Number 11 • 2015

Assessing Impacts of Fire and Post-fire Mitigation on Runoff and Erosion from Rangelands

Purpose: To provide an overview of the immediate and short-term hydrologic impacts of fire on infiltration, runoff, and erosion by water, and of the effectiveness of various mitigation treatments in the reduction of runoff and erosion in the years following the fire.

In Brief:

- ***Amplified runoff and erosion responses*** are most likely where fire increases bare ground to 50 to 60 percent and slopes exceed 15 percent. Extensive bare ground promotes accumulation of runoff and formation of high velocity concentrated flow, capable of entraining and transporting a high sediment load.
- ***Runoff and erosion responses*** are likely enhanced on steep slopes and under high rainfall intensity. Rainfall intensity and bare ground are strong predictors of post-fire responses. The hydrologic and erosion recovery period for rangelands will vary with precipitation and ground cover in the years following burning and is influenced by ecological site and pre-fire conditions.
- ***Risk assessment tools are available*** to assist in evaluation of post-fire conditions and their effects on runoff and erosion.
- ***Effectiveness of post-fire stabilization treatments*** depends on magnitude, intensity, and duration of the rainfall events following fire; ability of the treatment to increase surface cover or trap sediment; persistence of the treatment; and interaction of the treatment with vegetation and ground cover reestablishment.

Fire Impacts on Infiltration, Runoff Generation, and Erosion

Wildfires are a natural component of rangeland ecosystems, but fires can pose hydrologic hazards for ecological resources, infrastructure, property, and human life. There has been considerable research conducted on the effects of fire on hydrologic processes and sediment movement over the point (<20 ft^2) to patch or hillslope (100 to 320 ft^2) spatial scales in shrublands and woodlands of the western United States (Pierson et al. 2011; Williams et al. 2014a). Nearly all of this work has been conducted using rainfall simulation and overland flow experiments.

Sagebrush rangeland burned by the Soda Fire (2015) within the Reynolds Creek Experimental Watershed, southwestern Idaho. The photo shows extensive bare ground associated with high rates of surface runoff and formation of high velocity concentrated flows.
Photo credit: USDA Agricultural Research Service.

Table 1. Site characteristics, runoff, and sediment yield from rainfall simulations (60 min except where noted) on unburned and high, moderate, and low-severity burned shrublands (Pierson et al. 2002, 2008, 2009) and woodlands (Pierson et al. 2013; Williams et al. 2014b, Pierson et al. 2015).

Ecosystem	Microsite	Burn severity	Plot size (ft^2)	Slope (%)	Time post-fire (month)	Rainfall intensity (in h^{-1})	WDPT[A] (s)	Bare soil (%)	Canopy cover (%)	Ground cover (%)	Runoff coef.[B] (%)	Sediment yield (lb ac^{-2})
Sagebrush rangeland	Coppice	Unburned	5	35–60	12	2.6	–	7	88	93	11	20
		Moderate	5	35–60	12	2.6	–	97	11	3	34	270
		High	5	35–60	12	2.6	–	98	13	2	37	195
	Interspace	Unburned	5	35–60	12	2.6	–	89	18	12	24	35
		Moderate	5	35–60	12	2.6	–	95	16	5	26	105
		High	5	35–60	12	2.6	–	99	5	1	49	1320
Sagebrush rangeland	Coppice	Unburned	5	30–40	1	3.3	200	1	100	99	30	110
		High	5	30–40	1	3.3	102	99	1	1	37	365
	Interspace	Unburned	5	30–40	1	3.3	220	6	74	94	49	215
		High	5	30–40	1	3.3	97	99	4	1	30	190
Sagebrush rangeland	Coppice	Unburned	5	35–50	1	3.3	286	2	84	98	39	150
		Moderate–High	5	35–50	1	3.3	261	42	10	58	76	1630
	Interspace	Unburned	5	35–50	1	3.3	110	25	31	75	63	1740
		Moderate–High	5	35–50	1	3.3	117	84	0	16	55	6290
	–	Unburned	350	35–50	1	3.3	–	24	57	76	4	70
	–	Moderate–High	350	35–50	1	3.3	208	76	0	24	27	8810
Juniper woodland	Tree Coppice	Unburned	5	10–25	12	4[D]	42	0[E]	17	100	23	475
		High	5	10–25	12	4[D]	54	88[E]	5	12	58	1840
	Shrub Coppice	Unburned	5	10–25	12	4[D]	3	41[E]	117	59	20	55
		High	5	10–25	12	4[D]	11	94[E]	21	6	23	1280
	Interspace	Unburned	5	10–25	12	4[D]	3	88[E]	20	12	63	320
		High	5	10–25	12	4[D]	3	93[E]	21	7	51	1200
Juniper woodland	Tree Coppice	Unburned	140	10–25	12	4[D]	–	18[E]	26	82	13	430
		High	140	10–25	12	4[D]	–	73[E]	15	27	58	9660
	Inter–canopy	Unburned	140	10–25	12	4[D]	–	89[E]	18	11	50	2430
		High	140	10–25	12	4[D]	–	88[E]	32	12	50	5100
Pinyon-juniper woodland	Tree Coppice	Unburned	140	10-15	12	4[D]	–	6[E]	27	94	5	320
		Moderate	140	10-15	12	4[D]	–	27[E]	6	73	14	700
	Inter–canopy	Unburned	140	10-15	12	4[D]	–	64[E]	39	36	47	1980
		Moderate	140	10-15	12	4[D]	–	86[E]	23	14	43	3090
Utah juniper woodland	Tree Coppice	Unburned	140	15–20	12	4[D]	–	15[E]	21	85	10	590
		Moderate	140	15–20	12	4[D]	–	68[E]	3	32	51	16885
	Inter–canopy	Unburned	140	15–20	12	4[D]	–	79[E]	19	21	45	2640
		Moderate	140	15–20	12	4[D]	–	81[E]	17	19	42	4380

[A]Water drop penetration time (WDPT) is an indicator of strength of soil water repellency as follows: <5 s wettable, 5-60 s slightly repellent, 60-600 s strongly repellent.

[B]Runoff coefficient is equal to cumulative runoff divided by cumulative rainfall applied. Value is multiplied by 100 to obtain percent.

[C]Data presented from south-facing slopes only.

[D]Simulated storm applied immediately following 45 min simulation of 64 mm h^{-1} rainfall.

[E]Includes rock cover and ash; bare areas of rock and bare soil were extensive due to woodland encroachment.

Studies indicate runoff and erosion by water may increase 2- to 40-fold immediately post-fire over scales of <20 ft^2, and 6-fold and 125-fold respectively at the hillslope scale (Table 1). Few rangeland studies have evaluated the impacts of fire on hydrologic and erosion processes at hillslope to landscape or watershed scales (e.g., paired watersheds). Studies from mountainous forested settings indicate hillslope erosion can approach 24 to 40 tons per acre annually the first few years following burning, and recovery to pre-fire erosion rates may take four to seven years (Robichaud 2009). Numerous anecdotal reports have documented large-scale flash flooding and debris flow events following intense rainfall on burned rangelands. Reports of flooding and debris flow events commonly document that these landscape-scale processes are initiated by increased plot-scale to hillslope runoff and soil loss following fire.

Fire primarily alters hydrology and erosion processes by consumption of the protective ground cover and organic matter. The exposed bare soil becomes susceptible to increased runoff generation and sediment detachment and transport (Figure 1). The first order effect is increased water availability for runoff generation. Fire-removal of plants and litter reduces rainfall interception and surface water storage, promotes rapid runoff, and decreases ground surface protection against raindrop impact and soil detachment by overland flow. Fire effects on infiltration and runoff generation are increased where soil water repellency persists post-fire or is enhanced by burning. Soil water repellency is commonly found within the first few inches of soil underneath unburned sagebrush, and pinyon and juniper litter on rangelands and its strength may increase or decrease with burning (Pierson et al. 2008, 2009, 2013).

Coarse-textured soils are thought to be prone to water repellency, but water repellent soil conditions have also been documented for fine-textured soils. Fire-induced increases in runoff and soil loss are typically greater from areas underneath shrubs and trees than interspaces between woody plant canopies. Canopy locations commonly have greater post-fire sediment availability and stronger soil water repellency than interspaces between canopies.

Increased post-fire runoff generally facilitates formation of highly erosive concentrated flow and increased soil erosion on hillslopes. Homogenous bare soil conditions (bare ground >50 to 60 percent) in the immediate post-fire period allow overland flow to concentrate into high velocity flows with greater erosive energy and transport capacity than processes occurring at the point scale (Figure 1). Concentrated flow moves soil detached by rainsplash and sheetflow downslope while also eroding sediment from within the flow path. Concentrated flow is the dominant water-based erosion process in the first one or two years post-fire and is accentuated by steep, bare hillslopes coming together. Accumulation of water and sediment on hillslopes can result in resource-, property-, and life-threatening erosion events. For example, a nine minute convective rainstorm on burned rangeland hillslopes along the Boise Front Range, Idaho, generated flooding and mud-flows in the City of Boise. The flooding was driven by intense rainfall and formation of concentrated flow on bare, strongly water repellent soils with reduced water storage capacity and low surface roughness. Similar hydrologic and erosion responses to convective storms have been reported for burned cheatgrass sites and woodlands in Utah and Colorado. The likelihood or risk of such large-scale flooding events is related to the spatial connectivity of susceptible surface conditions and the occurrence of runoff generating rainfall. Great Basin plant community conversions to invasive annual grass (e.g., cheatgrass and red brome) and climate trends that promote wildfire activity increase the likelihood that rangelands will be exposed to runoff and erosion generating storms and thereby likely enhance long-term soil loss associated with frequent re-burning.

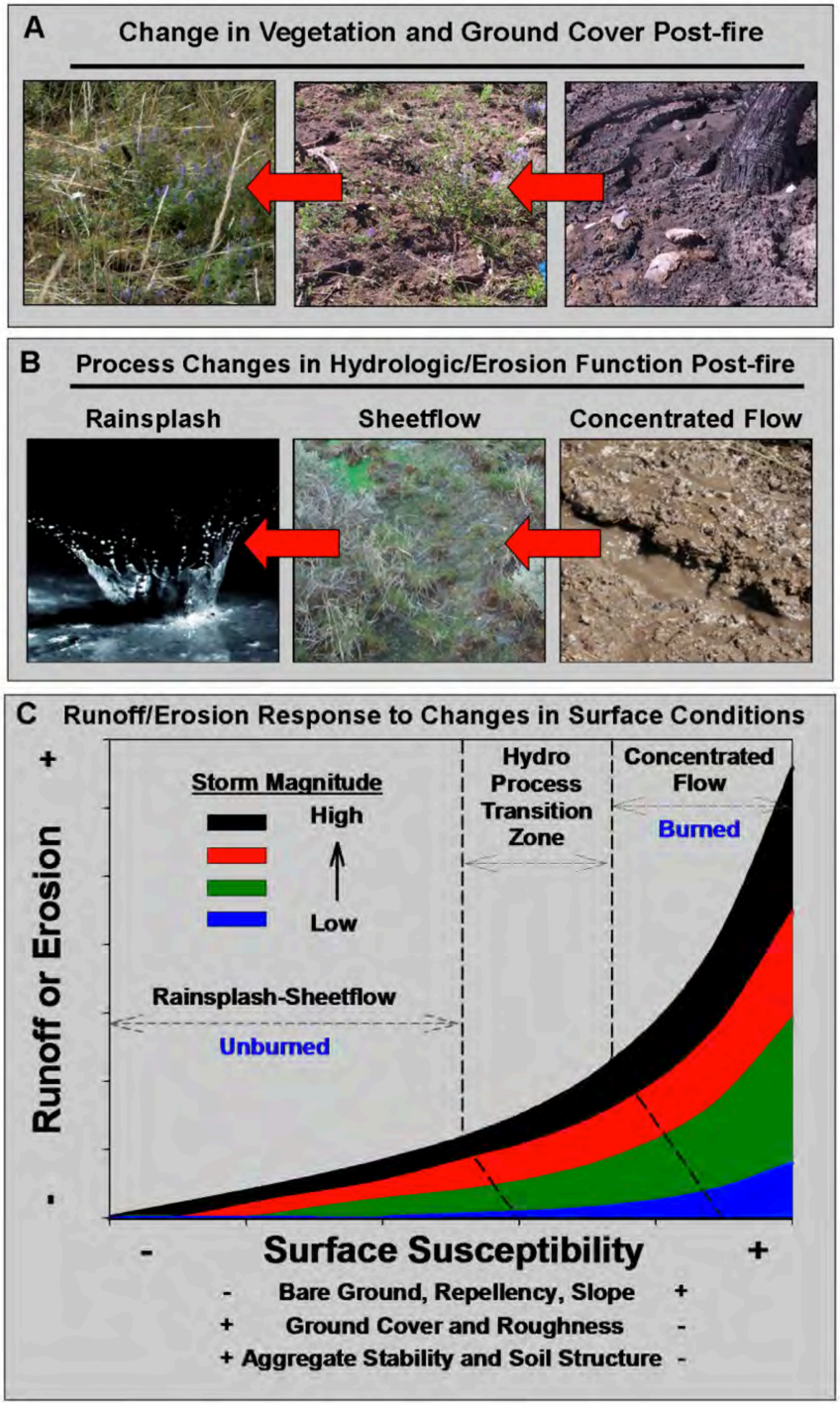

Figure 1. A) Change (recovery) in vegetation and ground surface conditions following burning; B) the shift in hydrologic processes from concentrated flow-dominated to rainsplash-dominated; and C) the decline in runoff or erosion response and shift in dominant erosion processes with decreasing surface susceptibility. Bare water repellent soil conditions in the immediate post-fire period facilitate runoff generation and promote formation of high-velocity concentrated flow. The decline in runoff or erosion response with time post-fire is strongly related to changes in ground surface conditions that trap and store water and sediment and inhibit concentrated flow. Modified from Williams et al. (2014a, b) and Miller et al. (2013).

Post-fire Hydrologic Recovery

The relative hydrologic recovery of burned rangelands is primarily influenced by the pre-fire vegetation and ground cover characteristics, fire severity, and post-fire weather and land use that affect vegetation recovery. Pre-fire vegetation and ground cover influence variability in burn severity and post-fire plant recruitment (Miller et al. 2013). Burn severity relates to the degree of impact of fire on vegetation and soil. High severity burns on productive shrublands may consume nearly 100 percent of the plants and litter, but runoff and erosion can return to pre-fire levels within a few years post-fire (Pierson et al. 2011). Rainfall simulation studies of burned mountain sagebrush communities have found that runoff post-fire returns to pre-fire levels within one growing season and that post-fire soil erosion returns to near pre-fire levels once bare ground declines to near 60 percent, usually within two to three growing seasons depending on post-fire precipitation. Other rangeland studies in the Great Basin indicate bare ground commonly returns to pre-fire levels within two to four years. Burning a Phase II to III woodland on a mountain big sagebrush ecological site increased hillslope scale runoff and erosion 4- and 20-fold from areas underneath tree canopies the first year post-fire (Williams et al. 2014b). Erosion remained elevated underneath burned junipers two years post-fire due to delayed plant establishment and bare ground persistence. Burning had no effect on hillslope-scale runoff and erosion in intercanopy areas (areas between tree canopies) the first year post-fire. Two years post-fire less erosion occurred from burned than unburned intercanopy areas probably due to well-distributed intercanopy herbaceous reestablishment post-fire.

Although relative hydrologic recovery of rangelands appears to occur within one to three years post-fire, rangelands likely remain susceptible to runoff and erosion during extreme events until overall site characteristics (e.g., live plant and litter biomass) are similar to pre-fire conditions. Rangeland ecosystems with warm/dry soil temperature/moisture regimes may require longer periods to recover hydrologically than cool/moist sites and may be vulnerable to cheatgrass invasion and subsequent re-burning. Hydrologic recovery and resilience of woodland-encroached sagebrush sites have received only minor attention in the literature. Burning may represent a potential restoration pathway for pinyon and/or juniper expansion in sagebrush steppe on cool/moist ecological sites. However, less productive sites or sites with minimal pre-fire herbaceous cover may exhibit less hydrologic resilience post-fire with respect to Phase II woodlands and intact sagebrush communities. Regardless of the soil temperature/moisture regime and pre-fire state, short-term post-fire hydrologic recovery is likely delayed by land use activities and/or drought conditions that inhibit vegetation and ground cover establishment.

Assessing Post-fire Risk

Numerous tools have been developed in recent years to aid in the assessment and prediction of post-fire hydrologic and erosion risk, including literature, sampling methods and devices, and predictive technologies to aid or guide post-fire assessments, response forecasting, and decision making. This factsheet does not allow for detailed descriptions of the numerous available tools, but provides references to some of the most widely used resources.

- ***A synthesis of fire effects on vegetation and soils*** for rangelands in the context of ecological site characteristics is in Miller et al. (2013).
- ***Field methodology for assessing soil burn severity*** and suggestions for integration of soil burn severity mapping with other predictive technologies is provided by Parsons et al. (2010).
- ***Use of mini-disk infiltrometers*** for rapid assessment of infiltration and hydrologic effects of soil water repellency (Robichaud and Ashmun 2013).
- ***The Rangeland Hydrology and Erosion Model (RHEM***) provides simultaneous comparisons of runoff and erosion predictions across multiple sites with varied conditions and has recently been enhanced for application to disturbed rangelands (Al-Hamdan et al. 2015). The model requires relatively minimal user input of commonly obtained site characteristics (e.g., slope angle, distance, and shape; soil texture; and canopy and ground cover) and delivers runoff and erosion predictions at the annual time scale and for various return-interval runoff events.
- ***The Erosion Risk Management Tool (ERMiT***) is a post-fire erosion prediction tool that estimates hillslope response based on user input for climate, soil texture, dominant vegetation type, slope gradient and length, and soil burn severity (Robichaud et al. 2007). ERMiT predicts the probability of a given hillslope sediment yield for an individual storm in each of five years following burning and provides assessment of the effectiveness of various mitigation treatments.

Many of the tools noted above are described in more detail in a recent review by Robichaud and Ashmun (2013). Additionally, recent journal articles by Pierson et al. (2011) and Williams et al. (2014a) provide reviews of fire impacts on rangeland hydrologic response and assessing post-fire hydrologic vulnerability and risk.

Mitigation of Post-fire Runoff and Erosion

The mitigation of post-fire runoff and erosion from rangelands has not been extensively studied. Therefore, much of what we know regarding effects of post-fire mitigation strategies comes from studies in forests (Robichaud et al. 2010). Post-fire runoff and erosion stabilization treatments generally are from one of the following categories: 1) erosion barriers, 2) mulches, or 3) chemical soil surface treatments. Post-fire seeding is addressed in several Great Basin Factsheets and therefore is not discussed here. The effectiveness of each of these types of treatments depends on many factors, including: 1) burn severity conditions, 2) magnitude of storm events (that is, storm intensity/duration), 3) type and quality of installation or treatment, 4) persistence of the treatment, and 5) interaction of the treatment with vegetation and ground cover recruitment.

- ***Erosion barriers*** can be constructed of downed logs, straw wattles, or lines of straw bales and are commonly used to trap runoff and promote sediment deposition immediately upslope. Erosion barriers can be effective at trapping runoff and sediment from low intensity storm events, but are often overtopped by runoff during moderate to extreme events. Sediment storage capacity behind erosion barriers can also be filled by the first few sediment producing events, minimizing the beneficial effect for subsequent storms. Proper installation is paramount to the effectiveness of erosion barriers, as improper barrier installation can amplify erosion. Robichaud et al. (2010) provides a review of erosion barrier effectiveness in reducing post-fire runoff and erosion and provides methods for estimating erosion barrier performance.

- ***Mulch treatments*** are increasingly applied to mitigate post-fire erosion. Mulch is applied to increase ground cover and thereby protect the soil surface from raindrop impact, increase infiltration, and reduce overland flow volume, velocity, and sediment movement. Mulch treatments may consist of aerially or manually distributed agricultural straw (wheat, barley, rice), wood-based mulch (shreds or strands) or wet application of a hydromulch, made up of organic fibers and seeds bonded by a tackifier. On burned forested sites application of more than 50 percent ground cover of wood, strand mulch resulted in persistence of some mulch on sites four and seven years post-treatment, limited negative impact on vegetation, and substantially reduced annual sediment yield (by 79 to 96 percent) the first year post-fire. Wheat straw mulch application increased ground cover by 56 to 87 percent across all sites, but reduced first year sediment yield (by 97 to 99 percent) at only two of four sites where it was applied partly due to site-specific differences in straw distribution and vegetation recovery. Hydromulch treatment generally persists for weeks to months and had limited beneficial effect on post-fire runoff and erosion especially with high rainfall intensity events. Better hydromulch treatment effectiveness has been observed in Southern California with low intensity rainfall and rapid vegetation establishment.

- ***Chemical Surface Treatments*** are made from various soil binding agents which are sprayed or applied dry with pellets. When the wet binding solution dries, it forms a web of polymers that coats the surface soil particles. The treatment degrades within months after application. In a southern California post-fire study, little benefit was observed from this treatment on reducing soil erosion (Robichaud et al. 2010).

Overall, beneficial effects of treatments over the first four years are typically associated with the initial effect on ground cover, the persistence of the treatment, and vegetation recovery. Wood strands and agricultural straw mulch both may reduced sediment yield, but the wood strands show greater persistence against the effects of wind and water over time. Needle cast from low to moderate severity fires on burned pinyon and juniper woodlands may provide a natural mulch-type surface protection against runoff and erosion in the first year post-fire by limiting bare ground exposure to rainfall and aiding infiltration into water repellent soils.

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Websites

The Rangeland Hydrology and Erosion Model, RHEM:
http://dss.tucson.ars.ag.gov/rhem/

The Erosion Risk Management Tool, ERMiT:
http://forest.moscowfsl.wsu.edu/fswepp/

Burned Area Emergency Response Tools:
http://forest.moscowfsl.wsu.edu/BAERTOOLS