Hydrologic and erosion responses to wildfire along the rangeland–xeric forest continuum in the western US: a review and model of hydrologic vulnerability

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Abstract. The recent increase in wildfire activity across the rangeland–xeric forest continuum in the western United States has landscape-scale consequences in terms of runoff and erosion. Concomitant cheatgrass (Bromus tectorum L.) invasions, plant community transitions and a warming climate in recent decades along grassland–shrubland–woodland–xeric forest transitions have promoted frequent and large wildfires, and continuance of the trend appears likely if warming climate conditions prevail. These changes potentially increase overall hydrologic vulnerability by spatially and temporally increasing soil exposure to runoff and erosion processes. Plot and hillslope-scale studies demonstrate burning may increase event runoff or erosion by factors of 2–40 over small-plot scales and more than 100-fold over large-plot to hillslope scales. Reports of flooding and debris flow events from rangelands and xeric forests following burning show the potential risk to natural resources, property, infrastructure and human life. We present a conceptual model for evaluating post-fire hydrologic vulnerability and risk. We suggest that post-fire risk assessment of potential hydrologic hazards should adopt a probability-based approach that considers varying site susceptibility in conjunction with a range of potential storms and that determines the hydrologic response magnitudes likely to affect values-at-risk. Our review suggests that improved risk assessment requires better understanding in several key areas including quantification of interactions between varying storm intensities and measures of site susceptibility, the varying effects of soil water repellency, and the spatial scaling of post-fire hydrologic response across rangeland–xeric forest plant communities.

Additional keywords: cheatgrass, climate change, fire effects, grass-fire cycle, Great Basin, hydrologic risk, invasive plants, juniper, pinyon, runoff, sagebrush, wildland–urban interface, woodland encroachment.

Introduction

Wildfire activity is increasing along the rangeland–xeric forest continuum of the interior western United States (US; Littell et al. 2009; Miller et al. 2009; Litschert et al. 2012; Balch et al. 2013). A vast expanse of the western US is dominated by an arid to semi-arid climate with less than 100-cm annual precipitation (Fig. 1a) and vegetation that transitions from rangelands to pinyon–juniper woodlands (Pinus spp., Juniperus spp.) or xeric ponderosa pine (Pinus ponderosa Lawson & C. Lawson) forests across low- to mid-elevations (Fig. 1b). Over the past decade, more than 1 × 10⁶ ha of the western US were burnt by wildfire annually, and much of this was along the rangeland–xeric forest continuum (NIFC 2012). Periods of recurring high wildfire activity in the western US are not unprecedented in the paleo-record (Pierce et al. 2004; Heyerdahl et al. 2008a, 2008b; Whitlock et al. 2008, 2011; Marlon et al. 2012) but the frequency of large fires (>400 ha) and annual area burnt have increased in recent decades (Westerling et al. 2006; Keane et al. 2008; Morgan et al. 2008; Littell et al. 2009; Miller et al. 2011a).

Cheatgrass (Bromus tectorum L.) invasion is the primary cause of increased fire frequency and annual area burnt on sagebrush rangelands throughout the western US (Keane et al. 2008; Miller et al. 2011a; Balch et al. 2013). The species is now a major plant constituent on 4 × 10⁶–7 × 10⁶ ha of sagebrush rangelands in the Great Basin alone (Fig. 1b; Knapp 1996; Bradley and Mustard 2005; Miller et al. 2011a). Cheatgrass infill of areas between woody plants affects wildfire activity by increasing the horizontal continuity of fuels and the likelihood...
Fig. 1. Map of annual precipitation (a) (Prism Climate Group 2012) and landcover (b) (USGS 2012) across the western United States. The approximate geographic area of the study domain is delineated by the bold black line in each map. The boundary of the Great Basin Desert (rangeland and woodland region with high wildfire activity) is delineated with a dashed black line on the landcover map.
of ignition (Fig. 2a; Brooks et al. 2004; Link et al. 2006; Davies et al. 2012). Fire return intervals in cheatgrass-infested rangelands are commonly 10-fold shorter than those for intact sagebrush–bunchgrass communities (Miller et al. 2011a). Frequent re-burning of cheatgrass-invaded rangelands promotes a grass-fire cycle that in turn perpetuates cheatgrass dominance (Knapp 1996; Brooks et al. 2004; Davies et al. 2012; Balch et al. 2013). Cheatgrass produces more seeds post-fire than do native species (Humphrey and Schupp 2001) and commonly out-competes native bunchgrasses for soil nutrients and water (Harris 1967; Mack and Pyke 1983; Aguirre and Johnson 1991; Duke and Caldwell 2001). The higher seedling vigour and reproduction potential of cheatgrass relative to other species promote a decline in site species richness and evenness with increasing cheatgrass coverage (Mack 1981; Melgoza and Nowak 1991). Repeated fires over short rotations kill newly established shrubs and perennial grasses, exhaust native seed sources and propagate highly flammable cheatgrass monocultures (Fig. 2b; Welch 2005; Davies et al. 2012).

Woodland expansion and infill on rangelands have made much of the western US prone to large severe wildfires (Keane et al. 2008; Romme et al. 2009). Native pinyon and juniper species have dramatically increased their range in the past 150 years and currently occupy more than $3.0 \times 10^6$ ha of the western US (Miller and Tausch 2001; Davies et al. 2011; Miller et al. 2011a). Range expansion has primarily occurred through encroachment into sagebrush communities (Fig. 3a). Early-succession woodlands are now burning in large, high-severity wildfires due to heavy woody-fuel loading and extensive horizontal-to-vertical fuel connectivity (Fig. 3b; Miller and Tausch 2001). Tree infill on late-succession woodlands (Fig. 3c) and extreme fire weather have increased the occurrence of large, high-severity woodland fires in recent decades (Keane et al. 2008). Cheatgrass invasion into pinyon–juniper woodlands (Fig. 3d) across the western US has amplified the risk of large-scale fires associated with the annual grass-fire cycle (Young and Evans 1978; Tausch 1999; Getz and Baker 2008; Shinneman and Baker 2009). Historical wildfire regimes in pinyon and juniper woodlands consisted of high-severity fires every few hundred or more years (Baker and Shinneman 2004; Romme et al. 2009). Therefore, severity of modern woodland wildfires is within the historical range of variability, but the relatively high frequency of large fires and annual area burnt on woodlands in the past 20 years is likely unprecedented (Keane et al. 2008).

Much of the interior western US now exists in a state in which rangeland and woodland wildfires stimulated by cheatgrass and dense fuels have a greater likelihood of progressing upslope into xeric forests where fire activity is also increasing (Keane et al. 2008; Nelson and Pierce 2010; Balch et al. 2013). Wildfire activity in western xeric forests is dictated by low fuel moisture and cyclonic weather conducive to ignitions and fire spread (Heyerdahl et al. 2002; Gedalof et al. 2005; Heyerdahl et al. 2008a; Morgan et al. 2008; Taylor et al. 2008; Whitlock et al. 2008; Miller et al. 2009). In recent decades, warmer winter and spring air temperature trends at mid-elevations in the western US have resulted in decreased snowpacks (Mote et al. 2005; Regonda et al. 2005; Knowles et al. 2006; Trenberth et al. 2007; Bonfils et al. 2008; Niyak et al. 2010), earlier spring snowmelt and streamflow (McCabe and Clark 2005; Regonda et al. 2005; Stewart et al. 2005; Pederson et al. 2011) and drier fuels (Westerling 2006). These shifts have lengthened fire seasons and increased fire frequency and area burnt in western forests (Pierce et al. 2004; Westerling et al. 2006; Morgan et al. 2008; Pierce and Meyer 2008; Littell et al. 2009).

Climate projections forecast geographic and elevation shifts in fuels that influence fire activity and a persistence of current fire trends along the rangeland–xeric forest continuum (Bradley et al. 2009; Balch et al. 2013). Abatzoglou and Kolden (2011) suggested cheatgrass invasibility and the length of the fire season in the Great Basin will be enhanced by a warmer climate and an increase in wet winters. Wisdom et al. (2003) estimated at least 35% of Great Basin shrublands remain at high risk of woodland encroachment, potentially pre-conditioning these areas to extreme fire behaviour (Keane et al. 2008). Miller and Tausch (2001) forecasted that land area covered by dense woodlands and the occurrence of high severity woodland fires will increase substantially in the next 40 or more years. Across the interior west, cheatgrass is migrating upslope (Keeley and McGinnis 2007; McGilvey et al. 2009; Griffith and Loik 2010;
Bromberg et al. 2011), potentially introducing the grass-fire cycle at higher elevations and in xeric forests. Xeric forests adjacent to grass-dominated hillslopes will likely undergo more frequent burning than those distant from grass-dominated hillslopes (Gartner et al. 2012). Projections of climate and plant community transitions are highly variable (Bradley 2009), but most forecast warming, increased dry-season cyclonic storms, longer fire seasons and greater wildfire activity across the rangeland–xeric forest domain of the western US (Price and Rind 1994; Flannigan et al. 2000; Whitlock et al. 2003; Brown et al. 2004; Gedalof et al. 2005; Running 2006; Flannigan et al. 2009; Spracklen et al. 2009; Littell et al. 2010; Abatzoglou and Kolden 2011).

Paleo-erosion records link periods of high wildfire activity in the western US with flooding and increased erosion (Meyer et al. 1995, 2001; Meyer and Pierce 2003; Pierce et al. 2004; Pierce and Meyer 2008; Pierce et al. 2011). In recent decades, extensive damage to natural resources, property, and city infrastructures, and loss of human life have been well documented for post-fire flood events in the western US (Cannon et al. 2001a; Moody and Martin 2001a; Klade 2006; Cannon et al. 2011). Our ability to accurately forecast these effects and the potential hazards for values-at-risk is limited with respect to current wildfire activity (Miller et al. 2011b). Resource managers in the western US are challenged with rapidly evaluating fire effects on ecosystems, determining potential hazards to values-at-risk and conducting cost-benefit analyses of mitigation options (Calkin et al. 2007; Robichaud et al. 2010a). The capability of risk assessments to accurately evaluate hazards and apportion mitigation expenditures requires continued improvement in understanding fire effects, development of predictive technologies, and transfer of information and tools to resource managers (Robichaud et al. 2009; Robichaud and Ashmun 2013).

Current knowledge of fire effects on soils, runoff and erosion is largely based on field studies of sagebrush rangelands (Artemisia spp.; Pierson et al. 2001, 2002, 2008a, 2008b, 2009), semi-arid woodlands (Pierson et al. 2013; Williams et al. 2013), chaparral (see DeBano et al. 1998; Shakesby and Doerr 2006), forests (Robichaud et al. 2000; Benavides-Solorio and MacDonald 2001, 2005; Larsen et al. 2009; Robichaud et al. 2010a, 2010b) and Mediterranean scrublands (Cerdà 1998; Cerdà and Doerr 2005, 2008; Shakesby 2011). These studies offer valuable insight into post-fire watershed response and development of hydrologic risk assessment strategies associated with increasing wildfire activity. In this paper, we review current understanding of the hydrologic effects of increasing wildfire activity across the rangeland–xeric forest continuum in the interior western US (Fig. 1) and determine key knowledge...
Hydrologic and erosion responses to wildfire activity

The combustion of organic matter in soils can alter soil structure, increase bulk density and decrease porosity and infiltration capacity (Giovannini et al. 1988; Giovannini and Lucchesi 1997; Hester et al. 1997; Pierson et al. 2001, 2002; Hubbert et al. 2006; Stoof et al. 2010). Aggregate stability promotes infiltration and soil resistance to erosion and may be unaffected, reduced or increased by burning. Moderate- to high-severity burning of soils stabilised by organic matter commonly reduces aggregate stability through combustion of the binding agent (Mataix-Solera et al. 2011). Some studies have found an increase in aggregate stability after fire associated with formation of hydrophobic soils (Mataix-Solera and Doerr 2004; Arcenegui et al. 2008; Jordán et al. 2011). Aggregate stability of soils with high clay content may be enhanced by high-severity burning due to thermal fusion of clay particles into coarser particles (Giovannini et al. 1988; Giovannini and Lucchesi 1997; Mataix-Solera et al. 2011). However, fusion of clay to silt or sand particles can increase soil erosion due to the loss of the cohesive properties inherent to clay soils (Badia and Martí 2003; Hubbert et al. 2006). Burning may also reduce the role of invertebrates, microorganisms, and fungal mycorrhizae in facilitating soil aggregation and infiltration (DeBano et al. 1998; Shakesby and Doerr 2006; Mataix-Solera et al. 2009).

Soil heating may alter or create hydrophobic and/or hyper-dry soil conditions (Krammes and DeBano 1966; DeBano and Krammes 1974; DeBano et al. 1998; Doerr et al. 2000; Hubbert et al. 2006; Pierson et al. 2008b; Doerr et al. 2009a; Moody et al. 2009; Pierson et al. 2009; Moody and Ebel 2012). During fires, organic matter combustion at the soil surface radiates heat into the soil profile, potentially causing partial pore structure collapse (DeBano et al. 1998; Stoof et al. 2010; Ebel 2012, 2013).

Fire effects on soils, runoff and erosion

Water availability and surface soil conditions

The first-order effect of fire on runoff and erosion is decreased interception. Unburnt shrubs and conifers can intercept as much as 35% and 80% of rainfall during high and low intensity storms, decreasing water available for runoff and erosion (Rowe 1948; Hamilton and Rowe 1949; Skau 1964; Tromble 1983; Owens et al. 2006). Rainfall interception by rangeland plants can reduce erosivity of high-intensity rainfall by 50%, thereby decreasing soil detachment by rain drop (Wainwright et al. 1999; Martínez-Mena et al. 2000). Numerous studies in forested areas have found rainfall erosivity and its dissipation by cover to be primary factors controlling post-fire erosion rates (Inbar et al. 1998; Moody and Martin 2001b; Benavides-Solorio and MacDonald 2005; Spigel and Robichaud 2007; Robichaud et al. 2008; Moody and Martin 2009; Robichaud et al. 2013a, 2013b). Reduction of vegetation by fire may also result in less snow accumulation and subsequent decreases in soil water recharge and vegetation recovery. Spatial and temporal patterns of snow accumulation and melt exert significant control on soil water input, vegetation recruitment and productivity, and hydrologic processes in snow-dominated semi-arid landscapes (Flerchinger et al. 1998; Flerchinger and Cooley 2000; McNamara et al. 2005; Seyfried et al. 2009; Williams et al. 2009; Ebel et al. 2012a). Dense shrub cover (2.2 plants m⁻²) can intercept and store 37–61% of snowfall on rangelands (Hull 1972; Hull and Klomp 1974). Reduced snow accumulation after fire may have minor influence on soil water storage where seasonal snowmelt input is substantial enough to return soils to field capacity (Ebel et al. 2012a).

Hydrologically important soil properties are strongly influenced by organic matter and soil fauna and microorganisms that are altered to varying degrees by burning (Raison 1979; Certini 2005; Shakesby and Doerr 2006; Mataix-Solera et al. 2009, 2011). Soil organic matter is combusted at temperatures above 200°C and is completely consumed at 450–500°C (DeBano et al. 1998; Neary et al. 1999). These temperatures are well within the range of those commonly reported for rangeland and xeric forest soils during wildfire (Wright and Bailey 1982; Neary et al. 1999). The combustion of organic matter in soils can alter soil structure, increase bulk density and decrease porosity and infiltration capacity (Giovannini et al. 1988; Giovannini and Lucchesi 1997; Hester et al. 1997; Pierson et al. 2001, 2002; Hubbert et al. 2006; Stoof et al. 2010). Aggregate stability promotes infiltration and soil resistance to erosion and may be unaffected, reduced or increased by burning. Moderate- to high-severity burning of soils stabilised by organic matter commonly reduces aggregate stability through combustion of the binding agent (Mataix-Solera et al. 2011). Some studies have found an increase in aggregate stability after fire associated with the formation of hydrophobic soils (Mataix-Solera and Doerr 2004; Arcenegui et al. 2008; Jordán et al. 2011). Aggregate stability of soils with high clay content may be enhanced by high-severity burning due to thermal fusion of clay particles into coarser particles (Giovannini et al. 1988; Giovannini and Lucchesi 1997; Mataix-Solera et al. 2011). However, fusion of clay to silt or sand particles can increase soil erosion due to the loss of the cohesive properties inherent to clay soils (Badia and Martí 2003; Hubbert et al. 2006). Burning may also reduce the role of invertebrates, microorganisms, and fungal mycorrhizae in facilitating soil aggregation and infiltration (DeBano et al. 1998; Shakesby and Doerr 2006; Mataix-Solera et al. 2009).

Soil temperatures of 40–210°C are fatal for most fungi and soil organisms, and organic matter combustion and nutrient volatilisation at soil temperatures above 200°C reduce the primary food source for soil fauna production (DeBano et al. 1998; Neary et al. 1999; Certini 2005; Mataix-Solera et al. 2011). Finally, soil moisture retention, a key component of plant and soil fauna productivity, can also be adversely affected by burning due to loss of soil organic matter, pore structure and surface insulation by litter (DeBano et al. 1998; Stoof et al. 2010; Ebel 2012, 2013).

Soil heating may alter or create hydrophobic and/or hyper-dry soil conditions (Krammes and DeBano 1966; DeBano and Krammes 1974; DeBano et al. 1998; Doerr et al. 2000; Hubbert et al. 2006; Pierson et al. 2008b; Doerr et al. 2009a; Moody et al. 2009; Pierson et al. 2009; Moody and Ebel 2012). During fires, organic matter combustion at the soil surface radiates heat into the soil profile and vaporises organic substances. Some of these substances are translocated downward along temperature gradients until they condense, forming a variable-thickness hydrophobic patch (DeBano et al. 1970; Savage et al. 1972; Savage 1974; DeBano et al. 1976; DeBano 2000; Doerr et al. 2004). Naturally occurring or ‘background’ soil water repellency has been commonly observed beneath unburnt conifers and shrubs (Lebron et al. 2007; Madsen et al. 2008; Pierson et al. 2008b; Doerr et al. 2009b; Pierson et al. 2009, 2010, 2013; Williams et al. 2013) and is typically unaffected by soil temperatures <175°C. Soil temperatures of 175–270°C may enhance ‘background’ water repellency or create hydrophobic soil conditions (Doerr et al. 2000, 2009a). Water repellency breaks down or is destroyed at soil temperatures of 270–400°C (Savage et al. 1972; DeBano et al. 1976; Giovannini and Lucchesi 1997; Doerr et al. 2004). Fire-enhanced or -induced soil water repellency is commonly found within a few centimetres of the soil surface and rapidly decreases in strength with increasing soil depth (Doerr et al. 2009a). Repellency strength and its effect on runoff pre- and post-fire is highly variable in space and time due to inherent variability in pre-fire vegetation, soil properties and conditions, and burn severity (Dekker et al. 2001; Huffman et al. 2001; MacDonald and Huffman 2004; Woods et al. 2007; Pierson et al. 2008b; Woods and Balfour 2008; Pierson et al. 2009, 2010; Stoof et al. 2011; Bodi et al. 2013; Williams et al. 2013). The effects of repellency on runoff generation are even more severe under hyper-dry (extremely dry) conditions immediately following high-severity fire. Extreme heating during high-severity fire can dry out small and large pores within the upper soil profile, potentially causing partial pore structure collapse...
Hyper-dry conditions require soils to be rewet before capillary and gravity-driven infiltration can occur (Moody and Ebel 2012).

Runoff and erosion at the small-plot scale

Small plot (0.7 × 0.7 m) rainfall simulation studies by the authors (see Table 1) on steeply sloped (35–60%) sagebrush hillslopes demonstrate the effects of vegetation cover removal, surface alteration and soil water repellency on post-fire runoff and erosion from rangelands and woodlands. For example, Pierson et al. (2002) investigated the hydrologic effects of wildfire on north- and south-facing sagebrush hillslopes 1 year after the Eighth Street Fire, near Boise, Idaho. Only the south-facing hillslope results are presented here. Runoff and erosion pre-fire were low from shrub coppices (areas beneath shrub canopies) and interspaces (areas between shrub canopies) due to rainfall interception by the canopy and litter and high surface roughness (Table 1). Moderate- and high-severity burning reduced vegetation and litter biomass by 75–99% and decreased surface roughness by 40%. Approximately 30–50% of applied rainfall post fire was lost to runoff over the nearly uniformly bare surface (Table 1). Fire had a greater effect on erosion than on runoff (Table 1) and severe burning increased soil erosion 10-fold from coppices and 40-fold from interspaces (Table 1). Higher runoff rates following fire were attributed to decreased interception, persistence of pre-fire soil water repellency, and reduced surface water detention following litter removal and reduced surface roughness. Increased erosion following burning was attributed to greater raindrop detachment and more efficient sediment transport, as well as increased erodibility on interspace microsites.

A 3-year investigation by Pierson et al. (2001, 2008a, 2008b; Table 1) measured infiltration, runoff, and erosion from rainsplash and sheetflow following the Denio Fire, in Nevada. The fire removed nearly all of the canopy and ground cover from well-vegetated, steep sagebrush hillslopes. Runoff increased by 20% immediately following burning on shrub coppices but decreased on interspaces by 40% (Table 1). The difference between runoff on burnt and unburnt coppices was attributed to the removal of canopy and ground cover by fire on strongly water repellent soils. Decreased runoff from interspace areas was associated with removal of water-shedding senescent vegetation (Pierson et al. 2001) and fire-reduced soil water repellency (Table 1). A decrease in soil water repellency by 50–60% on all plots 1 year after fire was concurrent with a nearly 40% increase in infiltration (Fig. 4a). A subsequent 40–50% increase in soil water repellency on all plots 2 years after fire coincided with a 5–15% decrease in infiltration (Fig. 4a; Pierson et al. 2008a, 2008b). Overall, canopy and ground cover removal controlled water availability whereas the strength of soil water repellency exerted greater influence on infiltration and runoff. Interestingly, burning increased erosion from coppices 3-fold but had no effect on interspace erosion (Table 1). The differing responses were attributed to a more erodible surface and greater runoff on coppices after burning. Erosion 1 year after fire was greatly reduced on all plots and similar for burnt and unburnt conditions. Two years after fire, burnt coppice plots generated 3–14 times more erosion than all other plots. Soil water repellency and infiltration were the only other variables showing the same temporal trend, implicating runoff and continued increased erodibility as causal factors (Pierson et al. 2008a).

Pierson et al. (2008b, 2009; Table 1) measured infiltration, runoff and erosion from small-plot rainfall simulations on burnt and unburnt sagebrush hillslopes the year of, and 1 year following, the Breaks Prescribed-Fire in the Reynolds Creek Experimental Watershed, Idaho. The fire reduced canopy cover to 0–10% (Table 1) and litter cover to 36 and 14% for shrub coppice and interspace plots. Runoff doubled on coppice plots immediately after fire due to canopy and ground cover reductions, decreased surface roughness and strong post-fire soil water repellency (Table 1). Burning of interspaces reduced runoff (Table 1). One year after fire, a significant decrease (by 70%) in soil water repellency on burnt and unburnt coppices and nearly uniform slight soil water repellency across all plots resulted in a 2-fold increase in infiltration (Fig. 4b). As in the Pierson et al. (2008a) study (Table 1), cover influenced water availability, but the strength of soil water repellency exerted a greater influence on infiltration (Fig. 4b) and runoff of available water. The fire had an even greater effect on erosion than on runoff (Table 1). Reductions in canopy and ground cover increased sediment yield 10-fold on coppices and 3-fold on interspaces. Fire-induced increases in erosion on coppices were attributed to greater runoff and erodibility after fire whereas significantly increased erodibility alone explained the post-fire erosion increase from interspaces (Pierson et al. 2009).

Benavides-Solorio and MacDonald (2001, 2002; Table 1) measured runoff from burnt and unburnt areas of a ponderosa pine forest in the Colorado Front Range, Colorado. Runoff (Table 1) from plots burnt at high severity was well correlated ($R^2 = 0.81$) with the strength of soil water repellency. Runoff was not well correlated with percentage slope or bare ground. Benavides-Solorio and MacDonald (2001) concluded that soil water repellency and soil moisture, as a controller of repellency strength, were the primary controls on runoff. Percentage bare soil explained 79% of erosion on all plots, and soil water repellency explained 43% of the variability in erosion on plots burnt with high-severity fire (Benavides-Solorio and MacDonald 2001). Erosion on moderate- and high-severity burnt plots was 2 and 16 times greater than those on unburnt or low-severity plots (Table 1).

In a forest study, Woods and Balfour (2008) evaluated the effects of ash on runoff from rainfall simulation plots 1 month following high-severity wildfire. Rainfall was applied to 0.5-m$^2$ plots at 75-mm h$^{-1}$ intensity for 1 h. They found that ash provided 15 mm of water storage capacity and protected the soil surface from sealing immediate after fire. Time-to-ponding was 12 min longer and cumulative infiltration was 20 mm greater on ash- than on ash-free plots. Nine months after the fire, ash-covered and ash-free plots exhibited similar runoff behaviour. Similar ash cover and runoff relationships have been reported in studies by Cerdà and Doerr (2008), Larsen et al. (2009), Woods and Balfour (2010) and Ebel et al. (2012b). Bodí et al. (2011) found that ash may alter soil wettability, inducing surface soil water repellency when ash is hydrophobic and reducing surface soil water repellency when ash is wettable. In a laboratory rainfall simulation study, Bodí et al. (2012) found that a saturated ash layer promoted runoff generation from wettable soils and that an unsaturated ash layer of more than 5-mm depth protected the soil surface from rainsplash erosion.
Table 1. Site characteristics, runoff coefficients and sediment yield from rainfall simulations (60 min except where noted) on unburnt (unb) and high-, moderate- (mod) and low-severity burnt semi-arid rangelands (Pierson et al. 2001, 2002, 2008a, 2008b, 2009), woodlands (Pierson et al. 2013; Williams et al. 2013) and forests (Benavides-Solorio and MacDonald 2001; Johansen et al. 2001; Williams et al. 2013). Maximum observation time for all WDPT data was 300 s with exception of study by Benavides-Solorio and MacDonald (2001, 2002) with a maximum observation time of 120 s. All data are based on average WDPTs measured over 0- to 5-cm soil depth, beginning at the mineral soil surface. Bulk density and soil water content were measured near the soil surface (4-cm depth). Runoff coefficient is equal to cumulative runoff divided by cumulative rainfall applied. Value is multiplied by 100 to obtain percentage runoff divided by cumulative rainfall applied. Value is multiplied by 100 to obtain percentage.

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<th>Study (ecosystem)</th>
<th>Microsite</th>
<th>Burn severity</th>
<th>Plot size (m²)</th>
<th>Slope (%)</th>
<th>Time post-fire (month)</th>
<th>Rainfall intensity (mm h⁻¹)</th>
<th>WDPT (s)</th>
<th>Bulk density (g cm⁻³)</th>
<th>Soil water content (%)</th>
<th>Bare soil canopy cover (%)</th>
<th>Ground cover (%)</th>
<th>Live plant biomass (kg ha⁻¹)</th>
<th>Litter biomass (kg ha⁻¹)</th>
<th>Surface roughness (mm)</th>
<th>Runoff coefficient (%)</th>
<th>Sed. yield (kg ha⁻¹)</th>
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²Data presented from south-facing slopes solely.
²Simulated storm applied immediately following 45-min simulation of 64-mm h⁻¹ rainfall.
²Includes rock cover and ash; bare areas of rock and bare soil were extensive due to woodland encroachment (Pierson et al. 2013).
²Canopy cover excludes tree cover removed to conduct the rainfall simulation experiments.
²Data presented for Bobcat Fire only.
²Rainfall applied for 60 min under dry conditions, followed by 24-h hiatus, 30 min of rainfall, 30-min hiatus and 30-min rainfall. Total rain applied was 120 mm.
and improved infiltration into water repellent soils by fingered sub-surface flow. The study also found multiple rain events altered physical and hydraulic properties of the ash layer and reduced its effectiveness to buffer runoff generation and soil erosion. Likewise, Larsen et al. (2009) indicated that the positive effect of ash on infiltration is likely short-lived, and that soil sealing following winnowing of ash particles may promote runoff, especially on water repellent soils (e.g. Onda et al. 2008).

Runoff and erosion processes at large-plot to hillslope scales

Large-plot scale effects of burning are generally greater for erosion than for runoff due to a change from rainsplash–sheet–flow to concentrated flow as the dominant process. Steep slope angles on burnt hillslopes promote concentration of runoff (Pietraszek 2006; Spigel and Robichaud 2007; Pierson et al. 2009; Al-Hamdan et al. 2012a, 2013). Concentrated flow has a higher velocity than sheetflow and is therefore capable of eroding and transporting more sediment. Pierson et al. (2009) measured a 7-fold increase in runoff from 32.5 m$^2$ rainfall simulation plots immediately following burning of steeply sloped sagebrush rangeland (Table 1). Greater runoff under burnt than unburnt conditions was attributed to a 3-fold ground cover reduction, canopy removal, decreased surface roughness, persistent soil water repellency and formation of high-velocity concentrated flowpaths. Runoff returned to pre-fire levels within one growing season due to a 3-fold reduction in strength of soil water repellency and ground cover recovery to 40%. Burning increased erosion more than 120-fold (Table 1, Fig. 5a) as a result of high velocity concentrated flow and greater runoff after fire. Cumulative runoff from consecutive 12-min releases of 7, 12, 15 and 21 L min$^{-1}$ of concentrated flow was 406 L on burnt plots immediately following fire and 144 L on unburnt plots. Mean erosion from concentrated flow experiments was 14 363 g on the burnt plots and 2420 g on unburnt plots (Pierson et al. 2009). Concentrated flow velocities were 1.5–2.6 times higher on burnt than on unburnt plots the year of the fire and increased exponentially with increasing bare ground (Fig. 5b). Erosion from artificial rainfall and simulated concentrated flow

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**Fig. 4.** Infiltration of simulated rainfall (85-mm-h$^{-1}$ intensity) and strength of soil water repellency (measured as water drop penetration time, WDPT) on sagebrush rangeland in Nevada, USA (a) (Pierson et al. 2008a, 2008b) and Idaho, USA (b) (Pierson et al. 2009).
on burnt hillslopes approached that of unburnt hillslopes once ground cover recovered to near 60% (40% bare ground) two growing seasons after fire (Fig. 5a).

Limited data are available for large-plot-scale runoff and erosion from pinyon–juniper communities. Pierson et al. (2013) and Williams et al. (2013) measured runoff and erosion from 13-m² rainfall simulations in burn and unburnt areas of a western juniper (J. occidentalis Hook.) site 1 year after fire (Table 1). Runoff from unburnt areas beneath junipers and from the intercanopy area between trees was negligible (2–6 mm) for a 64 mm h⁻¹, 45-min duration storm on dry antecedent moisture conditions. Runoff from the same storm applied to burnt tree and intercanopy plots generated 17 and 4 mm of runoff. The study applied a higher intensity (102 mm h⁻¹, 45 min) simulated storm to all plots within ~30 min of the simulation under dry conditions (Table 1). Runoff was greater for the high intensity storm, but the effects of burning on runoff were significant only for tree plots. Runoff from tree plots was four times higher for burnt than unburnt conditions and was equivalent to that of the intercanopy (Table 1). Approximately 50% of rainfall applied to burnt and unburnt intercanopy plots was converted to runoff. Erosion was high from unburnt intercanopy plots and increased 2-fold in the intercanopy after fire. Erosion increased more than 20-fold on tree plots after fire (Table 1). Williams et al. (2013) attributed the lack of fire effects on runoff from intercanopy plots to the already high runoff rates. Increased runoff and erosion following burning of tree plots was attributed to fire removal of dense litter cover on water repellent soils and formation of concentrated flow (Pierson et al. 2013; Williams et al. 2013).

The effects of burning and storm intensity on large-plot-scale runoff and erosion from semi-arid forests are well documented (see Robichaud et al. 2000; Cerda and Robichaud 2009; Moody and Martin 2009). Johansen et al. (2001; Table 1) found that runoff from rainfall simulations on burnt and unburnt areas of a ponderosa pine site was positively correlated (r = 0.76) with percentage bare soil, and that time to runoff was negatively correlated (r = 0.67) with percentage bare soil. Burning increased runoff and erosion 2- and 25-fold (Table 1). Soil water repellency was highly variable spatially and had minimal effect on runoff. Erosion was strongly correlated with percentage bare soil (r = 0.84). Wagenbrenner et al. (2006) found that hillslope soil erosion (1900 m² plots) from burnt forests of the Colorado Front Range returned to pre-fire levels once ground cover increased to 60%. Benavides-Solorio and MacDonald (2005) used silt fences (190–6600 m²) to measure post-fire erosion from forested slopes (25–45%) in the Colorado Front Range over varying fire severities. Over the 2-year study, percentage bare soil explained ~64% of the variability in soil erosion (n = 48). Approximately 90% of the sediment collected was delivered by high-intensity convective storms. Bare soil and rainfall erosivity explained 65% of sediment production variability. Sediment yield decreased exponentially with time after fire and was highest where bare soil approached and exceeded 60%. Soil water repellency was weakly correlated with sediment production from all plots (R² = 0.30), but was more strongly correlated for the high-severity plots (R² = 0.40). Concentrated flow played an important role in post-fire erosion rates on converging topography (Benavides-Solorio and MacDonald 2005). Spigel and Robichaud (2007) used silt fences (~100-m² contributing area) to measure erosion responses from severely burnt, sloping (50–60% gradient) forest sites in Montana. They concluded that rainfall intensity was the dominant control on erosion from individual storms. More than 2000 g m⁻² of soil was eroded during short-duration, high-intensity storms (75-mm h⁻¹ intensity, at least 10-min duration) on sites with 60–90% bare soil and water-repellent soils. Ground cover and soil conditions influenced responses for low-intensity storms, but storms exceeding ~70-mm h⁻¹ intensity over 10-min intervals led to substantial erosion regardless of site conditions. Spigel and Robichaud (2007) observed prominent, dense rill or concentrated flow networks during high intensity storms.

Runoff and erosion at hillslopes to watershed scales
Flooding and extensive soil erosion are common where high-intensity storms occur over large areas of recently burnt, sloping terrain along the rangeland–xeric forest continuum (Craddock 1946; Cannon 2001; Cannon et al. 1998, 2001a, 2001b; Meyer et al. 2001; Moody and Martin 2001a; Pierson et al. 2002; Pierce et al. 2004; Klade 2006; Cannon et al. 2008; Pierce et al. 2011). Large erosion events following wildfires are typically triggered by runoff and progressive sediment bulking (Cannon et al. 2001a). For example, a torrential rainstorm 2 months after the South Canyon Fire in Colorado caused nearly 90 runoff-triggered debris-flow events that inundated a 13–14-ha area with ~70,000 m³ of soil (Cannon et al. 1998, 2001a). The fire occurred on steep (30–70%) pinyon–juniper and shrub-dominated hillslopes. Increased runoff and erosion from rainsplash and sheetflow on bare soils facilitated formation of concentrated-flow networks and gullies with high erosive energy and sediment transport capacity. Debris flows developed during the storm mainly through bulking as the flows moved downslope, entralained material and converged in drainage channels with accumulations of wind-blow sediment. Flow velocities were estimated at 3–9 m s⁻¹ (Cannon et al. 1998). Pierson et al. (2002) documented a runoff-triggered response to a short-duration high-intensity storm on steep sagebrush hillslopes 1 year after the 1996 Eighth Street Fire (6070 ha) along the Boise Front Range, Idaho. A 5–10-year return-interval storm (67 mm h⁻¹) lasting 9 min generated concentrated flow networks, flash flooding and mudflows from bare (90–100% bare ground), water-repellent soils with reduced water storage capacity and low surface roughness. In an adjacent basin on the Boise Front, similar conditions immediately following multiple cheatgrass-fuelled wildfires in 1959 resulted in widespread flooding and extensive property damage (Klade 2006). Meyer et al. (2001) reported that a short-duration, high-intensity storm on severely burnt ponderosa pine hillslopes in Idaho generated runoff-triggered debris flows. They found incised concentrated flow paths on the steeply sloping terrain integrated into gullies more than 1 m deep. The gullies promoted high-velocity, erosive discharge that generated sediment-laden flows reaching the North Fork Boise River. Debris flows on burnt hillslopes can also be initiated by debris slides or shallow landslides of large masses of saturated sediment (Meyer et al. 2001; Meyer and Pierce 2003; Wondzell and King 2003; Pierce et al. 2004; Parise and Cannon 2012). Debris slides are most common 4 years or more following burning of forested areas due...
largely to declining root strength of dead trees (Meyer et al. 2001; Meyer and Pierce 2003). The studies described above clearly demonstrate that plot- to hillslope-scale effects potentially influence hydrologic and erosional responses to intense rainfall over contiguous burnt terrain.

**Hydrologic risks associated with altered fire regimes**

Clearly, increased wildfire activity along the rangeland–xeric continuum poses significant environmental, social and economic consequences associated with flooding and erosion. More frequent and larger fires increase the likelihood and potential magnitude of onsite and offsite effects. More frequent exposure, as a result of burning surface cover, subjects the soil surface to repeated erosion from frequently occurring storms and increases the probability that the soil surface will be exposed when less-frequent, high-intensity rainfall events occur. Larger fires create more extensive surface exposure. Annual soil loss from burnt hillslopes in sloping terrain can be 60–100 Mg ha\(^{-1}\) the first year following fire and may take 4–7 years to return to background levels (Mayot et al. 2007; Robichaud 2009). Such losses are detrimental if repeated on 5–10-year rotations. Loss of biologically important surface soils may be particularly critical for rangelands where soil formation takes decades (Allen 1946). Multiple post-fire flooding events over a 1-year-old 300 \(\text{ha}\) ponderosa pine site (Neary et al. 2012). The event flooded 85 homes, caused one death and substantially damaged city infrastructure. Post-fire mitigation expenditures exceeded US$14 million (Coconino County 2011).

Post-fire hillslope hydrologic vulnerability can be conceptualised as a function of storm magnitude (i.e. rainfall intensity) and site susceptibility (Fig. 6). In this model, storm-specific hydrologic vulnerability represents potential runoff and erosion responses for different site susceptibilities. Site susceptibility is defined by the conditions of the soil surface, cover characteristics and topography, and, therefore, encompasses burn severity as well as other key inherent site characteristics (e.g. slope, rock cover, soil erodibility) that influence hydrologic and erosion responses. For a storm of uniform intensity, hydrologic response increases exponentially with increases in site susceptibility due to a shift in hydrologic process dominance from rainsplash and sheetflow to concentrated flow (Fig. 6). Overall hydrologic vulnerability or response increases with increasing storm intensity due to amplified rainfall erosivity and greater water input with higher rainfall intensity. Fire removal of cover and decreased surface roughness increase water available for runoff over point- to small-plot scales and facilitate formation of concentrated flow paths over larger spatial scales. Runoff generation is enhanced where infiltration is inhibited by water-repellent soil conditions and on steep slopes. Fire-induced increases in erodibility and decreased surface protection against rainsplash facilitate soil detachment at small scales and promote sediment delivery by sheetflow and concentrated flow paths over larger spatial scales. Increased erosion with increasing land area results from sediment bulking of the flow as it moves downslope, potentially causing mudslides or debris flows (Cannon et al. 1998, 2001a).

Our qualitative model (Fig. 6) potentially presents a framework with which future quantitative advancements in risk assessment may be made. Kaplan and Garrick (1981) suggested risk, \(R\), be defined based on a set of triplets,

\[
R = \{ s_i, p_i, x_i \}, \quad i = 1, 2, \ldots n
\]

where \(s_i\) refers to the \(i\)th scenario or set of conditions, \(p_i\) is the probability of the \(i\)th scenario occurring, and \(x_i\) is the consequence of the \(i\)th scenario. Risk is quantified under this structure by tabulating triplets for all potential scenarios and computing a cumulative probability curve. Site susceptibility and storm intensity (or return interval) in our model of hydrologic vulnerability (Fig. 6) define the \(i\)th scenario \((s_i)\), resulting in the \(i\)th hydrologic response or consequence \((x_i)\). Vulnerability curves shown for the respective storm intensities in Fig. 6 can be thought of as a family of risk curves (Kaplan and Garrick 1981). The probability of the \(i\)th occurrence \((p_i)\) and hydrologic response \((x_i)\) is the combined probability of susceptibility and storm occurrence that define the \(i\)th scenario. The potential for damages to values-at-risk is associated with the magnitude of the hydrologic response \((x_i)\), shown by vulnerability curves in Fig. 6, and those damages can be considered as secondary...
consequences resulting from the $x_i$ hydrologic response. Of course, assessing potential harm to values-at-risk requires knowledge of the storm and/or runoff magnitudes necessary to cause the respective damage (for example, see Cannon et al. 2008, 2011). Clearly, such damages occur on western US landscapes (Cannon et al. 1998, 2001a; Meyer et al. 2001; Moody and Martin 2001a; Pierson et al. 2002; Klade 2006; Cannon et al. 2008) and their occurrences will likely be amplified by ongoing increases in wildfire activity. We propose that recent advances in understanding and quantification of fire effects from small-plot to hillslope scales provide an initial point for populating fire effects models in a probabilistic framework that incorporates probabilities of site susceptibility, storm occurrence and magnitude of hydrologic response (e.g. Robichaud et al. 2007; Cannon et al. 2010). The Erosion Risk Management Tool (Robichaud et al. 2007) is one model that, in part, utilises the above conceptual framework to predict hillslope-scale soil erosion in probabilistic terms based on site-specific climate, vegetation, soil texture, burn severity and topography.

Knowledge gaps in the assessment of post-fire hydrologic risk

This review of post-fire hydrology and erosion studies offers insight into potential confounding issues in the field interpretation of post-fire hydrologic vulnerability. The studies reviewed from burnt rangelands and forested sites (Table 1) demonstrate that field assessments may be challenged by spatial and temporal variability in fire effects and post-fire site conditions, and inherent differences in recovery rates for runoff vs. erosion. For example, Pierson et al. (2002) found that runoff and erosion on burnt sagebrush rangeland was significantly greater on south-facing than on north-facing slopes 1 year following wildfire. Overland flow generated on south-facing slopes during a convective thunderstorm caused intense flash flooding. Assessment of north-facing slopes alone would not have detected the potential storm response. Runoff and erosional responses may also exhibit temporal variation that masks fire effects. Annual variation in climate influences vegetative recovery, litter recruitment, soil erodibility and soil water repellency. Pierson et al. (2008a, 2008b, 2009) reported that temporal variability in naturally occurring (not fire-induced) soil water repellency on burnt sagebrush sites exerted greater influence on runoff than did direct fire effects. Pierson et al. (2009) observed that soil erosion from burnt sagebrush coppices exhibited significant temporal variability, but it was not determined whether this resulted from differences in infiltration, runoff or erodibility. Finally, the conditions required for hydrologic stability differ for runoff vs. erosion, and for rainsplash–sheetflow processes vs. concentrated flow (Pierson et al. 2008a; 2009). Pierson et al. (2008a, 2009) and Benavides-Solorio

Fig. 6. Conceptual model of hillslope-scale hydrologic vulnerability (runoff and erosion response, y-axis) for varying site susceptibility (x-axis) and rainfall intensity. Site susceptibility is defined by the surface soil, ground cover and topographic conditions that affect runoff and erosion responses. Symbols indicate directional increase (+) or decrease (−) in respective variable. Hydrologic vulnerability and response increases exponentially as ground cover, roughness, aggregate stability and soil structure decrease, and bare ground and soil water repellency increase. Responses are amplified with increasing hillslope angle. Rainsplash and sheetflow processes dominate on gentle portions of the vulnerability curves, where conditions are hydrologically stable (unburnt state); concentrated flow dominates where curves steepen and conditions become hydrologically unstable (burnt state). The transition zone occurs where decreased surface protection or increased water availability facilitate concentrated flow initiation. Hydrologic responses are generally greater with increasing rainfall intensity. Potential values-at-risk for varying magnitudes of hydrologic response are shown to illustrate potential consequences of respective runoff and erosion events. Acceptance and likelihood of damage to values-at-risk are illustrated by the arrow on the right side of the figure. Figure is modified from Pierson et al. (2011).
and MacDonald (2001, 2002) have shown that fire effects are greater with respect to erosion than to runoff. Our review of field studies on fire effects indicates that post-fire assessments focusing on one aspect of hydrologic vulnerability (e.g. runoff) or on one process (e.g. rainsplash) may not accurately reflect fire effects. Meaningful field studies of landscape-scale effects may require multiple year assessments, annual control treatments and field evaluation of runoff and erosion at different scales, and should include assessment of rainsplash, sheetflow and concentrated flow processes. However, such comprehensive studies are seldom possible or practical. Investigations that focus on a single hydrologic parameter or process at only one scale should therefore acknowledge the potential errors associated with broad-scale inferences on overall hydrologic vulnerability.

The qualitative model presented in this study (Fig. 6) illustrates the general hydrologic and erosional relationships affected by ongoing plant community transitions and increased fire activity in the western US, but our current ability to populate the model relating to this problem is confounded by several key issues. First, we are still learning how the variables that define site susceptibility at different spatial scales interact to influence hydrologic and erosion responses. Second, current understanding is inadequate with regards to quantifying effects of within-storm varying rainfall intensity and site conditions. Third, knowledge of how to incorporate soil water repellency and its inherent variability in space and time into predictive models is particularly limiting. Fourth, runoff and erosion data are extremely scant for many plant communities. Finally, advancements in predictive erosion models have been made (e.g. Robichaud et al. 2007; Nearing et al. 2011; Wagenbrenner et al. 2010; Al-Hamdan et al. 2012b), but most models remain focused at the hillslope scale given the lack of watershed-scale data sources. Spatial scaling of hydrologic and erosion processes has long been difficult for scientists, which remains a problem for landscape-scale modelling. Scaling limitations further inhibit linkages of plot- and hillslope-scale responses to offsite effects on values-at-risk (Cawson et al. 2012). Nevertheless, current models based on plot-to-hillslope scale knowledge provide a means of predicting post-fire hillslope responses and evaluating mitigation efforts.

Summary and conclusions

Increased wildfire activity associated with cheatgrass invasions, plant community transitions and a warming climate along the rangeland-xeric forest continuum in the western US poses hydrologic risks to natural resources, property and human life. Large and frequent fires promote loss of biologically important soils and increase the likelihood of damaging flood and mass erosion events. Projections of climate warming suggest that current trends towards an increase in wildfire activity are likely to continue. Future climate scenarios also predict large-scale shifts in plant communities that may further enhance wildfire activity in the rangeland-xeric forest continuum. Field studies of post-fire runoff and erosion have advanced our understanding of key physical processes and have contributed to hydrologic and erosion model development. In our review, we present a conceptual model of post-fire hydrologic vulnerability and risk based on current understanding, and we identify remaining knowledge gaps that limit post-fire risk assessment. We found that current understanding is lacking in several key areas with regard to quantitative modelling of post-fire hydrologic responses and effects on values-at-risk. Current knowledge is particularly deficient regarding the interacting effects of hydrologic variables (i.e. varying rainfall intensity, infiltration, runoff generation) and spatially variable post-burn conditions and topography. Knowledge of how to incorporate soil water repellency and its variability into hydrologic models is critically limited. Finally, most physically based models are designed to simulate hillslope-scale responses and are not directly applicable to current landscape-scale fires extending across diverse watersheds with steeply sloping xeric forest and rangeland plant communities. Our review suggests that future post-fire risk research should focus on advancing understanding in the key areas noted above and on probability-based modelling of the interacting controls on post-fire responses across relevant spatial scales and for changing climate conditions.

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