the watershed. Each time a new time-intensity pair is received from a rain gauge this piece-wise planar rainfall intensity approximation is recomputed over the watershed.

The geometric configuration between model element centroids and rain gauge locations need only be computed once by KINEROS2 to compute simple weighting coefficients that can simply be applied for all time-intensity gauge pairs throughout the storm event. If initial soil saturation is specified in the event version of KINEROS2, it will be interpolated using the same spatial interpolation coefficients.

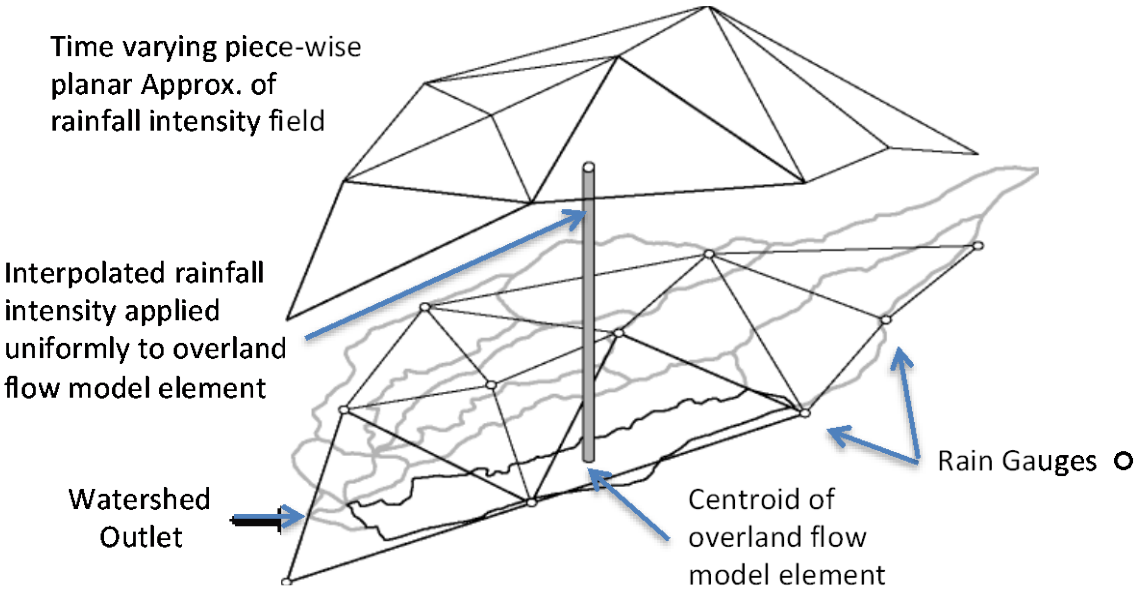
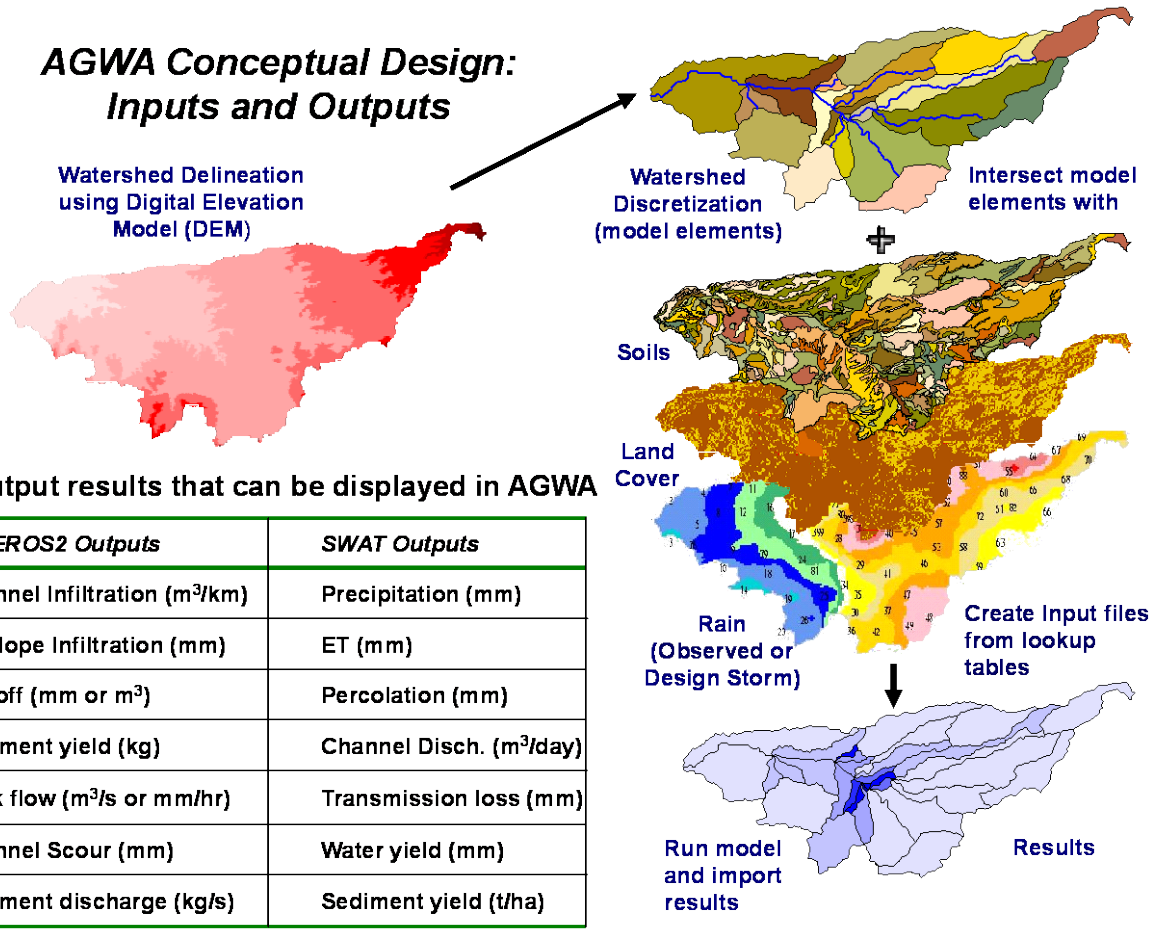


Figure 2. Diagrammatic representation of the KINEROS2 rainfall interpolation procedure.
KINEROS2 is somewhat unique in that it computes the flow depth, infiltration rate, and sediment concentration at each finite difference node considering soil moisture conditions, upstream runoff and the current rainfall intensity. Many watershed models input the rainfall hyetograph into an infiltration model to compute an excess rainfall hydrograph which is then routed down an impervious surface. Because KINEROS2 has interactive infiltration and routing it can more realistically address runoff-runon conditions when there are distinct

transitions in soils or land cover (i.e. runoff from a burned area flowing unto non-burned area). Depending on the intensity of rainfall and how it fluctuates in time and space an overland flow model element can also fluctuate from actively contributing runoff to not contributing runoff. The interpolated hyetograph and resulting hydrograph (if there is runoff) is computed and saved for each model element. For a given rainfall event a complete water balance and the associated error estimate is computed for each model element. AGWA can import the KINEROS2 output for each model element (e.g. total runoff, peak runoff rate, total infiltration, erosion, etc.) into the GIS environment and display the results for a given event or for the difference in two events (i.e. pre-burn and post-burn) to highlight at-risk areas to target mitigation efforts (Figure 3).



Output results that can be displayed in AGWA

KINEROS2 Outputs	*SWAT Outputs*
Channel Infiltration (m^3/km)	Precipitation (mm)
Hillslope Infiltration (mm)	ET (mm)
Runoff (mm or m^3)	Percolation (mm)
Sediment yield (kg)	Channel Disch. (m^3/day)
Peak flow (m^3/s or mm/hr)	Transmission loss (mm)
Channel Scour (mm)	Water yield (mm)
Sediment discharge (kg/s)	Sediment yield (t/ha)

Figure 3. AGWA Conceptual Design: Inputs and Outputs

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Vegetation as a First-order Control on Post-wildfire Erosion: A Cross-scale Study Integrating Field and Satellite Data

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Change to infiltration capacity caused by fire effects on soils accounts for only one of three primary controls on runoff and erosion following wildfire. A second is increase in effective rainfall input, both quantity and rate, caused by removal of overstory vegetation. The third is reduced attenuation of overland flow resulting from loss of litter and duff. Direct effects of vegetation disturbance on post-fire erosion remain largely unexplored.
We combined field survey, geospatial analysis, and statistical analysis to assess the effects of fire severity on (1) the probable occurrence of post-fire gully rejuvenation (GR), (2) the influence of burn mosaic structure on the probable occurrence of GR, and (3) the effect of fire severity on the slope and area thresholds of channel initiation. Working in five burned areas of Montana and Idaho, we mapped 269 primarily first-order catchments, 111 cases of GR, and 99 observations of fresh gully heads. We quantified fire severity using a new metric, the vegetation disturbance index (VDI). We calculated the VDI as the spatial mean value from the full scale (0-255) burned area reflectance classification (BARC) maps. Based on published studies, we interpret the VDI as vegetation change by wildfire and therefore a measure of fire severity. We used binary logistic regression to estimate the probability of GR (pGR) occurrence and generated classification models. The response variable was GR versus no-GR and the independent variables were VDI, catchment area, elongation ratio, relief ratio, and percent pre-fire shrub. We characterized the spatial structure of burn mosaics using percent catchment area and contagion (aggregation and fragmentation) of fire severity classes within each catchment. We assessed burn mosaic structure relative to pGR using step-wise regression. To study slope-area thresholds, we delineated source areas above gully heads and regressed relief ratio against area. We stratified the regression by fire severity levels and tested for the effects of fire severity on slope-area relationships (as defined by $S = kA^{-\theta}$ and $S{:}A=\boldsymbol{f}(\mathrm{VDI})$) and via statistical tests using MANOVA.

Vegetation disturbance alone best explained occurrence of gully rejuvenation (classification accuracy = 0.71 and discrimination (AUC) = 0.77). Adding catchment elongation and percent pre-fire shrub improved explanatory power (accuracy = 0.74, AUC = 0.79). Distinct patterns of local anomalies (fire hose effect, mid-slope riparian vegetation, and concentration of high severity burn in upper catchment extent) qualitatively explained exceptions to responses predicted by the data models (GR v. no-GR). The spatial structure of

burn mosaics was strongly related to pGR with a stronger correlation between percent area burned at highest severity levels and pGR (R^2=0.93, $p<0.001$) than between contagion and pGR ($R^2<0.78$, $p<0.001$). Step-wise regression revealed thresholds of landscape organization and pGR that define a transition zone between VDI = 155-195 through which the occurrence of GR is associated with preferential distribution of severely burned area in the upper catchment extent. Fire severity influenced the slope-area relationship of the source area and the location of freshly incised channel heads as evidenced in the strong linear correlation between the slope-area scaling exponent (**θ**) and VDI (adj. $R^2<0.86$, $p<0.05$ and adj. $R^2<0.96$, $p<0.01$ depending on data grouping). Source areas were significantly less steep under highest levels of fire severity (mean relief ratio above gully heads dropped from 0.43 to 0.34, $p>0.001$).

The results from these three lines of evidence infer that the overall degree of vegetation disturbance by wildfire exerts first-order controls on post-fire erosion response. This study highlights need for broad-scale empirical and modeling studies to understand the process mechanisms through which the magnitude and patterns of vegetation disturbance directly change rainfall delivery and resistance to overland flow and consequently alters channel initiation thresholds.

Biomass Burning in Northern Sub-Saharan Africa and its Potential Impact on Surface Water Dynamics

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Seasonal biomass burning is widespread across the northern sub-Saharan African (NSSA) region, which is bounded on the north and south by the Sahara and the Equator, respectively, and stretches East-West across Africa. This region accounts for about 25% of the total global annual carbon emissions from biomass burning. These wildfires, which occur yearly during the regional dry season (October – March), are observed from satellite. The fire regime in the NSSA is characterized by human induced dry-season burning, with savanna ecosystem types (savannas and woody savannas) accounting for 86% of the fires, whereas grasslands account for ~5%, implying that the remaining landcover types share less than 9%. These results are based on counts of fire detections from the MODIS sensors aboard the NASA Terra and Aqua satellites. In terms of fire intensity, based on MODIS measurements of fire radiative power (FRP) per satellite footprint size (or pixel) of approximately 1×1 km at the sub-satellite point, the average power released is observed to be on the order of 25 MW per pixel, which is similar to the magnitudes observed in the Eastern US, but less than half of the ~60 MW/pixel observed in Western US, Alaska, and Canada. On the other hand the count of fire observations in NSSA exceeds by far that of any other part of the world, and in particular is over 10 times those of any region of North America. The rainy season in NSSA is clearly distinct from the wildfire season, and lasts from April to September, with a steep rainfall gradient that goes from >1000 mm/year at Latitude 10ºN (savanna dominated) down to <100 mm/year at 15ºN (grassland dominated), decreasing to almost 0 mm/year as the landscape transitions from savanna/grassland (Sahel) landcover type to the arid Sahara desert starting around 20ºN. The NSSA region has an overall gentle relief pattern, with topographic elevations generally in the range of 200 m to 400 m above mean sea level (amsl) across the Sahel belt (where the wildfires are most dominant), and becoming lower toward the coasts, with the exception of a few mountainous domains such as central to southern Cameroun (generally > 500 m) with the Cameroun Mountain peaking at ~4,000 m and the East African mountain range (generally > 1,000 m amsl) with Mounts Kenya and Kilimanjaro peaking at ~5,000 m and ~6,000 m amsl, respectively. There are quite a few prominent rivers and streams all along the southern part of the region, most flowing mainly southward toward the Atlantic Ocean. The northern (grasslands) part of the region contains a large distribution of ephemeral streams and dry valleys that can get flooded during occasional high-intensity or long-duration rains. Surface infiltration is dominant in the northern parts (15ºN – 20ºN latitudes) of the NSSA, with the tendency for root-zone

and deep-soil infiltration increasing as one moves southward across the grasslands, savannas, woody savannas, down toward the coastline and forested regions.

Over the years, the NSSA region has suffered frequent severe droughts that have caused tremendous hardship and loss of life to millions of its inhabitants due to the rapid depletion of the regional water resources, as exemplified by the dramatic drying of Lake Chad. Biomass-burning activity is believed to be one of the drivers of the regional water cycle because of the high concentration and frequency of wildfires in this region, as there have been over 10 times more satellite fire detections per unit area each year and the fire intervals are on the order of a few years compared to decades or centuries in parts of North America. A decreasing trend in biomass burning from about 2006 to the present showed a corresponding increasing trend in rainfall in West Africa but an opposite trend in East Africa. A cause-and-effect relationship has not yet been established, although it has been shown that the effect of wildfires on the water cycle can be expressed through changes in the surface water processes, including runoff and erosion. An interdisciplinary research effort sponsored by NASA is presently being focused on the NSSA region, to better understand possible connections between the intense biomass burning across the region and the water cycle. Based on detailed analysis of relevant satellite products for various parts of the NSSA region, we are finding significant covariance (positive or negative) between various parameters of the two phenomena, particularly fire radiative power fluxes, surface albedo, precipitation, and surface evaporation. In this presentation, we will discuss interesting results as well as the path toward improved understanding of the environmental change dynamics due to biomass burning and related surface water processes in the NSSA region.

Modeling Post-wildfire Sediment Availability, Supply, and Transport

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The rates of erosion and sediment transport on the landscape are controlled by the interplay between the erosive forces of surface runoff and the resisting forces of surface cover, modulated by the propensity of soils for erosion, and local availability of soils. Loss of surface cover by wildfires, and post-wildfire changes in the hydrologic response of basins often tip the long-term balance between erosive and resisting forces of landscapes, and could lead to extreme geomorphic response. The magnitude of the geomorphic response is strongly related to the availability of soils on hillslopes and sediment storage in channels. This talk presents a holistic view of modeling post-wildfire landscape response using the CHILD landscape evolution model (Tucker et al., 2001).

In CHILD storms can be generated statistically using the Poisson rectangular pulses rainfall model with three parameters: mean rainfall intensity, duration, and interstorm period, or observed rainfall can be used. At each model element soil moisture within a hydrologically active layer is modeled through the balance of input (infiltration) and output (evapotranspiration, ET, and leakage) fluxes, and lateral moisture exchange. Runoff is generated when the rainfall rate exceeds the soil infiltration capacity, or when the soil is fully saturated. Soil water repellence is represented by reducing the infiltration capacity of the surface, which gradually increases with the establishment of understory vegetation following wildfires. ET between storms is driven by the rate of potential ET (PET) reduced by a coefficient that reflects plant water stress calculated using soil moisture. Vegetation grows as a function of ET, and dies as a result of disturbances and aging.

Mass of sediment is conserved in each grid cell. Soil availability is limited to the depth of soil above bedrock (or saprolite). Soil production through weathering is modeled using the negative exponential model in which soil production decreases with soil depth. Fluvial incision and sediment transport are modeled following an excess shear stress formulation using overland flow discharge. Shear stress available for sediment detachment and transport empirically decreases with surface vegetation biomass. Hillslope diffusion follows the non-linear diffusion law. Local deposition occurs when sediment input from surrounding landscape is larger than the local sediment transport capacity. The model can be used as a numerical framework that can integrate field-scale empirical understanding for predicting landscape-scale eco-geomorphic dynamics. The model is used to for proof-of-concept simulations in a semi arid basin. A series of model runs are conducted to explore the factors that control post-fire sediment transport magnitudes, including fire frequency, storm properties, soil production rates, and illustrate the model's ability to simulate an actual fire-

related erosion event following the Cerro Grande fire in New Mexico. Model results provide information to help manage post-wildfire erosion and develop adaptations for climate change impacts in fire-prone landscapes.

Citation:

Tucker, G.E., Lancaster, S.T., Gasparini, N.M., Bras, R.L., 2001. The Channel-Hillslope Integrated Landscape Development model (CHILD). In: Harmon, R.S., Doe, W.W. III (Eds.), Landscape Erosion and Evolution Modeling. Kluwer Academic, New York, pp. 349-388,

Post-wildfire Debris Flows in Southern British Columbia

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A number of post-wildfire debris flows and other landslides occurred after the extreme wildfire season of 2003 in the southern interior of British Columbia. Such events had not been previously reported in Canada. Because of the concerns generated by these events, the BC Forest Service developed a risk analysis procedure for post-wildfire natural hazards in interface areas. As part of this work, we conducted a research project on areas burned by four large wildfires in 2007 and 2009, to examine runoff, erosion, and mass movement processes following wildfire.

Three of the research sites are in the Columbia Mountains, part of the "inland rainforest", which is characterized by high relief, dense coniferous forest (cedar, hemlock, spruce, fir), and a snowmelt-dominated hydrologic regime. One of the sites is in Douglas-fir and lodgepole pine forest of the drier Okanagan valley. These areas resemble parts of the western Rocky Mountain and intermontane plateau regions of the northwestern United States, although they typically have a longer winter, greater snowfall, and less intense summer rainfall. The 2-year, 30-minute rainfall intensity in the region ranges from 12 to 18 mm/hr. The historical natural fire regime varies across the region, ranging from 100-200 year stand replacement fires in the wetter Columbia Mountains, to 0-35 year low severity fires in the drier valleys. The region experiences hot, dry summers in some years, which can result in high-severity wildfires in those years. Most forest soils are derived from glacial deposits, and although soil erodibility has not been systematically measured, it may be lower than in environments characterized by residual soils.

Post-wildfire landslides observed in the study included debris slides (which may occur on open slopes, and are typically infiltration-triggered), and debris flows (saturated slurries which flow in steep, confined channels, and are typically runoff-triggered). Debris floods (sediment-laden floods with less than 50% sediment by volume, typically occurring in channels not sufficiently steep to support debris flows) were also observed. Although they are not landslides, they were included in the inventory as they form a continuum with debris flows, and the two can be difficult to distinguish on initial inspection. Rockfall is common following wildfire on steep slopes, but in this study, no individual rockfalls large enough to be termed landslides occurred.

In the four years following the 2007 and 2009 wildfires under study, eleven significant debris flow events occurred, one of which caused a fatality, as well as three debris slides. We have documented a total of 36 debris flows, debris slides, and debris floods following the 2003, 2007 and 2009 wildfires. Our observations on the causes of these events have improved our ability to assess the risks of post-wildfire landslides which can threaten public safety and infrastructure.

Post-wildfire landslides occurred in three seasons: spring, summer, and fall. Three types of weather event have triggered the landslides: spring snowmelt, high-intensity summer

rainstorms, and long-duration, low-intensity fall rainstorms. Drainage diversion or concentration by old logging roads was a significant factor in some events. Debris flows were by far the most common type of landslide, and the most common initiating mechanism was high peak flow in channels. Most sediment in these events was derived from the channels, not from erosion in burned areas. A variety of hydrologic changes contributed to the initiation of post-wildfire landslides, including increased snow accumulation, more rapid snowmelt, loss of forest floor, and water-repellent soils.

Estimates of debris flow volumes and surveys of source areas were made after events in accessible locations, for the 2007 and 2009 wildfires under detailed study. Nearby hillslope silt fence plots yielded 0.001 to 10 Mg/ha in the three years after the wildfires. Debris flow volumes ranged from a few hundred to 5000 m^3, which if averaged over the contributing drainage areas, represent yields of about 50 to 500 Mg/ha. Clearly defined initiation points were observed in the channels of most debris flows, which combined with measured yields demonstrate that most sediment originated in the channels, and that there was minimal contribution from eroded soil in burned areas. Some of the debris flows following the 2003 wildfires were much larger, up to 30,000 m^3. Although their source areas were not studied in detail, aerial observations indicated that most of the events originated at discrete points in the channel, and that most sediment was derived from channel erosion.

The maximum 30-minute rainfall intensities observed in the three years after the 2007 and 2009 wildfires ranged from 16 to 24 mm/hr. Some debris flow events occurred during moderate rainfalls, but most occurred in the spring in response to high rates of snowmelt. Increased snow accumulation and higher peak snowmelt rates were the most significant post-wildfire hydrologic impacts observed in the study, with respect to the likelihood of debris flows and other mass movement events. Following the 2003 wildfires, there were anecdotal reports of locally high (but unmeasured) rainfall intensities, which may have been responsible for some debris flow and flood events. Extensive water repellency was observed in several of the 2003 wildfires, and was believed to be an important factor in at least four events. However, strong water repellency was not common in the 2007 and 2009 wildfires, although soil burn severity was severe over much of the burned area as indicated by other measures.

The events following several recent severe wildfire seasons in southern British Columbia demonstrate that the likelihood of debris flows and other mass movement events in susceptible channels is significantly increased following severe wildfire in this northerly, snow-dominated environment. However, in most watersheds not affected by such events, only minimal increases in sediment yield have been observed.

How Does Post-Wildfire Water Runoff Become a Debris Flow? Insights from Observations and Modeling of Debris-Flow Surge Initiation, Magnitude, and Frequency

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Runoff during intense rainfall in burned watersheds can sometimes initiate highly destructive debris flows. While a variety of conceptual and physically based models have been proposed for this initiation process, there is a lack of consensus regarding the mechanics by which water runoff can transform loose sediment into flowing debris. To better understand this entrainment process we monitored flow stage and rainfall in the headwaters of two small catchments: a recently burned area in southern California (0.01 km^2) and a bedrock-dominated alpine basin in central Colorado (0.06 km^2) that has a similar hydrologic response to rainfall as the burned areas in southern California. Stage observations at both sites display distinct patterns in debris-flow surge characteristics relative to rainfall intensity (I). We observe small, quasi-periodic surges at low I; large, quasi-periodic surges at intermediate I; and at high I, a single large surge is followed by small-amplitude fluctuations about a more steady high flow. Video footage of surge formation lead us to the hypothesis that these flow patterns are controlled by upstream variations in channel slope, in which low-gradient sections act as "sediment capacitors," temporarily storing incoming bedload transported by water flow and periodically releasing the accumulated sediment as a debris-flow surge. To explore this hypothesis, we develop a simple one-dimensional morphodynamic model of a sediment capacitor that consists of a system of coupled equations for water flow, bedload transport, slope stability, and mass flow. This model reproduces the essential patterns in surge magnitude and frequency with rainfall intensity observed at the two field sites and provides a new framework for predicting the runoff threshold for debris-flow initiation in a burned area.

Modelling the Distribution of Sediment Loads from Post-wildfire Debris Flows in SE Australia

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The inherently random spatio-temporal overlap of wildfire and intense rainfall drives the processes that lead to characteristic sediment load distributions in burned, forested catchments. Recent studies have shown that in SE Australia high magnitude loads are caused by debris flows, rather than by 'regular' erosion, and that these debris flows are not as infrequent as previously thought. We present a probabilistic model that calculates the distribution of annual loads from debris flows based on this recent system understanding and data. In a Monte-Carlo simulation, fire weather conditions and fire initiation probabilities are randomly sampled from a 40-year database of wildfires in Eastern Victoria. If sampled, a wildfire is initiated at a random location in the vicinity of the catchment of interest, and simulated with PHOENIX, a deterministic fire-spread model (Tolhurst et al., 2008). Rainfall is simulated on a 5x5 km grid, which was observed to be the typical extent of a high-intensity burst of a storm causing debris flows. Assuming independence of each storm covering the catchment area, the yearly maximum intensity of a 12 minute duration burst is sampled from an Intensity-Frequency-Duration curve for each cell and used for deterministic stream power calculation in headwater catchments of ca. 2 ha. Sediment availability was modelled with an exponential decay function with time after wildfire on data for different burn conditions and forest types. We use modelled stream power and measured available sediment of observed debris flows to determine critical combinations of stream power and sediment availability that initiate debris flows, and use tested empirical formulations for debris flow volume calculations at the larger sub-catchment scale. Application to a catchment of 337 km² yielded a probability distribution of approximately exponential shape, and long-term denudation rates of 10-73 mm ka^{-1}, from the dominant debris flow process, corresponded well with previous estimates in the region.

Citation:

Tolhurst, K.G., Shields, B.J., Chong, D.M., 2008. PHOENIX: development and application of a bushfire risk management tool. Australian Journal of Emergency Management 23: 47-54.

Scaling of Post-wildfire Debris Flows: Relationships to Aquatic Ecology and Atmospheric Processes

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While extreme events (floods and debris flows) are rare in individual streams or reaches an extreme event is commonplace somewhere within an ensemble of streams. The relation between event frequency and magnitude depends on the size of area considered and the spatial continuity of events. Some of the more extreme geomorphic events affect only a limited spatial area. Area limitations relate to the spatial extent of event triggers such as wildfires, thunderstorms, or rain-on-snow. Understanding the spatial extent of extreme events is important in approaching the frequency-magnitude relation for burned areas ranging from a few square kilometers to a few thousand square kilometers and clarifying the role of extreme events at different spatial scales. Sequential mapping of channel reorganizing events from aerial photography records dating back 40 years in the Boise River basin reveal important characteristics of severe disturbances in a spatial context. The most relevant to this discussion is that there is little coherence in extreme events beyond 10 km of stream distance. Patterns of presence and absence for fish species occupying these streams may reflect historic patterns of extinction and colonization following catastrophic disturbance. These patterns and recent data on apparent gene flow among streams suggest that scaling of ecological processes is concordant with the patterns of channel disturbance we have identified here. There is evidence that this scale relates more to the scale of driving convective storms than to pre-existing land disturbances such as wildfire, logging, or grazing. The spatial extent of events may serve as a valuable metric of event magnitude to gauge their ecological influence.

Causes of Post-wildfire Runoff and Surface Erosion: What we Know and What Should we do?

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Numerous studies have documented the dramatic increase in surface runoff and erosion after high-severity wildfires, but the underlying cause(s) are still a matter of considerable controversy. The observed increases in runoff have been variously attributed to: 1) increased soil water repellency (SWR); 2) soil sealing, which itself is a complex function of the loss of cover, physical soil characteristics, and presence of ash; 3) hyper-dry conditions immediately after burning; 4) reduced surface roughness and resulting increase in overland flow velocities. The increase in surface erosion is generally attributed to the increased surface runoff, and this view is supported by some studies showing rilling and gullying--rather than rainsplash and sheetwash--to be the primary source of post-fire sediment. However, other processes contributing to the increase in erosion include: 1) reduced aggregate stability and changes in the particle-size distribution due to soil heating; 2) increased rainsplash due to the loss of surface cover and afore-mentioned changes in particle-size distribution. The problem is that most studies have documented associations rather than process-based explanations, the dominant processes can change over time, and the dominant controls probably vary with site conditions and burn severity. Hence the objectives of this poster are to: 1) summarize existing knowledge in order to better identify the key processes; and 2) suggest a series of experiments to more precisely identify the controlling processes under different site conditions and over time.

Soil water repellency (SWR) has been commonly cited as the primary cause of the observed increase in runoff, but this is called into question by the high spatial variability observed in the field, the longer persistence of the increased runoff and erosion relative to the duration of the fire-induced SWR, and the fact that mulching greatly reduces erosion but does not greatly alter the underlying soil. Studies from both untreated and mulched areas consistently show a strong linkage between percent bare soil and erosion rates, but these observational studies do not clearly identify the underlying mechanism(s) at the pore scale. Soil sealing has been suggested as a primary cause of the increase in runoff and erosion, but soil sealing is itself the consequence of multiple interacting factors. Ash has been shown to protect the soil surface, absorb rainfall, and induce sealing, but the ash is very transient and the results are not always consistent.

A series of experimental manipulation experiments and modeling studies at the pore, plot, and hillslope scale are needed to help untangle the multiple interactions and contributing factors. Examples might include: 1) rainfall simulations with a mixture of water and ethanol to eliminate the effect of SWR; 2) rainfall simulations with a mesh suspended just above the plot to absorb raindrop energy and eliminate the effect of rainsplash; 3) repeated rainfall simulations in the lab or on fixed plots in the field to identify the conditions under which soil sealing occurs; 4) removing the surface cover from unburned plots followed by rainfall simulations to isolate the effect of cover from other post-fire changes; 5) conducting lab or field experiments where mulch is placed either on the hillslopes but not in convergent rills, or

vice versa; this could help separate the role of rainsplash and sheetwash from rilling and gullying; 6) use physically-based models to quantify the changes in peak flows and surface erosion at different spatial scales that could result from just changing surface runoff velocities without altering the other soil and cover factors that are normally affected by wildfires; and 7) a similar modeling approach could be used to quantify the individual and interacting effects of some of the other key soil and cover changes following wildfires. The combination of such experiments and modeling studies, when conducted in different environments, could greatly help us to disentangle the present confusion over the relative contribution of different post-fire changes to the observed increases in runoff and erosion. It is hoped that this poster can help stimulate proposals to conduct such studies.

An Idealized Model of Plant and Soil Dynamics

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Following wildfire events the landscape commonly becomes denuded of vegetation cover, resulting in systems prone to soil loss and degradation. In this context soil dynamics are an intricate process balanced between pedogenesis, a relatively slow process, and erosion which depends on many inert (e.g. soil texture, slope, precipitation and wind) and biological factors such as vegetation properties, grazing intensity, and human disturbance.

We develop a simple homogenous model of the global dynamics of the interactions between vegetation and soil using a system of two nonlinear differential equations describing this interdependence, assuming a double feedback between plants that control erosion and soil availability that facilitates plant growth:

$$\frac{dV}{dt} = rV\left(K - \frac{K}{1+aS} - V\right) \qquad (1)$$

$$\frac{dS}{dt} = \sigma - \varepsilon S e^{-cT} \qquad (2)$$

where V and S represent vegetation cover and soil availability, respectively. Vegetation growth is similar to the classical logistic model with a growth rate of r (yr^{-1}), however, the "carrying capacity" (K) is dependent on soil availability (a^{-1} is the amount of soil where vegetation is reduced by half). Soil influxes at a constant rate σ ($mm \cdot yr^{-1}$) and is eroded at a constant rate ε (yr^{-1}), while vegetation abates this process modeled as a decreasing exponent of the effectiveness of vegetation in reducing soil erosion (c). Parameter values were chosen from a variable range found in the literature (r = 0.01 yr^{-1}, K = 75%, a^{-1} = 1, σ=1 $mm \cdot yr^{-1}$, ε = 0.1 yr^{-1}, c= 0.08).

Complex properties emerge from this model. At certain parameter values ($cK \leq 4$) the model predicts one of two steady states – full recovery of vegetation cover or a degraded barren environment. Boundary conditions exist where bi- stability arises and the system may change states ($cK>4$ and $\lambda_1 \leq \sigma/\varepsilon \leq \lambda_2$, where λ is an expression relating c, K and a). We propose that erosion rate seems to be the determining factor moving the system to the different outcomes.

The model predicts that certain ecosystems will be highly stable in one of two states – maximum or minimum vegetation (vegetated or denuded of vegetation), while others might be bi-stable transitioning between these two states through changes in parameter values. This bi-stability is an indicator of hysteresis, possibly indicating the ability of the system to shift leading to sudden and dramatic changes; and in doing so this model formalizes the concept shown by Davenport et al. (1998) and others. Following the establishment of these interrelationships, the role of disturbances, such as wildfires, was

simulated. Repeated wildfires that mimic forced perturbations of the numerical solution can cause the system to cross the separatrix, separating the basins of attraction of the two stable states. In this scenario, the model predicts that the system will ultimately converge on the minimally vegetated steady state, and therefore, the long term dynamics of this coupled soil-vegetation dynamical system. We demonstrate this for various wildfire regimes.

The Post-wildfire Response Domain in the Pacific Northwest Region of Oregon and Washington, U.S.A.

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To facilitate comparisons of post-wildfire hydrologic and erosional responses from disparate areas across the globe, a conceptual model called the post-wildfire response domain has been proposed by Moody et al. (2013). A post-wildfire response domain is comprised of the fire regime, precipitation regime, and hydro-geomorphic regime. A description of the components of the Pacific Northwest post-wildfire response regime is the purpose of this presentation. The Pacific Northwest is a geographical region in Washington and Oregon in the western United States that is bounded by the Pacific Ocean on the west and the crest of the Cascade Mountains on the east. The southern extent of this region is delimited by the Klamath Mountains on the border between California and Oregon. The northern part of the region has no defining geographical barrier but shares some similarities with an adjacent zone stretching from the Canadian border northward along the coast of Alaska (Bailey, 1998; Marine Ecoregion Division M240). The mountainous belt closest to the Pacific Ocean, the Oregon and Washington Coast Ranges, is separated from the more eastward Cascade Mountains by a flat, intra-mountain zone known as the Willamette Valley in Oregon and the Puget Trough in Washington. In northern Washington the coastal area is dominated by the Olympic Mountains. The elevation of this region ranges from sea level to over 4,500 meters. Except for the oak woodlands in the Willamette Valley, the vegetation is primarily coniferous with areas of hardwood trees in riparian areas and dry valley margins (Cohen et al. (2002).

The Pacific Northwest exhibits a complicated pattern of fire regimes. The Coast Range of Oregon, the middle to northern Cascade Mountains, and the Olympic Mountains have a high-severity regime characterized by infrequent (>100 years), high-intensity, stand-replacing fires (Agee, 1990). The west-central Cascade Mountains, San Juan Islands and Puget Trough, and the mid-elevations of the Cascade Mountains have a moderate-severity fire regime with a fire return interval of 25-100 years, partial stand replacement and a mosaic of high and low burn severity (Agee, 1990). Areas that have a low-severity fire regime are primarily the oak woodlands of the Willamette Valley (Agee, 1990). These oak-dominated areas had frequent, low intensity fires with a natural frequency of <25 years. Recently, a more complex mixed severity fire regime has been proposed to characterize the intra-mountain and western Cascade zones (Perry et al., 2011). This mixed severity fire regime has a distribution of high and low severity patches, gradients between those patches, and controls exerted by aspect and elevation. According to Perry et al. (2011), mixed severity fire regimes are poorly understood and documented, but the conceptual underpinning of the term allows a better description of the highly variable effects of fire seen in large areas of the landscape and may explain some of the variability in post-wildfire responses.

The rainfall regime of the Pacific Northwest is classified as Pacific, Medium (Moody and Martin, 2009) with a seasonal distribution of precipitation with a maximum in the winter and a summer minimum. The range of typical 2-year return interval, 30-minute rainfall

intensities is 20 to 36 mm hr^{-1}. Mean annual rainfall amounts range from 3,000 mm in the coastal mountain areas to 1,000 mm in the flat intra-mountain zone, although precipitation over 6,350 mm has been recorded in the Olympic Peninsula (Franklin and Dryness, 1973). A trend of more precipitation falling as rain instead of snow has been documented in this area for the period 1949-2004 (Knowles et al., 2006), which has implications for: (1) the length of the window of vulnerability for post-wildfire erosion (Moody and Martin, 2009), and (2) the sediment availability, i.e. the balance between the rates of soil production and removal of soil by post-wildfire erosion (Roering and Gerber, 2005). Furthermore, the Pacific Northwest has rain-on-snow events, with higher elevations more susceptible than lower elevations (McCabe et al., 2007), which may result in an increase in post-wildfire runoff and erosion associated with this type of event.

As defined by Moody et al. (2013), the hydro-geomorphic regime is a function of the topographic slope, soil hydraulic properties, soil and sediment erodibility, and sediment supply. In the Pacific Northwest, this regime is influenced by the geologic history of the Pacific Northwest and the active tectonism. The region is at the western edge of the North America plate and the Cascadia subduction zone where the Juan de Fuca plate plunges under the continent is only 80 km offshore. Coastal areas are steep and tectonically active, and when subjected to high precipitation amounts, are susceptible to landslides and soil creep. Slopes in the Cascade Mountains are also steep. An early study (Sartz, 1953) documented splash erosion from raindrop impact as one style of post-wildfire response in the Oregon Coast Ranges. Later studies in the Oregon Coast Range (Bennett, 1982; Roering and Gerber, 2005; Jackson and Roering, 2009) measured dry ravel (in this relatively wet regime) during or immediately after wildfire that created colluvial wedges of sediment. Landslides can mobilize the wedges of sediment for several years after a wildfire. Debris flows are another response during this time period, resulting from the eventual failure of roots of trees burned during the wildfire. Moreover, saturated soil conditions resulting from the high mean annual precipitation promote debris flow and landslide responses. Dry ravel was also measured immediately after wildfire in the western slopes of the Oregon Cascade Mountains, and the sediment transport was shown to be more substantial during the dry season than wet season, especially on south-facing slopes (Mersereau and Dyrness, 1972). Overland flow was minimal as a result of low rainfall intensities and high soil permeabilities. This suggests that water repellency and runoff-related erosion are not the primary mechanisms that produce post-wildfire responses in the Pacific Northwest. Rather, post-wildfire soil transport is a function of slope steepness, soil saturation, aspect, and vegetation cover (Mersereau and Dyrness, 1972). Given the small-scale spatial variability (1- 10^4 m^2) of soil types, soil erodibility (K-factor, Renard et al., 1997), slopes, and aspect in the entire region, it is difficult to make any large-scale generalizations about the hydro-geomorphic regime using the metric (product of slope and the soil erodibility factor, K) suggested by Moody et al., 2013.

One rather surprising conclusion that can be drawn from the limited set of studies in the Pacific Northwest is that post-wildfire responses may be established during dry conditions, but triggered during wet conditions. Thus, dry ravel is an important post-wildfire erosion response in the first year after wildfire, accounting for 10-20% of the long-term erosion in the Oregon Coast Range (Jackson and Roering, 2009). But several years after wildfire, debris flows and shallow landslides are the dominant post-wildfire erosion

responses, promoted by high infiltration rates (Sartz 1953; Mersereau and Dyrness, 1972) and subsequent soil saturation. Although steepness (slope) plays a definitive role, the K-factor does not capture the sensitivity of the soils to the dominant post-wildfire erosion mechanisms (dry ravel, debris flows, and landslides) and, therefore, the suggested hydro-geomorphic metric may not be appropriate in the Pacific Northwest post-wildfire response domain. Overall, the steep slopes, high mean annual precipitation (rather than low rainfall intensities), high infiltration rates and long fire recurrence intervals are probably adequate discriminators of the post-wildfire response domain of the Pacific Northwest, and would allow useful comparisons and contrasts with other post-wildfire response domains across the globe.

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Wildfire Burn Severity Assessments from Satellite Data: A Review of Available Products and User Considerations

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Burn severity assessments are available for an increasing number of US wildfires. The US Geological Survey and US Forest Service share responsibility for the Monitoring Trends in Burn Severity (MTBS) and DOI Burned Area Emergency Response (BAER) programs that use satellite imagery to produce nationally consistent burn severity products used by the fire management, rehabilitation, and post-wildfire effects research communities. When mapping a specific wildfire the MTBS and/or DOI BAER programs generally create a suite of images or GIS data layers including:

Postfire image – This image is generally derived from Landsat Thematic Mapper TM, Enhanced TM (ETM) or the Operational Land Imager (OLI) satellite data and processed to standards that include a top of atmosphere (TOA) reflectance correction. In limited cases when Landsat data are not available other satellite data may be used. MTBS post-wildfire scenes are selected for either an initial or extended mapping assessment. An initial assessment is typically conducted with a post-wildfire image acquired within a few weeks to months following a wildfire. This assessment type is especially relevant for ecosystems that exhibit a rapid post-wildfire vegetation response (i.e., herbaceous and shrubland systems) that may obscure the extent of the wildfire in a relatively short period of time. The extended assessment is generally conducted with post-wildfire imagery acquired during the growing season following a wildfire in order to capture the delayed first order effects (e.g., latent tree mortality) and dominant second order effects that are ecologically significant (e.g., initial site response and early secondary effects). For the DOI BAER program, post-wildfire images are acquired immediately after fire containment, to facilitate for the generation of assessments within the window of time required by BAER teams, usually 1 -14 days after containment. Due to BAER team reporting time constraints, imagery selected for DOI BAER assessments may be less than optimal due to clouds, shadows, smoke, and active fire.

Prefire image – These images are generally derived from Landsat (TM/ETM/OLI) data and processed to standards that include a top of atmosphere (TOA) reflectance correction. Pre-wildfire images are selected to match the seasonality and phenology of the post-wildfire image regardless of the assessment type. Due to the availability of multiple pre-wildfire images the images are usually free of smoke, cloud/shadow, and active fire.
NBR/dNBR/RdNBR image (s) – Images showing continuous burn severity are derived for each wildfire. If a wildfire was mapped using only a post-wildfire image generally a normalized burn ratio (NBR) image is provided. Most often, pre- and post-wildfire images are available and differenced NBR (dNBR) and/or relative dNBR (RdNBR) images are derived to characterize continuous burn severity. When non-Landsat images are used to assess a wildfire, it is likely the alternative satellite image will not possess a short wave

infrared (SWIR) band similar to band 7 for Landsat 7 and 8 satellites. In these cases the normalized difference vegetation index (NDVI) may be used to derive a continuous burn severity index.

Thematic Burn Severity image – This image is a thematic map depicting severity as unburned, low severity, moderate severity and high severity. The image may also possess increased greenness (increased post-wildfire vegetation response) and no-data (clouds, shadow) classes. For DOI BAER program assessments a 256 class thematic map is also distributed. This map is derived by rescaling and slightly compressing the full precision dNBR image (integer format) to a byte or 0-255 image. Thresholds are then selected to characterize non-burn, low severity, moderate severity, high severity and a non-data class if required. This map is easily adjusted by BAER team GIS staff if local expertise, field sampling or other local information is available to further refine the burn class thresholds.

Fire Perimeter – The MTBS program routinely generates a fire perimeter derived by interpreting the post-wildfire and NBR/dNBR/RdNBR images. The perimeter is distributed in ESRI shapefile format. The DOI BAER program generally does not distribute a perimeter file as most wildfire incidents have an official perimeter established at the event. Local fire management staff may use all delivered images to adjust or refine the official fire perimeter.
FGDC Metadata – For MTBS, FGDC-compliant metadata is provided in two file formats (text and XML documents) that include the geospatial information and associated datasets used to map the fire. . The DOI BAER program provides only a metadata text file.
Fire Maps – For the MTBS program, two visualization products are created for each wildfire, one in PDF format and another in KMZ format. The PDF map portrays the post-wildfire image and fire severity summarized by severity class and associated acres. The KMZ map displays pre-wildfire, post-wildfire, fire severity and burn perimeter layers. The DOI BAER program provides only a post-wildfire image in “jpg” format.

For proper use of the products described above it is essential users understand these products in terms of available geographic coverage, specific processing methodologies, timing of assessments, and variations in source data quality, assessment comparability, and calibration.

Post-wildfire Response Domains and the Relative Importance of Post-wildfire Erosion in the USA Rocky Mountains

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Conifer forests predominate in the Rocky Mountain region of the western USA, but a wide range of elevation (1000-3500 m) and latitude (32°N to 49°N) has generated a diverse set of conifer communities, fire adaptations, and associated fire regimes. Frequent low-severity wildfires recurring on timescales of a few years to a few decades have been typical of ponderosa pine (*Pinus ponderosa*) stands at lower elevation (~1000 m at 49°N to ~2300 m at 32°N), a species well-adapted to survive surface fire. These low-severity wildfires are usually associated with limited erosional response, but various studies indicate that high-severity stand-destroying wildfires and major erosion have impacted ponderosa forests in the late Holocene, in particular during megadroughts, and severe wildfires have become more common in recent decades with historic fire suppression, rising temperatures, and severe drought. Mixed conifer stands including Douglas-fir (*Pseudotsuga menziesii*) are common in middle elevations (~1500 m at 49°N to ~2800 m at 32°N) and experience wide spectrum of fire frequency, from a decade or less in open stands in dry environments, to several hundred years in very moist settings, thus severity and erosional response can vary markedly. Dense stands of lodgepole pine (*Pinus contorta*) are common in high-elevation (up to 3400 m) and colder regions of the Rocky Mountains from Colorado north, where high-severity fires at long intervals of 200-400 years or more are often followed by major erosion and debris-flow generation. These trees lack adaptations to survive wildfire, but regenerate very effectively following severe stand-destroying fire. Wildfire also infrequently extends into the subalpine zone (~1800 m at 49°N to ~3500 m at 32°N), characterized by long-lived whitebark (*Pinus albicaulis*) and limber pines (*Pinus flexilis*) and subalpine fir (*Abies lasiocarpus*) in the central Rocky Mountains. Severe fires can also affect piñon-juniper communities (*Pinus edulis-Juniperus sp.*), deciduous aspen (*Populus tremuloides*) and Gambel oak stands (*Quercus gambelii*), and low-elevation sagebrush-grasslands, but erosional responses are less understood. Across different vegetation types, the steep slopes and confined canyons of many Rocky Mountain landscapes increase the "chimney effect" and thus the probability of severe wildfire.

Rocky Mountain precipitation regimes are characterized by overall low to moderate annual totals (500-1800 mm), where total precipitation, the proportion falling in winter, and the proportion as snow all generally increase with elevation. The relative importance of summer precipitation is thus greater at lower elevations, and also tends to increase toward the south and east with the greater influence of Gulf of Mexico moisture and the North American Monsoon. In all areas, however, major post-wildfire erosion and flood and debris-flow generation is most commonly associated with rain falling on severely burned slopes in short-duration and low-recurrence interval (2-5+ yr) summer convective storms. In such storms, high rainfall intensities maintained over periods < 10 minutes may be sufficient for major surface runoff generation leading to debris flows and floods; this set of processes dominates post-wildfire erosion. Field evidence suggests that greatly enhanced surface runoff is primarily a function of surface sealing processes and increased connectivity and smoothness

of overland flow paths on steep slopes when vegetation and litter cover is removed. Soil water repellency likely plays a role, but several field studies indicate it was not a key factor in runoff generation (e.g., Meyer and Wells, 1997; Cannon, 2002; Larsen et al., 2009). In general, those basins with high relief, steep slopes, and erodible soils lacking a rocky mantle and with smooth and well-connected flow paths in the post-wildfire condition are most prone to erosion. The contribution of slope erosion relative to channel incision appears to be minor in most post-wildfire debris-flows and floods, but this may stem in part from the difficulty of making accurate slope erosion measurements in unmonitored basins. Rapid evolution of the burned soil surface in the first few years after wildfire may also exert a strong influence on surface runoff generation, erodibility, and fine sediment availability important in controlling flow rheology.

Less commonly, heavy rain-on-snow events during major winter frontal storms have caused post-wildfire erosion in the form of shallow landslides, promoted by the loss of root cohesion with fire mortality and eventual decay. These infiltration- and saturation-induced landslides have a less certain link to fire effects, but have been observed in much greater frequency in burned areas than in adjacent unburned terrain. Dry ravel may be an important erosional process in areas of noncohesive soils (e.g. grus), but field observations suggest that it is mainly active in the raveling of gully walls of incised channels after post-wildfire floods and debris flows, helping to reload them for subsequent events. Geologic and geomorphic controls are quite variable in the region, e.g. relatively low relief and gentle slopes resulted in limited post-wildfire erosion over much of the central Yellowstone volcanic plateau, despite dramatic erosion in adjacent steeplands after the severe wildfires of 1988. In contrast, the granitic batholith region of central Idaho is characterized by continuous mountain ridge and canyon topography with a high percentage of the landscape susceptible to post-wildfire erosion.

Measurement of stratigraphic sections containing Holocene fire-related deposits in small valley-side alluvial fans provides a means to estimate the relative importance of post-wildfire erosion compared to other erosional processes in postglacial times. All estimates, however, are influenced by the fact that a significant proportion of modern fire-related fan deposits show no evidence of a post-wildfire origin (so % fire-related is underestimated), and that fire-related deposits are likely oversampled in nonrandom investigations (so % fire-related is overestimated). Fire-related deposits make up about 28% of the total thickness of alluvial deposits in the Sacramento Mountains of southern New Mexico, where fine-grained sedimentary rocks are susceptible to weathering and erosion in the unburned state, and precipitation in the relatively strong North American Monsoon both limits the fire season and promotes erosion, along with occasional prolonged heavy rains from dying tropical cyclones. In contrast, ~57% of deposits are fire-related in fans of the Jemez Mountains in northern New Mexico, where infiltration in the volcanic landscape may be generally higher in an unburned condition, and the summer monsoon is somewhat less active than in southern New Mexico; thus wildfire has a greater relative importance in promoting erosion. In northern Yellowstone steeplands, fire is responsible for about 33% of fan sedimentation, where high relief on exposed, erodible volcaniclastic rocks produces debris flows in the absence of wildfire. In the central Idaho batholith area, a more continuously soil-mantled landscape, ~50% of the fan sediment thickness consists of fire-related deposits. Overall, these estimates

of the fire-induced contribution to overall sediment yield are broadly consistent with those expected for Rocky Mountain landscapes within Swanson's (1981) conceptual model, as controlled by fire regime and geomorphic sensitivity.

In addition, within a given area, slope aspect may be a strong control on both the fire regime and relative importance of post-wildfire erosion. In comparison to southerly aspects in the Jemez Mountains study area, moister north-facing slopes have denser mixed conifer stands, greater soil and colluvium cover and higher infiltration rates, and undergo lower frequency-higher severity wildfires, resulting in ~77% of fan thickness from fire-related deposition. In contrast, south-facing slopes have more open ponderosa stands and a greater percentage of runoff-generating bare soils and exposed bedrock. These slopes readily produce sediment in an unburned condition, thus only about 39% of fan deposits below these slopes are fire-related. These observations suggest that post-wildfire erosion and hazard predictions may be expected to vary markedly with aspect on small spatial scales.

Postfire erosion is not in steady state in any of these areas, and is strongly influenced by climate change on ~10^2-10^3 yr timescales. Although large fire-induced debris flows have been relatively few in number in central Idaho over the last 2000 years, about 25% of the total fan deposit thickness resulted from these major debris flows in warmer Medieval times ~950 to 1150 CE, associated with severe megadroughts. Most areas where a significant sample of post-wildfire deposits have been dated show clustering of major events within warmer intervals and drought episodes in the Holocene, but fire regimes and erosion have also been influenced by long-term changes in forest composition. Fire-induced erosion has clearly become more evident along with rising temperatures and widespread severe wildfires in the Rocky Mountains over the last few decades, and will likely continue to increase in both relative importance and overall magnitude.

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Rapid Response Tools and Datasets for Post-fire Erosion Modeling: Lessons Learned from the Rock House and High Park Fires

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Once the danger posed by an active wildfire has passed, land managers must rapidly assess the threat from post-fire runoff and erosion due to the loss of surface cover and fire-induced changes in soil properties. Increased runoff and sediment delivery are of great concern to both resource managers and the public. On federal lands post-fire assessments and proposals to mitigate these threats are typically undertaken by interdisciplinary Burned Area Emergency Response (BAER) teams, while local teams are formed to address issues on burned lands managed by state and local governments. These teams are under very tight deadlines, so they often begin their analysis while the wildfire is still burning and typically must complete their plans within a couple of weeks. Many modeling tools and datasets have been developed over the years to assist BAER teams, but process-based and spatially explicit empirical models are currently under-utilized relative to simpler, lumped models because they are both more difficult to set up and require the preparation of spatially-explicit data layers such as digital elevation models, soils, and land cover. We are currently working to change this by preparing spatial data sets ahead of time that can be rapidly combined with burn severity maps and then used in spatially explicit process-based and empirical models for predicting post-fire erosion and run-off. Data is being gathered to support three models: GeoWEPP (Renschler 2003) used with Disturbed WEPP (Elliot 2004) input parameters, Ravel Rat a dry ravel model currently under development (Fu 2004), and for a spatial empirical debris flow model (Cannon et al. 2010).

These models share a common purpose of predicting post-fire erosion and a need for spatially explicit input data. The required inputs differ from model to model, for example Ravel Rat simulates sediment movement under the force of gravity alone, therefore rainfall and infiltration rates are not considered. However, all three models must address sediment availability and the quickest way to do this over a large wildfire is to use a burn severity map derived from remotely sensed data to help parameterize model inputs. Many methods exist for mapping burn severity, but the most widely accepted is the differenced Normalized Burn Ratio (NBR) algorithm (Key and Benson, 2006), which has been shown to be well correlated with field measurements of burn severity (Robichaud et al. 2007). These remotely derived maps rapidly provide spatial information on surface changes, but care must be taken in their application as optical measurements of surface change are not direct measurements of important model parameters such as post-fire surface cover and effective hydraulic conductivity. Whenever possible, the burn severity maps are improved upon by reclassifying the maps using field observations gathered by the BAER teams.

Sediment availability within the Ravel Rat model is dependent upon slope, vegetation density, vegetation stem diameter, angle of repose of the sediment, and burn severity. Sediment is assumed to be trapped behind plant stems and under roots on slopes that are

greater than the sediment's angle of repose. The amount of sediment available for transport is assumed to be related to burn severity as a high severity wildfire will consume the most vegetation and therefore be capable of releasing the most sediment for transport. The empirical debris flow model developed by Cannon et al. 2010 found that the area of a basin burned at moderate and high burn severity was a significant predictor of both debris flow probability and volume. In the WEPP model, burn severity is incorporated by changing several important parameters that impact modeled sediment availability. Reductions in surface cover due to a wildfire are modeled as part of the vegetation component. Currently the Disturbed WEPP model supports four soil textures (sand, clay, silt and loam) with two different levels of burn severity, low or high. The impacted parameters include increased soil albedo, increased rill and interill erodibility, and decreased effective hydrologic conductivity. These parameter changes lead to increased sediment availability and transport within the model.

Storms in the spatial empirical debris flow model are represented by total storm precipitation (mm) and intensity (mm/hr). To support the debris flow model we have reformatted spatial data layers from the NOAA Atlas 14 precipitation grids, as these maps provide statistical storm estimates of total precipitation for a given duration storm and a specified return interval. These NOAA data sets were created using historical weather station data and the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly *et al.* 1997), which used point station data, a digital elevation model, and other spatial data sets in order to generate spatial climate parameters. Currently we are not providing climate data for the WEPP based models as current data sources are readily available and fairly easy to use. In WEPP rainstorms can be characterized using real weather and climate data or these parameters can be simulated using the built in stochastic weather generator Cligen (Flanagan and Nearing 1995) to forecast the information needed to model run-off and erosion (mean daily precipitation, minimum and maximum daily temperatures, dew point, mean daily solar radiation, and mean daily wind speed and direction). Cligen is based on weather data from over 2,600 stations and can be modified using Rock:Clime (Elliot *et al.* 1999, http://forest.moscowfsl.wsu.edu/fswepp/) and PRISM to account for spatial variation and elevation effects.

Assembling the data needed to run spatially explicit erosion models can be a daunting task even without time constraints, therefore preparing the required input data ahead of time makes sense. We will demonstrate the benefits of being prepared by comparing two modeling examples from two recent wildfires. The first wildfire is the 2011 Rock House fire that burned 127,500 ha (315,000 acres) in Presidio and Jeff Davis Counties, Texas. This wildfire impacted a small national historical site - Fort Davis,which is located in a small watershed called Hospital Canyon (217 ha; 536 acres). Even though the area that needed to be modeled was small, the time needed to reformat soil and vegetation data for modeling in GeoWEPP meant that predictions could not be completed in a timely fashion for the National Park Service BAER team. In 2012 when the High Park fire burned 35,300 ha (87,200 acres) in Larimer County, Colorado the spatial soil, land cover and DEM layers were already prepared along with a methodology for rapidly merging satellite derived burn severity maps with the soil and vegetation data. The entire burn scar for the 2012 High Park fire was modeled in GeoWEPP in less than three days allowing the predictions to be available for

operational use by the BAER team. These two case studies clearly demonstrate the efficacy of preparing both the tools and datasets before they are needed.

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Modeling Wildfire Effects on Sediment Availability on Hillslopes

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Wildfires can increase sediment availability (amount and erodibility) on hillslopes in two ways. First, by producing a layer of non-cohesive material consisting of ash, and second, by exposing cohesive soils to high temperatures, which lowers the critical shear stress such that the fire-affected soil become non-cohesive. The ash layer combined with the layer of fire-affected soil creates a 'new' non-cohesive layer. The potential for wildfires to impact sediment availability; however, depends on the pre-fire soil conditions. For instance, an unstructured sandy soil with low cohesion would display a relatively small potential for an increased in sediment availability as a result of wildfire whereas there would be a relatively large potential for change in a cohesive, structured clay loam. A small potential for change in sediment availability implies that any observed changes in hillslope erosion rates as a result of wildfire is probably caused by changes in runoff processes rather than by changes in the sediment availability. The relative importance of sediment availability versus detachment and re-suspension has large implications for the exact mechanism by which wildfires trigger increased erosion and on the type of processes likely to be operating in systems recovering from wildfire. Current models of sediment availability on hillslopes that assume erosion is constant with depth are inherited from agricultural systems (where soils are relatively homogenous). This approach is poorly suited for representing first-order wildfire effects from the combustion and heating of soil.

Laboratory and field experiments were designed to understand the spatial and temporal changes in sediment availability or erodibility. The objectives of these experiments were:

i) to measure detachment rates as a function of depth below the surface soil in controlled laboratory experiments, and to evaluate the effect of roots (which secrete organic binding agents) and soil physical properties on detachment rates,
ii) to evaluate the temporal changes in sediment availability by using field erosion plot experiments with concentrated flow, and

iii) to link sediment availability to soil shear strength as a practical and relatively easy field measurement to make that could be incorporated into a standard set of sediment measurements.

Sediment erodibility of the 'new' non-cohesive surface layer varies spatially (i.e. with depth into the soil) and temporally after a wildfire. In fire-affected soil cores tested in a laboratory flume, there was an exponential decrease in erodibility, k_d (sediment flux per unit width / shear stress with units s m^{-1}) with depth that tended toward a constant erodibility of between 1.0 and 2.0 $\times 10^{-4}$ s m^{-1} at a depth of ~0.02 m. This depth of the non-cohesive surface layer represents an important source of available sediment during the post-wildfire period, particularly shortly after the initial burn impact. Additionally, these laboratory experiments indicated that root properties represent an important variable that can be used to predict erodibility, of fire-affected soil as a general linear model using root density, *RD* [kg m^{-3}] depth below the surface of the soil,d_s [m] and a term representing the interaction of depth and root density with the form:

$$\ln(k_d) = \beta_1 + \beta_2 d_s + \beta_3 RD + \beta_4 d_s RD + \varepsilon$$

where the βs are coefficients and ε is an error term.

Over short-time scales (seconds to minutes), the availability of non-cohesive soil in field erosion plots decreased exponentially with time due to depletion and exhaustion of the non-cohesive material in the surface layer. But, the proportion of non-cohesive soil that was available for erosion increased with increasing shear stress. We found that the amount of this non-cohesive material adjacent to the erosion plots correlated with measurements of soil shear strength. These measurements indicated the upper layer of non-cohesive soil was on the order of 0.01 m thick - similar to the laboratory experiments.

Linking the distribution of root properties in near surface soils with burn severity and the depth distribution of non-cohesive material is an interesting avenue for future studies and something, which may provide useful insight into the quantitative link between wildfire behavior, soil heating and sediment availability on hillslopes. Furthermore, it is important to develop a quantitative basis for representing ash as an input to sediment availability so that erosion rates from burned catchments can be evaluated in context of this additional source of sediment, which is unrelated to weathering.

We draw on these data from field and laboratory experiments to develop a new modeling approach which links soil heating to impacts on soil properties (such as root density) and subsequent effects sediment availability. The model provides a means for comparing different systems in terms the potential for change in sediment availability relative to undisturbed conditions (i.e. the perturbation) and can be combined with similar models for runoff generation to quantify the sensitivity of erosion processes to the impacts of wildfire.

Using Airborne and Terrestrial Lidar to Quantify and Monitor Post-wildfire Erosion Following the Las Conchas Fire, Jemez Mountains, New Mexico

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Current LiDAR technology provides an effective way to describe and quantify post-fire erosion features and their associated processes. In this study we use airborne laser scanning (ALS) and repeat terrestrial laser scanning (TLS) to measure biannual sediment yield to two debris-flow fans below neighboring small (approximately 1 km^2) upland catchments burned by the Las Conchas fire in 2011. Pre-existing ALS data (1-m resolution, >5-cm accuracy) is used as the pre-wildfire elevation data set. TLS survey data (0.05-m resolution, < 2-cm accuracy) was collected biannually over two years using TLS to determine the time dependence of the sediment yield response. Following an initial intense rainstorm shortly after the wildfire, the two catchments both produced debris flows consisting of mostly reworked valley fill. Debris-flow deposits such as levees and dammed material made up of poorly-sorted, matrix-supported sub-angular to angular clasts were observed throughout the catchments and on the fan surfaces. Immediately following the wildfire, post-fire deposition on the fan surface was highest, but decreased exponentially with time as less material was conveyed to the catchment outlet. This decrease may be due to a reduction in sediment availability following the regrowth of vegetation. Although the two basins are similar in both topographic and burn characteristics, one catchment yielded approximately twice as much sediment as the other. Possible explanations for the different responses include differences in precipitation, vegetation regrowth, and sediment availability. This study highlights the use of LiDAR for quantifying and monitoring sediment yield from fire-affected catchments.

Physical causes of rainfall threshold and connectivity for post-wildfire runoff

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The generation of runoff is normally considered a point scale process that can be explained by either infiltration excess, saturation or return overland flow mechanisms. This formulation of the process negates to understand the key question in that it is not how much rainfall is converted to rapid overland flow at a point but it is how much of that water is able to reach the river channel to form a flooding event and how much sediment it is able to erode and transport. Thinking of the runoff generation processes in these terms leads us to consider the processes within a more explicitly spatial and temporal framework.

The probability that water will reach the river channel is controlled by the flow pathway which the water takes and the associated variability in soil hydraulic properties along that pathway. The soil surface is often spatially variable, especially so in a post-wildfire context, and hence there is the possibility for transmission losses and disconnections in the flow. At the same time, the rainfall might be providing additional water that maybe converted into overland flow and the temporal pattern of the high intensity rainfall is therefore an important driver as it interacts with the flow travel distances. Hence, there is a balance between the driving rainfall, the spatial pattern of flow and the pattern of soil properties that will ultimately determine the hydrological and sediment connectivity. When the landscape is considered in this way, it leads to the concept that there are points in the landscape that exert more control on the connectivity than others and can be considered as 'connectivity threshold points'.

These patterns can be considered in space and time using a range of tools ranging from terrain analysis to simulation models. These tools include the Network Index based on flow path analysis, CRUM2D and CRUM3 simulation models and the software agent based hydroAgent approach. Each tool is able to offer a different insight into the processes leading to threshold based behaviour in runoff generation.

Monitoring the Spatial Distribution of Wildfire Erosion Processes

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The Fourmile Canyon wildfire burned in September 2010, 15 km west of Boulder, Colorado in a wildland-urban interface setting. We used repeat terrestrial LiDAR surveys to monitor the erosional evolution of a small basin within a high-intensity burn zone. The basin is 5500 m^2, and transitions from a ridge top to a concave hillslope with a colluvial channel. We chose to monitor erosion with terrestrial LiDAR to show the spatial distribution of upland erosion. This approach contextualizes erosional depths and patterns in terms of the local geomorphology, and provides enhanced information in contrast to traditional methods such as erosion pins.

The first LiDAR survey was conducted approximately three weeks after the wildfire and prior to any rainfall. Four additional surveys were performed between major rain storms during a two-year period following the wildfire. LiDAR results show that after the first major summer rain storm following the wildfire, the majority of erosion came from small drainages (i.e. convergent regions). Subsequent storms of a similar magnitude show patches of erosion, independent of landscape position. The change in process from primarily channel erosion to spatially heterogeneous erosion indicates a geomorphic transition, and this erosional sequence appears to be related to the change in surface material roughness with time.

Analysis of the LiDAR data shows that immediately following the wildfire the hillslopes had few roughness elements, and the channelized drainages contained a few boulders separated by straight reaches with low roughness. After the first major rain storm, the channel incised deeper than the adjacent hillslopes, and a cobble lag was left mantling the channel bed. The median size of surface roughness elements within the channel increased by 5 cm, but more importantly, the channel connectivity was disrupted after the initial erosion. Long straight reaches within the channel were eliminated, decreasing concentrated flow connectivity. This change in bed material did not prevent further erosion, but controlled the erosion pattern. For example, no long-term rilling or gully erosion was sustained within the basin. Consequently, this study suggests that the pattern and mode of erosion is highly dependent on the surface roughness as well as the post-wildfire hydrology, which is the erosion driver.

Drivers of Debris-laden Flow Volume: the Role of Fire Severity and Basin Topography

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The volume of material moved by a debris-laden flow is often used as a proxy for hazard to nearby homes and other highly valued resources. Previous work has established that the probability of debris-laden flows increases following wildfires of moderate and high severity in the western US, but little is known about the drivers of debris-laden flow volume. We hypothesize that debris-laden flow volume is a function of five major drivers: topography, precipitation intensity and amount, vegetation factors, soil hydraulic properties, and material availability. Wildfire can produce changes in the last three of these drivers. In the case of vegetation factors, moderate- and high-severity fire consume the majority of overstory and understory vegetation, decreasing interception by canopy, litter, and duff layers, and enhancing accumulation of overland flow. A second change produced by wildfire is that the availability of small material is increased, both through exposure of the soil surface and generation of ash. Soil properties may be changed by fire in multiple ways including: hydrophobicity may increase, decrease, or stay the same, ash may clog soil pores, and raindrops may cause compaction. In total, these changes serve to increase effective precipitation and overland flow during high-intensity short-duration storms, and decrease resistance to erosion. Due to the currently limited state of knowledge, we offer a qualitative exploration of factors affecting debris-laden flow volume, as well as a preliminary quantitative analysis (see Riley et al. 2012 for a catalog of debris flows).

In four recently burned watersheds in Montana and Idaho, we collected data on the area inundated by debris-laden flow fans as well as the thickness of the most recent deposit, from which we calculated volume, and the locations of the gully head (or point at which incision by a debris-laden flow initiated). Study areas include Sleeping Child Creek in the Sapphire Mountains of Montana (fan number=16), Laird Creek in the Bitterroot Mountains of Montana (n=17), Rooks Creek (n=3) and Warm Springs Creek in the Smoky Mountains of Idaho (n=6). In 35 of 42 cases, a single rejuvenated gully led to the debris-laden flow fan. However, in some cases, adjacent zero-order watersheds experienced gully rejuvenation and the debris-laden flows coalesced in the valley, delivering material to a single fan. The number of watersheds

delivering material to a single fan ranged from two (n=2) to three (n=2) to four (n=2) to six (n=1) to as many as nine (n=1).

The ratio of fan volume to contributing area varied across two orders of magnitude, from a minimum of 0.0002678 to a maximum of 0.05339 m^3/m^2, roughly following a negative exponential distribution. The high variability in this ratio suggests that other factors besides contributing area play a strong role in determining the volume of debris-laden flows.

We then used stepwise linear regression with backwards selection to investigate the strength of several factors expected to drive debris-laden flow volume, including data on topography and fire severity. Unfortunately, reliable data are lacking on precipitation amount and intensity, since the debris-laden flows occurred at remote locations in mountainous canyons during convective storms that produced highly localized precipitation. We also lacked information on soil properties such as erosion rate, permeability, porosity, extent and pattern of hydrophobicity. Debris-laden flow volume was the response variable, and independent variables included total contributing area (if there was more than one contributing area for a fan, their area was summed), total basin length (summed for all contributing areas), Vegetation Disturbance Index (the mean VDI is a proxy for fire severity, and was calculated by weighting the VDI of each contributing area by its area), and relief ratio (weighted by the area of each contributing area). Of these, the only variable with explanatory power was contributing area, which explained about 34% of the variation in debris-laden flow volume (adjusted R^2=0.34). Including average VDI, total basin length, and relief ratio did not increase the goodness-of-fit of the model, as measured by Akaike's Information Criterion (AIC): a full model with all four variables had an AIC of 581.45, while a model including only catchment area had an AIC of 576.43, with the lower value being preferred.

Fire severity is thus more strongly related to the probability of a debris-laden flow than to its volume. The majority of variation in debris-laden flow volume remains unexplained by these preliminary results. Of primary importance, further research is necessary to quantify the effect of wildfires on overland flow. In addition, more information on soil properties is desirable, but may be difficult to acquire, since the spatial distribution of hydrophobicity and ash can fluctuate over a period of weeks following a wildfire, and timing of debris-laden flow events is uncertain. These results also point to the importance of topographic rather than fire severity controls on debris-laden flow volume, and suggest further investigation of factors such as basin curvature and runout length.

Citation:

Riley, K. L., Bendick, R., Hyde, K.D., 2012. Debris flow magnitudes: a global catalog. Pangaea: Data Publisher for Earth and Environmental Science.

Tracking Post-wildfire Changes in Instream Sedimentation, Channel Dynamics, and Large Wood Loading

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Longer term hydrologic and sedimentologic changes following wildfire depend on several factors, including burn severity, landscape susceptibility to erosion, post-wildfire storm history, and rate of vegetation reestablishment. Results from an on-going study following the 2000 Boulder Creek (moderate-to-severe) burn within the Little Granite Creek watershed near Jackson, WY show a series of post-wildfire disturbances that contribute sediment to channels over time. These include sedimentation from erosion of channel banks and adjacent terraces and hillslopes driven by the input and movement of large, burned wood 8-12 years after the wildfire.

Baseline data on discharge, bedload and suspended sediment concentrations had been collected during 13 pre-wildfire runoff seasons at Little Granite Creek, presenting an opportunity for re-instrumentation of the site to quantify post-wildfire increases in sediment loads and flow. Runoff is derived primarily from snowmelt, with peak flows in mid-June for a period of 1-2 weeks (average peak discharge is 200 cfs; 5.7 m^3 s^{-1}; 1.5-year return discharge is 210 cfs, 5.9 m^3 s^{-1}; Ryan and Emmett, 2002). Summer storms (pre-wildfire) produce only minimal (< 25 cfs; <0.71 m^3 s^{-1}) rises in the hydrograph; the 2-yr, 1-h storm is about 17 mm h^{-1}. The watershed is characterized by steep slopes underlain by sandstone and claystone. Areas are prone to large-scale mass wasting classified predominantly as earthflow or slump; within the burned area, 60% of the mapped landslides have been classified as these types. These larger failures become particularly problematic during years with heavy snowfall when saturated conditions prevail and destabilize deep-seated failure planes. The unvegetated streamside exposures become a chronic source of fine sediment in the watershed. Consequently, baseline suspended sediment concentrations can be relatively high (on the order of 1000 mg L^{-1}).

Prior to burning, forest cover was dominated by Lodgepole pine, classified as the persistent Lodgepole pine (*Pinus contorta*) community type, with various understory shrubs and graminoids. Fire return frequency for this forest type has been estimated between 200 and 300 years. However, tree-ring data (unpublished) on Lodgepole pine in the burned riparian area of the Boulder Creek wildfire show a common age of about 100 years, suggesting a cohort of recruits from a previous burn.

Although the first 3 years after the wildfire were relatively dry (low snowpack, low rainfall) suspended sediment measured during the few summer storms showed substantially elevated concentrations (maximum instantaneous values 10,000 to 48,000 mg L^{-1}) during the first year (2001). This was followed by lower concentrations in 2002 (between 1200 and 5000 mg L^{-1}) and 2003 (< 800 mg L^{-1}), signaling a return to baseline values. Although highly

elevated concentrations were measured during storms, a greater portion of the total load was generated during snowmelt runoff (54%) compared to storms (44%) for the first year.

The results from our sediment monitoring lacked some of the more dramatic responses that have been observed in other watersheds following wildfire. In other environments, moderate-to-high intensity rainstorms caused significant flooding, widespread debris flows and channel incision and aggradation. A few higher intensity storms (< 2 year recurrence interval) occurred at Little Granite Creek, but they did not trigger this type of response. Instead, ash and charcoal rich discharges and heavily sediment laden flows were observed without physical evidence of debris flows, as defined by channel incision into previously unchanneled areas. Speculatively, this type of response may be typical during periods of continued drought and in the absence of widespread, significant rainfall, representing one type of response on a continuum of effects following wildfire. The nature of the underlying sedimentary geology and mass wasting patterns that contribute fines to the network likely also play a role.

More recent work in the watershed (2008, 8 years post-wildfire) showed elevated estimates of suspended sediment concentration that were between 1000 and 5000 mg L^{-1}. The expected suspended sediment load for the given runoff that year was 40 t km^{-2} while the calculated value was over 100 t km^{-2}, more than double the pre-wildfire suspended sediment load. We tentatively attribute the elevated loads to channel destabilization from the introduction of wood from burned riparian areas and hillslopes where instream wood pieces have doubled and tripled in number. Associated changes to the channel include: 1) increase in the size and number of jams; 2) coarse sediment deposition within and behind jams; 3) channel avulsions; 4) erosion of banks and terraces by re-directed flows; and 5) multiple new sources of fine sediment from bank instability. Continued monitoring in the summer of 2013 may help verify trends in sediment loads and processes that impact the sediment supply more than a decade post-wildfire.

Citation:

Ryan, S.E., Emmett, W.W., 2002. The nature of flow and sediment movement in Little Granite Creek near Bondurant, Wyoming. U.S. Department of Agriculture, General Technical Report RMRS-GTR-90, 49 p.

The Organic Component in Post-wildfire Sediments: Erodibility, Transport and Implications for the Global Carbon Cycle

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Post-wildfire sediment fluxes are not discriminated into their organic and inorganic components in most studies although both differ in terms of transport behavior and environmental effects. Perhaps the most important, but largely overlooked, effect of post-wildfire erosion, transport and deposition of the pyrogenic (fire-modified) organic component concerns the carbon (C) cycle.

The significance of the soil erosion-induced C sink in the global C cycle has recently been recognized, but current research mainly focuses on agricultural landscapes. Post-wildfire landscapes, however, are likely to also contribute significantly to this global sink as they *i)* affect 330-430 Mha per year; *ii)* suffer an enhanced soil erosion; and *iii)* are the 'production sites' of Pyrogenic Carbon (PyC, also known as charcoal, black carbon or biochar). PyC has an intrinsic high resistance to environmental degradation and, therefore, a high potential for long-term C sequestration.

In post-wildfire landscapes most PyC is produced or deposited on the ground and in the surface soil layer. Its low density (typically 0.1-0.6 g cm^{-3}) makes it highly susceptible to wind and water erosion. In addition, it is often hydrophobic nature (water drop penetration time >1h) it is likely to facilitate floating during sheet wash erosion. To date, PyC fluxes by erosion have been poorly quantified and empirical relations between soil erosion and PyC movement need yet to be established. Knowledge of its erodibility, transport behavior, fluxes and the nature of its deposition sites is essential in understanding the ultimate role of PyC as a long-term C sink.

Substantial efforts are already being made by the soil science and geomorphology communities to measure and model post-wildfire soil erosion and sediment fluxes, but the material is usually considered as a whole. In this presentation, we (i) summarize the properties and environmental relevance of PyC and (ii) suggest the inclusion of simple PyC measures into standard methods for measuring post-wildfire sediment erosion. For example, where sediment fluxes are estimated based on collection of material in sediment traps, representative samples could be analyzed to determine the ratios of total, inorganic, organic and/or pyrogenic C to total sediment mass. Total, organic and inorganic C concentrations can be easily determined by elemental analyses. For PyC quantification, a wide range of methods can be used, some of them inexpensive and available in most laboratories (e.g. chemo-thermal oxidation and acid dichromate oxidation methods; Hammes et al., 2007).

These simple measures would allow post-wildfire PyC fluxes to be quantified and compared not only to other sedimentary processes but also to other carbon flux mechanisms. Adding a PyC component to ongoing monitoring studies and/or applying already established methods in new investigations focusing on PyC would constitute a major advance in understanding the wider impacts of post-wildfire erosion and

sedimentation processes, with implications for carbon accounting, climate modeling and prediction, and wildfire management.

Citation:

Hammes, K., Schmidt, M.W.I., Smernik, R.J., et al. 2007. Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. Global Biogeochemical Cycles 21: GB3016.

Post-wildfire Erosion Response and Recovery, High Park Fire, Colorado

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In June 2012 the High Park Fire burned 35,400 ha west of Fort Collins, Colorado. The burned area is a complex mosaic of burn severities and coniferous forest types. The objectives of this study are: 1) to document how post-fire erosion rates vary with rainfall characteristics, snowmelt, surface cover, post-fire vegetative recovery, and other site characteristics; and 2) to use these data to calibrate and apply the Revised Universal Soil Loss Equation (RUSLE) across the entire burned area. Twenty-two sediment fences and eight tipping-bucket rain gages were installed in summer 2012 in areas burned at moderate to high severity. Percent bare soil ranged from 45-70%, and mean soil water repellency at the different sites ranged from weak to moderate (3-16% ethanol) with the strongest repellency at 2-4 cm beneath the soil surface. The relatively low rainfall after the sites were installed meant that sediment production rates in 2012 were less than less than 0.1 Mg/ha at 17 sites and 0.6-3.0 Mg/ha at five sites; only one site produced sediment from snowmelt.

The modeling component of the research will use field measurements, detailed LiDAR and hyperspectral data collected by the National Ecological Observatory Network (NEON) Airborne Observation Platform (AOP) in fall 2012, and additional satellite imagery from RAPIDEYE. The field measurements and LiDAR data will be used to calculate the slope length and steepness factors for RUSLE at each study site. Change in percent ground cover over time at each site will be calculated from field-measured cover transects and the normalized difference vegetation index (NDVI) as measured from the hyperspectral data. The model will be calibrated using field measured sediment production data, then applied to the entire burn area. Preliminary results indicate relatively rapid recovery because most of the wildfire burned at low to moderate severity, soils are favorable for vegetation regrowth, and there was abundant late spring moisture in 2013.

The Hydrologic and Erosion Response to Wildfire in Humid Watersheds in the Summer and Winter Rainfall Regime Areas of South Africa

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The humid, mountainous watersheds of South Africa are especially important as they are the primary source of fresh water in the generally semi-arid South Africa. Erosion and sedimentation is a threat as the water supply system depends on large water storage facilities that are progressively losing capacity. The mountain ecosystems in these watersheds are all fire-adapted, and fire frequencies tend to be high. This paper describes the role of fire in the erosion process in these watersheds.

The mountain watersheds of the eastern seaboard are in the form of a rugged escarpment. The main block of the Drakensberg range receives high amounts of rainfall (mean of 1400 mm/y), primarily in the summer months (85% falls between October and March), and frequently in high intensity thunderstorms accompanied by lightning. By one estimate, about 40% of annual rainfall falls in erosive storms (>12.5 mm with a 5-minute maximum intensity of at least 25 mm/h). The 10-year return period storm has a 30-minute intensity of around 40 mm/h. The rugged topography (local relief of 1600 m and average slopes of 30 – 50%) and rainfall intensity indicate a high geomorphic risk. The warm, humid climate would suggest conditions suitable for the development of forest, but instead a fire sub-climax grassland dominates. Fire frequency is high, with a fire interval of typically 1 – 3 years, but severity is consequently low. Wildfires remove the moribund grass sward, keep down the woody vegetation and maintain the dominance of grasses. Recovery of the grass cover after wildfire is extremely rapid. Under this regular fire regime, erosion rates related to wildfire tend to be small, relative to a modest background erosion rate (0.1 – 1 t/h/yr in undisturbed basins). Over-grazing and cultivation pose a much greater risk. Extreme erosion has been recorded on rare occasions where timber plantations have burned in wildfires though (one instance of 37 t/ha in a single year).

In the mountains of the Mediterranean-type climate of the South-western parts of South Africa, rainfalls are again high (1000 – 3000 mm/y) and the topography even more rugged than the eastern seaboard. An indication of the topography is given by 9 small research basins (all less than 400 ha in size) with mean relief of 832 m and mean channel slope of 35%. However, the soils tend to be coarse (loamy sands to sandy loams) and most rainfall occurs in long-duration, low-intensity winter storms (median and peak 15-minute rainfall intensity, measured over a 20-year period, were 5.5 and 59 mm/h, respectively). The result is low background erosion rates when measured at the basin scale (varying between 0.001 and 1 tonne/ha/yr in the above 9 basins). The vegetation is the unique “fynbos” which is exceedingly diverse and strongly fire-adapted. Fire frequencies are lower, with a fire interval of 8 – 20 years thought to be optimal for the maintenance of the full array of botanical diversity. In the long, dry summers though, fire severity can be extreme, and fire-associated erosion, though generally uncommon, has been high in some cases (up to 6 t/ha/yr).

Mechanisms and Controls on Post-High Park Fire Sediment Delivery in the South Fork Cache la Poudre Basin: Preliminary Results

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The 2012 High Park fire burned over 35,000 ha within the Cache la Poudre basin. Pre-fire vegetation was sub-alpine dominated by mature lodgepole pine characterized by infrequent, high intensity fires with estimated recurrence intervals of over 100 years. Previous studies suggest that post-wildfire erosion in the Colorado Front Range is driven by large convective storms rather than annual snow melt processes.

Earlier work by Moody and Martin (2001) and Pietraszek (2006) identified a 30-minute rainfall intensity of 10 mm h^{-1} as a potential threshold in a non-linear runoff, and erosion response, respectively. The 2-year, 30-minute rainfall intensity for the burned area is 30 mm h^{-1}. As part of the US Forest Service's Burned Area Emergency Response (BAER) analysis, aerial mulching on severely burned hillslopes was recommended within the National Forest Systems (NFS) lands to help minimize flood runoff and soil erosion. Small areas within NFS lands were mulched during late summer 2012 with further mulching using agricultural straw planned for early summer 2013. Questions about the effectiveness of mulching on limiting hillslope sediment transport to downstream receiving waters have been raised, as well as the effect of burned-area runoff on water quality. Qualitative observations of post-wildfire channel morphology and turbidity suggest that small tributaries of the South Fork Cache la Poudre River are delivering substantial amounts of sediment to the main stem Cache la Poudre, a source of drinking water for Fort Collins and Greeley.

The objective of this research is to evaluate the controls on sediment transport from one mulched and one reference basin. Both basins have 3rd order channels that transport sediment directly to the South Fork Cache la Poudre. Sonic sensors, tipping bucket rain gauges that trigger automatic cameras, and water quality probes will be deployed in early summer 2013 at surveyed cross sections along one 1st, 2nd, and 3rd order channel in each basin. Coupling rain gauges with automatic cameras will link rainfall events of different

depth and intensity to the timing and magnitude of runoff within 1st, 2nd, and 3rd order channels. Repeat surveys of each cross section following runoff-generating storm events will quantify sediment delivery and changes in channel morphology on an event basis, linking hydrologic response to geomorphic response within each basin. Elucidating the mechanisms and controls on post-wildfire sediment transport will increase understanding of (i) sediment transport distances for different magnitude and duration flows, (ii) thresholds for propagation of in-channel headcuts, (iii) aggradation and degradation within different sized channels, (iv) temporary storage and flushing of sediment under various rainfall/runoff scenarios, and (v) how these processes differ in areas without mulch. Soil water repellency testing in both basins will inform the role of SWR in hydrologic response in each basin. In addition, surface water quality will be assessed in both basins via measurements of total suspended solids, major cations, trace elements, nutrients, and dissolved organic carbon.

Previous studies on post-fire erosion processes have focused predominantly on the plot and hillslope scale; whether or not these findings can be scaled up to small basins is unclear. Comparison of hydrologic and geomorphic response in a mulched and unmulched basin will further understanding of controls on runoff and sediment delivery at different spatial scales.

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Twenty-five Years of Wildfire Experience and 'Established Truths'

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Embarking on a new research field in mid-life may not necessarily be the smartest career move, but can come with some unexpected benefits. One such benefit is that the naïvety of the 'outsider' may lead him or her to address underlying assumptions that the long-standing wildfire researcher may have long since accepted. In this presentation, several perceived 'truths' encountered, puzzled over and eventually challenged are considered with respect to research in Portugal and Australia.

High-severity wildfire = substantial post-fire soil erosion. When post-wildfire research began in the Mediterranean during the early 1980s, the available body of mainly US research presented a headline message of major impact and significant soil losses caused by high-severity wildfire. Because of a human legacy of degraded soil in fire-prone terrain, however, much post-wildfire erosion is supply- rather than transport-limited in the Mediterranean. Consequently, post-fire soil losses even at small scales and following high-severity fire can be modest, often much smaller than those associated with common agricultural practices in the region, and, not infrequently, smaller even than the estimated low rates of soil renewal from weathering and/or from Saharan aeolian dust inputs.

The same set of important controls on post-wildfire erosion applies to each post-burn situation. Whilst some post-wildfire variables may well be universally applicable (e.g. post-wildfire rainfall characteristics), local factors, it seems, can assume important roles particularly with respect to restricting post-wildfire erosion. For example, in mature semi-natural eucalypt forests on the sandstone tablelands of south-east Australia, research showed that soil losses following high-severity wildfire were much larger, for example, than those measured in Portugal, but restricted mainly to a surface organic-rich layer found re-deposited in large amounts along stream channels, and recorded in ground-level change measurements and cosmogenic nuclide evidence. Unexpectedly, however, the underlying sandy subsoil seemed to undergo limited removal from the slopes despite being apparently highly erodible and water-repellent. The following local factors were implicated: ants' nest galleries providing preferential flow routes below the water-repellent upper soil, micro-terrace – litter dam complexes trapping eroded minerogenic sediment on relatively low-angled slopes, together with survival of comparatively fine roots near the soil surface and rapid post-fire root development both anchoring the minerogenic soil particles.

In burned terrain in Portugal, a number of 'local' factors were found to limit post-fire erosion. For example, an intricate 'mosaic' land-use pattern and slopes criss-crossed by obstructions such as tracks and abandoned terraces are common. These characteristics can considerably reduce post-wildfire erosion at hillslope and catchment scales. High stone content in the soil can reduce erosion by providing structural stability, and by promoting the development of a rapidly-forming and highly effective protective surface stone lag, which can be more important than vegetation in reducing soil loss for years after burning.

Strongly developed soil water repellency is a major cause of increased post-wildfire runoff and erosion. From research in Portugal, it became apparent that attributing any geomorphological effect post-fire specifically to repellency can be extremely difficult, because a number of post-fire changes (e.g. reduced interception, reduced rainfall storage, typically increased supply of erodible sediment) can also induce increased runoff and erosion. If water repellency was having an effect following fire, it was reasoned that this was due to its 'activation' under burned conditions following its 'dormancy' under unburned conditions. Furthermore, its effect might be cancelled out by an extremely high stone content, providing preferential flow routes through the water repellent soil. The role of root holes, soil cracks and wettable soil patches providing such routes might actually be overshadowed in very stony soils.

Wildfire is geomorphologically an important agent of landscape change in rugged fire-prone terrain. On the sandstone tablelands in south-east Australia, comparison of denudation by contemporary wildfire and long-term non-fire-related processes suggested that wildfires were in fact geomorphologically not very significant in the forested landscape. It was reasoned that weather characteristics both leading up to and following wildfire were dominated by dry El Niño conditions, which favoured wildfire ignition but not extreme rainfall events during the early post-fire period while the soil was still vulnerable to erosion. In Portugal, despite a high frequency of often severe fires in recent decades, geomorphological change on much of the rugged fire-prone terrain has been minimal.

It has taken much of a quarter of a century to question these 'truths' for the two research areas in question, and at least some of the queries seem to have resonated with other researchers and not dismissed summarily. The overriding message learned has been that ideas developed in one burned landscape should not be unquestioningly transferred to another.

Effect of Wildland Fire on Runoff and Erosion in Semi-arid Rangelands

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Wildfire is a natural and important component in many ecosystems, including semi-arid southwestern rangelands. Post-fire runoff and erosion rates, as well as recovery rates of semi-arid rangeland are not well known. Rainfall simulator experiments were conducted across southeastern Arizona on grass-dominated and grass-shrub mixed sites. Experiments were conducted quickly following a wildfire and again one year later, with some plots revisited four years after the wildfire. Burn severity was not quantified, but as these were mostly grass fires low severity was assumed. Soils did not show hydrophobic response. Rainfall simulator plots of two different sizes, large (12.18 m^2) and small (0.75 m^2) were installed on burned and unburned hillslopes within the same ecological site. Hillslopes had an average slope of 12%, typical K-factors of 0.43, and aspects of north, east and south. An oscillating boom multi-intensity rainfall simulator was used to apply steady rainfall rates ranging from 65-160 mm/hr. Sediment discharge from the small plots was assumed to be due to raindrop splash detachment only. Sediment discharge from the large plots was a combination of raindrop splash detachment, transport, deposition and flow detachment. The dominant erosion process was determined by comparison of sediment yields from the two sized plots. Plots were bound on all but the downhill side, where a flume was installed to quantify runoff and grab samples were taken to quantify sediment yield. Prior to simulation ground cover was measured by a line-point intercepting method, where 400 points were measured on large plots, and 49 points were measured on small plots. Sediment yields from the plots were correlated to ground cover with both burned and unburned sites giving typical R^2 values of 0.7-0.8 for the mixed grass-shrub sites. Ground cover for the sites ranged from 50-70 percent for unburned conditions, 20-40 percent the year of the burn, and 70-95 percent four years after the burn.

Typical sediment yields for grass dominated plots the year of the wildfire were 0.3-1 kg/m^2 and the typical sediment yield for plots with a shrub component the year of the wildfire were 1.5-2.5 kg/m^2. Plots with shrub mounds within a plot saw at least twice as much sediment yield as grass dominated plots, but saw little difference in runoff. All plots where in a state of net erosion after the wildfire, and typically stayed at that state one year after the wildfire. Plots revisited four years after a wildfire had moved into a state of net deposition with raindrop splash detachment being the dominant erosion process. Results

from these experiments are being used to parameterize raindrop splash, flow detachment and infiltration components of the Rangeland Hydrology and Erosion Model (RHEM).

Automated Geospatial Watershed Assessment Tool (AGWA): Developing Model Parameters Using Precipitation and Runoff Records from Gauged Watersheds

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New tools and functionality have been incorporated into the Automated Geospatial Watershed Assessment Tool (AGWA) to assess the impacts of wildfire on runoff and erosion. AGWA (see: www.tucson.ars.ag.gov/agwa) is a GIS interface jointly developed by the USDA-Agricultural Research Service, the U.S. Environmental Protection Agency, the University of Arizona, and the University of Wyoming to automate the parameterization and execution of a suite of hydrologic and erosion models (RHEM, WEPP, KINEROS2 and SWAT). Through an intuitive interface, the user selects an outlet from which AGWA delineates and discretizes the watershed using a Digital Elevation Model (DEM). The watershed model elements are then intersected with terrain, soils, and land cover data layers to derive the requisite model input parameters. With the addition of a burn severity map AGWA can be used to model post-wildfire runoff and erosion response from a watershed. By applying the same design storm to burned and unburned conditions, a rapid assessment of the watershed can be made and areas that are most prone to flooding can be identified (Goodrich et al. 2005).

Pre and post-wildfire precipitation and runoff records from several gauged forested watersheds (Marshall Gulch, Arizona; Starmer Canyon, New Mexico; and Bonita Canyon,

Arizona) can be used to make improvements to post fire model input parameters. Rainfall and runoff pairs will be selected from these records and the KINEROS2 model will be calibrated by selecting optimal values for saturated hydraulic conductivity and hydraulic roughness (i.e. Manning roughness coefficient). Several objective functions will be used in the calibration process and events will be withheld from the calibration data for validation. Previous calibration results indicate that saturated hydraulic conductivity following fire will be extremely low (0.39-7.54 mm h^{-1}) and overland flow roughness (channel 0.008-0.193 $m^{-1/3}$ s and hillslope 0.014-1.175 $m^{-1/3}$ s) will be similar to bare ground (Canfield et al. 2005). Hydraulic roughness values recover quickly during vegetative re-growth, while saturated hydraulic conductivity recovers at a slower rate. For individual rain storms, peak discharge is more significantly changed by wildfire than runoff volume. Runoff characteristics are expected to return to pre-fire conditions within several years based on initial results. The AGWA modeling system will facilitate the integration of research studies on infiltration, overland flow and erosion processes with different temporal and spatial rainfall representations to predict downstream runoff and sediment transport response.

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Post-wildfire soil erodibility

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The concept of soil erodibility developed in the geomorphic literature and has been applied widely and successfully for the prediction of erosion rates in agricultural systems. In recent decades conceptual models of erodibility developed in an agricultural context have been adapted for burnt mountainous landscapes. In many cases these conceptual models of erodibility explicitly and implicitly incorporate a range of assumptions such as: 1) the nature of the dominant erosion process (eg, interill, rill, channel, etc), 2) the idea of erodibility as a constant in time, 3) the factors that affect soil erodibility, 4) the way in which detachment forces combine with transport capacity, and 5) the scale-independence of the dominant process. However a growing body of data indicates that these key assumptions can be inappropriate in many burnt landscapes.

For example, erodibility is often represented as the constant of proportionality between the erosive force (eg. shear stress, rainfall erosivity, excess streampower, etc) and the detachment rate. This structure implicitly assumes there is no limitation on sediment supply. This is probably reasonable in many situations, however in the case of burnt forests, wildfires may generate only a shallow, finite supply of non-cohesive sediment. Field experiments have shown that as erosion (and recovery) progresses, this supply diminishes, and the erosive process may become supply limited. New conceptual models of erodibility should attempt to capture both the generation and the depletion of this finite erodible layer.

Erodibility is also often treated as scale-independent. Many datasets and experiments have now illustrated large scale dependencies for runoff generation and for sediment transport in burnt mountainous landscapes. As a result, erodibility values will vary depending on the scale of measurement. Scaling issues arise due to a complex mixture of process-shifts, spatial variability in physical properties, and erosion event dynamics. Examples of these kinds of scaling effects will be analysed from the literature and from new unpublished data, and the implications for post-fire erosion predictions explored.

In summary, in this presentation we draw on the literature and new data from burnt catchments with contrasting soils (with median saturated conductivities varying from zero to 100's mm h^{-1}) and burn severities (ranging from unburnt to extreme wildfire

conditions) at scales ranging from $1m^2$ to 100's km^2 and explore conceptual models of erodibility more suited to steep, mountainous, burnt environments.

Hydrophobicity Following Wildfire on an Arid, Alluvial Soil

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Wildfires in the arid areas of the western U.S. are not uncommon, and the likelihood of wildfires is predicted to increase. The immediate and long-term effects of wildfires on soil erosion by wind and water are of critical concern to land resource and contaminant transport managers alike, but the specific effects of wildfires on arid soils are not well-known. Vegetation in arid regions is sparse resulting in an open canopy landscape, and the distribution of wildfire-related soil hydrophobicity reflects this pattern. This study addresses the extent and distribution of soil hydrophobicity around a single burned tree (*Juniperus osteosperma*) approximately two months after the 2011 La Madre Fire near Las Vegas, NV. Soil hydrophobicity was determined along 12 transects radiating out from the tree trunk surface at 30° angles. Using the water drop penetration time method, hydrophobicity was measured at seven distances along each transect (0 – 2.4 m from the trunk), at the mineral soil surface (depth = 0 cm), and at four depths (2, 4, 7, and 10 cm) below the surface.

Observed absorption times ranged from less than 5 seconds to over 400 seconds. The resulting three-dimensional distribution of soil hydrophobicity resembled a torus encircling the tree trunk with maximum values approximately 40 cm away from the trunk and at a depth of 2 cm. Virtually no hydrophobicity was found below a depth of 7 cm. We will compare these results with a second sampling of hydrophobicity two years after the burn and include associated infiltration capacity measurements. These findings can be used as a first estimate of the distribution of soil hydrophobicity below burned juniper trees to aid in characterization of soil condition, infiltration, and runoff as well as erosion potential following a wildfire.

Modeling the Effect of Fuel Treatments on Post-wildfire Runoff and Erosion: A Case Study at Zion National Park

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Zion National Park is located in southwestern Utah and is within the Temperate Desert Mountains ecoregion as defined by Malamud et al. (2005). The area of the planned prescribed fire has varying fire regimes and fire return intervals: white fir forests are characterized by surface fires with a <35 year return period; pinyon/juniper woodlands display replacement fires and also have a <35 year return period; while quaking aspen/big tooth maple forests and ponderosa pine/gamble oak woodlands have mixed severity fires with a 35-100 year return period. However, much of the area's current forest conditions are different from historical conditions due to over a century of fire suppression efforts (*Zion National Park Fire Management Plan.* 2004).

Southwestern Utah is characterized by hot summers in which most large wildfires occur followed by monsoon thunderstorms (*Zion National Park Fire Management Plan.* 2004). It is within the Arizona rainfall type with medium intensity condition as defined by Moody and Martin (2009). This rainfall type is defined by having a 2-year, 30-minute rainfall intensity of between 20-36 mm/hr. According to the National Oceanic and Atmospheric Administration (2013), the 2-year, 30-minute storm for centroid of the planned prescribed burn area has a depth of 13.6 mm (with 90% confidence intervals of 11.7-16.0 mm).

The hydro-geomorphic regime of Zion National Park is characterized by steep slopes and easily eroded soils. Half of the soil complexes within the park are rock, and 80% have high erosion potential. Bedrock/slickrock exposures are common (*Zion National Park Fire Management Plan.* 2004). According to the STATSGO database, the area of the planned prescribed fire contains two soil map units (Natural Resources Conservation Service 2013). One map unit is 80% rock outcrop, with the remaining soils having K factors ranging between 0.20-0.32 and saturated hydraulic conductivities ranging from 5.1-510 mm/h. The

other type contains a mix of soils with K factors ranging from 0.20-0.43, with the most prominent soils having K factors of 0.32-0.37. Saturated hydraulic conductivities for this soil type range from 0.00-150 mm/h. Deep and narrow slot canyons can see quick flash floods as a result of these conditions.

Post-fire precipitation results in dramatic increases in peak runoff and sediment yields. Since it has been shown that post-fire effects can be reduced by fuel treatments, these treatments can be an important method for park managers to lessen the impact of post-fire runoff and erosion events (Anderson et al. 1976, Wohlgemuth et al. 1999). This study outlines a spatial modeling approach that combines fire severity and hydrological models in order to model the effects of fuel treatments on post-fire hydrological impacts.

A case study involving a planned prescribed fire at Zion National Park was used to demonstrate the approach. In order to aid park managers, prescribed fires were modeled under varying environmental conditions using FlamMap and the First Order Fire Effects Model (FOFEM) within the Wildland Fire Assessment Tool (WFAT) (Tirmenstein et al. 2012). WFAT was then used to evaluate the effectiveness of the prescribed fire on mitigating wildfire severity by simulating and comparing two scenarios: a wildfire on an untreated landscape, and a wildfire on a treated landscape. The resulting wildfire severities were then used to change land cover and infiltration characteristics (such as saturated hydraulic conductivity and hillslope roughness) in the Kinematic Runoff and Erosion Model (KINEROS2) (Goodrich et al. 2012). Fire severity was determined using the Keane Fire Severity Index, which couples basal area mortality, non-canopy fuel consumption, and soil heating metrics (Keane et al. 2010). Design storms of various durations and intensities were then input into KINEROS2 within the Automated Geospatial Watershed Assessment Tool (AGWA) over the burned areas to illustrate how prescribed fires mitigated post-wildfire erosion and runoff. The results will not only help park managers envision the impact a prescribed fire will have on wildfire severity and post-wildfire runoff/erosion, but also what environmental conditions for the prescribed fire will best mitigate post-wildfire hydrological impacts. Initial modeling results for a 2-year 30-minute design storm indicate that the planned prescribed burn could reduce post-wildfire peak flow by up to 30% and post-wildfire sediment loss up to 35% within the watershed.

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The Effects of Varying Rainfall Representations on Post-wildfire Runoff Response in the KINEROS2/AGWA Model

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Spatial representation of precipitation is one of the most difficult aspects of modeling post-fire runoff and erosion events. The impact of post-fire convective rainstorms, especially in watersheds in the southwestern United States, depends on the spatial relation between the locations of high intensity rainfall and the areas of high severity burns. This study uses the KINEROS2/AGWA (Goodrich et al., 2013) model to compare several spatial and temporal representations of a rain storm following the 2006 Kolob Fire in Zion National Park, UT. The first representation will be a design storm in which a uniform depth of rainfall is applied to the entire watershed. The duration and depth will be averaged from storm total precipitation NEXRAD radar data. A SCS Type II hyetograph will be used to distribute the rainfall temporally. The second representation will vary the rainfall pattern spatially by applying different rainfall depths to different parts of the watershed based on the storm total precipitation radar data. SCS Type II hyetographs will still be applied, but total precipitation depths will vary across the watershed as dictated by the radar data. The third representation will incorporate digital hybrid reflectivity radar data at 4-5 minute scans to vary rainfall both temporally and spatially over the watershed. For each scan the roughly 1 km by 1 degree radial radar pixels of estimated precipitation intensity are input into KINEROS2 for the duration of the storm. Simulated runoff from each precipitation representation will be compared to illustrate how rainfall representation can change modeled hydrologic response. Outputs will also be compared to an estimate of peak discharge at a downstream stream gage.

The 2006 Kolob Fire began on June 24 and was contained on June 30. It burned 7,136 hectares of mostly climax pinyon/juniper woodland inside and outside of Zion's park boundaries. The burn area covered both flat mesa terrain and steep canyons leading to North Creek and the Virgin River. 20% of the North Creek watershed was burned. Herbicide was extensively applied following the wildfire to prevent exotic cheatgrass invasion and native grass seed application was performed as well (National Park Service 2006). On August 1, 2007 a convective thunderstorm occurred over the North Creek watershed, with the areas of highest rainfall intensity centered over areas of high burn severity from the Kolob Fire. The

highest rainfall depth totals were between 75-100 mm, which caused a major flood downstream in North Creek and also along the main channel of the Virgin River (Sharrow 2012).

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Automated Geospatial Watershed Assessment Tool (AGWA): Computer Demonstration of Applications for Fire Management and Rapid Post-wildfire Watershed Assessment

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The Automated Geospatial Watershed Assessment (AGWA) tool is a GIS interface developed by the USDA-Agricultural Research Service, the U.S. Environmental Protection Agency, the University of Arizona, and the University of Wyoming to automate the parameterization and execution of a suite of hydrologic and erosion models (RHEM, WEPP, KINEROS2 and SWAT -see: www.tucson.ars.ag.gov/agwa or http://www.epa.gov/esd/land-sci/agwa/). New tools and functionality have been incorporated into AGWA to assess the impacts of wildfire on runoff and erosion. Through an intuitive interface in AGWA the user selects a watershed outlet. AGWA then delineates and discretizes the watershed using a Digital Elevation Model (DEM). The discretization, represented by overland flow and channel model elements, is then intersected with terrain, soils, and land cover data layers to derive initial estimates of the requisite model input parameters based on observations, experimental data, and research literature. Based on fire severity maps AGWA modifies several model input parameters, including the curve number, percent cover, and hillslope roughness (i.e. Manning's roughness coefficient) to reflect the spatial effect of the wildfire in the case of SWAT. For KINEROS2, the hydraulic conductivity and hillslope roughness values are modified. With increased fire severity, the curve number used in SWAT increases, while percent cover and hillslope roughness decrease according to relationships derived from data analysis of two burned watersheds (Canfield et al., 2005).

Rainfall can be modeled in a variety of ways according to user preference. All methods distribute rainfall evenly over a user-specified rainfall area. Within KINEROS2, users can use a precipitation-frequency grid downloaded from NOAA's Precipitation Frequency Data Server or interpolate from the NOAA TP 40 rainfall frequency atlas (http://hdsc.nws.noaa.gov/hdsc/pfds/). Alternatively, users may enter time-depth or time-intensity pairs to model rainfall. Users may also enter a storm duration and depth, and KINEROS2 will use SCS type II methodology to distribute rainfall temporally. SWAT uses daily rainfall totals for any period of record, collected from gages. For SWAT, a Thiessen polygon method is used to distribute rainfall spatially over the watershed according to the nearest gaging station. When multiple rain gages are specified for a KINEROS2 simulation, a piece-wise planar precipitation intensity surface is derived over the watershed. The rainfall intensity over the centroid of each overland flow modeling element is than applied to that element. When a new rainfall intensity is read into the model this process is repeated. Research is currently underway to link KINEROS2 to weather radar to support real-time flood forecasting (Unkrich et al. 2010). KINEROS2 has also been run using NEXRAD-MPE data on military installations in California, Arizona, and New Mexico (Lyon 2013).

Simulations of pre- and post-fire runoff and erosion allow managers to rapidly identify resources and infrastructure that are at risk or need rehabilitation. In AGWA, tools have been developed to assess the effect of post-fire treatments (e.g. straw mulch), evaluate the risk to ponds and reservoirs, and to evaluate the effects of pre-fire fuel treatments (thinning, prescribed fire) on post-fire runoff and erosion (see related poster by Sidman et al., this conference). Case studies from the 2011 Wallow fire in Arizona, the 2011 Las Conchas fire in New Mexico, and an assessment of a prescribed fire treatment at Zion National Park will be demonstrated.

AGWA can be used to address many of the current research issues related to post-wildfire runoff and erosion processes as defined by Moody et al. (2013). AGWA supports several physically-based, distributed hydrology and erosion models. The modeling framework supports the organization and synthesis of empirical data from different post-wildfire domains in order to better understand how wildfire affects the interaction between the precipitation, infiltration, runoff, and erosion processes. AGWA can ingest different forms of precipitation data, including real-time weather radar, which will support the analysis of different time-interval metrics and rain profiles. As research is completed AGWA can update its parameterization to better represent the relationship between burn severity and soil properties, and provide a tool for managers.

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High Latitude Post-wildfire Response Domains: Montane, Boreal, and Taiga

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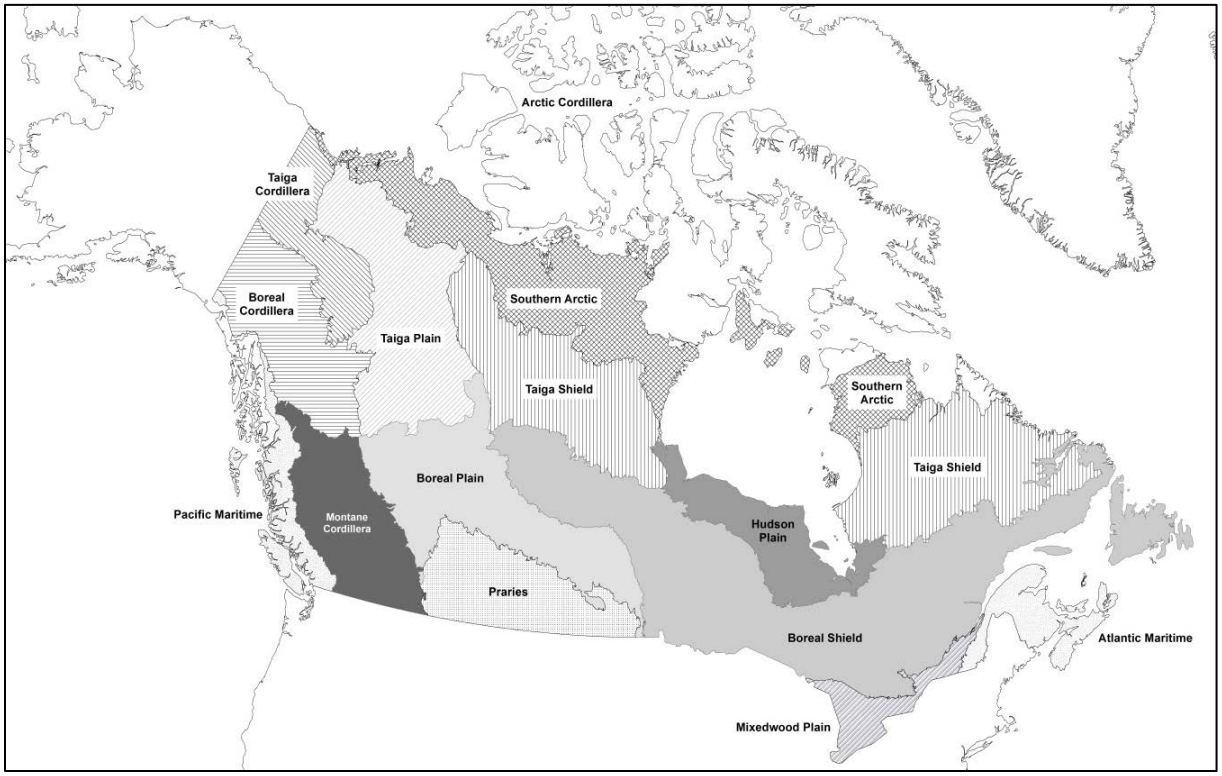
Climate change associated with increased frequency and severity of wildfires has been occurring in high-latitude regions of the globe at a rate twice as fast as that evident elsewhere in the world. In northern North America, strongly variable hydro-climatic settings (climate, physiography, and geology) and vegetation zones form unique conceptual groups of post-fire response domains reflected by the distinct ecological zones of this region (see figure below). These response domains probably reflect meaningful differences in the behavior of the four runoff and erosional process regimes (rainfall, infiltration, runoff, erosion) from those of other regions. Extensive peatlands in boreal and taiga regions and permafrost features further to the north (taiga and sub-arctic regions) represent unique features that likely play a major modifying role in post-fire runoff and erosional response domains of high latitude regions.

Most of the wildfires in Canada occur from April-August with the greatest area burned during June/July. This is synchronized with the timing of snowmelt, peak summer precipitation and runoff across much of the region. Western and west-central boreal and taiga ecozones experience the greatest annual area burned (0.5-1.2 % of total land area) with mean fire return intervals from 80-200 years (Stocks et al. 2003, Flannigan et al. 2009). Mixed precipitation regimes are particularly important in this high-latitude region where the relative role of both rainfall and snowmelt processes form runoff process regimes that differ from more southerly latitudes. Hourly rainfall storm intensities are greatest in southern regions of Canada (25-60 mm h^{-1} for 10-year return period storms) compared to <8-25 mm h^{-1} in northern boreal, taiga, and sub-arctic regions where convective storms are less frequent. However, runoff associated with snowmelt processes dominates the hydrology of the region.



Similarly, the interaction of snowmelt dominated precipitation processes with glacial history and geology of the Canadian Shield, Western Sedimentary Basin, and Cordilleran regions establish potentially unique post-wildfire erosional response domains. While development of broad erodibility indices are not nearly as well developed as those available in the U.S., the correspondence of regional wildfire patterns with surficial geology provide clues to potential erosional and runoff response domains across this region.

Potentially unique modifiers of these domains include extensive peatland regions with deep organic matter deposits (typically 2-5 m. depth) in boreal and taiga regions, and solifluction processes (permafrost melt / mass wasting) in northern forested regions of the taiga and sub-arctic. These modifiers will likely drive differential post-fire responses from those evident in more southerly latitudes.

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Characterizing the Primary Material Sources and Dominant Erosional Processes for Post-wildfire Debris-flow Initiation in a Headwater Basin using Multi-temporal Terrestrial Laser Scanning Data

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The primary sources of material and dominant erosional processes that initiate post-fire debris-flows are poorly documented. Improving the understanding of how and where material is eroded from a watershed by a post-fire debris-flow requires precise measurements of topographic change and the identification of likely process types at a given location. Geomorphic change detection using high-resolution multi-temporal topographic data permits the precise location and measurement of erosion and deposition over time. Morphometric analysis provides a means to segregate a landscape in order to infer the dominant types of erosional processes operating within a drainage basin. In this study, we combine area-slope and curvature analysis of a steep (average gradient = 0.81m/m), small (0.01km^2) headwater drainage basin with geomorphic change detection analysis of multi-temporal terrestrial laser scanning data. Area-slope analysis provides a well-established, process-based approach for distinguishing locations dominated by hillslope processes from those dominated by incision by channel processes (e.g. fluvial erosion or debris-flow erosion). Planimetric curvature analysis of hillslope locations permits further segregation of the drainage basin into locations characterized by convergent or divergent flow, which are used to make inferences regarding the type of hillslope processes (raveling, raindrop-impact induced erosion, overland flow, rilling) at a given location. Results are used to segregate the study basin into four morphometrically defined process domains: a hillslope-divergent zone, a hillslope-convergent zone, a transitional zone and an incisional debris-flow zone.

We mapped ravel deposits, rill locations, debris-flow deposits and fluvial deposits in order to test our inferences of process-types based upon the morphometric analysis. We then compare the geomorphic map of the study basins to process interpretations based on morphometrically defined process domains to test if this method is useful for characterizing the spatial extent of different erosional processes. Inferences based on the form of the area-slope curve and planimetric curvature measures prove to be strongly correlated with the location of mapped process -types within the study basin. We identify that hillslope-divergent and hillslope-convergent areas were the primary sources of material over the period of analysis in the study basin. The results of these analyses indicate hillslope erosion is the primary source of material during post-fire debris-flow initiation in a small, steep headwater basin. Furthermore, our results support the utility of interpretations of geomorphic process dominance from area-slope relations and curvature. As these interpretations are typically associated with analysis over longer timescales, we demonstrate that morphometric definition

of process domains may also be applicable at the scale of a debris-flow producing rainstorm in a recently burned watershed. Further work is needed to determine how these results vary with increasing drainage basin size, evolving debris-supply conditions and material properties, and how these data might scale upwards for use with coarser resolution measurements of topography.

Use of Sediment Derived Paleoflood Records to Analyze Prehistoric Depositional Characteristics of a Fire-susceptible Forested Watershed

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Severe wildfires in the arid Southwestern U.S. make watersheds highly susceptible to post-fire flooding, sediment mobilization, and debris flows. Wildfires have increased in size and severity as a result of land use practices including fire suppression throughout the twentieth century, and climate change that has increased the occurrence of drought. Forest restoration treatments are being planned and implemented to reduce the risk of severe wildfire and subsequent flooding and erosion that can have negative impacts on communities at the wildland-urban interface (WUI) and communities downstream of forested watersheds. The City of Flagstaff, AZ, is currently planning forest restoration in the headwaters of the Rio de Flag watershed of the Dry Lake Hills to reduce the risk of post-fire flooding. The Dry Lake Hills area includes two sub-basins in the center of the Rio de Flag watershed, the Schultz Creek (17 km^2) and Spruce Avenue Wash (20 km^2) sub-basins, which cover roughly 30% of the total watershed area. These watersheds are steeply sloped, with watershed relief ratios of 0.204 and 0.240, respectively, and vegetated with dense ponderosa pine and mixed conifer forest. Prior to European settlement, these forests were fire-adapted and experienced low-to-moderate severity surface fires with an occurrence frequency averaging every 2-12 years (Covington and Moore, 1994), but human activities over the last century such as fire suppression has increased the density of the forests to be unnaturally dense and more susceptible to severe wildfire. The potential for soil erosion ranges from slight to severe depending on soil type as defined by the 1995 Coconino National Forest Terrestrial Ecosystems Survey. The climate is semi-arid with a bimodal precipitation distribution. The wettest season is in late summer from July to October, and a second wet season occurs from December to March.

The prehistoric sediment record of the Dry Lake Hills area watershed is being analyzed to determine the individual watershed's sediment responses to wildfire and post-wildfire precipitation. Analytic techniques include radiocarbon dating of macroscopic charcoal in the soil, allowing periods of deposition following wildfires to be determined. Sediment records in the region indicate lower fire frequency and increased fire severity in the late Holocene compared to prehistoric times (Jenkins, 2007; Joyal, 2004). Comparison of the prehistoric sediment record with modern sediment responses during post-wildfire flooding in adjacent basins will contribute to predictions of erosion potential in post-wildfire floods on

the Dry Lake Hills and in the Rio de Flag through Flagstaff. Hydrologic and hydraulic modeling based on changes in forest density as a result of restoration will be constructed using Hydrologic Engineering Center software, useful for the variety of programs, compatibility with ArcGIS, and free availability. The models will be coupled with the sediment record analysis to predict how forest restoration will affect peak flood flows, rates of erosion and deposition, and ultimately the potential for damage to communities at the WUI in the event of severe fire. HEC-RAS Sediment Transport simulations will provide estimates of the volume of sediment that could be mobilized in current and restored conditions, which can be compared with sediment deposition observed in the sediment record.

Biological Modification of Sediment Transport Processes in Wildfire Impacted River Systems

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The frequency and severity of large-scale natural disturbances, such as wildfire, in many forested regions of the globe has significantly increased in recent decades. Delivery of sediment from these wildfire impacted landscapes to receiving streams is governed by hydrological and geomorphic processes that occur over a wide range of spatial and temporal scales. These processes dramatically increase the rates and magnitudes of sediment yields relative to those observed in reference (unburned) watersheds. Wildfires change the physical and chemical characteristics of sediment, thereby impacting its transport properties in receiving streams. Moreover, increased nutrient availability in wildfire impact streams can result in significant post-fire biofilm development on riverbeds. Biological activity and biomat formation changes the characteristics of deposited sediment (i.e., particle structure, morphology, size, porosity, shape, degree of consolidation) and may significantly alter erosion processes. Specifically, this type of biological modification can change erosion thresholds substantially and alter the source, transport and fate of sediments in streams draining forested landscapes because factors such as critical shear stress for erosion, erosion depth, sediment settling velocity and sediment porosity can be markedly modified by biological activity. Accordingly, an understanding of biological modification of sediment and its associated transport in wildfire impacted river systems is critical to better describing, quantifying and modeling propagation of sediment to downstream environments.

This paper presents the current state of knowledge regarding 1) the effects of wildfire on the physical (particle size, morphology, density, porosity and settling velocity) and transport (erosion and deposition) properties of sediment in streams and 2) the impacts of biological modification on the stability and transport of cohesive sediment in wildfire impacted streams. Implications of the Lost Creek wildfire on sediment transport in the

Crowsnest River, Alberta are discussed in the context of using flow and sediment transport models (MOBED, RIVFLOC).

Can Pore-clogging by Ash Explain Post-fire Runoff and Erosion?

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Worldwide, forest and other land-clearing fires affect an area larger than the contiguous western United States each year, causing economic and ecological havoc. Fire can greatly increase a landscape's vulnerability to flooding and erosion events, and ash is thought to play a large role in controlling runoff and erosion processes after wildfire. Although ash can store rainfall and thereby reduce runoff and erosion for a limited period after wildfire, it is also frequently suggested that clogging of soil pores by ash is the cause for the increase in runoff and erosion after wildfire. Evidence for this is however incomplete, as to date, research has solely focused on identifying the presence of ash in the soil, while the actual flow processes associated with the infiltration and pore-clogging of ash remain a major unknown. Naturally, the mere presence of ash in the soil does not mean that it clogs pores and blocks infiltration to the point that runoff or ponding occurs. Pore clogging depends not just on the presence of ash in the pores, but also on its amount, attachment processes, and mobility, and its location in the pores.

To investigate whether ash can clog soil pores to the point that infiltration is blocked, we performed a set of laboratory experiments in which we visualized and quantified pore-scale infiltration of water and ash in sand with a range of textures. We used fine, coarse and mixed quartz sand that was cleaned by the HCl-heat method to remove impurities, and wildfire ash collected from a Douglas Fir stand burned in the 2010 Fourmile Canyon wildfire (Colorado, USA). Infiltration experiments were performed in a 1x1x10 cm transparent column filled with sand and a 1-cm layer of ash, and a 45 mm h^{-1} rainfall rate was applied using a pump. Pore-scale flow and attachment processes were visualized using a bright-field microscope connected to a computer, while infiltration of

ash was quantified with a spectrophotometer. Pore-clogging was assessed during each 2-hr infiltration experiment, and was defined as the blocking of infiltration to the point that ponding was observed. Three replicates were performed per treatment. As observed in previous experiments by the authors, the far majority of the ash remained on the sand surface during the 2-hr infiltration experiments. However, microscope images and real-time video showed that ash did infiltrate into the soil pores, which was confirmed by spectrophotometer measurements. Despite frequent assumptions in the literature, pore-clogging was not observed: ponding did not occur during any of the runs, and microscope images showed that even when ash particles or flocs appeared to be fixed in a pore, they regularly disaggregated and moved position. Interestingly, small particles were even observed to pass these flocs, indicating that though ash may be temporarily positioned in pores, water can still move through.

Although these experiments confirm field and lab observation of ash infiltrating into soil pores (i.e. the process leading to the presence of ash in pores), we have not observed any clogging of pores to the point that infiltration is blocked and ponding is observed. Neither have we been able to create conditions at which clogging occurs. For instance, even at extremely high rainfall intensity (1500 mm h^{-1}), ponding was not observed and microscope images again confirmed that the few ash particles temporarily located in pores were mobile and moved with the water. Based on this, we conclude that at least for the sandy soils evaluated in this study, pore-clogging by ash is highly unlikely to be a controlling factor of the typical wildfire-related increase in runoff and erosion.

Changes in Flow Characteristics in Burnt Areas after Forest Management

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The largest forest fire ever recorded in Israel, burning from 2 to 6 December 2010, destroyed more than 2500 ha of natural and planted vegetation on Mount Carmel. Removal and clear-cutting of the burnt *Pinus halepensis* stands close to roads and recreation sites was started soon after the wildfire; while it was only two years later that forest managers began to remove the burnt trunks from the dense forest.

The study area is located at Mount Carmel, an isolated mountain ridge, rising from the eastern Mediterranean Sea shore of Israel to an elevation of 546 m a.s.l. The climate of this region is sub-humid, mild Mediterranean with an average annual rainfall of 750 mm at the highest elevations. Given the severity (upon 27% burnt in high severity fire result of field survey in 2011 summer) of the wildfire and the size of the burnt area, this study analyzes the effect of the post-fire management practices on soil-vegetation dynamics, runoff and erosion, and evaluates the most appropriate method to remove the burnt trunks.

The study erosion plots (silt fences) were set during the third winter after the wildfire (2012/2013) following a massive cutting and removal of burnt logs. Four silt fences, two at the polar and two at the equatorial aspects, were placed on steep slopes (> 30%) of the Rakit stream. Silt fence size is 4 meter in average. Soil texture composition in equatorial-facing slope (EFS) is: 20.2% sand, 41.2% silt and 38.5% clay compared to 32.7% sand, 33.7% silt and 33.5% clay in the polar-facing slope (PFS). The organic matter content is higher in the north 10.2% compared to 6.7% in EFS. Sediment yield was sampled following three effective rainfalls. The PFS contributed 3.1 kg vs. 31.2 kg collected in the EFS. The composition of the eroded sediment was relatively similar, although the soil composition in the EFS slope was much finer: 27.7% sand, 35.6% silt and 36.7% clay compared to 28.7% sand, 33.6% silt and 37.7% clay. In an adjacent watershed, the EFS received 390 mm compared to 361 mm in the PFS, meaning, addition of 29 L/m^2 on the PFS. Consequently, given the nature of the shallow eroded soils and higher rainfall amounts, the erosion potential of the EFS is much higher; evidently, sediment yields following management practices are elevated. On both aspects, vegetation was sampled for relative coverage along four line-transects of 30 m each (vegetation was divided into four groups: 'trees', 'shrubs', 'potential herbaceous' and 'rock').

The plots were mapped and pictured from constant reference points to monitor and detect changes in vegetation cover and flow patterns (Fig.1). Preliminary results indicated a distinctive rill-patterned (small-scale channeled flow) development following the clear cutting, even in places where total vegetation coverage exceeded 97%. The movement of run-off water and eroded soil over the recovering slopes followed the flow lines and rills. The transition from sheet flow immediately after the wildfire, when the slopes were denuded of vegetation, towards rills developed between the emerging shrubs, altered the timing, quantity and texture of the eroded sediments.

Figure 1: Erosion plot **(**silt fence**)** on the equatorial-facing slope; connected rills and flow patterns are marked.

Wildfires are the Key to Unlocking Sediment Stored in Channels

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Drainage networks in headwaters act as sediment stores, filling with hillslope sediment from colluvial processes and small erosion events over time. In undisturbed conditions this sediment is locked up, only becoming available when a critical process threshold is reached. Disturbances, such as wildfire, reduce thresholds for runoff initiated processes such as channel and debris flows, causing otherwise stored channel sediment to become available. This has implications for sediment transport, storage and downstream impacts. In south-east Australian forests the transport of stored sediment may be linked primarily to mass failure processes (saturation) in some systems and quick runoff response (infiltration excess) in others. A single wildfire may burn examples of both systems. Thus, the level of stored sediment made available depends on the wildfire, storm and landscape properties.

This study integrated landscape scale assessment of debris flow and channel initiation with hillslope scale runoff measurements to investigate how variability in system properties, associated with surface runoff potential, influences downstream sediment movement in headwater channels. Aerial photographs and spatial datasets were used to determine location of debris flow and channel initiation (evacuation) in single headwater catchments across a burnt landscape. The degree of channel erosion across the burnt landscape was strongly related to landscape aridity, as measured using the aridity index proposed by Budyko (1958):

$$AI = \frac{R}{PL}$$

Where R is the mean annual net radiation, P is the mean annual precipitation and L is the latent heat of vaporization for water. Aridity index values across Victoria range from 0.5 to 11. Results showed a significant difference ($p < 0.05$) between the average aridity of headwater catchments which produced debris flows (n=65) and those which did not (n=157). Additionally, stepwise multiple regression analysis of data suggests inclusion of landscape aridity is important in the prediction of debris flow producing catchments. Following these findings, hillslope runoff plots have been established along an aridity gradient in a recently burnt area to investigate how runoff potential varies with aridity and the implication this might have for runoff initiated processes.

Results suggest that the long term balance between solar radiation and precipitation (i.e. aridity) may be an important factor in predicting whether wildfire is a local geomorphic control. Where wildfire is important for making stored channel sediment available through debris flows, the increase in entrainment rates will depend on

the longer term accumulation and distribution of sediment within the channel, fire regime, and the starting position of the debris flow. Previous studies suggest channel sediment entrainment rates of 0.6 to 9.93 m^3 per metre of channel are possible in post-wildfire debris flow conditions (Nyman *et al.*, 2011; Santi *et al.*, 2008). However, in wetter landscapes the wildfire regime may be less important as a control on sediment release from channels compared with dryer systems. As aridity can be determined for large areas using remotely sensed data, it is well suited for predicting sediment movement following disturbance and for use in assessments of hydro-geomorphic risk in burnt areas.

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Post-wildfire Response Domains in the Patagonian-Andean Region of Chile and Argentina

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In the Patagonian-Andean region of South America, a recent increase in the frequency and severity of large wildfires has triggered substantial concern among land managers and the general public. In this presentation, to provide general context I first synthesize the current understanding of the factors driving these large wildfires and their ecological consequences. Then, for selected ecosystem types with the best studied fire regimes I summarize their characteristics using the post-wildfire framework for organizing runoff and erosion responses.

For general context, I first address the following key questions about several extreme wildfires in the Patagonian-Andean region of southern Argentina and Chile in the late 1990s and early 2000s: 1) Are there historical precedents for the extent and severity of these recent wildfires? 2) To what extent can large, severe wildfires be attributed to influences from modern humans, either indirectly through land-use practices or directly through ignition? 3) What are the relation of these wildfires to climatic trends and variability in major climate drivers (i.e. El Niño Southern Oscillation and the Southern Annual Mode)? (4) What are the medium-term ecological consequences of these wildfires, particularly in terms of the resiliency of the burned ecosystems?

The second part of the talk summarizes current knowledge of post-wildfire responses for the following ecosystem types: 1) mesic forests and xeric woodlands dominated by *Araucaria araucana* (evergreen conifer) and *Nothofagus* species (southern beeches) at c. 37 to 40°S; 2) xeric woodlands dominated by *Austrocedrus* (evergreen conifer) at the ecotone with the Patagonian steppe at c. 37 to 43°S; and 3) mesic forests dominated by the deciduous *Nothofagus pumilio* extending from c. 37 to 55°S. For each of these ecosystem types, I describe their fire regimes, precipitation regimes, and hydro-geomorphic regimes, and for comparative purposes I identify the closest analogue ecosystem types and fire regime types in the western U.S. In exploring opportunities for comparative research on the post-wildfire response domains of temperate latitudes of the western Americas, I stress the need for integrating research on post-wildfire runoff and erosion responses with ecological research aimed at understanding positive feedbacks that are increasing the flammability of some of these ecosystem types.

Strengths and Weaknesses of the Revised Morgan-Morgan-Finney Model in Predicting Post-wildfire Erosion

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Wildfires are widely regarded as an important, if not the most important, agent of soil erosion and, hence also of land degradation in Mediterranean forests. Soil erosion models modified for application to burnt areas can provide useful means of assessing medium- to long-term impacts of this landscape-disturbing agent, which can complement small-scale, short-term field monitoring, as well as acting as important decision-making tools to support post-fire management. The first wildfire-related application of the revised Morgan-Morgan-Finney (MMF, Morgan 2001) soil erosion model was reported by Fernández et al. (2010). The revised MMF model used the concepts by Meyer and Wischmeier (1969) and Kirkby (1976), and separates the soil erosion process in two phases: the water phase and the sediment phase. The water phase determines the energy of rainfall available for soil particles detachment from the soil and the volume of runoff. In the sediment phase, rates of soil particle detachment by rainfall and runoff are determined along with the transport capacity of runoff. Predictions of total particle

detachment and transport capacity are compared and erosion rate is equated to the lower of the two rates, differing from the RUSLE methodology where all the inputs are used to predict as one single output--the erosion rate.

Wildfire-specific modifications were applied to the model in studying burnt pine and shrubland areas subject to different fire severities in NW Spain. This modified model was successful in providing soil erosion rates that were close to those measured in the field. The present study also assesses the performance of the revised MMF model when applied to burnt areas in north-central Portugal, following several further modifications concerning fire-induced changes on vegetation cover and soil properties. Specifically, the improvements were: (i) the introduction of seasonal rather than annual changes in model parameters (rainfall (R), hydrological depth of soil (EHD), evapotranspiration (Et/Eo), soil moisture content at field capacity (MS), ground cover, (GC)) in order to accommodate the substantial differences in seasonal runoff and erosion reported by Prats et al. (2012) in north-central Portugal for pine and eucalypt stands after a wildfire; and (ii) the inclusion of the effect of seasonal soil water repellency variations on runoff predictions by changing the MS parameter, using data from the same study. In the present study, runoff and erosion rate predictions following wildfire were carried out and produced predictions that closely matched the field results reported by Prats et al. (2012) and thus broadened the applicability of the results compared with the study by Fernández et al. (2010).

In order to evaluate the ability of the modified model to perform accurately in other burnt areas, validation was performed using a dataset of other wildfire-affected pine and eucalypt sites in north-central Portugal following wildfire (Shakesby et al. 1996). This application, carried out without further calibration, produced acceptably accurate estimates of erosion on the burned control plots with no treatments, with a level of performance that was similar to that achieved when applied to the original calibration plots, which is therefore a strong indication of robust model calibration.

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Changes in Runoff Following Wildfire in Eastern Arizona

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The Wallow Fire burned over 217,000 ha in eastern Arizona in 2011, including three catchments (117-227 ha) that had been used for water yield experiments between 1962 and 1983. Pre-fire and post-fire precipitation and runoff from the catchments were used to quantify fire-induced changes in runoff frequency, magnitude, and timing as well as hydrograph shape. The annual maximum instantaneous peak discharge rates during the 21-year pre-fire record ranged from 0.0018 to 0.48 m^3 s^{-1} and the annual hydrograph was dominated by snow melt. There was no change in runoff relative to the winter precipitation in either of the two post-fire melt periods. In one catchment 31 rainfall-initiated storm flows were measured in 2011-2012, and 9 of these exceeded the pre-fire peak discharge rate by as much as 3.1 times. Similar responses were measured in the other two catchments, where the pre-fire peak flows were exceeded by a factor as high as 18. With the exception of one 2-year return period storm that affected the two larger catchments, each of the post-fire summer flows was caused by relatively frequent rain storms with 30-min maximum intensities much lower than 2-yr value. The increase in runoff from the summer storms caused a shift in the mean timing of the annual 24-hr peak discharge from 8 June during the pre-fire period to 14 August after the fire. The post-fire storm hydrographs had much shorter storm durations than the pre-fire storms, and this resulted in a significant increase in the mean slope of the hydrographs' rising and falling limbs. These results can be used to improve predictions of post-fire runoff using unit hydrographs and other modeling approaches, and may have implications for riparian or aquatic habitat.

Significance of Connectivity and Post-wildfire Runoff

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Amplified hillslope soil loss from rain storms following wildfire results from the evolution of runoff and erosion processes across spatial scales. At point to small-plot scales, soil is detached and transported a short distance by rainsplash and sheetflow. Soil transport by water over larger scales is enhanced by high-velocity concentrated flow. Progressive sediment bulking of overland flow over hillslope scales can result in resource damaging mudflows and debris flows. This evolution of sediment transport at this large scale is well-linked to increased connectivity of runoff sources along a hillslope. We present results from a suite of field studies and well documented post-fire erosion responses that demonstrate evolution of these processes from the small-plot to hillslope scales.

Our emphasis is on the connectivity of susceptible surface conditions and the ensuing shift in dominant runoff and erosion processes across spatial scales. By connectivity, we refer to the continuity of runoff-generating bare areas and the convergence of overland flow sources that result in increased cross-scale erosion. Connectivity is well represented by the percentage of bare ground, and its influence on runoff and erosion responses for a given storm is strongly governed by the susceptibility of the bare surface and storm intensity. The susceptibility of the soil surface is defined by burn severity as well as inherent soil properties (i.e., texture/structure, water repellency, erodibility), antecedent soil water content, and topography. Our results are from field studies along the rangeland-xeric forest continuum of the interior western United States, but the overall inferences are applicable for sloping lands in arid- to semi-arid landscapes across the globe.

Modeling Short- and Long-Term Water Repellency Effects on Post-wildfire Infiltration and Runoff

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Fire induced soil water repellency (WR) is a common characteristic of burnt soils. Nonetheless, the rates, magnitude and the persistence of this phenomenon are highly variable, spatially and temporally. Five predominant mechanisms have been described as generating water repellency in soils: a) fungal and microbial activity, b) growth of particular vegetation species, c) organic matter content, d) heating of the soils by wildfires and e) soil characteristics.

The natural WR is related to the coating of soil particles with hydrophobic compounds leached from the organic matter (OM) accumulations, by products of microbial activity and/or fungal growth. Fire-induced WR is related to volatilizing of hydrophobic organic compounds in the burnt soil. After a wildfire, WR is typically found as a non continuous layer of variable thickness on the soil surface or a few centimeters beneath it. Soil water repellency has major impacts on infiltration capacity, overland flow generation, runoff amounts and sediment yields.

Although numerous studies describe the mechanisms and persistence of the short-term effects of fire on soils and geomorphic processes, further research is needed to explain its long-term dynamics. We synthesized from *in situ* research data and published information to develop a mathematical model describing the long-term properties of WR in soils. Using non-linear regression analysis methods we compare among different variants of the model, in order to assess the relative role of vegetation on water-repellency dynamics and its effects on runoff and erosion processes. The post-wildfire short-term dynamics are characterized by a rapid increase in hydrophobicity (time scale of weeks), generated by the heating of organic compounds during the wildfire. Following this phase a long-term decrease (months) in hydrophobicity occurs due to erosion, leaching, and the breakdown of the water repellent layer. Slow formation of water repellent substances in the soil (time scale of years) generated by microbial and flora activities results in a gradual increase of hydrophobicity.

In parallel, infiltration experiments were carried out *in situ*, and using a rainfall simulator. Results obtained from this set of experiments suggest that a complex set of interactions exists between water repellency, ash and vegetation cover. Ultimately, vegetation cover plays the key role in determining infiltration/runoff rates. Non-burned bare soils exhibited the highest runoff rates whereas litter-covered non-burned soils exhibited the lowest (Figure 1). Apparently, on the exposed soils a sealing layer is rapidly generated, yielding high runoff values, whereas the litter cover dampens the effects of the raindrops. Burned soils exhibited intermediate rates relative to the non-burned soils, which depended on the presence of ash. No runoff was generated in the burned soils for up to 40 mm of

simulated rainfall. Once this threshold value was achieved, runoff begun to form, and it was partially dependent on the presence of ash, but not directly correlated with water repellency properties. Ash bearing soils exhibited lower runoff rates (~ 11 mm h^{-1}) compared to exposed burned soils - ~22 mm h^{-1} (Figure 1), suggesting a sponge-like mechanism generated by the ash.

These responses should be viewed in light of the relevant spatial and temporal scales. While water repellency may peak following a wildfire, its spatial expression might be local. Further its effects might be offset by the presence of ash. The temporal expression of these processes is nullified by the presence of vegetation and litter cover. In the long run the response of the geomorphic system to disturbances such as wildfires depends on the capacity of vegetation recovery.

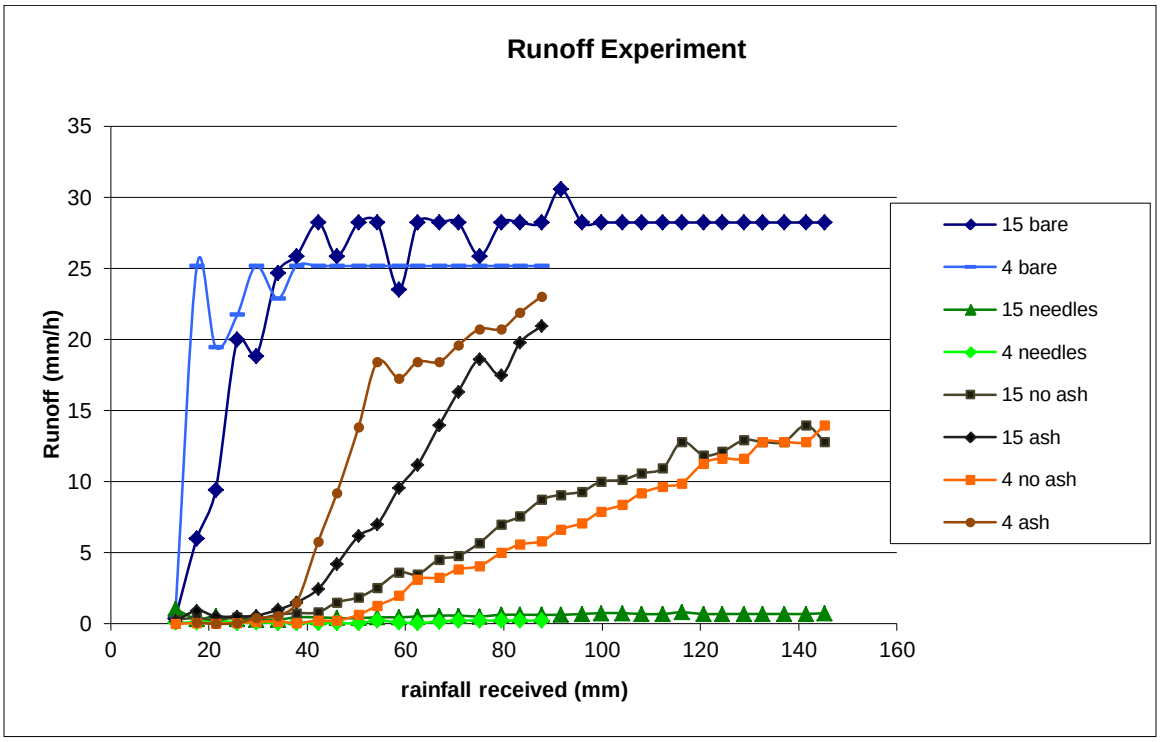

Fig. 1: Rainfall simulator experiment.

Hillslope Erosion and Small Watershed Sediment Yield Before and After a Wildfire in Southern California

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In 2002, a wildfire burned over an ongoing sediment flux study in the steep, chaparral-covered foothills of the San Gabriel Mountains of southern California, USA. The study area had previously burned in 1960, and estimates of current fire return intervals for the region range from 20-80 years. Southern California experiences a Mediterranean climate with cool wet winters and hot dry summers. Average annual rainfall for the study area is 714 mm (75-year record), with a local 2-year, 30-minute rainfall intensity of 29 mm hr^{-1}. Located at 915 m in elevation, median slopes in the study area are 0.55 and the minimum calculated soil erodibility k-factor is 0.13, yielding a hydro-geomorphic regime (K*S) value of 0.07. Hillslope erosion was measured in 30 cm collector traps. These traps were serviced multiple times per year to separate wet season from dry season erosion. Small watershed (1-3 ha) sediment yield was measured annually in earthen debris basins. Three of the watersheds were in mixed chaparral vegetation and one was in type-converted grass. One of the chaparral watersheds was burned in a prescribed fire in 2001 and did not re-burn in the wildfire. Hillslope erosion and small watershed sediment yield data were collected for 7 or 8 years prior to burning then for 5 or 6 years following fire, including the complete post-fire erosion record. Continuous rainfall was measured in a centrally-located weighing bucket recording raingage. After the wildfire, first-year rainfall totaled 615 mm with a peak 30-minute intensity of 14 mm hr^{-1}. Following the prescribed burn, first-year rainfall measured 252 mm with a peak 30-minute intensity of 33 mm hr^{-1}. Rainfall totals in subsequent post-fire years ranged from 408-1848 mm with peak 30-minute intensities of 17-49 mm hr^{-1}. Prior to fire, annual hillslope erosion was an order of magnitude less under grass vegetation compared to chaparral (0.02-0.41 kg m^{-2} yr^{-1}), dry season erosion was equal to wet season erosion in all watersheds, but sediment yield was only minor at the watershed scale (0-4.35 m^3 ha^{-1} yr^{-1}). In the first year following fire, hillslope erosion was similar for both vegetation types (2.28-6.82 kg m^{-2} yr^{-1}), dry season erosion doubled but wet season erosion increased by an order of magnitude compared to pre-fire levels, and sediment yield was similar for all watersheds (23.3-37.6 m^3 ha^{-1} yr^{-1}). Hillslope erosion rates and small watershed sediment yields returned to pre-fire levels in subsequent post-fire years (0.07-0.26 kg m^{-2} yr^{-1}; 0-4.51 m^3 ha^{-1} yr^{-1}). Hillslope erosion and sediment yield was only slightly less after the prescribed fire compared to the wildfire. These results can serve as a benchmark for validating models of post-fire sediment response for planning and risk assessment in southern California chaparral environments.

Hydrologic and Geomorphic Responses of Burned Basins in the Southwestern U.S.A.

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The southwestern U.S.A. has a complex variety of forest types, physiographic characteristics, and rainfall regimes that affect post-fire hydrology and geomorphology. In Arizona and New Mexico alone, there are five regional rainfall regimes, as defined by the 2-year, 30-minute intensity (I_{30}^{2yr}), and six different physiographic provinces. Forests across the region have varying components of oak, piñon-juniper, pines, and conifers depending on elevation and climate. Since the late-1800s, fire regimes in the southwest have been dramatically altered due to livestock grazing, fire suppression, fuels build up and climate change. Forests that once burned by frequent, low-intensity surface fires (i.e. Ponderosa pine), or less frequent, more intense wildfires with mosaics of burn severities (i.e. mixed conifer), now tend to burn by large crown fires that leave extensive patches of moderate and high burn severity. Historic mean fire recurrence intervals for southwestern forests ranged from 5-15 years for lower elevation pine/piñon-juniper/oak forests, 8-20 years for Ponderosa pine forests, and 10-25 years for mixed conifer forests. To place southwestern watersheds in a hydro-geomorphic framework, recently burned basins were plotted according to a local I_{30}^{2yr} rainfall regime (x-axis) and a hydro-geomorphic component, KS, described by mean basin slope and a soil erodibility factor (y-axis). When comparing only basins with sediment yield or discharge data, a distinct pattern emerges with burned basins clustered by physiographic provinces. This pattern also holds when plotting a single I_{30}^{2yr}:KS value for each fire and appears to be most strongly controlled by rainfall regime. If, however, basins with qualitative response data (occurrence of debris flows, or only floods, in the drainage basin) are also included, the clustering by physiographic provinces blurs but the two basin populations plot separately with debris-flow basins plotting higher on the hydro-geomorphic regime (y-axis) than flood basins. This is likely controlled by slope as the soil erodibility factor is generally consistent between basins. Hence, post-fire hydrologic and geomorphic responses of burned basins in Southwestern U.S. reflect both regional and local influences.

Erosion and Sedimentation in the 2012 Bagley Fire, Eastern Klamath Mountains, Northern California, USA

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The 2012 Bagley Fire burned about 18,000 hectares in late summer 2012 on the Shasta-Trinity National Forest, immediately south of McCloud, California. It occurred in steep, rugged terrain near the eastern margin of the Klamath Mountains Province, and was underlain primarily by metasedimentary rock. In November and December of 2012, intense storms hit the fire area with estimated return intervals of 25-50 years, based on a 24 hour storm total in excess of 22 cm. Post-storm field reconnaissance revealed very extensive hillslope erosion, loss of road stream crossings, scouring of low-order channels and delivery of a large volume of sediment to higher order streams. Squaw Creek, located in the center of the fire area, remained extremely turbid for two months after the storms, which was a very unusual post-fire response for this region. It delivered sediment and woody debris to the Shasta Lake reservoir, and gravel and sand aggraded lower gradient reaches. Rainfall from January to May, 2013 was very sparse (near-record low amounts), and as a result, aggraded channels will likely persist through summer 2013.

Traditional as well as new techniques will be used to quantify sediment mobilization, transport, and deposition. Goals of this project are to characterize relative roles of surface erosion and landslides in delivering sediment to channels, to develop a preliminary sediment budget, and also to identify links between fire severity and roads with erosional processes. Another goal is to evaluate pre-storm predictions of peak flow magnitudes, and debris flow occurrence in burned watersheds. Air photos and field observations will be used to quantify scour/deposition in channels, slope wash, rilling, gullying, and landslides on hillslopes. Monumented channel cross sections established prior to the wildfire will be resurveyed, and reservoir deposition will be evaluated with bathymetric surveys. Preliminary findings will be tabulated in late summer 2013. LiDAR data will become available soon after that, and will be used to refine estimates of erosion and deposition. Key objectives of the project are to characterize and quantify post-fire erosional processes, evaluate effectiveness of burned area emergency response (BAER) treatments, guide future forest management, and provide hands-on experience to young earth scientists in evaluating post fire watershed response. Lastly it is to set the stage for longer term monitoring of watershed recovery from this fire.

A chasm exists between measurement protocols that are practicable for researchers versus operational efforts by the U.S. Forest Service at the National Forest level toward assessment of post-fire erosion and sedimentation processes. Research level erosion measurements are typically quantified in per-unit-area terms, requiring substantial human and monetary capital to arrive at estimates. This level of effort is not typically feasible for operational (management) level assessments. The latter vary wildly in protocol approaches and tend to rely upon more qualitative and ocular methods, presenting distinct disadvantages in discriminating process-related differences among sites and over time. Here we present practical operational-level methods for characterizing post-fire erosion and sedimentation processes, which are quantitative and useful for making comparisons that are ultimately intended to guide management options and prioritize active management needs.

We propose the following basic measurement techniques for assessing sediment erosion and deposition. Hillslope erosion processes will be assessed along 100 meter transects, measuring width, depth, and other pertinent physical parameters of erosion features. This will include a consolidated survey of sheet (inter-rill) erosion, rills, gullies, shallow landslides, as well as hillslope re-deposition. In general, all metrics will be converted to cross-sectional area for analysis. This will not quantify erosion in terms of per-unit-area (i.e. tons/ha), so results may not be used to validate or refine erosion models, which is a desired objective of research-level efforts. However, the methods proposed do represent a practical quantitative measure, and are therefore useful for making relative comparisons with statistical context. Additional covariate data taken on transects will include slope gradient, live vegetation cover, surface cover, soil texture and rock content, soil burn severity, soil water repellency, and surface infiltration (using a Mini Disk Infiltrometer from Decagon Devices, Inc.). Desired erosion response comparisons include soil burn severity classes, watershed slope positions, stand types (young plantations, older plantations, mature natural stands), and management effects (BAER treatments, salvage logging). All of these variables can be pro-rated on an area-basis in GIS to synthesize erosion processes at hillslope and watershed scales.

The volume of landslide erosion will be estimated by measuring erosional hollows created by landslides, using a combination of air photo interpretation and field sampling of cross sectional areas. Estimates will be refined with LiDAR-derived high resolution DEM's, using existing algorithms for measuring the volume of voids.
Debris flow and channel erosion will be estimated by establishing sampling sites to measure the cross sectional area of eroded material in scoured reaches of the channel network. Air photos and field sampling will be used to determine which channel reaches experienced actual debris flows as opposed to flood or sediment laden flows. The determination will be based on field observations of new deposits, and criteria will be developed from the literature.

Aggradation in large streams will be evaluated by re-surveying pre-existing stream channel condition inventory (SCI) reaches. This will be done according to US Forest Service SCI protocols, and cross sections will be measured to centimeter precision. Particle size will also be characterized. This effort will not yield depositional volumes, but rather, will show

changes in bed elevation and particle size, and will provide insights into sediment supply and transport processes and potential effects on fish habitat. Deposition in the Shasta Lake reservoir will be measured with repeated bathymetric surveys with a precision to tens of centimeters. Unfortunately, no pre-event surveys of the reservoir are known to exist, so estimates of deposition from the 2012 storm events will be very rough, and based upon comparisons with available pre-reservoir topographic surveys. Changes in volume in subsequent years will be captured by repeat bathymetric surveys. Bathymetric data will be augmented by field surveys and test pits to determine sediment accumulation in parts of the reservoir which are exposed annually by seasonal drawdown. Lastly, sediment production from two small watersheds within the fire area will be measured at debris catchment basins, and this information compared to volumes predicted by various models.
From the sum of these efforts, various map products can be generated to inform land managers and help guide decisions on post-fire rehabilitation and restoration needs in coming years. Additionally, this information can be used to develop a preliminary sediment budget for watersheds in the fire area.

To place the Bagley Fire area in a broader context of post-wildfire response domains (as in Moody, et al. 2013), we propose the following to characterize the fire, precipitation, and hydro-geomorphic regimes. The fire regime is a frequent-recurrence, mixed-severity regime, with a fire return interval of approximately 12-16 years. The mixed-severity characterization is qualitative; because most recent fires have BARC and RAVG imagery routinely available, these burn severity products could be used to parameterize typical mixes of burn severity (soil or vegetation) as a standard fire regime descriptor. The precipitation regime has a 2-year, 30-minute rainfall intensity of 18 mm h^{-1}, typically produced from long-duration Pacific winter frontal storms with localized cells of high-intensity rain. The 2-year, 6-hour rainfall amount, used conventionally in CA for the statewide Erosion Hazard Rating system, is 64 mm. The Hydro-geomorphic regime has not been fully characterized, but this will be accomplished with available soil K-factor and slope data, along with dominant geomorphic processes as interpreted from geomorphic mapping, and channel networks as identified by a standardized contributing area algorithms applied to a high resolution DEM.

Analysis of Forest Fires Impact in Semi-Arid Zones and Identification of Desertification Process in Algeria

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Forest in the Algerian steppe is ecologically diverse, but with unfavourable climate conditions and the effect of wildfires we have noted deterioration of the physical environment particularly, and of the natural forest (e.g. *Pinus halepensis, Quercus ilex, Pistacia lentiscus*) This deterioration of forests provokes an unbalance of environment, which produces overland flow erosion that contributes to desertification. In the Algerian forest ecosystem wildfires usually start during the summer season, early June to late October, and in August multiple wildfires are often observed. Wildfires generally burn in the same ecosystem every year. Where climatic conditions are favourable, wildfire is an ecological agent and an integral part of the evolution of the ecosystems. The specific regeneration of plants is influenced greatly by the regime of wildfire (season of fire, intensity, interval), which leads to the recuperation of the vegetation after wildfire. Algeria has a Mediterranean climate with a long summer period (6 month) between the months of May until October. Winter precipitation is usually from December until February. Precipitation varies by regions with 600-800 mm y^{-1} in the subhumid coastal zones, 300-400 mm y^{-1} in the semi-arid steppe zones, and 100-200 mm y^{-1} in the arid desert zones. The forests are mainly located in the Mountains of the Tell zone. The Tell, are formed by a succession of mountain, coastal and sublitoral ranges, and plains. The topography is steep, rising from sea level to the top of the Hauts Plateau with an elevation of about 700 m in 100 km, and to the Atlas Sahara Mountains with an elevation of about 2000 m located about 300 km from the coast. In this survey, we used the images from the ALSAT-1 to detect zones with risk of forest fire and their impact on the natural's forests in the region of Tlemcen on the northern side of the Hauts Plateau. A detailed thematic analysis of forest ecosystems by using remote sensing data (picture ALSAT-1), has allowed us to identify and classify forests according to their floristic components. We also identified the extent of forest fires in this area. Some parameters as the slope (0-6, 6-12, 12 -25, 25-100 %), the proximity to roads and the forests formations were studied with the goal of determining the zones of risk of forest fire. Cross layer information in a GIS permitted us to classify the forest area in terms of the degree of fire risk in a semi-arid environment, which does not promote regeneration against the invasion of steppe species that promote desertification.