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Vegetation, ground cover, soil, rainfall simulation, and overland-flow experiments before and after tree removal in woodland-encroached sagebrush steppe: the hydrology component of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP)

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Abstract. Rainfall simulation and overland-flow experiments enhance understanding of surface hydrology and erosion processes, quantify runoff and erosion rates, and provide valuable data for developing and testing predictive models. We present a unique dataset (1021 experimental plots) of rainfall simulation (1300 plot runs) and overland-flow (838 plot runs) experimental plot data paired with measures of vegetation, ground cover, and surface soil physical properties spanning point to hillslope scales. The experimental data were collected at three sloping sagebrush (*Artemisia* spp.) sites in the Great Basin, USA, each subjected to woodland encroachment and with conditions representative of intact wooded shrublands and 1–9 years following wildfire, prescribed fire, and/or tree cutting and shredding tree-removal treatments. The methodologies applied in data collection and the cross-scale experimental design uniquely provide scale-dependent, separate measures of interrill (rain splash and sheet flow processes, 0.5 m^2 plots) and concentrated overland-flow runoff and erosion rates ($\sim 9\,m^2$ plots), along with collective rates for these same processes combined over the patch scale (13 m^2 plots). The dataset provides a valuable source for developing, assessing, and calibrating/validating runoff and erosion models applicable to diverse plant community dynamics with varying vegetation, ground cover, and surface soil conditions. The experimental data advance understanding and quantification of surface hydrologic and erosion processes for the research domain and potentially for other patchy-vegetated rangeland landscapes elsewhere. Lastly, the unique nature of repeated measures spanning numerous treatments and timescales delivers a valuable dataset for examining long-term landscape vegetation, soil, hydrology, and erosion responses to various management actions, land use, and natural disturbances. The dataset is available from the US Department of Agriculture National Agricultural Library at https://data.nal.usda.gov/search/type/dataset (last access: 7 May 2020) (doi: https://doi.org/10.15482/USDA.ADC/1504518; Pierson et al., 2019).

1 Introduction

Rangelands are one of the most common occurring sparsely vegetated wildland landscapes around the world. These lands cover about half of the world's land surface and about 31 % (> 300 million ha) of the land surface in the US (Havstad et al., 2009). The patchy vegetation structure typical to these water-limited landscapes regulates connectivity of runoff and erosion sources and processes and thus controls hillslope-scale runoff and sediment transport (Pierson et al., 1994; Wainwright et al., 2000; Wilcox et al., 2003; Ludwig et al., 2005). Runoff and erosion in isolated bare patches on well-vegetated rangelands occur as splash–sheet (rain splash and sheet flow) processes. Sediment entrained by raindrops and shallow sheet flow in bare patches typically moves a limited distance downslope before deposition immediately upslope of and within vegetated areas (Emmett, 1970; Reid et al., 1999; Puigdefábregas, 2005; Pierson and Williams, 2016). Disturbances such as intensive land use, plant community transitions, and wildfire can alter this resource-conserving vegetation structure and thereby facilitate increases in runoff and soil loss through enhanced connectivity of overland-flow and sediment sources during rainfall events (Davenport et al., 1998; Wilcox et al., 2003; Pierson et al., 2011; Williams et al., 2014a, 2014b, 2018). The negative ramifications of woody plant encroachment and wildfire have been extensively studied on rangelands around the world, and this work has advanced understanding of runoff and erosion processes for these commonly occurring ecosystems (Schlesinger et al., 1990; Wainwright et al., 2000; Shakesby and Doerr, 2006; Shakesby, 2011; Pierson and Williams, 2016). Recent widespread plant community transitions and trends in wildfire activity and associated amplified runoff and erosion rates spanning rangelands to dry forests throughout the western US (Williams et al., 2014b) and elsewhere (Shakesby, 2011) underpin a need for compiling data sources that further contribute to process understanding and improved parametrization of rangeland hydrology and erosion predictive technologies.

Sagebrush rangelands in the western US are an extensive ($\sim 300\,000\,km^2$) and important vegetation type that have undergone substantial degradation associated with encroachment by pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands, invasions of fire-prone annual cheatgrass (*Bromus tectorum* L.), and altered fire regimes (Davies et al., 2011; Miller et al., 2011, 2019). Pinyon and juniper woodland encroachment of sagebrush vegetation can have negative hydrologic impacts (Miller et al., 2005; Petersen and Stringham, 2008; Pierson et al., 2007, 2010; Petersen et al., 2009; Williams et al., 2014a, 2018). Encroaching trees outcompete understory sagebrush and herbaceous vegetation over time and thereby increase bare ground and connectivity of runoff and sediment sources (Miller et al., 2000; Bates et al., 2000, 2005; Petersen et al., 2009; Pierson et al., 2010; Roundy et al., 2017). Extensive well-connected bare patches in the later stages of woodland encroachment propagate broadscale runoff generation and soil loss during storms events. Runoff from splash–sheet processes during these events combines along hillslopes to form concentrated overland flow with high sediment detachment rates and ample transport capacity (Pierson et al., 2010; Williams et al., 2014a, 2016c). Amplified soil loss over time perpetuates a woodland ecological state and long-term site degradation (Petersen et al., 2009). Land managers commonly employ various mechanical treatments and prescribed and natural fires to reduce tree cover and reestablish sagebrush vegetation and associated resource-conserving hydrologic function (Bates et al., 2000, 2005, 2014, 2017; Pierson et al., 2007; Miller et al., 2014; Roundy et al., 2014; Williams et al., 2018). However, managers are challenged with predicting potential vegetation and ecohydrologic effects of tree removal across diverse woodland landscapes and with determining the appropriate type and timing of available treatment options. Invasions of fire-prone cheatgrass following prescribed and natural fires are particularly problematic. This annual grass commonly invades open patches on woodlands at lower elevations or on warmer sites, subsequently increases wildfire frequency, and potentially promotes long-term loss of surface soil and nutrients associated with recurrent burning and fire-induced runoff events (Pierson et al., 2011; Wilcox et al., 2012; Williams et al., 2014b).

Land managers around the world need improved understanding of runoff and erosion processes for the various disturbances common to rangelands and need improved tools for predicting responses to and making decisions on a host of management alternatives. Managers rely on local understanding and conceptual and quantitative science-based models to aid management decisions. Local knowledge is often variable, and data necessary to populate conceptual and science-based models are likewise limited given vast rangeland domain. Vegetation and ground cover inventories and field-based experiments are primary resources for informing conceptual models (Petersen et al., 2009; Chambers et al., 2014, 2017; Williams et al., 2016a). Rainfall simulation and overland-flow experiments likewise provide data for developing, evaluating, and enhancing quantitative hydrology and erosion predictive technologies (Flanagan and Nearing, 1995; Robichaud et al., 2007; Wei et al., 2009; Nearing et al., 2011; Al-Hamdan et al., 2012a, 2012b, 2013, 2015, 2017; Hernandez et al., 2017). To address this need, we present an ecohydrologic dataset containing 1021 experimental plots. The dataset consists of rainfall simulation (1300 plot runs, 0.5 to $13\,m^2$ scales) and overland-flow (838 plot runs, $\sim 9\,m^2$ scale) experimental data with paired measures of vegetation, ground cover, and surface soil physical properties spanning point to hillslope scales (Pierson et al., 2019). The experimental data were collected at multiple sagebrush rangelands in the Great Basin, USA, each with woodland encroachment, sampled in untreated conditions, and following fire and mechanical tree-removal treatments over a 10-year period. The dataset therefore represents diverse vegetation, ground cover, and surface soil conditions common to undisturbed and disturbed rangelands in the western US and elsewhere. The resulting dataset contributes to both process-based knowledge and provision of data for populating, evaluating, and improving conceptual and quantitative hydrology and erosion models.

2 Study sites and experimental design

A series of vegetation, soils, rainfall simulation (Figs. 1 and 2a–c), and overland-flow experiments (Fig. 2d–e) were completed at three pinyon and juniper woodlands historically vegetated as sagebrush shrublands. The study sites were selected from a network of sites as part of a larger study on the ecological impacts of invasive species and woodland encroachment into sagebrush ecosystems and the effects of sagebrush restoration practices, the Sagebrush Steppe Treatment Evaluation Project (SageSTEP, http://www.sagestep.org/, last access: 7 May 2020). Study site climate, physical, and vegetation attributes are provided in Table 1. All data were collected in summer months in years 2006–2015, with sampling years varying by site and by treatment area within each site (see Table 2). Vegetation and ground cover were patchy and sparse at the sites when the study began in 2006 (Table 1). Tree-removal treatments (prescribed fire, tree cutting, tree shredding (bullhog)) were applied at the Marking Corral and Onaqui sites in 2006 (late summer and autumn) to evaluate effectiveness of pinyon and juniper removal in reestablishing sagebrush vegetation and ground cover, improving hydrologic function, and reducing erosion rates. The Castlehead site burned by wildfire in summer 2007 before tree-removal treatments could be applied, and wildfire was assessed as a prescribed natural-fire tree-removal treatment for that site. At all three sites, a cut tree (downed tree) treatment was placed across a subset of large rainfall and overland-flow plot bases (Fig. 2e) within various treatments to measure effects of downed trees on surface hydrology and erosion processes. This additional treatment was applied in 2007 and 2015 to some plots in cut treatment areas at Marking Corral and Onaqui and in 2008 and 2009 in unburned areas at Castlehead. Treatment applications and descriptions and the study experimental design are explained in earlier papers by Pierson et al. (2010, 2013, 2014, 2015) and by Williams et al. (2014a, 2019a, 2020), and all treatments for each site each year are provided in Table 2.

A suite of biological and physical attributes at each site were measured at point, small rainfall plot ($0.5\,m^2$), overland-flow plot ($\sim 9\,m^2$), large rainfall plot ($13\,m^2$), and hillslope plot ($990\,m^2$) scales. Soil bulk density of the near surface (0–5 cm depth) was sampled as a point measure in interspace microsites between plants, shrub coppice microsites underneath shrub canopies, and tree coppice microsites underneath tree canopies. The bulk density sampling was conducted by the compliant cavity method within all treatment areas 1–2 years after respective treatments. Surface soil texture was quantified as a point measure using grab samples (0–2 cm depth) from interspace, shrub coppice, and tree coppice microsites within all treatment areas at Marking and Onaqui in 2006 prior to treatments and within unburned and burned treatment areas at Castlehead in 2008. Vegetation and ground cover were measured at small rainfall, large rainfall, and overland-flow plot scales and at the hillslope-scale pre- and posttreatment in all treatment areas at Marking Corral and Onaqui as well as in unburned and burned treatment areas at Castlehead. Vegetation and ground cover measures on rainfall simulation and overland-flow plots were used to evaluate resisting and driving forces on surface hydrology and erosion processes and to quantify treatment effects on cover components at those plot scales. Sampling of vegetation and ground cover on rainfall simulation and overland-flow plots

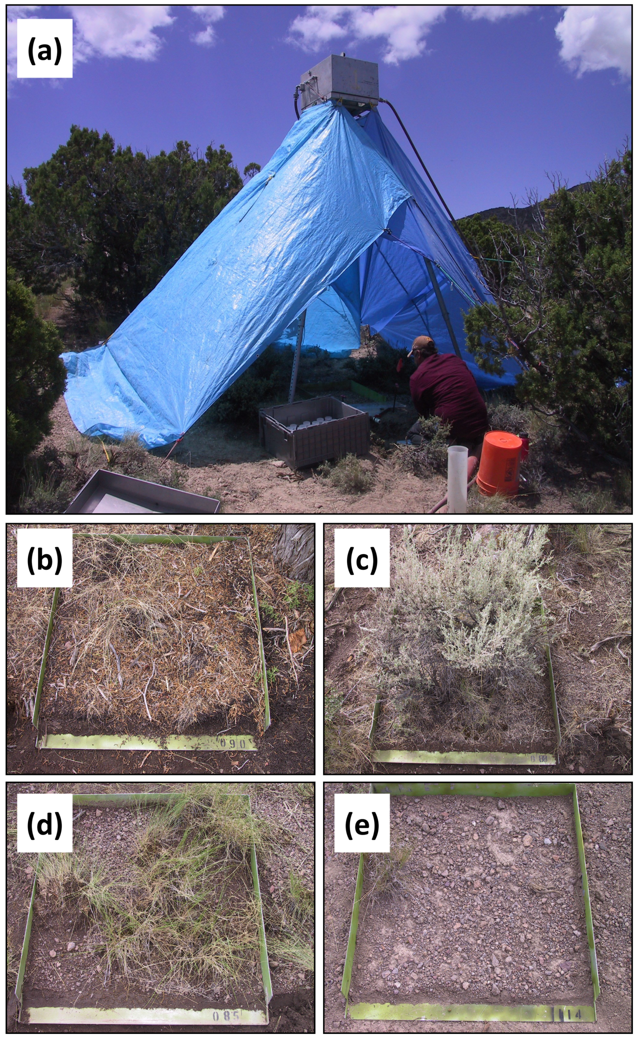

Figure 1. Photographs of small-plot rainfall simulator **(a)** and example small rainfall plots on tree coppice **(b)**, shrub coppice **(c)**, and interspace **(d, e)** microsites as applied in this study.

Table 1. Topography, climate, soil, tree cover, and understory vegetation at the Castlehead, Marking Corral, and Onaqui sites prior to treatments. Data are from Pierson et al. (2010, 2015) or Williams et al. (2014a) except where indicated by footnote.

	Castlehead, Idaho, USA (42°26′50″ N, 116°46′39″ W)	Marking Corral, Nevada, USA (39°27′17″ N, 115°06′51″ W)	Onaqui, Utah, USA (40°12′42″ N, 112°28′24″ W)
Woodland community	western juniper[1]	single-leaf pinyon[2]/ Utah juniper[3]	Utah juniper[3]
Elevation (m) – aspect	1750 – SE facing	2250 – W to SW facing	1720 – N to NE facing
Mean annual precip. (mm)	364[4]	299[4]	298[4]
Mean annual air temp. (°C)	7.4[4]	6.9[4]	9.2[4]
Slope (%)	10–25	10–15	10–15
Parent rock	basalt and welded tuff[5]	andesite and rhyolite[6]	sandstone and limestone[7]
Soil association	Mulshoe-Squawcreek-Gaib[5]	Segura-Upatad-Cropper[6]	Borvant[7]
Depth to bedrock (m)	0.5–1.0[5]	0.4–0.5[6]	1.0–1.5[7]
Soil surface texture	sandy loam, 59 % sand, 37 % silt, 4 % clay	sandy loam, 66 % sand, 30 % silt, 4 % clay	sandy loam, 57 % sand, 37 % silt, 7 % clay
Tree canopy cover (%)[8]	26[1]	15[2], 10[3]	26[3]
Trees per hectare[8]	158[1]	329[2], 150[3]	476[3]
Mean tree height (m)[8]	5.2[1]	2.3[2], 2.4[3]	2.4[3]
Juvenile trees per hectare[9]	28[1]	296[2], 139[3]	154[3]
Shrubs per hectare[10]	2981	12065	4914
Intercanopy bare ground (%)[11]	88	64	79
Common understory plants	*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle and Young; *Artemisia nova* A. Nelson; *Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle; *Purshia* spp.; *Poa secunda* J. Presl; *Pseudoroegneria spicata* (Pursh) A. Löve; *Festuca idahoensis* Elmer; and various forbs		

[1] *Juniperus occidentalis* Hook. [2] *Pinus monophylla* Torr. and Frém. [3] *Juniperus osteosperma* [Torr.] Little. [4] Estimated from a 4 km grid for years 1989–2018 from Prism Climate Group (2019). [5] Natural Resources Conservation Service (NRCS) (2003). [6] NRCS (2007). [7] NRCS (2006). [8] Trees > 50 cm height: values for Castlehead include data from Williams et al. (2014a) and one additional year. [9] Trees 5 to 50 cm height: for Castlehead mean based on data from Williams et al. (2014a) and one additional year. [10] Shrubs ≥ 5 cm height: for Castlehead mean based on data from Williams et al. (2014a) and one additional year. [11] Intercanopy refers to the area between tree canopies consisting of shrubs, grasses, and interspaces between plants (shrub–interspace zone).

in untreated areas (control and unburned) and treated areas varied by site and year as described in Table 2. Vegetation and ground cover measures at the hillslope scale (site characterization plots) were conducted to describe site level cover conditions prior to and over time after treatment. Site characterization plots were installed and sampled prior to treatment (2006) in all treatment areas at Marking Corral and Onaqui and were resampled 1 year (2007) and 9 years (2015) after treatment. Castlehead site characterization plots were installed and sampled in unburned and burned areas 1 year after the fire (2008) and were resampled the second year postfire (2009).

Rainfall simulations and overland-flow experiments were employed at the different plot scales to quantify specific scale-dependent runoff and erosion processes (Pierson et al., 2010; Williams et al., 2014a). Small-plot rainfall simulations (Fig. 1) were applied to quantify runoff and erosion by splash–sheet processes. Each small rainfall plot was installed, as described by Pierson et al. (2010) and Williams et al. (2014a), to occur on either a tree coppice, shrub coppice, or interspace microsite (Fig. 1b–e). Small plots at Marking Corral and Onaqui were installed and sampled in control and all other treatment areas in 2006 before application of the tree-removal treatments and were left in place for subsequent sampling 1 year (2007), 2 years (2008), and 9 years (2015) after treatment. Small plots at Castlehead were installed and sampled in unburned and burned areas 1 year after the fire (2008) and left in place for subsequent sampling the second year after fire (2009). Large-plot rainfall simulations (Fig. 2a–b) were used to quantify runoff and erosion from combined splash–sheet and concentrated overland-flow processes. Each plot was installed, as described by Pierson et al. (2010) and Williams et al. (2014a), on either a tree zone (tree coppice and area just outside tree canopy drip line) or a shrub–interspace zone (intercanopy area between tree canopies) inclusive of shrub coppice and interspace microsites (Fig. 2). Large plots at Marking Corral and Onaqui were installed and sampled in all treatment areas in 2006 im-

Table 2. Number of plots sampled by plot type (site characterization vegetation plots and small-plot rainfall, large-plot rainfall, and overland-flow simulation plots) at each study site (Castlehead, Marking Corral, and Onaqui) by treatment and microsite (small plots – tree coppice, shrub coppice, and interspace; large plots and overland flow – tree zone and shrub–interspace zone (intercanopy)) combination each year of the study. Control refers to untreated areas at Marking Corral and Onaqui sites. Unburned refers to areas immediately adjacent to, but outside of, the wildfire area (burned treatment) at the Castlehead site. Downed tree subtreatments (cut–downed tree and unburned–downed tree) refer to plots with a single downed tree across each respective plot within the specified associated treatment (cut or unburned). Tree and shrub coppice microsites are areas underneath or previously (prior to treatment) underneath tree and shrub canopy, respectively. Interspace microsites are areas between tree and shrub coppice microsites. Tree zone microsites are areas underneath, or previously underneath, and immediately adjacent (just outside canopy drip line) to a tree canopy. Shrub–interspace zones are the areas between tree canopies, collectively inclusive of shrub coppice and interspace microsites (the intercanopy).

		Site characterization vegetation plots (990 m^2)		
Year	Treatment	Castlehead	Marking Corral	Onaqui
2006	Control	–	6	9
2007	Bullhog	–	–	3
	Burned	–	3	3
	Cut	–	3	3
2008	Unburned	3	–	–
	Burned	3	–	–
2009	Unburned	3	–	–
	Burned	3	–	–
2015	Bullhog	–	–	3
	Burned	–	3	3
	Cut	–	3	3

		Small-plot rainfall simulation plots (0.5 m^2)								
		Castlehead			Marking Corral			Onaqui		
Year	Treatment	Tree coppice	Shrub coppice	Interspace	Tree coppice	Shrub coppice	Interspace	Tree coppice	Shrub coppice	Interspace
2006	Control	–	–	–	24	13	23	23	21	36
2007	Control	–	–	–	8	5	7	4	3	3
	Bullhog	–	–	–	–	–	–	10	10	30
	Burn	–	–	–	8	4	8	5	5	10
2008	Control/ unburned	8	8	8	4	2	4	4	3	3
	Burned	5	5	10	8	4	8	5	5	10
2009	Unburned	3	3	4	–	–	–	–	–	–
	Burned	5	5	10	–	–	–	–	–	–
2015	Control	–	–	–	8	4	6	8	6	6
	Bullhog	–	–	–	–	–	–	5	5	10
	Burned	–	–	–	8	4	6	5	5	10
	Cut	–	–	–	8	4	6	5	5	10

mediately before treatment application (controls) and were extracted following sampling. New plots were installed and sampled in treatment areas at Marking Corral and Onaqui in 2007, 1 year posttreatment, and were then extracted. Large rainfall plots at Castlehead were installed and sampled in unburned and burned areas in 2008, 1 year after the fire, and were then extracted. Overland-flow simulations (Fig. 2d–e) were conducted on large rainfall plots (Fig. 2a–c) at Marking Corral and Onaqui in 2006 and 2007 immediately following respective rainfall simulations. Overland-flow simulations were conducted in control and treated areas at those sites in 2008 and 2015, but those plots were not subjected to rainfall simulation. Castlehead overland-flow simulations in 2008, 1 year postfire, were run on large rainfall simulation plots following rainfall simulations and, in 2009, 2 years postfire, were run on newly installed plots without rainfall simulations. Overland-flow experiments conducted on large rainfall simulation plots had borders on all sides and con-

Table 2. Continued.

Year	Treatment	Large-plot rainfall simulation plots (13 m²)					
		Castlehead		Marking Corral		Onaqui	
		Tree zone	Shrub–interspace zone	Tree zone	Shrub–interspace zone	Tree zone	Shrub–interspace zone
2006	Control	–	–	12	12	18	18
2007	Bullhog	–	–	–	–	4	4
	Burned	–	–	6	6	6	6
	Cut	–	–	–	6	–	6
	Cut–downed tree	–	–	–	6	–	6
2008	Unburned	6	6	–	–	–	–
	Unburned–downed tree	–	6	–	–	–	–
	Burned	6	6	–	–	–	–

Year	Treatment	Overland-flow simulation plots (∼ 9 m²)					
		Castlehead		Marking Corral		Onaqui	
		Tree zone	Shrub–interspace zone	Tree zone	Shrub–interspace zone	Tree zone	Shrub–interspace zone
2006	Control	–	–	12	12	18	18
2007	Bullhog	–	–	–	–	4	4
	Burned	–	–	6	6	6	6
	Cut	–	–	–	6	–	6
	Cut–downed tree	–	–	–	6	–	6
2008	Control Unburned	6	6	3	3	2	2
	Unburned–downed tree	–	6	–	–	–	–
	Burned	6	6	6	6	6	6
2009	Unburned	6	6	–	–	–	–
	Unburned–downed tree	–	6	–	–	–	–
	Burned	6	6	–	–	–	–
2015	Control	–	–	5	5	5	5
	Bullhog	–	–	–	–	5	5
	Burned	–	–	5	5	5	5
	Cut	–	–	5	5	5	5
	Cut–downed tree	–	–	–	5	–	5

– Indicates not applicable, no plots.

tained a collection trough for runoff measurement at the plot base (Fig. 2c; Pierson et al., 2010, 2013, 2015; Williams et al., 2014a). Overland-flow simulations run independent of rainfall-simulation experiments were conducted on borderless plots but contained a runoff collection trough at the downslope plot base (Fig. 2d–e; Pierson et al., 2013, 2015; Williams et al., 2014a, 2019a, 2020).

3 Field methods

3.1 Hillslope-scale site characterization plots

Understory vegetation and ground cover and overstory tree cover at the hillslope scale at each site were sampled on 30 m × 33 m site characterization plots using a suite of line–point and belt transect methods and various tree measures (see Pierson et al., 2010; Williams et al., 2014a). Foliar and ground cover on each site characterization plot were recorded

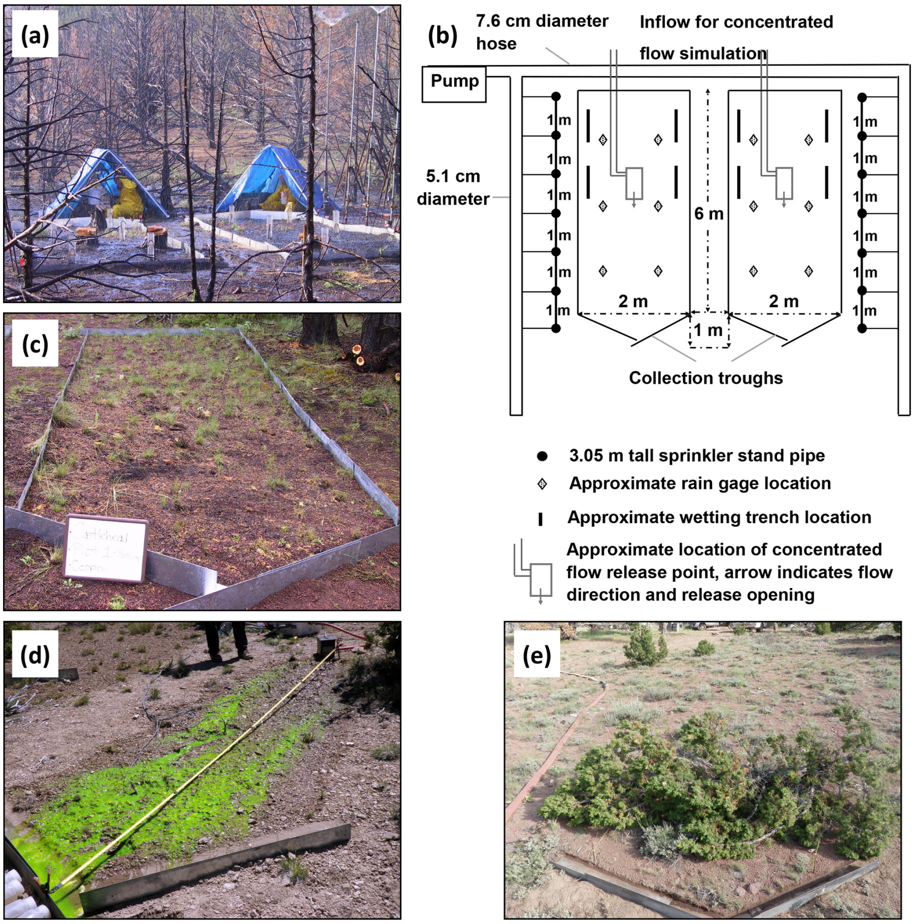

Figure 2. Images showing paired large rainfall plots during rainfall simulations **(a)**, experimental setup of paired large rainfall plot simulation experiments **(b)**, a fully bordered large rainfall simulation plot on a tree coppice microsite **(c)**, a borderless overland-flow simulation plot and experiment on an intercanopy (shrub–interspace) microsite **(d)**, and a borderless overland-flow simulation plot with a cut, downed tree on an intercanopy microsite **(e)**, all as respective examples as applied in this study.

for 60 points (50 cm spacing) along each of five line–point transects (30 m in length; spaced 5–8 m apart) for a total of 300 sample points per plot. Percent cover by each sampled cover type was derived for each plot as the number of respective cover-type hits divided by the total number of points sampled. Multiple canopy layers were possible, and therefore the total foliar cover across all sampled cover types potentially exceeded 100 %. The number of live tree seedlings of 5–50 cm height and shrubs exceeding 5 cm height were quantified along three belt transects on each plot. Each of the three belt transects on each plot were centered along a foliar/ground cover line–point transect, sized 2 m wide × 30 m long and spaced 6 m apart. Shrub and tree seedling densities were calculated for each plot as the total number of respective individuals tallied along the three belt transects divided by total belt transect area (180 m^2). The number of live trees > 0.5 m in height was quantified for each plot, and tree height and minimum and maximum crown diameters were measured for each live tree. A crown radius for each live tree was derived as one-half the average of measured minimum and maximum crown diameters. Individual tree crown area (tree cover) was calculated as equivalent to the area of a circle, derived with the respective crown radius. Total tree cover for each plot was quantified as the sum of measured tree cover values on the plot.

3.2 Small rainfall simulation plots and experiments

Foliar cover, ground cover, and ground surface roughness on all small rainfall plots were quantified using point frame methods explained in Pierson et al. (2010). Foliar and ground cover on each plot were sampled at 15 points spaced 5 cm apart along each of seven transects spaced 10 cm apart and oriented parallel to hillslope contour (105 sample points per plot). Percent cover for each cover type sampled on each plot was derived from the frequency of respective cover-type hits divided by the total number of points sampled. Multiple canopy layers were allowed, and therefore total foliar cover across all cover types potentially exceeded 100 %. A rela-

Table 3. Select foliar cover and ground cover measures on hillslope-scale site characterization plots (990 m^2) in cut and burned treatment areas at the Marking Corral and Onaqui sites 1 year prior to tree removal (2006) and 1 year (2007) and 9 years (2015) after tree-removal treatments.

		Marking Corral			Onaqui		
Site characteristic		Untreated 2006[1]	Cut 2007[2]	Cut 2015[2]	Untreated 2006[1]	Cut 2007[2]	Cut 2015[2]
Foliar cover	Shrub (%)	14.6	14.3	28.7	3.4	5.0	16.9
	Grass (%)	12.4	21.4	30.2	7.3	13.7	27.1
	Forb (%)	1.0	3.7	1.4	3.2	12.1	7.4
Ground cover	Litter (%)	46.1	46.0	47.6	26.2	41.6	35.8
	Rock (%)[3]	22.0	11.3	1.3	29.8	22.3	17.0
	Bare soil (%)	26.4	40.5	42.5	37.7	29.1	35.7
		Marking Corral			Onaqui		
Site characteristic		Untreated 2006[1]	Burn 2007[4]	Burn 2015[4]	Untreated 2006[1]	Burn 2007[4]	Burn 2015[4]
Foliar cover	Shrub (%)	17.7	6.2	8.7	0.9	0.4	10.7
	Grass (%)	4.8	10.0	63.1	6.2	3.4	39.7
	Forb (%)	0.1	10.6	0.9	3.3	6.0	14.3
Ground cover	Litter (%)	47.4	31.4	40.3	34.4	29.7	34.7
	Rock (%)[3]	25.4	16.5	12.8	29.0	31.6	21.6
	Bare soil (%)	26.8	52.0	39.7	31.1	35.9	29.5

[1] Data from Pierson et al. (2010) but restricted to plots in areas subsequently cut or burned at the respective site × treatment combination. [2] Data from Williams et al. (2019a). [3] Rock fragments > 5 mm in diameter. [4] Data from Williams et al. (2020).

tive ground surface height at each sample point on each plot was determined by a metal ruler as the distance between the ground surface and a level line (top of point frame). Ground surface roughness for each plot was then derived as the mean of standard deviations of ground surface heights for each of the transects sampled on the respective plot. Litter depth on each plot was measured along the outside edge of the two plot borders located perpendicular to the hillslope contour. Measurements were made to the nearest 1 mm using a metal ruler at four evenly spaced points (15 cm apart) along the two plot borders. An average litter depth was derived for each plot as the average of the eight litter depth measures.

Soil water repellency of the mineral soil surface and at depths near the mineral soil surface (0–5 cm depths) was measured immediately adjacent (∼ 50 cm away) to each small rainfall plot immediately before rainfall simulation using the water drop penetration time (WDPT) method (see Pierson et al., 2010). Litter and ash cover were carefully removed from the mineral soil surface prior to application of the WDPT. Eight water drops (∼ 3 cm spacing) were then placed on the mineral soil surface, and the time required for infiltration of each drop was recorded up to a 300 s maximum. The WDPT was then repeated at 1 cm soil depth increments until 5 cm soil depth was reached. For each sampled depth, 1 cm of soil was excavated immediately underneath the previously sampled area, and the WDPT procedure was repeated with eight drops. A mean WDPT for each sampled soil depth on each plot was recorded as the average of the eight WDPT (s) samples at the respective depth. Soils were classified as wettable where mean WDPT < 5 s, slightly water repellent where mean WDPT ranged from 5 to 60 s, and strongly water repellent where mean WDPT > 60 s.

Surface soil moisture and aggregate stability were also sampled for each small rainfall plot prior to rainfall simulations. Soil samples were collected at 0–5 cm depth immediately adjacent to each small rainfall plot and were subsequently analyzed in the laboratory for gravimetric soil water content. Some samples were excluded from the dataset due to poor sealing of soil cans in the field. Aggregate stability of the surface soil on each plot was determined using a modified sieve test on six soil peds approximately 2–3 mm thick and 6–8 mm in diameter (see Pierson et al., 2010). Each soil ped sampled on each plot was assigned to one of the following classes, as defined by Herrick et al. (2005): (1) < 10 % stable aggregates, 50 % structural integrity lost within 5 s; (2) < 10 % stable aggregates, 50 % structural integrity lost within 5–30 s; (3) < 10 % stable aggregates, 50 % structural integrity lost within 30–300 s; (4) 10 %–25 % stable aggregates; (5) 25 %–75 % stable aggregates; or (6) 75 %–100 % stable aggregates. An average aggregate stability was derived for each plot as the arithmetic mean of the classes assigned to the six aggregate samples for the respective plot.

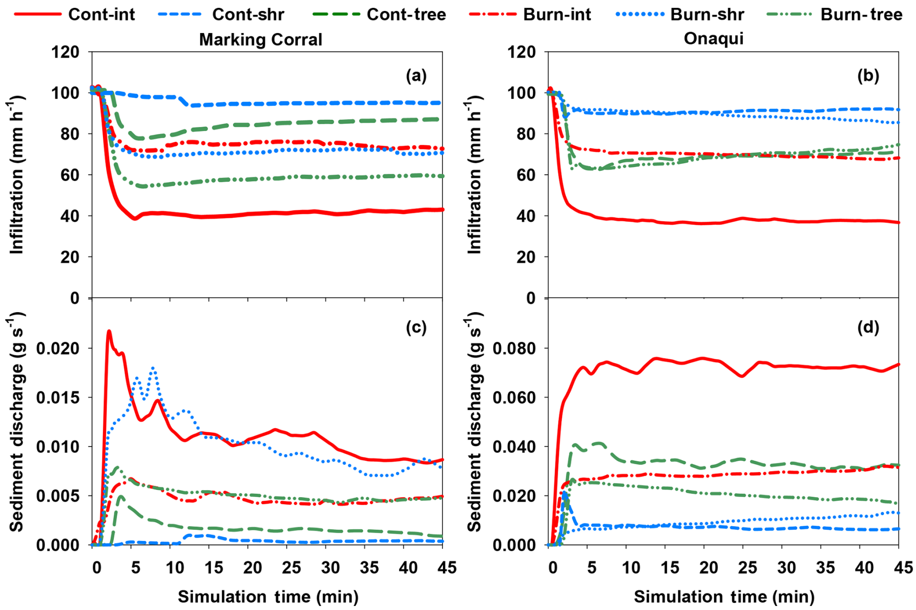

Figure 3. Example infiltration (**a**: Marking Corral; **b**: Onaqui), calculated as applied rainfall minus measured runoff, and sediment discharge (**c**: Marking Corral; **d**: Onaqui) time series data generated from a subset of the small-plot rainfall simulation dataset. Example subdataset is from wet-run rainfall simulations in untreated (cont) and burned (burn) interspace (int), shrub coppice (shr), and tree coppice (tree) microsites at the Marking Corral and Onaqui study sites 9 years following prescribed fire. The data illustrate the long-term impacts of burning and associated changes in surface conditions on infiltration and sediment discharge. Figure modified from Williams et al. (2020).

Rainfall was applied to small rainfall plots at approximate intensities of 64 mm h^{-1} (dry run) and 102 mm h^{-1} (wet run) for 45 min as explained in Pierson et al. (2010). The dry run was applied to dry antecedent soil conditions, and the wet run was applied to wet soil conditions, $\sim$ 30 min after the dry run. Rainfall was applied to small rainfall plots by a Meyer and Harmon-type portable oscillating-arm rainfall simulator fitted with 80–100 Veejet nozzles (Fig. 1a; Meyer and Harmon, 1979; Pierson et al. 2010, 2013, 2014; Williams et al., 2014a, 2019a, 2020). The applied rainfall kinetic energy (200 kJ ha^{-1} mm^{-1}) and raindrop size (2 mm) were within approximately 70 kJ ha^{-1} mm^{-1} and 1 mm respectively of values reported for natural convective rainfall (Meyer and Harmon, 1979). Rainfall amount applied to each plot during rainfall simulation was estimated by integrating a pan catch of a 5 min calibration run prior to each rainfall simulation plot run. Total rainfall amount was estimated on plots where debris and/or vegetation prevented placement of calibration pans. In such cases, the estimated rainfall amount was derived as the average of all calibration runs for the respective simulation date. Timed plot runoff samples were collected at 1–3 min intervals throughout each 45 min rainfall simulation and were subsequently analyzed in the laboratory for runoff volume and sediment concentration. Cumulative runoff and sediment amounts were obtained for each runoff sample by weighing the sample before and after drying at 105 °C (Pierson et al., 2010). Runoff samples were not filtered at any stage of laboratory processing. A mean runoff rate (mm h^{-1} and L min^{-1}) was derived for each sample interval as the interval runoff divided by the interval time. Sediment discharge (g s^{-1}) for each sample interval was calculated as the cumulative sediment for the sample interval divided by the interval time. Sediment concentration for each sample interval was obtained by dividing cumulative sediment by cumulative runoff (g L^{-1}). Some field samples were discarded from the final dataset because of laboratory errors or various issues noted on field data sheets (e.g., spillage and bottle overrun).

3.3 Large rainfall simulation plots and experiments

Vegetation and ground cover were measured on large rainfall simulation plots using line–point methods as described by Pierson et al. (2010) and Williams et al. (2014a). Foliar cover and ground cover on large rainfall plots were recorded for 59 points with 10 cm spacing along each of five transects (6 m long, spaced 40 cm apart) oriented perpendicular to the hillslope contour, with 295 sample points per plot. The percentage cover by each sampled cover type for each plot was derived as the number of point contacts or hits for each respective life-form divided by the total number of points sampled on the respective plot. Multiple canopy layers were allowed, and therefore total foliar cover across all sampled cover types potentially exceeded 100 %. Cut trees placed on a subset of rainfall simulation plots (see experimental design above) were excluded from foliar and ground cover measurements. However, various attributes of downed trees (e.g., length (height) and crown width) were measured

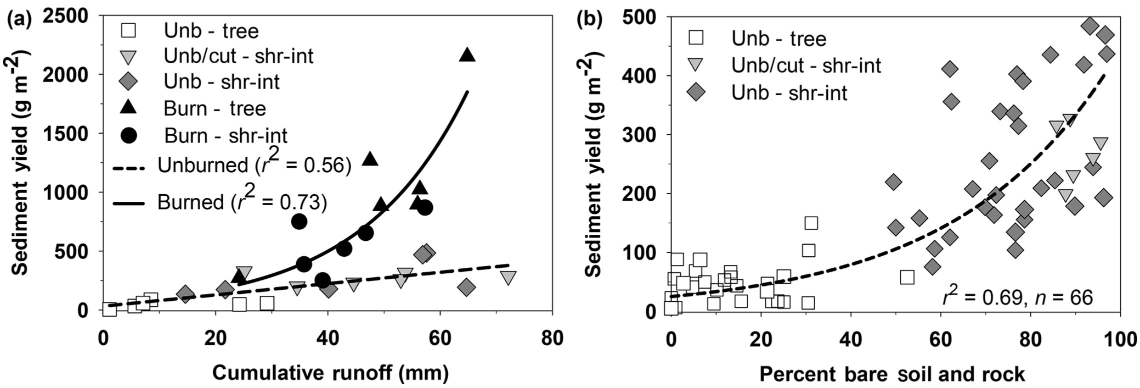

Figure 4. Example relationships/correlations in large rainfall plot cumulative runoff and sediment yield for unburned (untreated (unb) and cut (cut) treatments) and burned (burn) tree (tree) and intercanopy (shrub–interspace, shr-int) plots at the Castlehead site **(a)** and bare ground (bare soil plus rock cover) and sediment yield for unburned (unb) and cut treatment (cut) tree and intercanopy plots across all study sites (Castlehead, Marking Corral, and Onaqui) **(b)**. The relationship in runoff and sediment yield **(a)** demonstrates the initial (1 year) impact of burning on sediment availability and elevated sediment delivery (for tree coppices in this study) as commonly reported in fire studies (Pierson and Williams, 2016). The relationship in bare ground and sediment yield **(b)** shows the typical increase in sediment yield where bare ground exceeds 50 %–60 % as commonly reported for rangelands (Pierson et al., 2008, 2009; Williams et al., 2014b). Figures modified from Pierson et al. (2013) and Williams et al. (2014a).

and are reported. Ground surface roughness for each plot was calculated as the average of the standard deviations of ground surface heights measured across the line–point cover transects. The relative ground surface height at each sample point was calculated as the distance between a survey transit level line above the point and the ground surface. Distances in excess of 20 cm between plant canopies (canopy gaps) and plant bases (basal gaps) were measured along each of the line–point transects on each plot. Average canopy and basal gap sizes were calculated for each plot as the mean of all respective gaps measured in excess of 20 cm. Additionally, maximum canopy and basal gap sizes were calculated for each plot as the maximum of all respective gaps measured in excess of 20 cm. Percentages of canopy gaps and basal gaps representing 50 cm incremental gap classes (i.e., 51–100, 101–150 cm, etc.) were derived for each transect and averaged across the transects on each plot to determine gap-class plot means.

Rainfall was applied to pairs of large rainfall plots (Fig. 2a–b) at the same dry-run and wet-run target rates and sequence and durations as described above for small rainfall plots (Pierson et al., 2010; Williams et al., 2014a). Each paired rainfall simulation was run with a Colorado State University (CSU)-type rainfall simulator (Fig. 2a–b; Holland, 1969). The CSU-type design delivers rainfall energy at approximately 70 % of that for a natural convective rainfall event and produces rainfall drop diameters within approximately 1 mm of natural rainfall (Holland, 1969; Neff, 1979). The applied simulator design consists of seven stationary sprinklers evenly spaced along each of the outermost borders of the respective rainfall plot pair, with each sprinkler elevated 3.05 m above the ground surface. Total rainfall applied to large rainfall plots was quantified from the average of six plastic rainfall depth gages organized in a uniform grid within each plot. Runoff from direct rainfall on the large-plot collection troughs (trough catch, Fig. 2b) was quantified by sampling collection trough runoff before plot-generated runoff occurred. Once plot runoff occurred, timed samples of runoff were collected at 1–3 min intervals throughout each 45 min simulation run and were subsequently analyzed in the laboratory for runoff volume and sediment concentration as with small-plot rainfall simulation runoff samples. Sample weights were adjusted to appropriately account for trough catch, as described by Pierson et al. (2010). Some field samples were discarded from the final dataset because of laboratory errors or various issues noted on field data sheets (e.g., spillage and bottle overrun). Runoff and erosion rates were determined consistent with methods for small-plot rainfall simulations.

3.4 Overland-flow simulation plots and experiments

Vegetation and ground cover on overland-flow plots were measured using methods consistent with those on large rainfall simulation plots. For overland-flow plots that underwent rainfall simulation, foliar and ground cover measures were derived from the large rainfall plot line–point transect data but were restricted to the lower 4 m of the respective plots. Foliar and ground cover on overland-flow plots not subjected to rainfall simulations were recorded at 24 points with 20 cm spacing, along each of nine line–point transects (4.6 m in length, spaced 20 cm apart) oriented perpendicular to the hillslope contour, for a total of 216 points per plot. Percentage cover for each cover type sampled on each plot was derived from the number of point contacts or hits for each respective cover type divided by the total number of points

Table 4. Soil texture and bulk density variables and data structure for those measures for all study sites. Abbreviations in the table example are as follows: juniper_cop refers to juniper coppice microsites, shrub_cop refers to shrub coppice microsites, and pinyon_cop refers to pinyon coppice microsites.

Site	Microsite	Percent sand	Percent silt	Percent clay	Bulk density ($g\,cm^{-3}$)
Castlehead	interspace	50.4	43.7	5.9	1.04
Castlehead	juniper_cop	65.3	31.5	3.2	0.72
Castlehead	shrub_cop	61.8	34.6	3.6	0.76
Marking Corral	interspace	63.5	32.3	4.3	1.35
Marking Corral	juniper_cop	74.4	23.2	2.3	1.05
Marking Corral	pinyon_cop	68.4	28.3	3.4	1.1
Marking Corral	shrub_cop	59.9	35.4	4.7	1.14
Onaqui	interspace	57.4	36.2	6.5	1.07
Onaqui	juniper_cop	58.9	35.6	5.4	0.83
Onaqui	shrub_cop	56.2	36.9	6.9	1.02

Table 5. Example (subset) of vegetation and ground cover variables and data structure for measures on hillslope-scale site characterization plots (990 m^2) at the study sites. Abbreviations in the table example are as follows: Fol. Cvr. refers to foliar cover, and JUOC refers to western juniper (*Juniperus occidentalis* Hook.).

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Fol. Cvr. shrub (%)	Fol. Cvr. grass (%)	Fol. Cvr. forb (%)	–	Live shrubs (> 5 cm) per ha	Dead shrub (> 5 cm) per ha	JUOC trees (> 0.5 m) per ha	JUOC trees (5–50 cm) per ha
SC_CH_BURN1	Castlehead	2008	Burn	Yes	0	5.3	6.3	–	0	722	0	0
SC_CH_BURN2	Castlehead	2008	Burn	Yes	0	3.7	5.7	–	0	611	0	0
SC_CH_BURN3	Castlehead	2008	Burn	Yes	0	5	4	–	0	1389	0	0
SC_CH_UNB1	Castlehead	2008	Unburned	No	0	13.3	6.7	–	222	278	222	5.5
SC_CH_UNB2	Castlehead	2008	Unburned	No	4	26.3	6.7	–	1944	778	162	4.7
SC_CH_UNB3	Castlehead	2008	Unburned	No	14.7	12.3	6.3	–	4056	1944	121	4.2
SC_CH_BURN1	Castlehead	2009	Burn	Yes	0	22	17	–	56	278	0	0
SC_CH_BURN2	Castlehead	2009	Burn	Yes	0	12.7	25.3	–	111	2500	0	0
SC_CH_BURN3	Castlehead	2009	Burn	Yes	0	16.3	26.3	–	0	1833	0	0
SC_CH_UNB1	Castlehead	2009	Unburned	No	1	19.3	2	–	5278	2056	212	5.9
SC_CH_UNB2	Castlehead	2009	Unburned	No	14.7	46.3	7	–	722	56	111	6.2
SC_CH_UNB3	Castlehead	2009	Unburned	No	18.3	39	14.3	–	5667	2056	121	4.6
–	–	–	–	–	–	–	–	–	–	–	–	–
SC_ON_CUT1	Onaqui	2015	Cut	Yes	8.9	41.6	11.3	–	6389	0	0	0
SC_ON_CUT2	Onaqui	2015	Cut	Yes	21	21	7.1	–	10667	0	0	0
SC_ON_CUT3	Onaqui	2015	Cut	Yes	20.8	18.7	3.9	–	10611	0	0	0

sampled within the plot. As on large rainfall plots, total foliar cover across all cover types potentially exceeded 100 % given multiple canopy layers were allowed. Cut trees placed on a subset of overland-flow plots (see experimental design above) were excluded from foliar and ground cover measurements. However, various attributes of downed trees (e.g., length (height) and crown width) were measured and are reported. The ground surface roughness for each overland-flow plot was calculated as the average of the standard deviations of the ground surface heights across the foliar/ground cover line–point transects. The relative ground surface height at each cover sample point was calculated as the distance between a survey transit level line above the respective sample point and the ground surface. Canopy and basal gaps exceeding 20 cm on overland-flow plots were recorded along each line–point transect. Average and maximum canopy and basal gaps were derived consistent with methods for large rainfall simulation plots. Percentages of canopy and basal gaps representing 50 cm incremental gap classes (i.e., 51–100, 101–150 cm, etc.) were derived for each transect and averaged across the transects on each plot to determine gap-class plot means, similar to large rainfall plots.

Datalogger-controlled flow regulators (see Pierson et al., 2010, 2013, 2015; Williams et al., 2014a, 2019a, 2020) were used to apply concentrated flow release rates of 15, 30, and 45 $L\,min^{-1}$ to each overland-flow plot. Flow was routed into and through a metal box filled with Styrofoam pellets and was released through a 10 cm wide mesh-screened opening at the box base (Fig. 2d; see Pierson et al., 2010). Each flow release on each plot was applied for 12 min from a single release point located 4 m upslope of the collection trough apex. Flow release rate progression on each plot was consecutive from 15 to 30 to 45 $L\,min^{-1}$. Flow samples were collected at various time intervals (usually 1 to 2 min) for each

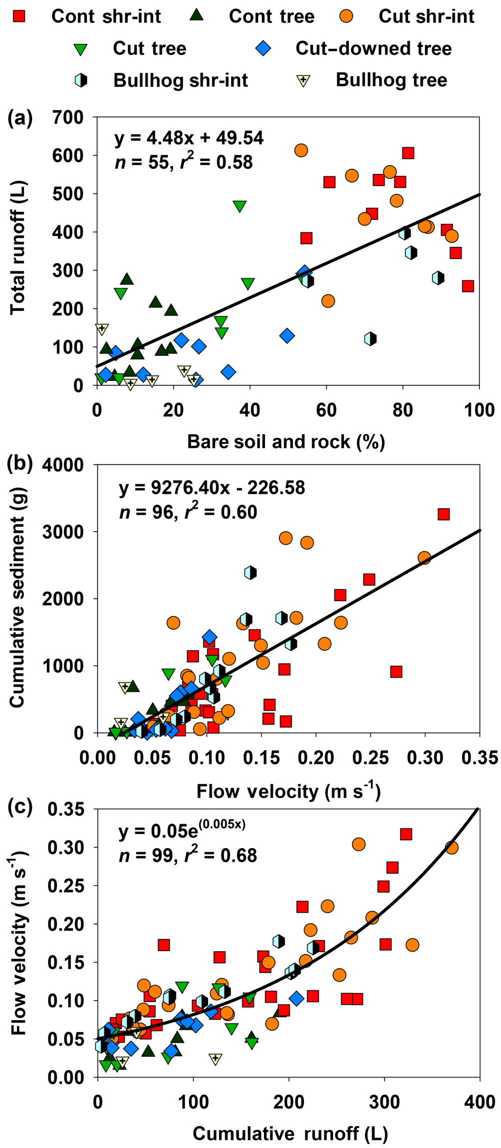

Figure 5. Example relationships/correlations in runoff and bare ground (bare soil plus rock cover) **(a)**, cumulative sediment and overland-flow velocity **(b)**, and overland-flow velocity and runoff **(c)** derived from a subset of the overland-flow dataset for the Marking Corral and Onaqui sites, as presented in Williams et al. (2019a). Data from overland-flow simulations on untreated/control (cont) plots, cut treatment (cut) plots without and with a cut, downed tree (cut–downed tree), and bullhog plots (bullhog, Onaqui site only) in tree (tree) and intercanopy (shrub–interspace, shr-int) microsites 9 years after respective tree-removal treatments. The data demonstrate that, for the studied conditions, runoff is largely regulated by bare ground, sediment delivery is controlled by flow velocity, and flow velocity is strongly correlated with the amount or runoff.

Table 6. Example (subset) of rainfall simulation, vegetation, ground cover, and soil variables and data structure for measures on small rainfall simulation plots (0.5 m^2) at the study sites. Abbreviations in the table example are as follows: Fol. Cvr. refers to foliar cover, Grd. Cvr. refers to ground cover, WDPT refers to water drop penetration time, shrub_cop refers to shrub coppice microsites, pinyon_cop refers to pinyon coppice microsites, and juniper_cop refers to juniper coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Applied rain dry run (mm)	Applied rain wet run (mm)	Slope (%)	Random roughness (mm)	–	Fol. Cvr. shrub (%)	Fol. Cvr. grass (%)	Grd. Cvr. bare soil (%)	Grd. Cvr. rock (%)	WDPT at 0 cm (s)	–
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	48	76	16.3	15	–	51.4	25.7	23.8	8.9	3	–
SP_MC_CONT82	Marking Corral	2006	Control	No	pinyon_cop	48	76	22.2	26	–	18.1	0	0	0	7	–
SP_MC_CONT83	Marking Corral	2006	Control	No	interspace	48	76	12.8	12	–	0	54.3	20.7	47.8	3	–
SP_MC_CONT84	Marking Corral	2006	Control	No	shrub_cop	48	77	12.8	29	–	78.1	19	13.6	4.9	3	–
SP_MC_CONT85	Marking Corral	2006	Control	No	interspace	48	76	20.7	12	–	0	34.3	38.1	30.9	3	–
SP_MC_CONT86	Marking Corral	2006	Control	No	pinyon_cop	47	76	13.6	15	–	0	2.9	0	0	3	–
SP_MC_CONT87	Marking Corral	2006	Control	No	interspace	44	77	9.6	14	–	4.8	35.2	48.9	13	3	–
SP_MC_CONT88	Marking Corral	2006	Control	No	shrub_cop	45	76	11.2	22	–	61.9	18.1	17	3.4	3	–
SP_MC_CONT89	Marking Corral	2006	Control	No	juniper_cop	48	78	9.9	10	–	0	1.9	0	0	38	–
SP_MC_CONT90	Marking Corral	2006	Control	No	juniper_cop	48	78	17.5	12	–	0	26.7	0	1	51	–
SP_MC_CUT91	Marking Corral	2006	Cut	No	interspace	48	78	9.5	4	–	0	0	37.1	61.9	3	–
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SP_ON_CONT78	Onaqui	2015	Control	No	shrub_cop	46	74	18.1	17	–	42.9	8.6	14.4	27.8	30	–
SP_ON_CONT79	Onaqui	2015	Control	No	interspace	46	74	19.2	13	–	0	7.6	24.1	59.5	3	–
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	47	75	17.5	19	–	72.4	12.4	31.6	16.8	3	–

Table 7. Example (subset) of rainfall simulation, vegetation, ground cover, and soil variables and data structure for measures on large rainfall simulation plots (13 m^2) at the study sites. Abbreviations in the table example are as follows: Fol. Cvr. refers to foliar cover, Grd. Cvr. refers to ground cover, Avg. refers to average, juniper_cop refers to juniper coppice microsites, and pinyon_cop refers to pinyon coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Applied rain dry run (mm)	Applied rain wet run (mm)	Slope (%)	Random roughness (mm)	–	Fol. Cvr. shrub (%)	Fol. Cvr. grass (%)	Grd. Cvr. bare soil (%)	Grd. Cvr. rock (%)	Avg. canopy gap (cm)	Avg. basal gap (cm)
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	39	65	11.1	19	–	9.2	8.8	16.3	6.1	100	164
LP_MC_CUT38	Marking Corral	2006	Cut	No	juniper_cop	47	87	12.2	19	–	7.5	8.8	5.4	2	77	157
LP_MC_CUT39	Marking Corral	2006	Cut	No	intercanopy	37	63	10.4	18	–	29.8	18	44.1	5.4	83	121
LP_MC_CUT40	Marking Corral	2006	Cut	No	intercanopy	50	96	9.6	14	–	11.5	8.8	28.1	49.2	59	94
LP_MC_CUT41	Marking Corral	2006	Cut	No	intercanopy	40	67	8.8	18	–	21.4	13.9	27.2	22.8	76	125
LP_MC_CUT42	Marking Corral	2006	Cut	No	intercanopy	46	88	9.5	15	–	18.6	19.7	24.1	31.2	86	131
LP_MC_CUT43	Marking Corral	2006	Cut	No	pinyon_cop	39	72	9.3	20	–	0.3	3.4	0	0.7	428	499
LP_MC_CUT44	Marking Corral	2006	Cut	No	pinyon_cop	50	93	8.1	18	–	0.7	1.7	0	1	427	435
LP_MC_CUT45	Marking Corral	2006	Cut	No	pinyon_cop	46	94	9.1	15	–	10.8	4.4	0	1.4	113	168
LP_MC_CUT46	Marking Corral	2006	Cut	No	pinyon_cop	47	83	13	21	–	9.8	8.5	1	3.7	127	243
LP_MC_CUT47	Marking Corral	2006	Cut	No	intercanopy	41	80	12.1	25	–	26.9	19.4	32.9	29.5	69	110
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
LP_CH_BURN28	Castlehead	2008	Burn	Yes	juniper_cop	43	77	15.2	12	–	0	3.7	33.6	50.2	43	101
LP_CH_BURN29	Castlehead	2008	Burn	Yes	intercanopy	48	87	14.8	22	–	0	5.8	54.2	44.7	36	56
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	42	83	14.7	17	–	0	6.8	33.6	54.2	31	42

Table 8. Example (subset) of overland-flow, vegetation, and ground cover variables and data structure for measures on overland-flow simulation plots ($\sim 9\,m^2$) at the study sites. Abbreviations in the table example are as follows: Avg. refers to average, juniper_cop refers to juniper coppice microsites, and pinyon_cop refers to pinyon coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Avg. width 15 L min^{-1} at 3 m (cm)	Avg. width 30 L min^{-1} at 3 m (cm)	Avg. width 45 L min^{-1} at 3 m (cm)	–	Avg. velocity 15 L min^{-1} ($m\,s^{-1}$)	Avg. velocity 30 L min^{-1} ($m\,s^{-1}$)	Avg. velocity 45 L min^{-1} ($m\,s^{-1}$)	Avg. canopy gap (cm)	Avg. basal gap (cm)
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	2	10	28	–	−999	0.029	0.036	67	92
RI_MC_CUT38	Marking Corral	2006	Cut	No	juniper_cop	0	30	32	–	0	−999	0.058	78	156
RI_MC_CUT39	Marking Corral	2006	Cut	No	intercanopy	42	33	43	–	0.07	0.122	0.148	70	93
RI_MC_CUT40	Marking Corral	2006	Cut	No	intercanopy	50	38	53	–	0.085	0.127	0.131	55	100
RI_MC_CUT41	Marking Corral	2006	Cut	No	intercanopy	37	61	59	–	0.028	0.067	0.107	59	106
RI_MC_CUT42	Marking Corral	2006	Cut	No	intercanopy	47	61	52	–	0.05	0.066	0.1	86	109
RI_MC_CUT43	Marking Corral	2006	Cut	No	pinyon_cop	0	52	102	–	0	−999	0.038	333	333
RI_MC_CUT44	Marking Corral	2006	Cut	No	pinyon_cop	0	−999	−999	–	0	−999	−999	284	292
RI_MC_CUT45	Marking Corral	2006	Cut	No	pinyon_cop	0	0	−999	–	0	0	−999	131	172
RI_MC_CUT46	Marking Corral	2006	Cut	No	pinyon_cop	0	24	32	–	0	0.033	0.044	88	175
RI_MC_CUT47	Marking Corral	2006	Cut	No	intercanopy	64	64	52	–	0.062	0.098	0.127	79	85
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RI_ON_CUT131	Onaqui	2015	Cut	Yes	intercanopy	144	148	158	–	0.051	0.084	0.182	46	46
RI_ON_CUT133	Onaqui	2015	Cut	Yes	intercanopy	0	165	82	–	0	0.054	0.073	65	34
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	0	29	36	–	0	0.062	0.086	48	58

12 min simulation at each release rate. As with rainfall simulation samples, runoff samples were taken to the laboratory, weighed, oven-dried at 105 °C, and then reweighed to determine the runoff rate and sediment concentration. Also as noted above for rainfall simulation runoff samples, a small number of runoff samples were discarded because of laboratory errors or various issues noted on field data sheets (e.g., spillage and bottle overrun). Runoff and sediment variables for each flow release rate were calculated for an 8 min time period starting at runoff initiation. The resulting 8 min runoff and sediment variables were derived as explained for the 45 min rainfall simulations. The velocity of overland flow was measured using a concentrated salt tracer applied into the flow and electrical conductivity probes to track the mean transit time of the tracer over a set flow path length (usually 2 m; Pierson et al., 2010, 2013, 2015; Williams et al., 2014a, 2019a, 2020). The width, depth, and a total rill area width (TRAW) of overland flow were measured along flow cross sections 1, 2, and 3 m downslope from the flow release point (Pierson et al., 2010). The TRAW variable represents the total width between the outermost edges of the outermost flow paths at the respective cross section (see Pierson et al., 2008). Overland-flow simulations conducted on large rainfall simulation plots at Marking Corral and Onaqui in 2006 and 2007 and at Castlehead in 2008 were run approximately 2 h after respective rainfall simulations. Overland-flow simulations on plots not subjected to rainfall simulation at Marking Corral and Onaqui in 2008 and 2015 and at Castlehead in 2008 were conducted on soils prewet with a gently misting sprinkler (see Pierson et al., 2013, 2015; Williams et al., 2014a, 2019a, 2020).

4 Data application

Subsets of the dataset have been used to improve understanding of rangeland hydrologic and erosion processes, assess the ecohydrologic impacts of wildland fire and management practices on sagebrush rangelands, and improve and enhance rangeland hydrology and erosion models. Examples of data use for such applications are presented in Figs. 3–5. Pierson et al. (2010) applied pretreatment data across all plot scales and experiment types from Marking Corral and Onaqui to evaluate the ecohydrologic impacts of woodland encroachment on sagebrush rangelands. Studies by Pierson et al. (2014, 2015) assessed the initial (first and second year) effects of prescribed fire and mechanical tree-removal treatments on vegetation, ground cover, and hydrology and erosion processes at Marking Corral and Onaqui. Williams et al. (2014a) applied vegetation, ground cover, rainfall simulation, and overland-flow experiments from unburned and burned areas at Castlehead to evaluate the utility of fire to reverse the negative ecohydrologic impacts of juniper encroachment on rangelands and to frame conceptual concepts on process connectivity for burned and degraded rangelands

Table 9. Example (subset) of time series runoff and sediment data from small-plot rainfall simulations (0.5 m^2) at the study sites. Abbreviations in the table example are as follows: Conc. refers to concentration, and shrub_cop refers to shrub coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Run type	Runoff (yes or no)	Rainfall rate (mm h^{-1})	Runoff start time (mm:ss)	Simulation time (mm:ss)	Sample fill time (s)	Runoff (L min^{-1})	Sediment conc. (g L^{-1})	Runoff (mm h^{-1})	Sediment discharge (g s^{-1})
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Dry_run	No	64		00:00	0	0.000	0.00	0.000	0.0000
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Dry_run	No	64		44:00	0	0.000	0.00	0.000	0.0000
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	00:00	0	0.000	0.00	0.000	0.0000
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	05:10	0	0.000	0.00	0.000	0.0000
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	05:36	49	0.096	0.38	11.520	0.0006
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	06:30	60	0.095	0.10	11.436	0.0002
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	07:30	60	0.080	0.13	9.552	0.0002
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	08:30	60	0.074	0.00	8.840	0.0000
SP_MC_CONT81	Marking Corral	2006	Control	No	shrub_cop	Wet_run	Yes	102	05:11	09:30	60	0.068	0.30	8.110	0.0003
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	Wet_run	Yes	100	01:50	26:00	120	0.075	6.42	8.968	0.0080
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	Wet_run	Yes	100	01:50	29:00	120	0.077	6.29	9.250	0.0081
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	Wet_run	Yes	100	01:50	32:00	120	0.073	6.58	8.751	0.0080
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	Wet_run	Yes	100	01:50	35:00	120	0.065	6.55	7.783	0.0071
SP_ON_CONT80	Onaqui	2015	Control	No	shrub_cop	Wet_run	Yes	100	01:50	41:00	120	0.067	6.50	8.026	0.0073

Table 10. Example (subset) of time series runoff and sediment data from large-plot rainfall simulations (13 m^2) at the study sites. Abbreviations in the table example are as follows: Conc. refers to concentration, and juniper_cop refers to juniper coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Downed–cut tree (yes or no)	Run type	Rainfall rate (mm h^{-1})	Runoff start time (mm:ss)	Simulation time (mm:ss)	Sample fill time (s)	Runoff ($L\,min^{-1}$)	Sediment conc. ($g\,L^{-1}$)	Runoff ($mm\,h^{-1}$)	Sediment discharge ($g\,s^{-1}$)
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	00:00	0	0	0	0	0
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	08:14	0	0	0	0	0
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	09:05	20	0.294	19.08	1.357	0.094
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	10:08	15	0.464	14.56	2.142	0.113
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	12:08	15	0.627	8.74	2.894	0.091
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	14:08	16	0.476	11.11	2.196	0.088
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	16:08	15	0.625	10.69	2.883	0.111
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	18:08	15	0.554	10.47	2.556	0.097
LP_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	No	Dry_run	52	08:15	20:08	15	0.609	12.21	2.812	0.124
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	No	Wet_run	110	01:09	30:08	15	15.647	4.68	72.216	1.22
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	No	Wet_run	110	01:09	33:08	15	13.819	4.41	63.781	1.015
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	No	Wet_run	110	01:09	36:08	15	14.198	5.78	65.529	1.368
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	No	Wet_run	110	01:09	39:08	15	16.666	5.65	76.919	1.569
LP_CH_BURN30	Castlehead	2008	Burn	Yes	intercanopy	No	Wet_run	110	01:09	42:08	15	14.282	5.48	65.915	1.305

Table 11. Example (subset) of time series runoff and sediment data from overland-flow simulations ($\sim 9\,m^2$) at the study sites. Abbreviations in the table example are as follows: Conc. refers to concentration, and juniper_cop refers to juniper coppice microsites.

Plot ID	Site	Year	Treatment area	Treated (yes or no)	Microsite	Plot bordered all sides (yes or no)	Runoff 15 $L\,min^{-1}$ (yes or no)	Runoff 30 $L\,min^{-1}$ (yes or no)	Runoff 45 $L\,min^{-1}$ (yes or no)	Applied overland flow rate ($L\,min^{-1}$)	Simulation time (mm:ss)	Sample fill time (s)	Runoff ($L\,min^{-1}$)	Sediment conc. ($g\,L^{-1}$)
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	00:00	30	0.181	13.49
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	00:41	15	0.47	1.62
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	01:11	15	0.628	0.7
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	02:31	15	1.265	0.66
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	03:06	15	1.662	1.04
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	15	03:41	15	1.976	0.2
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	30	00:00	15	11.181	15.97
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	30	00:45	15	14.551	0.61
RI_MC_CUT37	Marking Corral	2006	Cut	No	juniper_cop	Yes	Yes	Yes	Yes	30	02:40	15	18.795	0.29
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	No	No	Yes	Yes	45	04:05	20	14.5	5.51
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	No	No	Yes	Yes	45	04:55	20	15.215	5.56
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	No	No	Yes	Yes	45	05:45	20	15.694	5.49
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	No	No	Yes	Yes	45	08:35	20	17.426	5.41
RI_ON_CUT134	Onaqui	2015	Cut	Yes	intercanopy	No	No	Yes	Yes	45	10:35	20	18.678	5.44

(Fig. 4). Pierson et al. (2013, 2015) evaluated the immediate effects of cut–downed trees on runoff and erosion processes on woodlands. Williams et al. (2019a, 2019b, 2020) applied data from all experimental plot scales and methods in untreated and treated areas at Marking Corral and Onaqui to evaluate the long-term ecohydrologic impacts of prescribed fire and mechanical tree-removal treatments on woodland-encroached sagebrush steppe (Table 3, Fig. 5). Al-Hamdan et al. (2012a, 2012b, 2013, 2015, 2017) applied subsets of the data to develop, test, and enhance various parameter estimation equations for flow hydraulics and erodibility parameters in the Rangeland Hydrology and Erosion Model (RHEM). Collectively, these studies have improved understanding of rangeland hydrology and erosion processes and informed both conceptual and quantitative models applicable to assessment and management of diverse rangelands (McIver et al., 2014; Pierson and Williams, 2016; Williams et al., 2016a, 2016b, 2016c, 2018; Hernandez et al., 2017).

5 Data availability

The full dataset is available from the US Department of Agriculture National Agricultural Library website at https://data.nal.usda.gov/search/type/dataset (last access: 7 May 2020) (doi: https://doi.org/10.15482/USDA.ADC/1504518; Pierson et al., 2019). The suite of files therein includes an abbreviated description and field methods; a data dictionary; geographic information for study sites; photographs of the study sites, field experiments, and experimental plots; and data files for vegetation, ground cover, soils, and hydrology and erosion time series measures spanning the associated plots scales. Subset examples of the data files are shown in Tables 4 (site level soil particle size and bulk density), 5 (site characterization plots), 6 (small rainfall plot attributes), 7 (large rainfall plot attributes), 8 (overland-flow plot attributes), 9 (small-plot rainfall simulation time series), 10 (large-plot rainfall simulation time series), and 11 (overland-flow simulation time series). Time series runoff and sediment data provided for rainfall simulations and overland-flow experiments do not account for carryover effects from one plot run to the next on a given plot in a given year (i.e., dry-run effects on wet-run simulations; effects of 15 $L\,min^{-1}$ overland flow releases on subsequent 30–45 $L\,min^{-1}$ overland flow releases). Data users should consider whether carryover effects impact respective applications and make applicable adjustments to acquired data.

6 Summary and conclusions

Rangelands are uniquely managed using ecological principles. As such, our functional understanding of regulating ecohydrologic processes, such as soil conservation and runoff moderation, is limited by our ability to track these processes in the context of interdependent land management decisions. Pinyon–juniper encroachment into sagebrush shrublands and the resulting management actions provide a model system for observing hydrologic processes under disturbances and interventions typical of extensively managed rangelands. To provide detailed understanding of ecohydrologic processes under realistic management conditions, we collected long-term data at multiple sites, spatial scales, and treatments. The combined dataset includes 1021 experimental plots and contains vegetation, ground cover, soils, hydrology, and erosion data spanning multiple spatial scales and diverse vegetation, ground cover, and surface soil conditions from three study sites and five different study years. The dataset includes 57 hillslope-scale vegetation plots (site characterization), 528 small rainfall simulation plots, 146 large rainfall simulation plots, and 290 overland-flow simulation plots. The hydrology and erosion experiments provide time series data for small rainfall plot, large rainfall plot, and overland-flow plot simulations. After excluding some time series rainfall and overland-flow simulation data due to various lab and equipment failures, the final time series dataset contains 1020 small rainfall, 280 large rainfall, and 838 overland-flow plot-run hydrographs and sedigraphs if plots without runoff are retained. Retaining only plots that generated runoff results in a time series dataset of 749 small rainfall, 251 large rainfall, and 719 overland-flow plot simulation hydrographs and sedigraphs. Overall, the hydrology and erosion time series dataset totals to 2138 hydrographs/sedigraphs including plots with no runoff and 1719 hydrographs/sedigraphs for plots that generated runoff. The methodology employed and resulting experimental data improve understanding of and provide quantification of separate scale-dependent (e.g., rain splash and sheet flow) and combined (e.g., interrill and concentrated flow/rill) surface hydrology and erosion processes for sagebrush rangelands and pinyon and juniper woodlands in the Great Basin before and after tree removal and for sparsely vegetated sites elsewhere. This separate and combined experimental approach yields a valuable data source for testing and improving isolated process parameterizations in quantitative hydrology and erosion models. The long-term nature of the dataset is unique and provides a substantial database for populating conceptual ecological models of changes in vegetation, ground cover conditions, and surface soils resulting from management practices and disturbances. Likewise, the combined data on short-term and long-term ecohydrologic impacts of management practices and fire provide valuable insight on trends in ecohydrologic recovery of rangeland ecosystems.

Author contributions. FBP, CJW, PRK, and OZA-H participated in the experimental design, data collection and reduction, and compilation of the dataset and manuscript. JCJ contributed to data reduction and compilation of the dataset and manuscript. All authors contributed to revisions of the submitted manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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