Fire and Invasive Plants Special Feature

Fire, Plant Invasions, and Erosion Events on Western Rangelands

Frederick B. Pierson,[1] C. Jason Williams,[2] Stuart P. Hardegree,[3] Mark A. Weltz,[4] Jeffry J. Stone,[5] and Patrick E. Clark[6]

Authors are [1]Research Leader and Supervisory Research Hydrologist, [2]Hydrologist, [3]Plant Physiologist, and [6]Rangeland Scientist, USDA–Agricultural Research Service, Northwest Watershed Research Center, Boise, ID 83712, USA; [4]Research Rangeland Management Specialist, USDA–Agricultural Research Service, Exotic and Invasive Weeds Research Unit, Reno, NV 89512, USA; and [5]Research Hydrologist, USDA–Agricultural Research Service, Southwest Watershed Research Center, Tucson, AZ 85719, USA.

Abstract

Millions of hectares of rangeland in the western United States have been invaded by annual and woody plants that have increased the role of wildland fire. Altered fire regimes pose significant implications for runoff and erosion. In this paper we synthesize what is known about fire impacts on rangeland hydrology and erosion, and how that knowledge advances understanding of hydrologic risks associated with landscape scale plant community transitions and altered fire regimes. The increased role of wildland fire on western rangeland exposes landscapes to amplified runoff and erosion over short- and long-term windows of time and increases the risk of damage to soil and water resources, property, and human lives during extreme events. Amplified runoff and erosion postfire are a function of storm characteristics and fire-induced changes in site conditions (i.e., ground cover, soil water repellency, aggregate stability, and surface roughness) that define site susceptibility. We suggest that overall postfire hydrologic vulnerability be considered in a probabilistic framework that predicts hydrologic response for a range of potential storms and site susceptibilities and that identifies the hydrologic response magnitudes at which damage to values-at-risk are likely to occur. We identify key knowledge gaps that limit advancement of predictive technologies to address the increased role of wildland fire across rangeland landscapes. Our review of literature suggests quantifying interactions of varying rainfall intensity and key measures of site susceptibility, temporal variability in strength/influence of soil water repellency, and spatial scaling of postfire runoff and erosion remain paramount areas for future research to address hydrologic effects associated with the increased role of wildland fire on western rangelands.

Resumen

Millones de hectáreas de pastizales en el oeste de Estados Unidos han sido invadidos por plantas arbustivas y anuales que han aumentado la función de los incendios forestales. La modificación de los regímenes de fuego implica cambios significativos para el escurrimiento y la erosión. En este documento resumimos lo que se conoce sobre los impactos de fuego sobre hidrología y la erosión en pastizales, y cómo ese conocimiento nos ayuda a comprender mejor los riesgos hidrológicos asociados con la transición en la comunidad de plantas y con el cambio en los regímenes de fuego. El aumento en la incidencia de los incendios forestales en los pastizales occidentales expone al paisaje a un aumento en el escurrimiento sobre un periodo a corto y largo plazo y a un incremento en el riesgo de daño a los recursos del suelo, agua, bienes y vidas humanas durante eventos extremos. Un aumento en el escurrimiento y la erosión después del fuego están en función de los cambios inducidos por el fuego en las características del sitio (es decir la cubierta del suelo, repelencia del agua del suelo, estabilidad de los agregados, y la rugosidad de la superficie) que definen la susceptibilidad del sitio. Sugerimos que se considere en general la vulnerabilidad hidrológica del sitio después del fuego en un marco probabilístico que prediga la respuesta hidrológica para un rango de posibles tormentas y la susceptibilidad del sitio y que identifique la magnitud de respuesta hidrológica donde los daños a los valores en riesgo son más probables. Identificamos los espacios claves del conocimiento que limitan el desarrollo de las técnicas predictivas para afrontar el papel en aumento de los incendios forestales a través de los paisajes de pastizales. Nuestra revisión de literatura sugiere cuantificar las interacciones de diferentes intensidades de precipitación y las principales medidas de susceptibilidad del sitio, la variabilidad temporal en la fuerza/influencia de la repelencia del agua del suelo y la escala espacial del escurrimiento y erosión después del fuego siguen siendo áreas primordiales para la investigación en el futuro para concentrarse en los efectos hidrológicos asociados con el creciente papel de los incendios forestales en los pastizales occidentales.

Key Words: cheatgrass, grass–fire cycle, pinyon–juniper, sagebrush steppe, soil loss

INTRODUCTION

Altered fire regimes associated with plant community transitions in the Great Basin, United States, have significant implications on rangeland runoff and soil loss. Larger expanses of Great Basin rangelands are burning each year due to plant community transitions, and, in many cases, are reburning

The US Dept of Agriculture (USDA) is an equal opportunity provider and employer.

This is Contribution Number 39 of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP), funded by the US Joint Fire Science Program.

Correspondence: Frederick B. Pierson, Research Leader and Supervisory Research Hydrologist, USDA–Agricultural Research Service, Northwest Watershed Research Center, 800 Park Blvd, Plaza IV, Suite 105, Boise, ID 83712, USA. Email: fred.pierson@ars.usda.gov

Manuscript received 14 October 2009; manuscript accepted 23 June 2011.

over shorter time intervals (Whisenant 1990; D'Antonio and Vitousek 1992; Knapp 1996; Miller and Tausch 2001; Brooks et al. 2004; Keane et al. 2008). Frequent and extensive fires increase the spatial susceptibility of these landscapes to accelerated runoff and erosion. Greater temporal exposure due to repeated burning increases potential long-term soil loss from frequently occurring low-return interval storms (1- to 10-yr events) and increases the likelihood that vulnerable conditions will prevail during less frequent, more damaging intense rainfall events. Numerous reports in the literature document flood events following intense rainfall on large rangeland and forest burns that have resulted in loss of human life and extensive damage to natural resources, property, and city infrastructures (for example see Craddock 1946; Cannon et al. 2001; Moody and Martin 2001; Pierson et al. 2002; Klade 2006; Cannon et al. 2011). Mitigating postfire impacts on these values-at-risk is particularly concerning along the ever-expanding wildland-urban interface (Stockmann et al. 2010).

Burned Area Emergency Response teams and resource managers in the western United States are challenged with evaluating fire effects on ecosystems and assessing potential hazards to values-at-risk. Postfire risk assessments include cost–benefit analyses of mitigation treatments. Treatment expenditures and implementation hinge on the value of the resources at risk and whether damage to respective values-at-risk will occur without mitigation (Calkin et al. 2007). The capability of postfire assessments to accurately evaluate risk and appropriate mitigation dollars is strongly dependent on advancement in understanding of fire effects on ecosystems. Annual expenditures on wildfire suppression and postfire mitigation are a function of risk assessment and fire activity. Billions of dollars are spent each year in the United States for wildfire suppression, and millions are spent annually on postfire mitigation (General Accounting Office 2003; Stockmann et al. 2010). The costs of large wildland fires in the United States can exceed $20 million per day (Running 2006).

The increasing role of wildfire on Great Basin rangelands and the potential costs associated with fire management and mitigation require advancement in the understanding of fire effects and development of risk assessment strategies. Risk implies some degree of uncertainty and potential damage to something of value (Kaplan and Garrick 1981). A hazard is the mechanism for or source of danger. Conceptually, risk then is the likelihood of a particular hazard occurring and generating damage, and that risk can be mitigated by safeguards. The first order safeguard for mitigating any risk is becoming aware of the risk and identifying what you know and do not know about it (Kaplan and Garrick 1981). It is in this vein that we seek to increase awareness of the hydrologic risks associated with the increased role of fire in the Great Basin. The primary purposes of this paper are 1) to summarize what is currently known about fire effects on rangeland runoff and erosion, and 2) to frame that knowledge in a conceptual model for advancing understanding of the hydrologic risks associated with invasive weeds and altered fire cycles in the Great Basin. Although our geographic focus is the Great Basin, we propose the general concepts may be extrapolated across western rangelands where plant community transitions have increased the role of wildfire on sloping terrain.

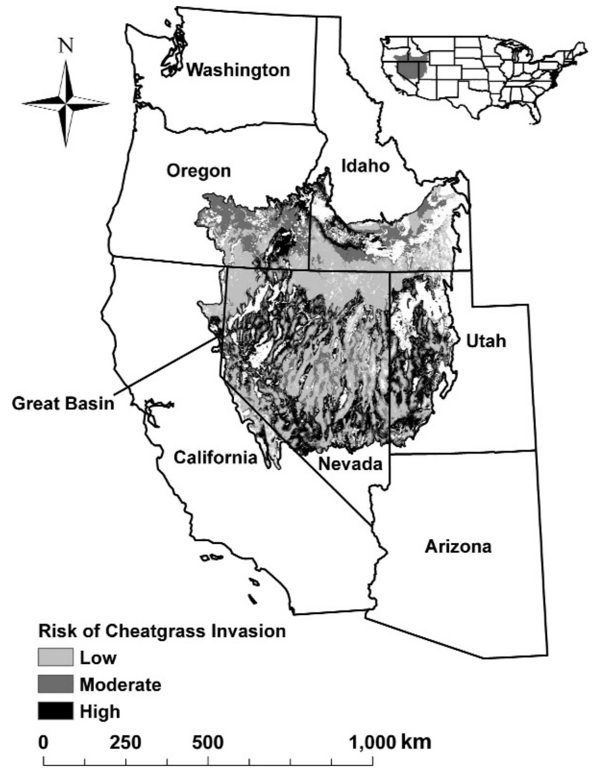

Figure 1. Map showing approximate risk (over next 30 yr) of cheatgrass invasion within the spatial extent of the Great Basin (~52 million ha) of the western United States. Data coverages and risk maps (Wisdom et al. 2003) were obtained from the US Geological Survey Sagebrush and Grassland Ecosystem Map Assessment Project database (SAGEMAP 2010).

PLANT COMMUNITY TRANSITIONS AND ALTERED FIRE REGIMES

Cheatgrass Invasion and the Grass–Fire Cycle

Cheatgrass invasion of western rangelands (Fig. 1) has altered the floristic and fuels structure of Great Basin sagebrush steppe (Young and Evans 1978; Whisenant 1990; Peters and Bunting 1994; Knapp 1996; West 2000; Brooks and Pyke 2001; Brooks et al. 2004). Cheatgrass was introduced into North America through grain contamination in 1889 (Mack 1981) and was well established on western rangelands by the 1920s. The species is now the major plant constituent on 4 to 7 million of the 18 million ha of sagebrush steppe in the Great Basin (Knapp 1996; West 2000). Shrubs and bunchgrasses on historic Great Basin sagebrush steppe sites were spaced (Fig. 2A) with bare areas and a sparse, discontinuous horizontal fuel bed in between plants (Brooks and Pyke 2001; Rice et al. 2008). Cheatgrass primarily invaded these open spaces, resulting in a continuous horizontal fuel structure (Fig. 2B; Whisenant 1990; Knapp 1996; Brooks and Pyke 2001; Brooks et al. 2004; Brooks 2008).

The continuous horizontal fuel structure of cheatgrass-invaded shrubland promotes more frequent and larger-scale wildland fires than reported for historical sagebrush steppe (Whisenant 1990; Peters and Bunting 1994; D'Antonio 2000; Brooks and Pyke 2001; Brooks et al. 2004; Keane et al. 2008). Historical fires were highly variable in size and severity,

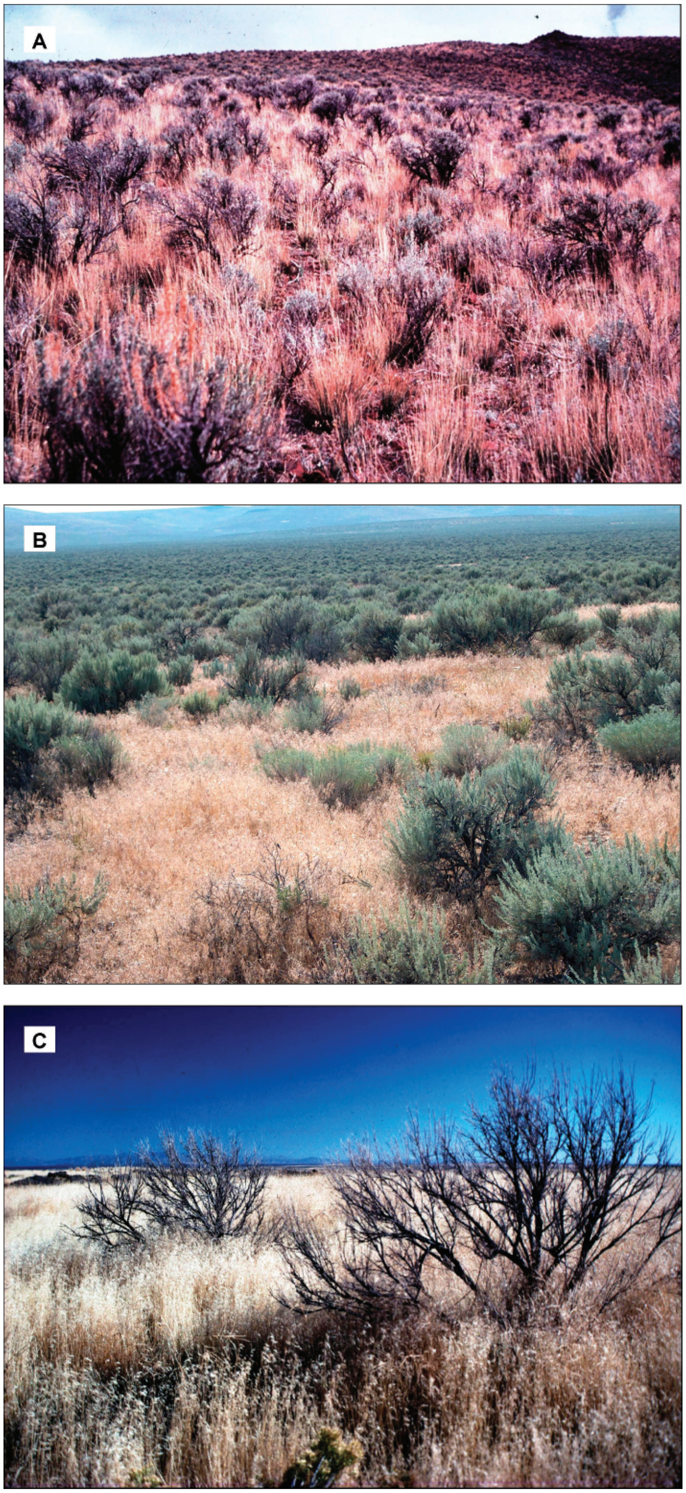

Figure 2. Sagebrush steppe in good ecological condition (**A**), with cheatgrass (*Bromus tectorum* L.) dominated interspaces (**B**), and following conversion to cheatgrass monoculture (**C**). Photographs 2A and 2C provided courtesy of Mike Pellant, Great Basin Restoration Initiative Coordinator, Bureau of Land Management, Boise, Idaho. Photograph 2B by authors.

and large severe fires were infrequent (100–150 yr). Small fires burned approximately every 20–40 yr (Houston 1973) and created a mosaic of perennial grass-dominated and shrub-dominated patches (Fig. 2A) that retarded fire spread. Current fire return intervals on many cheatgrass infested areas are 3–10 yr (Whisenant 1990; Brooks and Pyke 2001; Brooks et al. 2004). Great Basin rangelands with substantial cheatgrass coverage are 10 to 500 times more likely to burn than pristine sagebrush-bunchgrass communities (Hull 1965), and fire risk is near 100% where cheatgrass coverage approaches 50% (Link et al. 2006).

Shorter fire-free periods and larger-scale fires result in cheatgrass dominated systems and promote a reoccurring grass–fire cycle (Young and Evans 1975, 1978; Whisenant 1990; D'Antonio and Vitousek 1992; Knapp 1996; Brooks and Pyke 2001; Brooks et al. 2004). Cheatgrass is a prolific seed producer (Young et al. 1969; Humphrey and Schupp 2001; Hempy-Mayer and Pyke 2008) and readily establishes following disturbance (Steward and Hull 1949; Young and Evans 1978; Mack 1981; Knapp 1996; West and Yorks 2002). The species has high autumn germination rates and generates greater root growth during winter than native bunchgrasses (Hull 1963; Harris 1967, 1977; Link et al. 1990; Svejcar 1990; Aguirre and Johnson 1991; Nasri and Doescher 1995; Arredondo and Johnson 1998; Arredondo et al. 1998; Duke and Caldwell 2001). The greater seedling vigor and reproduction potential causes a decline in species richness and evenness with increased cheatgrass coverage (Mack 1981; Brooks and Pyke 2001). The postfire environment in many cases contains nearly 100% canopy cover of cheatgrass (Fig. 2C), particularly where frequently reoccurring fires precede wet years (Young et al. 1987; Billings 1994; Knapp 1996; West and Yorks 2002). Cheatgrass plants generally mature and die earlier than perennial grass species, thus lengthening the annual burn window (Keeley 2000; Keane et al. 2008; Rice et al. 2008). Low decomposition rates in the Great Basin also facilitate retention of dry, senesced plants in the interspaces (Knapp 1996). The recurring cycle of fuel accumulation, frequent burning, and postfire annual-weed dominance has been referred to as the alien grass–fire cycle (D'Antonio and Vitousek 1992; Brooks and Pyke 2001; Brooks et al. 2004).

Pinyon and Juniper Woodland Infill and Expansion

Recent infilling of trees in persistent woodlands and wooded shrublands of the Great Basin has increased the risk of occurrence of large, high-severity fires (Fig. 3; Tausch 1999; West 1999; Miller and Tausch 2001; Tausch and Hood 2007; Keane et al. 2008). The density and distribution of native pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands have increased 10-fold across the Great Basin and Colorado Plateau in the last 130 yr (Miller and Tausch 2001). These species now occur on 30 to 40 million hectares in the western United States and have formed expansive wooded shrublands (see Romme et al. 2009) in the Great Basin following 150–600% increases in occurrence on historical shrub steppe (Cottam and Stewart 1940; Gedney et al. 1999; West 1999; Tausch and Hood 2007; Miller et al. 2008). Historical fires in persistent woodlands were commonly high-severity, stand replacement burns that occurred in intervals of several hundred years or more (Baker and Shinneman 2004; Romme et al. 2009). Longer modern fire seasons and high fuel densities on persistent woodlands suggest much of the Great Basin

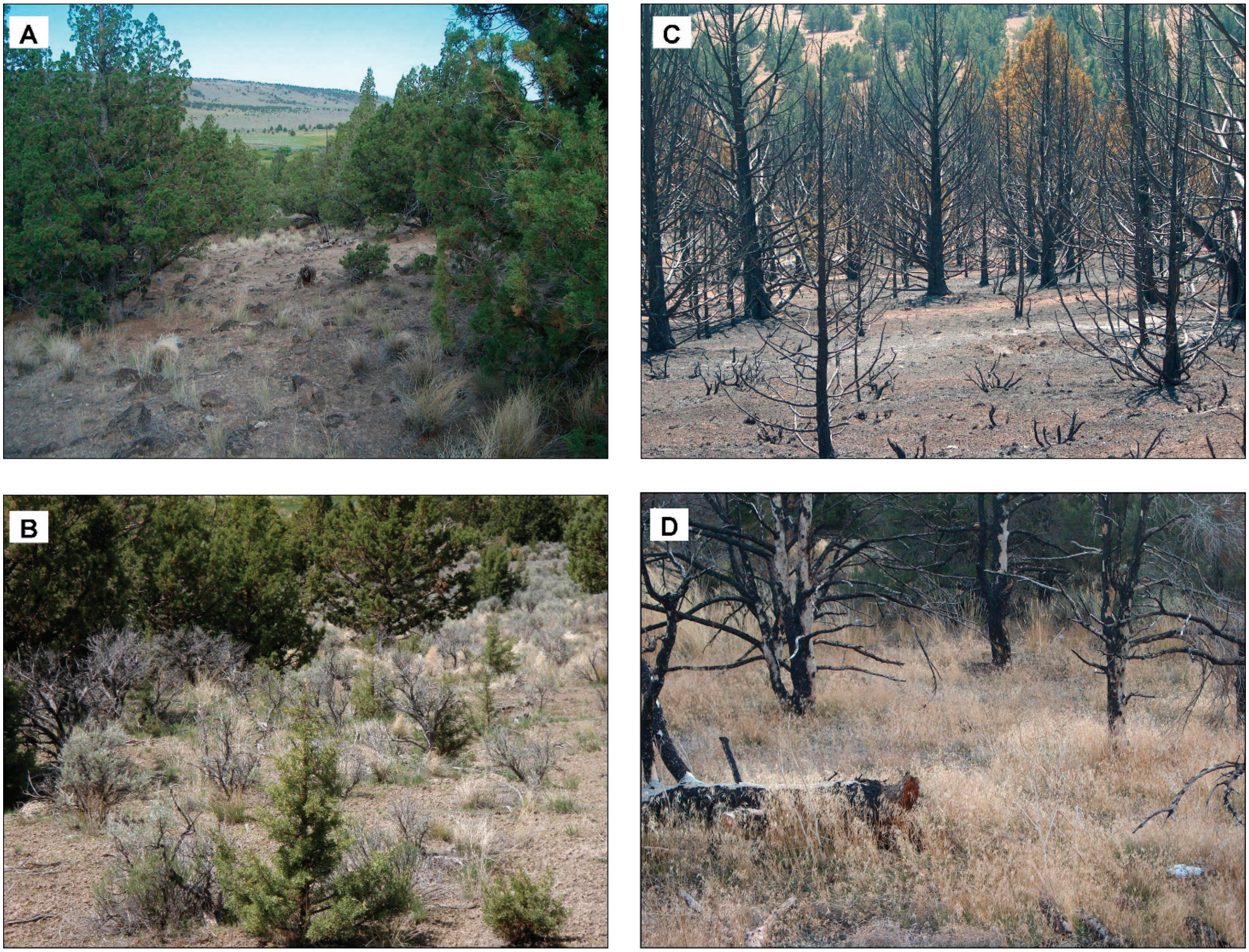

Figure 3. Juniper woodland with dense canopy structure (**A**), with ladder fuels (**B**), following high-severity wildfire (**C**), and after postfire cheatgrass invasion (**D**). Photographs by authors.

woodland expanse is poised for large, stand replacing wildfire (Keane et al. 2008; Romme et al. 2009). Increasing trends in large fires and area burned indeed have been reported over much of the pinyon–juniper range. Tree infill on modern woodlands has increased heavy fuel densities (Fig. 3A) across these landscapes, leading Miller and Tausch (2001) to suggest the representative area of closed woodland stands and the subsequent frequency of crown fires will increase substantially over the next 40+ yr. The role of fire is also expected to increase on densely stocked wooded shrublands where grass, shrub, and tree cover create ladder fuels (Tausch 1999; Miller and Tausch 2001; Miller et al. 2008; Romme et al. 2009). Ladder fuels (Fig. 3B) facilitate rapidly spreading, high-intensity and severe ground–surface–crown fires (Fig. 3C) that consume as much as 100% of overstory and understory cover. Cheatgrass invasion into persistent woodlands and wooded shrublands (Fig. 3D) has further increased the horizontal fuel structure and risk of large-scale fires on many sites within the Great Basin (Young and Evans 1978; Billings 1994; Tausch 1999; Miller et al. 2008).

FIRE EFFECTS ON RANGELAND HYDROLOGY AND EROSION

Hydrologic response (runoff and erosion) for a given storm is a function of the rainfall intensity and the resisting forces at or near the ground surface. We can conceptualize these resisting forces as defining the site susceptibility to a given rainfall intensity (Fig. 4). Susceptibility is a function of ground cover (or bare ground), surface roughness, aggregate stability, soil structure, soil water repellency, and hillslope angle. Fire affects hydrologic response by reducing the resistance and thereby increasing the susceptibility of the soil surface to runoff and erosion. Fire-induced increases in susceptibility coincide with shifts in prevailing hydrologic processes that dictate runoff and erosion rates (Fig. 4; Pierson et al. 2009). Most of the knowledge of fire impacts on rangeland hydrology is derived from rainfall simulation studies (Table 1) on hillslopes in the semi-arid sagebrush steppe (Pierson et al. 2001, 2002, 2008a, 2008b, 2009) and xeric forests (Benavides-Solorio and MacDonald 2001, 2002; Johansen et al. 2001) and studies of flood

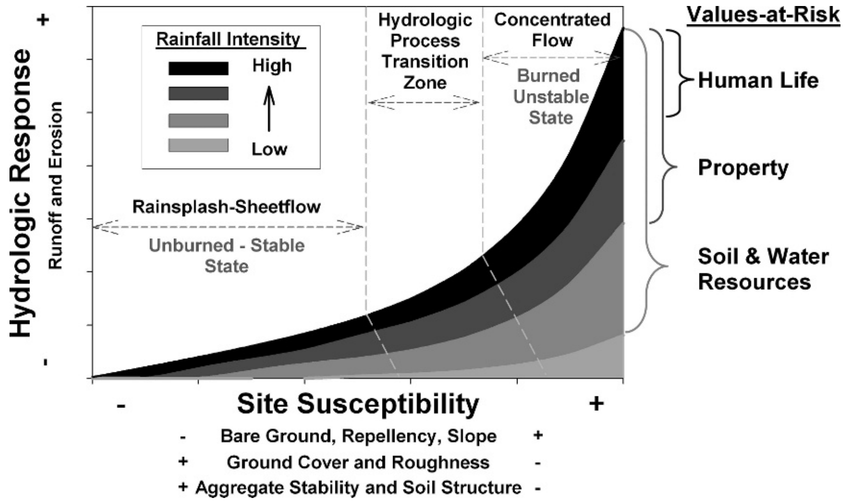

Figure 4. Conceptional hydrologic response (runoff and erosion responses) for varying site susceptibility and rainfall intensity. The different grey scale curves represent responses for different rainfall intensities across a range of site susceptibility. Site susceptibility (*x* axis) is defined by the surface conditions (shown in smaller font below the *x* axis title) that influence runoff and erosion response. Symbols illustrate direction increase (+) or decrease (−) in respective variable. Hydrologic 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 response curves where conditions are hydrologically stable (unburned state); concentrated flow dominates where curves steepen and conditions become hydrologically unstable (burned state). The transition zone occurs where decreased surface protection or increased water availability faciliate 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. Fire affects hydrologic response by increasing susceptibility (decreasing hydrologic stability) and causing an inherent shift in hydrologic process dominance. Large fires result in extensive, high susceptibility, and repeated landscape-scale burning over short time windows (3–10 yr) ensure repeated exposure of highly susceptibile conditions, increasing likelihood for damage to natural resources, property, and human life.

events following intense rainfall on recently burned landscapes (see Craddock 1946; Cannon et al. 1998, 2001; Meyer et al. 2001; Moody and Martin 2001; Pierson et al. 2002; Klade 2006; Cannon et al. 2011). Here, we summarize what is known by reviewing fire impacts on runoff and erosion processes at the point to small-plot (<2 m^2), large-plot/patch (10–30 m^2), and hillslope to landscape (multiple watersheds) scales and examining longevity of fire effects on hydrologic and erosional processes.

Point to Small-Plot Scale Effects

The magnitude of fire-induced increases in runoff and erosion depends on rainfall intensity, the degree of fire-induced changes in site susceptibility, and topography (Fig. 4). Rainsplash and sheetflow (see Kinnell 2005) are the dominant postfire hydrologic and erosion processes over point to small-plot scales. The primary resisting agents at this scale are canopy and ground cover, surface roughness, and soil stability. Fire removal of canopy and ground cover increases the water available at the soil surface through decreased interception, surface water storage, and infiltration. A fire-induced increase in bare ground reduces surface roughness, promotes rapid runoff generation, and diminishes the surface protection against soil detachment and entrainment by raindrop impact and sheetflow (Table 1; Benavides-Solorio and MacDonald 2001, 2002; Pierson et al. 2001, 2002, 2008a, 2008b, 2009). The overall effect on runoff generation is amplified where strongly water repellent soils persist postfire (Table 1) or water repellency is induced by burning (see DeBano et al. 1998). Soil loss is governed by the degree of soil surface protection, soil erodibility, and the amount of runoff (Pierson et al. 2008a, 2009). A fire-induced increase in runoff and erosion is commonly much greater for shrub coppice areas (areas underneath shrub canopies) than interspaces (areas between shrub canopies), and fire effects are generally higher for erosion than those for runoff (Table 1). Runoff and erosion may increase by a factor of 3 to more than 10, respectively, for shrub coppices (Table 1). Fire effects on interspace runoff and erosion may be negligible where prefire ground cover was low (Pierson et al. 2001, 2008a, 2009); however, increases by factors of 2 to 40, respectively, can occur where interspace vegetation is removed by fire (Pierson et al. 2002).

Large-Plot Scale Effects

Postfire runoff and erosion at the large-plot or patch scale (10s of m^2) are primarily related to the degree of canopy/ground cover removal, the relative homogeny of surface soil conditions, and the formation of concentrated flow paths. Greater water availability following burning (less interception/storage), decreased infiltration, and reduction of surface obstructions allow water to form deeper, concentrated flow paths with greater flow velocity, erosive energy, and sediment transport capacity than are produced by smaller-scale rainsplash and sheetflow processes (Moffet et al. 2007; Pierson et al. 2009; Al-Hamdan et al. 2011). Concentrated flow is enhanced on steep (Cannon et al. 1998, 2001; Meyer et al. 2001) or convergent (Benavides-Solorio and MacDonald 2005) slopes, and where overland flow is exacerbated by water repellent soils (Shakesby and Doerr 2006). A sharp increase in concentrated flow velocity and erosion are generally observed where ground cover is reduced below 40–50% ($>50\%$ bare ground; Pierson et al.

Table 1. Site characteristics, runoff coefficients, and sediment yield from rainfall simulations (60 min except where noted) on unburned (unb) and high- (high), moderate- (mod), and low-severity burned semi-arid rangelands (Pierson et al. 2001, 2002, 2008a, 2009) and forests (Benavides-Solorio and MacDonald 2001, 2002; Johansen et al. 2001).

Study	Microsite	Burn severity	Plot size (m^2)	Slope (%)	Time postfire (mo)	Rainfall intensity ($mm \cdot h^{-1}$)	WDPT (s)[1]	Bulk density ($g \cdot cm^{-3}$)[2]	Soil water content (%)[2]	Bare soil (%)	Canopy cover (%)	Ground cover (%)	Live plant biomass ($kg \cdot ha^{-1}$)	Litter biomass ($kg \cdot ha^{-1}$)	Surface roughness (mm)	Runoff coefficient (%)[3]	Sediment yield ($g \cdot m^{-2}$)
Pierson et al. 2002[4]	Coppice	Unb	0.5	35–60	12	67	—	1.21	~14	7	88	93	32 519	14 372	18	11	2
		Mod	0.5	35–60	12	67	—	1.28	~5	97	11	3	341	113	12	34	30
		High	0.5	35–60	12	67	—	1.21	~5	98	13	2	744	74	12	37	22
	Interspace	Unb	0.5	35–60	12	67	—	1.35	~14	89	18	12	519	1 721	18	24	4
		Mod	0.5	35–60	12	67	—	1.30	~5	95	16	5	520	212	12	26	12
		High	0.5	35–60	12	67	—	1.30	~5	99	5	1	134	61	10	49	148
Pierson et al. 2001, 2008a	Coppice	Unb	0.5	30–40	1	85	200	0.93	7	1	100	99	—	—	—	30	12
		High	0.5	30–40	1	85	102	1.22	1	99	1	1	—	—	—	37	41
	Interspace	Unb	0.5	30–40	1	85	220	0.94	5	6	74	94	—	—	—	49	24
		High	0.5	30–40	1	85	97	1.21	1	99	4	1	—	—	—	30	21
Pierson et al. 2009	Coppice	Unb	0.5	35–50	1	85	286	1.05	7	2	84	98	—	—	34	39	17
		Mod-High	0.5	35–50	1	85	261	1.09	3	42	10	58	—	—	11	76	183
	Interspace	Unb	0.5	35–50	1	85	110	1.21	3	25	31	75	—	—	18	63	195
		Mod-High	0.5	35–50	1	85	117	1.17	4	84	0	16	—	—	11	55	705
	—	Unb	32.5	35–50	1	85	—	1.07	2	24	57	76	12 125	9 517	21	4	8
	—	Mod-High	32.5	35–50	1	85	208	1.13	4	76	0	24	—	808	11	27	988
Benavides-Solorio and MacDonald 2001, 2002[5]	—	Low-Unb	1.0	20–25	1–3	79	65	—	2	1	—	99	—	—	—	55	80
	—	Mod	1.0	20–35	1–3	79	50	—	2	12	—	88	—	—	—	58	179
	—	High	1.0	20–45	1–3	79	60	—	2	77	—	23	—	—	—	66	1 280
Johansen et al. 2001[6]	—	Unb	32.5	5	3	60	—	—	~5	48		52	—	—	4.2	23	36
	—	High	32.5	7	3	60	—	—	~5	74		26	—	—	5.1	45	912

[1]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 strongly repellent (Bisdom et al. 1993).
[2]Measured near the soil surface (< 4 cm depth).
[3]Runoff coefficient is equal to cumulative runoff divided by cumulative rainfall applied. Value is multiplied by 100 to obtain percent.
[4]Data presented from south-facing slopes solely.
[5]Data presented for Bobcat Fire only.
[6]Rainfall 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.

2008a, 2009). Very few studies have quantified postfire runoff and erosion at the large-plot scale. Studies by Pierson et al. (2009) and Johansen et al. (2001) suggest large-plot scale runoff may increase more than sixfold and erosion 25- to 125-fold following burning (Table 1).

Hillslope to Landscape Scales Effects

Small- to large-plot scale fire effects on rangeland hydrology aggregated across a landscape can result in flash flooding, mudslides, and/or debris flows where intensive rain falls over extensive or contiguous burned areas. These events typically form by runoff-triggered erosion and progressive sediment bulking of the flow as it travels downslope (Cannon et al. 2001). Large erosion events have received only minor attention in literature on rangelands, but historical accounts demonstrate the danger that these events pose to downstream resources and communities (Cannon et al. 1998, 2001; Moody and Martin 2001; Pierson et al. 2002; Klade 2006). For example, wildfires fueled by cheatgrass burned extensive areas of rangeland and xeric forest along the Boise Front, near Boise, Idaho, in 1959 (3 640 ha) and 1996 (6 000 ha). An intense, convective rainstorm 2 wk after fires in 1959 resulted in widespread flooding and mud-flows that caused extensive (> \$3.0 million at current US dollar value) damage to property and infrastructure (Klade 2006). Similarly, a short-duration, high-intensity storm 1 yr following the 1996 Eighth Street Fire flooded portions of Boise and inundated the flooded areas with sediment (Pierson et al. 2002; Table 1). The flooding in 1997 was driven by intense rainfall on bare (90–100% bare ground), water repellent soils with reduced water storage capacity and low surface roughness. Most of the rainfall falling on the south-facing slopes ran off, forming concentrated flow networks (Pierson et al. 2002). Fire suppression and mitigation costs associated with the 1996 Eighth Street Fire exceeded \$4 million. In another case, a prolonged rain-on-snow event in 1996 near Boise produced extensive debris flows from a 7-yr-old xeric-forest fire site (1989 Lowman Fire) along the South Fork Payette River. A single event in one watershed discharged 14 600 m^3 of soil at a flow velocity of at least 12 $m \cdot s^{-1}$ (Meyer et al. 2001). Erosion from the multiple debris flows that occurred generated soil loss equivalent to several thousand years of nonfire associated erosion (low erosion rates) based on historical records (Meyer et al. 2001).

Landscape-scale flooding from burned areas has also been reported from other western US rangeland and forest settings along the wildland-urban interface (Craddock 1946; Agnew et al. 1997; Cannon et al. 1998, 2001; Elliot and Parker 2001; Moody and Martin 2001). In 1945, flooding following intense rainfall over a 1-yr-old 300+ ha cheatgrass burn site caused nearly \$500 000 (> \$6 million at current US dollar value) in damage to property in Salt Lake City, Utah (Craddock 1946). Adjacent rangelands in stable condition generated minor runoff and erosion from the same precipitation event. Similarly, runoff-triggered debris-flow events 2 mo following the South Canyon Fire near Glenwood Springs, Colorado, inundated a 13 to 14 ha area with approximately 70 000 m^3 of soil from a network of 15 stream channels (Cannon et al. 1998, 2001). The fire burned approximately 800 ha on steeply (30–70%) sloping hillslopes with cover of pinyon–juniper and mountain shrubs. Cannon et al. (2001) identified 84 debris flow initiations at the site following a torrential rainstorm (intensity not reported) event. The debris flows engulfed 30 vehicles traveling on a flow-intersected highway and forced two people into the Colorado River. In another study, Moody and Martin (2001) described hydrologic response to a 100-yr rainfall storm following the 4 690 ha Buffalo Creek Fire in steep, forested watersheds of the Colorado Front Range near Denver, Colorado. More than 60% of the burn was high severity. Two months postfire, a high-intensity (90 $mm \cdot h^{-1}$, 1 h) rainstorm caused flash flooding that killed two people (Agnew et al. 1997); unburned hillslopes adjacent to the fire generated very little surface runoff (Elliott and Parker 2001). Hillslope erosion following the Buffalo Creek Fire increased 150- to 240-fold. Approximately 1 101 000 m^3 of sediment was generated from interrill, rill, and in-channel processes during the first summer after the fire (Moody and Martin 2001). Postfire runoff events from the Buffalo Creek burned area discharged enough sediment into the Strontia Springs Reservoir to reduce storage capacity by one-third (Agnew et al. 1997; Moody and Martin 2001). The examples from the Boise Front Range (Meyer et al. 2001; Pierson et al. 2002; Klade 2006), Salt Lake City (Craddock 1946), Glenwood Springs (Cannon et al. 1998, 2001), and Denver (Moody and Martin 2001) areas presented here demonstrate the potential hydrologic responses to high-intensity rainfall following large-scale alteration of vegetation and ground surface characteristics.

Longevity of Effects Across Spatial Scales

The longevity of fire effects differ for runoff versus erosion and likely depend on how long the respective community requires to re-establish prefire ground cover and soil characteristics. Rainfall simulation experiments on sagebrush landscapes indicate postfire runoff rates return to prefire levels within one to two growing seasons or when ground cover returns to 40% (Pierson et al. 2001, 2002, 2008a, 2009). Pierson et al. (2008a, 2009) and Johansen et al. (2001) found postfire plot-scale erosion returns to prefire levels within two to three growing seasons or when ground cover approaches 50–60%. An examination of hillslope scale erosion from burned xeric forests suggests annual soil loss from natural rainfall events on sloping terrain can be as much as 60 $Mg \cdot ha^{-1}$ the first year following fire and generally returns to less than 0.5 $Mg \cdot ha^{-1}$ within 3 yr (see Spigel and Robichaud 2007; Robichaud et al. 2008). Annual erosion from unburned xeric forests is generally negligible (Robichaud et al. 2008; Larsen et al. 2009). These longevity estimates and cover thresholds likely are good relative indicators of hydrologic and erosional recovery with respect to commonly occurring storms; however, recovery relative to extreme events likely requires litter depths and soil conditions that may take 4 to more than 10 growing seasons to develop depending on climate and cover recruitment rates (Robichaud et al. 2000; Shakesby and Doerr 2006; Robichaud 2009). Furthermore, surface soil transported to and remaining in sideslopes and hillslope hollows postfire may serve as a source for downstream sediment pulses during subsequent high intensity storm and channel flushing events (Cannon et al. 2001; Meyer and Pierce 2003; Pierce et al. 2004; Moody and Martin 2009). For example, Meyer et al. (2001) estimated a residual 4 000 m^3 of soil remaining from a postfire debris flow event continued to contribute sediment to an adjacent river 4 yr following the original event.

HYDROLOGIC RISKS OF INCREASING WILDLAND FIRE

Figure 4 presents a conceptual model from which we can elaborate on what is known about the potential hydrologic effects of an increased role of fire on western rangelands and to identify critical knowledge gaps relative to future advancements. Literature has established postfire hydrologic response is a function of rainfall intensity (Benavides-Solorio and MacDonald 2005; Spigel and Robichaud 2007) and site susceptibility (Table 1), and that storm-specific hydrologic response increases exponentially where high site susceptibility promotes unstable hydrologic conditions and a requisite shift in hydrologic process dominance (Fig. 4; Cannon et al. 2001; Pierson et al. 2009). Shifts from infrequent and small to frequent, large burned areas increase the likelihood that convective storms moving through a region will encounter high site susceptibilities over landscape scales, potentially resulting in extensive soil loss, offsite flooding, and damage to values-at-risk. For example, recurring wildfires over cheatgrass dominated rangelands (Whisenant 1990; Brooks et al. 2004; Keane et al. 2008) ensure large tracks of land will exist in a hydrologically unstable state repeatedly on 5-yr to 10-yr cycles, increasing periodic high site susceptibility over short- and long-term time steps. These sites are subjected to infrequent short-term high soil losses from high intensity storms and long-term soil loss associated with frequently occurring low-intensity storms on highly susceptible conditions. Losses of biologically important surface soils is particularly critical given soil formation rates in the Great Basin (Harden 1990; Harden et al. 1991), especially where large fires are followed by drought years with minimal plant recruitment. The rates of soil loss are alarming given individual storm erosion estimates from plot-scale studies (Table 1) and potential first year postfire hillslope erosion rates of 60 to 100 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (see Robichaud et al. 2008). The increased threats to values-at-risk are even more concerning for western urban centers adjacent to steeply sloping cheatgrass infested rangelands (Pierson et al. 2002; Klade 2006) and densely stocked woodlands (Cannon et al. 1998, 2001). The likelihood of resource and property damaging flooding events is increasing in these areas due to the increased susceptibility over short- and long-term temporal windows.

Mitigation of hydrologic risks associated with an increased role of fire on western rangelands can be advanced by predictive technologies that answer three basic questions (see Kaplan and Garrick 1981): 1) what can happen, 2) how likely is the scenario to occur, and 3) if the scenario occurs, what are the consequences? The first question refers to a magnitude of hydrologic response for a given site susceptibility and storm occurrence. The second question refers to the likelihood or probability of the respective site susceptibility and storm co-occurring. The third question addresses the potential damage to resources-at-risk. Recent advances in understanding and quantification of fire effects across small-plot to hillslope scales provide an initial point for populating fire effects models in a probabilistic framework that incorporates combined probabilities of site susceptibility, storm occurrence, and magnitude of hydrologic response (i.e., Robichaud et al. 2007; Cannon et al. 2010). Of course, application of such models to mitigation of damage to values-at-risk also requires knowledge of the storm and/or runoff magnitudes required to cause damage to the respective resource/property (for example, see Cannon et al. 2008, 2011). Essentially, the hydrologic response curves shown in Figure 4 can be thought of as a family of risk curves (see Kaplan and Garrick 1981) for specified storms over a range of site susceptibilities. Damage to resources-at-risk is predicated on the magnitude of overall hydrologic response.

The presented qualitative model (Fig. 4) illustrates the general hydrologic and erosional relationships that are affected by ongoing plant community transitions and altered fire regimes in the Great Basin, but population of the model and development of predictive technologies are confounded by several key knowledge gaps. First, we are still learning how the variables that define site susceptibility (Fig. 4) across spatial scales interact to influence hydrologic response. Plot scale studies (Table 1; Robichaud et al. 2000; Moffet et al. 2007; Al-Hamdan et al. 2011) have identified and quantified the primary driving and resisting forces that dictate postfire hydrologic and erosional responses. In many cases, however, plot-scale studies sought to reduce experimental variability by focusing on a few primary independent variables (i.e., bare ground or ground cover) while isolating or fixing other variables like hillslope angle or rainfall intensity to constant values. For example, data for populating risk curves depicted in Figure 4 are extremely limited with respect to different rainfall intensities. Other variables like soil water repellency may strongly influence runoff generation from burned soils, but the effect may vary significantly in space and time (Doerr et al. 2000; Woods et al. 2007; Pierson et al. 2008b, 2009). Quantification of such temporal fluctuations and overall variable interactions is absent from most rangeland hydrology models. Advancements in predictive technologies have been made (i.e., Robichaud et al. 2007; Nearing et al. 2011), but rangeland models largely remain focused at the hillslope scale given the plot-scales at which data are available. Scaling limitations inhibit linkages of plot- and hillslope-scale responses to off-site impacts on values-at-risk. Even with limitations identified here, recent advancements offer insight into key measures needed to address hydrologic impacts associated with the increasing role of fire on Great Basin rangelands. We suggest quantifying interactions of storm magnitude and key measures that define site susceptibility, the spatial and temporal variability in effects of driving and resisting forces, and spatial scaling of postfire runoff and erosion remain paramount areas for future research.

IMPLICATIONS

The role of fire is escalating across western rangelands, and natural resources, city infrastructures, and lives are at risk. Elevated short- and long-term soil losses from western rangelands are likely to occur with more frequent fire-induced changes in site susceptibility over landscape scales. Damages to property and the risks to human life are also likely to increase where fire activity is intensified along the wildland-urban interface. Modern and historical reports demonstrate progressive sediment bulking of fire-induced increases in runoff and erosion from small- to large-plot scales can result in property damaging and life-taking landscape-scale flooding and erosion events. Such accounts are well documented across the western United States following large wildland fires adjacent to urban centers. Research from plot-to-hillslope scale studies provides a foundation for advancing understanding of effects of increased wildland fire activity on rangeland runoff and erosion and development of predictive technologies. Studies over a range of vegetation types, spatial and temporal scales, and burn conditions have established that ground cover, surface soil conditions/properties, soil water repellency, and hillslope topography define site susceptibility to postfire runoff and erosion. Postfire runoff and erosion are a function of rainfall intensity and site susceptibility, and the magnitude of postfire hydrologic response dictates potential damage to resources at risk. Postfire hydrologic response can be predicted by combining probabilities of susceptibility and storm occurrences. The likelihood of resource damage can be determined by linking storm response magnitudes with requisite damages to values-at-risk. Development of predictive technologies to address these issues would enhance postfire mitigation efforts and potentially reduce postfire expenditures aimed at preventing soil loss, flooding, and destruction of property.

Current knowledge remains wanting in several key areas that would advance quantitative model development. A major deficiency in current knowledge is in the interactions between hydrologic variables (i.e., soil moisture, water repellency, and infiltration) in complex field scenarios (i.e., spatially variable surface conditions and/or rainfall intensity). The literature is also strongly biased to a few plant communities (i.e., semi-arid grasslands and shrub-steppe, xeric ponderosa pine forests). Postfire runoff and erosion data are extremely limited for other fire-vulnerable plant communities where high-intensity, monsoonal precipitation events are common (i.e., Chihuahuan, Mojave, and Sonoran hot deserts). Current rangeland hydrology models remain largely unvalidated for watershed scales and extreme events. Risks of extreme events are expected to increase in coming decades based on projections of the greater role of wildfire and expectations of more intense precipitation regimes in the western United States. As the role of fire continues to increase on western rangelands, we suggest it is paramount that risk management research begins to integrate current knowledge into probabilistic terms and seek to advance our understanding and modeling of interacting controls on postfire hydrologic response across relevant spatial, temporal, and climatic scales.

LITERATURE CITED

Agnew, W., R. E. Labn, and M. V. Harding. 1997. Buffalo Creek, Colorado, fire and flood of 1996. *Land and Water* 41:27–29.

Aguirre, L., and D. A. Johnson. 1991. Influence of temperature and cheatgrass competition on seedling development of two bunchgrasses. *Journal of Range Management* 44:347–354.

Al-Hamdan, O. Z., F. B. Pierson, M. A. Nearing, J. J. Stone, C. J. Williams, P. R. Kormos, J. Boll, and M. A. Weltz. 2011. Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modeling. *Earth Surface Processes and Landforms*. (in review).

Arredondo, J. T., and D. A. Johnson. 1998. Clipping effects on root architecture and morphology of 3 range grasses. *Journal of Range Management* 51: 207–213.

Arredondo, J. T., T. A. Jones, and D. A. Johnson. 1998. Seedling growth of Intermountain perennial and weedy annual grasses. *Journal of Range Management* 51:584–589.

Baker, W. L., and D. J. Shinneman. 2004. Fire and restoration of pinyon-juniper woodlands in the western United States: a review. *Forest Ecology and Management* 189:1–21.

Benavides-Solorio, J. D. D., and L. H. MacDonald. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 15:2931–2952.

Benavides-Solorio, J. D. D., and L. H. MacDonald. 2002. Erratum: post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 16:1131–1133.

Benavides-Solorio, J. D. D., and L. H. MacDonald. 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* 14:457–474.

Billings, W. D. 1994. Ecological impacts of cheatgrass and resultant fire on ecosystems in the western Great Basin. *In:* S. B. Monsen and S. G. Kitchen [comps.]. Proceedings: Ecology and Management of Annual Rangelands; 18–22 May 1992, Boise, ID, USA. Ogden, UT, USA: US Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report, INT-GTR-313. p. 22–30.

Bisdom, E. B. A., L. W. Dekker, and J. F. T. Schoute. 1993. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma* 56:105–118.

Brooks, M. L. 2008. Plant invasions and fire regimes. *In:* K. Zouhar, J. K. Smith, S. Sutherland, and M. L. Brooks [eds.]. Wildland fire in ecosystems: fire and nonnative invasive plants. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-42, Volume 6. p. 33–45.

Brooks, M. L., C. M. D'Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *BioScience* 54:677–688.

Brooks, M. L., and D. A. Pyke. 2001. Invasive plants and fire in the deserts of North America. *In:* K. E. M. Galley and T. P. Wilson [eds.]. Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Tallahassee, FL, USA: Tall Timbers Research Station, Miscellaneous Publication Number 11. p. 1–14.

Calkin, D. E., K. D. Hyde, P. R. Robichaud, J. G. Jones, L. E. Ashmun, and D. Loeffler. 2007. Assessing post-fire values-at-risk with a new calculation tool. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, RMRS-GTR-205. 32 p.

Cannon, S. H., E. M. Boldt, J. L. Laber, J. W. Kean, and D. M. Stanley. 2011. Rainfall intensity-duration thresholds for postfire debris-flow emergency-response planning. *Natural Hazards*. DOI: 10.1007/s11069-011-9747-2.

Cannon, S. H., J. E. Gartner, M. G. Rupert, J. A. Michael, A. H. Rea, and C. Parrett. 2010. Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geological Society of America Bulletin* 122:127–144. DOI:10.1130/B26459.1

Cannon, S. H., J. E. Gartner, R. C. Wilson, J. C. Bowers, and J. L. Laber. 2008. Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. *Geomorphology* 96:250–269.

Cannon, S. H., R. M. Kirkham, and M. Parise. 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology* 39:171–188.

Cannon, S. H., P. S. Powers, and W. Z. Savage. 1998. Fire related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. *Environmental Geology* 35:210–218.

Cottam, W. P., and G. Stewart. 1940. Plant succession as result of grazing and of meadow desiccation by erosion since settlement in 1862. *Journal of Forestry* 38:613–626.

Craddock, G. W. 1946. Salt Lake City flood, 1945. *Proceedings of Utah Academy of Sciences, Arts, and Letters* 23:51–61.

D'Antonio, C. M. 2000. Fire, plant invasions, and global changes. *In:* H. A. Mooney and R. J. Hobbs [eds.]. Invasive species in a changing world. Washington, DC, USA: Island Press. p. 65–93.

D'Antonio, C. M., and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23:63–87.

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 1998. Fire's effects on ecosystems. New York, NY, USA: John Wiley and Sons, Inc. 352 p.

Doerr, S. H., R. A. Shakesby, and R. P. D. Walsh. 2000. Soil water repellency, its characteristics, causes and hydro-geomorphical consequences. *Earth System Science Reviews* 51:33–65.

Duke, S. E., and M. M. Caldwell. 2001. Nitrogen acquisition from different spatial distributions by six Great Basin plant species. *Western North American Naturalist* 61:93–102.

Elliott, J. G., and R. S. Parker. 2001. Developing a post-fire flood chronology and recurrence probability from alluvial stratigraphy in the Buffalo Creek watershed, Colorado, USA. *Hydrological Processes* 15:3039–3051.

Gedney, D. R., D. L. Azuma, C. L. Bolsinger, and N. McKay. 1999. Western juniper in eastern Oregon. Portland, OR, USA: US Department of Agriculture, Forest Service, NW-GTR-464. 53 p.

General Accounting Office. 2003. Wildland fires: better information needed on effectiveness of emergence stabilization and rehabilitation treatments. Washington, DC, USA: US General Accounting Office, Report GAO-03-430.

Harden, J. W. 1990. Soil development on stable landforms and implications for landscape studies. *Geomorphology* 3:391–398.

Harden, J. W., E. M. Taylor, C. Hill, R. K. Mark, L. D. McFadden, M. C. Reheis, J. M. Sowers, and S. G. Wells. 1991. Rates of soil development from four soil chronosequences in the southern Great Basin. *Quaternary Research* 35: 383–399.

Harris, G. A. 1967. Some competitive relationships between *Agropyron spicatum* and *Bromus tectorum*. *Ecological Monographs* 37:89–111.

Harris, G. A. 1977. Root phenology as a factor of competition among grass seedlings. *Journal of Range Management* 30:172–177.

Hempy-Mayer, K., and D. A. Pyke. 2008. Defoliation effects on *Bromus tectorum* seed production: implications for grazing. *Rangeland Ecology & Management* 61:116–123.

Houston, D. B. 1973. Wildfires in northern Yellowstone National Park. *Ecology* 54:1111–1117.

Hull, A. C. 1963. Competition and water requirements of cheatgrass and wheatgrasses in the greenhouse. *Journal of Range Management* 16: 199–204.

Hull, A. C. 1965. Cheatgrass: a persistent homesteader. *In:* Proceedings: Cheatgrass Symposium; 27–30 July 1965; Vale, OR, USA. Portland, OR, USA: US Department of Interior, Bureau of Land Management. p. 20–26.

Humphrey, L. D., and E. W. Schupp. 2001. Seed banks of *Bromus tectorum*-dominated communities in the Great Basin. *Western North American Naturalist* 61:85–92.

Johansen, M. P., T. E. Hakonson, and D. D. Breshears. 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes* 15:2953–2965.

Kaplan, S., and B. J. Garrick. 1981. On the quantitative definition of risk. *Risk Analysis* 1:11–27.

Keane, R. E., J. K. Agee, P. Fule, J. E. Keeley, C. Key, S. G. Kitchen, R. Miller, and L. A. Schulte. 2008. Ecological effects of large fires on US landscapes: benefit or catastrophe? *International Journal of Wildland Fire* 17:696–712.

Keeley, J. E. 2000. Chaparral. *In:* M. G. Barbour and W. D. Billings [eds.]. North American terrestrial vegetation. New York, NY, USA: Cambridge University Press. p. 201–251.

Kinnell, P. I. A. 2005. Raindrop-impact-induced erosion processes and prediction: a review. *Hydrological Processes* 19:2815–2844.

Klade, R. J. 2006. Building a research legacy: the Intermountain Station 1911–1997. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, RMRS-GTR-184. 259 p.

Knapp, P. A. 1996. Cheatgrass (*Bromus tectorum* L.) dominance in the Great Basin desert. *Global Environmental Change* 6:37–52.

Larsen, I. J., L. H. MacDonald, E. Brown, D. Rough, and M. J. Welsh. 2009. Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing. *Soil Science Society of America Journal* 73:1393–1407.

Link, S. A., G. W. Gee, and J. F. Downs. 1990. The effect of water stress on phenological and ecophysiological characteristics of cheatgrass and Sandberg's bluegrass. *Journal of Range Management* 43:506–513.

Link, S. O., C. W. Keeler, R. W. Hill, and E. Hagen. 2006. *Bromus tectorum* cover mapping and fire risk. *International Journal of Wildland Fire* 15:113–119.

Mack, R. N. 1981. Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. *Agro-Ecosystems* 7:145–165.

Meyer, G. A., and J. L. Pierce. 2003. Climatic controls on fire-induced sediment pulses in Yellowstone National Park and central Idaho: a long-term perspective. *Forest Ecology and Management* 178:89–104.

Meyer, G. A., J. L. Pierce, S. H. Wood, and A. J. T. Jull. 2001. Fire, storms, and erosional events in the Idaho batholiths. *Hydrological Processes* 15:3025–3038.

Miller, R. F., and R. J. Tausch. 2001. The role of fire in juniper and pinyon woodlands: a descriptive analysis. *In:* K. E. M. Galley and T. P. Wilson [eds.], Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. 27 November–1 December 2000; Tallahassee, FL, USA: Tall Timbers Research Station, Miscellaneous Publication No. 11. 15–30.

Miller, R. F., R. J. Tausch, E. D. McArthur, D. J. Johnson, and S. C. Sanderson. 2008. Age structure and expansion of pinyon-juniper woodlands: a regional perspective in the Intermountain West. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-RP-69. 15 p.

Moffet, C. A., F. B. Pierson, P. R. Robichaud, K. E. Spaeth, and S. P. Hardegree. 2007. Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire. *Catena* 71:218–228.

Moody, J. A., and D. A. Martin. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* 26:1049–1070.

Moody, J. A., and D. A. Martin. 2009. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. *International Journal of Wildland Fire* 18:96–115.

Nasri, M., and P. S. Doescher. 1995. Effect of temperature on growth of cheatgrass and Idaho fescue. *Journal of Range Management* 48:406–409.

Nearing, M. A., H. Wei, J. J. Stone, F. B. Pierson, K. E. Spaeth, M. A. Weltz, D. C. Flanagan, and M. Hernandez. 2011. A rangeland hydrology and erosion model. *Transactions of the American Society of Agricultural and Biological Engineers* 54:901–908.

Peters, E. F., and S. C. Bunting. 1994. Fire conditions pre- and post-occurrence of annual grasses on the Snake River Plain. *In:* S. B. Monsen and S. G. Kitchen [eds.]. Proceedings: Ecology and Management of Annual Rangelands. Ogden, UT, USA: US Department of Agriculture, Forest Service, General Technical Report, INT-GTR-313. p. 31–36.

Pierce, J. L., G. A. Meyer, and A. J. T. Jull. 2004. Fire-induced erosion and millennial-scale climate change in northern ponderosa pine forests. *Nature* 432:87–90.

Pierson, F. B., D. H. Carlson, and K. E. Spaeth. 2002. Impacts of wildfire on soil hydrological properties of steep sagebrush-steppe rangeland. *International Journal of Wildland Fire* 11:145–151.

Pierson, F. B., C. A. Moffet, C. J. Williams, S. P. Hardegree, and P. E. Clark. 2009. Prescribed-fire effects on rill and interrill runoff and erosion in a mountainous sagebrush landscape. *Earth Surface Processes and Landforms* 34: 193–203.

Pierson, F. B., P. R. Robichaud, C. A. Moffet, K. E. Spaeth, S. P. Hardegree, P. E. Clark, and C. J. Williams. 2008a. Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape. *Hydrological Processes* 22: 2916–2929.

PIERSON, F. B., P. R. ROBICHAUD, C. A. MOFFET, K. E. SPAETH, C. J. WILLIAMS, S. P. HARDEGREE, AND P. E. CLARK. 2008b. Soil water repellency and infiltration in coarse-textured soils of burned and unburned sagebrush ecosystems. *Catena* 74:98–108.

PIERSON, F. B., P. R. ROBICHAUD, AND K. E. SPAETH. 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* 15:2905–2916.

RICE, P. M., G. R. MCPHERSON, AND L. J. REW. 2008. Fire and nonnative invasive plants in the Interior West Bioregion. *In:* K. Zouhar, J. K. Smith, S. Sutherland, and M. L. Brooks [EDS.]. Wildland fire in ecosystems: fire and nonnative invasive plants. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-42, Volume 6. p. 141–171.

ROBICHAUD, P. R. 2009. Post-fire stabilization and rehabilitation. *In:* A. Cerdá and P. R. Robichaud [EDS.]. Fire effects on soils and restoration strategies, Volume 5 of Series: Land Reconstruction and Management. Enfield, NH, USA: Science Publishers. p. 299–320.

ROBICHAUD, P. R., J. L. BEYERS, AND D. G. NEARY. 2000. Evaluating the effectiveness of post-fire rehabilitation treatments. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, RMRS-GTR-63. 85 p.

ROBICHAUD, P. R., W. J. ELLIOT, F. B. PIERSON, D. E. HALL, AND C. A. MOFFET. 2007. Predicting postfire erosion and mitigation effectiveness with a web-based probabilistic erosion model. *Catena* 71:229–241.

ROBICHAUD, P. R., F. B. PIERSON, R. E. BROWN, AND J. W. WAGENBRENNER. 2008. Measuring effectiveness of three post-fire hillslope erosion barrier treatments, western Montana, USA. *Hydrological Processes* 22:159–170.

ROMME, W. H., C. D. ALLEN, J. D. BAILEY, W. L. BAKER, B. T. BESTELMEYER, P. M. BROWN, K. S. EISENHART, M. L. FLOYD, D. W. HUFFMAN, B. F. JACOBS, R. F. MILLER, E. H. MULDAVIN, T. W. SWETNAM, R. J. TAUSCH, AND P. J. WEISBERG. 2009. Historical and modern disturbance regimes, stand structures, and landscape dynamics in piñon-juniper vegetation of the western United States. *Rangeland Ecology & Management* 62:203–222.

RUNNING, S. W. 2006. Is global warming causing more, larger wildfires? *Science* 313:927–928.

SAGEMAP. 2010. SAGEMAP database, sagebrush assessment project, US Geological Survey. Available at: http://sagemap.wr.usgs.gov/SagebrushAssessment.aspx. Accessed 3 November 2010.

SHAKESBY, R. A., AND S. H. DOERR. 2006. Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* 74:269–307.

SPIGEL, K. M., AND P. R. ROBICHAUD. 2007. First year postfire erosion rates in Bitterroot National Forest, Montana. *Hydrological Processes* 21:989–997.

STEWARD, G., AND A. C. HULL. 1949. Cheatgrass (*Bromus tectorum* L.): an ecologic intruder in southern Idaho. *Ecology* 30:58–74.

STOCKMANN, K., J. BURCHFIELD, D. CALKIN, AND T. VENN. 2010. Guiding preventative wildland fire mitigation policy and decisions with an economic modeling system. *Forest Policy and Economics* 12:147–154.

SVEJCAR, T. 1990. Root length, leaf area, and biomass of crested wheatgrass and cheatgrass seedlings. *Journal of Range Management* 43:446–448.

TAUSCH, R. J. 1999. Historic pinyon and juniper woodland development. *In:* S. B. Monsen and R. Stevens [COMPS.]. 1999. Proceedings: Ecology and Management of Pinyon–Juniper Communities within the Interior West; 15–18 September 1997; Provo, UT, USA. Ogden, UT, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-P-9. p. 12–19.

TAUSCH, R. J., AND S. HOOD. 2007. Pinyon/juniper woodlands. *In:* S. M. Hood and M. Miller [EDS.]. Fire ecology and management of the major ecosystems of southern Utah. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, RMRS-GTR-202. p. 57–71.

WEST, N. E. 1999. Juniper-pinyon savannas and woodlands of western North America. *In:* R. C. Anderson, J. S. Fralish, and J. M. Baskin [EDS.]. Savannas, barrens, and rock outcrop plant communities of North America. London, England: Cambridge University Press. p. 288–308.

WEST, N. E. 2000. Synecology and disturbance regimes of sagebrush steppe ecosystems. *In:* P. G. Entwistle, A. M. DeBolt, J. H. Kaltenecker, and K. Steenhof [COMPS.]. Sagebrush Steppe Ecosystems Symposium: Proceedings; 21–23 June 1999; Boise, ID, USA: US Department of the Interior, Bureau of Land Management, Boise State Office, Publication Number BLM/ID/PT-001001+1150. p. 15–26.

WEST, N. E., AND T. P. YORKS. 2002. Vegetation responses following wildfire on grazed and ungrazed sagebrush semi-desert. *Journal of Range Management* 38:131–134.

WHISENANT, S. G. 1990. Changing fire frequencies on Idaho's Snake River plains: ecological and management implications. *In:* E. D. McArthur, E. M. Romney, S. D. Smith, and P. T. Tueller [COMPS.]. Proceedings: Symposium on Cheatgrass Invasion, Shrub Die-Off, and Other Aspects of Shrub Biology and Management. Ogden, UT, USA: US Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report, INT-276. p. 4–10.

WISDOM, M. J., M. M. ROWLAND, L. H. SURING, L. SCHUECK, C. WOLFF MEINKE, B. C. WALES, AND S. T. KNICK. 2003. Procedures for regional assessment of habitats for species of conservation concern in the sagebrush ecosystem. LaGrande, OR, USA: US Department of Agriculture, Forest Service, Pacific Northwest Research Station, March 2003 Report, Version 1. 153 p.

WOODS, S. W., A. BIRKAS, AND R. AHL. 2007. Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado. *Geomorphology* 86:465–479.

YOUNG, J. A., AND R. A. EVANS. 1975. Germinability of seed reserves in a big sagebrush community. *Weed Science* 23:358–364.

YOUNG, J. A., AND R. A. EVANS. 1978. Population dynamics after wildfires in sagebrush grasslands. *Journal of Range Management* 31:283–289.

YOUNG, J. A., R. A. EVANS, AND R. E. ECKERT. 1969. Population dynamics of downy brome. *Weed Science* 17:20–26.

YOUNG, J. A., R. A. EVANS, R. E. ECKERT, AND K. L. BURGESS. 1987. Cheatgrass. *Rangelands* 9:266–270.